RECONSTRUCTION OF 3^D SHAPE FROM SIDESCAN SONAR IMAGES USING SHAPE FROM SHADING TECHNIQUE

MAREK MOSZYŃSKI, KRZYSZTOF BIKONIS, ZBIGNIEW ŁUBNIEWSKI

Gdansk University of Technology, Department of Geoinformatics
Narutowicza 11/12, 80-233 Gdansk, Poland
lubniew@eti.pg.gda.pl

Side scan sonar (SSS) is one of the most widely used imaging systems in the underwater environment. It is relatively cheap and easy to deploy in comparison with more powerful sensors like multibeam echosounder or synthetic aperture sonar. Although, the SSS does not provide directly the seafloor bathymetry measurements. Its outputs are usually in a form of grey level acoustic images of seafloor. However, the analysis of such images performed by human eye allows creating semi-spatial impressions on seafloor relief and morphology.

The 3^D shape reconstruction from 2^D images using SFS approach is one of classical problems in computer vision. In the paper, the method based on Shape From Shading (SFS) technique for SSS images processing is presented. The 3^D seafloor relief is reconstructed using the information from both the currently processed and previous ping. The seafloor backscattering coefficient dependence on an incident angle, which is needed in the applied SFS algorithm scheme, is being estimated in the experimental way, i.e. by analysis of SSS image contents for the flat seabed region.

INTRODUCTION

3^D acoustic imaging of the seafloor has become increasingly important for different underwater engineering activities such as pipeline tracking, wreck inspection, mine hunting and seafloor monitoring and characterisation. At present, acoustic sensors offer the most reliable sight inside underwater environments for these purposes. They are characterised by longer range and wider angle coverage compared to video cameras or other sensors. Also, they are capable of providing satisfactory results of mapping the environment in turbid waters.

SSS is one of the most widely used imaging systems in underwater environment. It is relatively cheap and easy to deploy, in comparison with more powerful sensors like multibeam sonar or synthetic aperture sonar. However, it has some limitations, such as its inability to recover the seafloor depth or submerged object information directly. Most of very attractive images of seafloor and wrecks represents acoustic data obtained by modern multibeam sonars, which allow for their direct 3^D visualization [1]. However, many SSS 2^D images exist, that could be transformed into 3^D representation in an algorithmic way using the echo intensity information contained in grayscale images.

In the imaging sonar systems, the characteristics of acoustic energy backscattering by a target localised on seafloor is utilised. Some authors suggest that Lambert's Law provides a good fit to seabed backscattering dependence on an incident angle [2]. However, the authors propose their own approach to derive this dependence locally from experimental data.

In this paper, the method for 3^D seafloor shape reconstruction from SSS images, based on SFS approach, is presented. For estimation of bottom local depth at a given pixel of sonar image, the information from both currently processed and previous ping is utilised. It allows the local seabed surface element orientation to have two degrees of freedom. The local altitude gradient is estimated by SFS algorithm with use of the backscattering coefficient angular dependence function derived experimentally.

1. EXCERPT FROM THEORY OF SHAPE FROM SHADING

Several techniques of 3^D geometry reconstruction for seabed surface or submerged objects using side-scan sonar images has been reported [3, 4, 5]. Mainly, they use the techniques based on the problem inverse to image formation, namely Shape from Shading (SFS), which is one of classical problems in computer vision (see [6] for a collection of significant papers on SFS). The goal is to derive a 3^D scene description from one or more 2^D images. The recovered shape can be expressed in several ways: as depth $z(x, y)$, or with respect to the surface normal, surface gradient, and surface slant and tilt. The depth can be considered either as the relative distance from camera to surface points, or the relative surface height above the X-Y plane. The surface normal is the orientation of a vector perpendicular to the tangent plane for a given point on the object surface.

To solve the SFS problem, it is important to study how the images are formed. A simple model of image formation is the Lambertian model [6], in which the gray level at a pixel in the image depends on the light source direction and the surface normal. In SFS, given a grey level image, the aim is to recover the light source and the surface shape at each pixel of the image. However, real images do not always follow the Lambertian model. But even if we assume the Lambertian reflectance model and the known light source location, the problem is still not simple. This is because that if the surface shape is described in terms of the surface normal, we have a linear equation with three unknowns. And, if the surface shape is described in terms of the surface gradient, we have a non-linear equation with two unknowns. Therefore, finding a unique solution to SFS is difficult and it requires additional constraints.

Generally, the SFS techniques are divided into four groups: minimization, propagation, local and linear methods [6]. Minimization approaches share the feature of minimizing an energy function. The earliest techniques include Ikeuchi and Horn [7], Brooks and Horn [8], and Frankot and Chellapa [9]. Seven other techniques were also reviewed in this category. Since there are two unknowns for the surface gradient at each pixel, and only one value (the intensity) is known, the problem is underdetermined. Constraints need to be introduced, which are expressed as energy functions. The most common constraint is the brightness constraint which requires that the reconstructed pixel intensity matches the true pixel intensity. Other constraints include the smoothness constraint, integrability constraint, and intensity gradient constraint. Constraints can be used in combination in attempt to achieve the best results.

Propagation is the first SFS technique, which was proposed by Horn [6]. The main idea behind a propagation technique is that it starts estimating geometry from a given location in the image, and then the shape information is propagated to areas around the initial location. Horn uses ”characteristic strips” which, starting from a singular point, are expanded over the image.

Local approaches assume that the shape is locally spherical at any point. The two primary papers in this group are by Pentland [10] and Lee and Rosenfeld [11]. They use first and second derivatives of the intensity as input.

The key characteristic for linear approaches is that they linearise the reflectance map and then solve for the geometry. This is based on the assumption that the lower order components of the reflectance map dominate. The two approaches may be mentioned here, namely, Pentland’s technique from 1988 and Tsai & Shah’s algorithm from 1992.

2. APPLICATION OF SFS FOR SIDE SCAN SONAR IMAGE

Seafloor relief reconstruction from sonar image

In the construction of a seabed elevation map from side scan images, the SFS technique relays on calculating the local slope of bottom relief, given the image pixel intensity, the assumed dependence of bottom surface backscattering coefficient on incident angle (what corresponds to reflectance map in classical SFS), and the estimated local incident angle value. The following assumptions were made for the development of the algorithm for 3^D seafloor relief reconstruction [12]:

1. Straight line propagation path of acoustic wave in water column.
2. Reflectivity model is known.
3. Altitude *H* of the sonar transducer is known.
4. The local surface element orientation has two degrees of freedom.
5. The dimensions along vertical axis (*Z*) of an object to be reconstructed are small in comparison with the sonar transducer altitude.
6. The intensity (grey level) of a pixel in sonar image is proportional to the acoustical intensity of backscattered echo.

The geometry used in derivation of the reconstruction algorithm is presented in Fig. 1. The beam of a side scan sonar covers an angular sector from φ_{min} to φ_{max}.

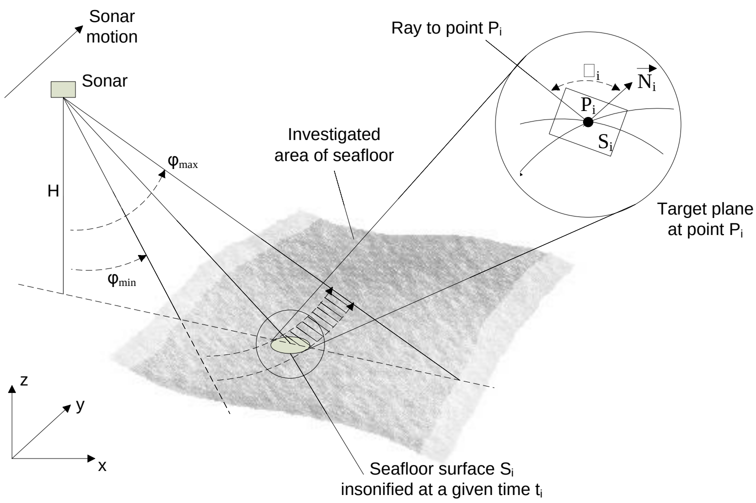

Fig.1. The geometry used in derivation of the seafloor relief reconstruction algorithm.

The relation between the time instant t_i in an echo envelope and the across-track coordinate x_i of a corresponding point P_i on seabed surface, may be expressed by

$$x_i = \sqrt{\left(\frac{ct_i}{2}\right)^2 - H^2} \tag{1}$$

where $t_i \geq \frac{2H}{c}$, c – sound speed in water.

At the time instant t_i, the seafloor surface S_i is insonified, the area of which may be for a flat bottom case expressed by the classical equation [2]:

$$S_i = \theta_V R_i \frac{c\tau}{2\sin\theta_i} \tag{2}$$

where Θ_V – the along tract transducer beamwidth, R_i – the range from the transducer to the point P_i, τ – the transmitted pulse length.

The 3^D bottom relief was reconstructed by estimation of an altitude $z(x, y)$ sequentially for consecutive discrete points (x, y) on a plane, using the scheme depicted in Fig. 2.

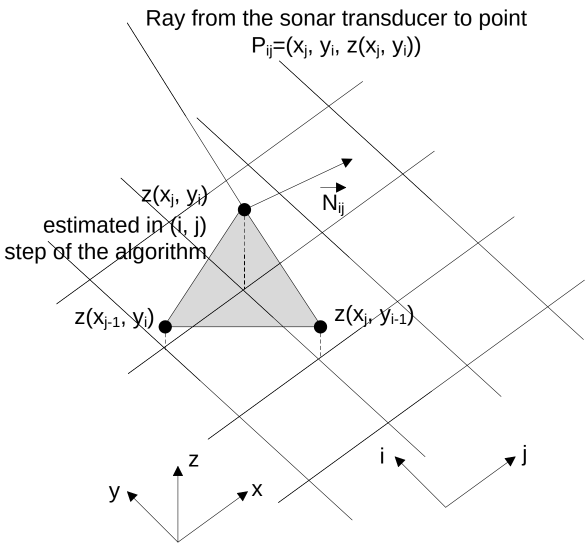

Fig.2. The estimation of the bottom altitude $z(x_j, y_i)$ from altitudes obtained in previous iterations $z(x_j\text{-}1, yi)$ and $z(xj, y_i\text{-}1)$.

For the (i, j) iteration (where i – number of processed line in the sonar image corresponding to one sonar ping, j – number of pixel belonging to this line), i.e. the point $P_{ij} = (x_j, y_i, z(x_j, y_i))$ altitude estimation, the local triangle facet was being taken into account, with vertices at two previously estimated points $P_{i-1\,j} = (x_j, y_{i-1}, z(x_j, y_{i-1}))$ and $P_{i\,j-1} = (x_{j-1}, y_i, z(x_{j-1}, y_i))$, and currently estimated point P_{ij}. Using the applied model, the value chosen for z_{ij} allows for calculation of normal $\overrightarrow{N_i}$ to the surface facet, the angle Θ_i and the local intensity I_i value, which then many be compared with that from the original sonar image. The analytical form of the expression for optimal z_{ij}, i.e. that giving I equal to a measured value, is impossible to obtain in a general case. On the other hand, it may be shown that in the applied model, $I_i(z)$ is a monotonic function of z variable within the range $[z_{ijmin}, z_{ijmax}]$, where z_{ijmin} corresponds to $\Theta_{ijmin} = 0°$ and z_{ijmax} to $\Theta_{ijmax} = 90°$. Therefore, the simple binary (bisection) algorithm, starting from initial $[z_{ijmin}, z_{ijmax}]$ searched interval, was used for z_{ij} estimation. It was the iterated algorithm which in k-th iteration proposed the new z_{ijkmid} as the midpoint of the current [z_{ijkmin}, z_{ijkmax}] interval, and then appropriately reduced the interval to its left or right half. Namely, if an echo intensity I calculated for z_{ijkmid} was less than intensity taken from the currently processed pixel of sonar image, the left half was chosen for the consecutive iteration, otherwise the right half was chosen.

Experimental estimation of seafloor backscattering coefficient dependence on an incident angle

As it was stated in the previous section, the reliable reflectance model (namely, here: the seafloor acoustic backscattering coefficient dependence on an incident angle) is a crucial element of the SFS-like 3^D object reconstruction procedure. Some authors suggest that the Lambert's Law provides a good fit to seabed backscattering dependence on an incident angle [2], but in general, the description of seafloor backscattering phenomenon is complicated. The backscatter from the seafloor is generally considered to be composed of a combination of surface and volume scattering, i.e. roughness interface scattering and scattering from inhomogeneities within the sediment volume. The detailed investigation of seafloor backscattering angular dependence, containing the theoretical modelling along with experimental verification, is described in [13]. It shows that although in several cases the application of Lambert Law might be allowed, in many others this law is not satisfied. This fact was also proved by further experiments. Taking it into account, the authors proposed their own approach here, which assumes the estimation of backscattering angular dependence coefficient locally for currently used experimental data. Let us assume that we may choose the region within the processed sonar image, where:

- the seabed surface is flat,
- the seabed surface material is the same for the whole chosen area.

Then (using also the assumptions from the previous subsection) we may state that the grey level of a given pixel in an analysed area should depend only on the experiment geometry (e.g. position of the source, the incident angle), the sonar calibration data, and the seafloor backscattering coefficient. If the investigated area covers some range of incident angle values, the backscattering coefficient angular dependence may be estimated for this range using pixel grey level values.

Sample results of this procedure are shown in Fig. 3 (see next section for the description of experimental data). The blue points corresponding to particular pixels have been plotted in (Θ_i, I_s/I_{os}) locations (the backscattered wave intensity I_s from a unit seabed surface area is normalized to incident wave intensity I_{os}). The Θ_i angle between the ray to point P_i on seafloor surface and normal to a plane tangent to surface at P_i does not need to be defined in vertical plane XOZ. The estimated angular dependence of backscattering coefficient has been shown by the red line.

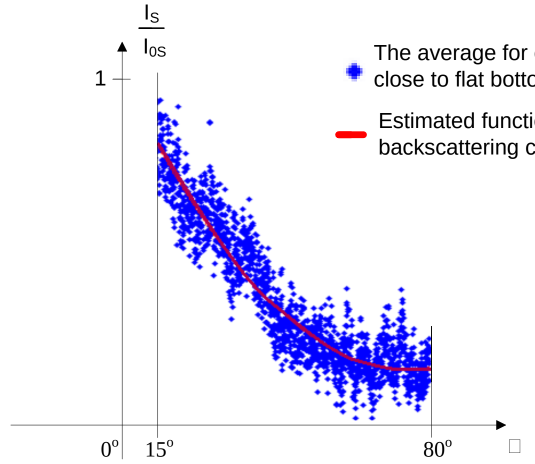

Fig.3. The estimated angular dependence of surface backscattering coefficient.

3. EXPERIMENTS AND RESULTS

The developed procedure of 3D seafloor relief reconstruction was tested on DF1000 dual frequency (100 and 500 kHz) side scan sonar data collected on the Gulf of Gdansk. For further processing the 500 kHz data were used as they represent the higher resolution entity. The specific areas was selected for calculation of seabed backscattering coefficient angular dependence as presented in Fig. 4.

The seabed backscattering coefficient angular dependence estimation results have been shown in Fig. 3 in the previous section.

The results of 3D seabed surface reconstruction are presented in Fig. 5 including the data marked in Fig. 4.

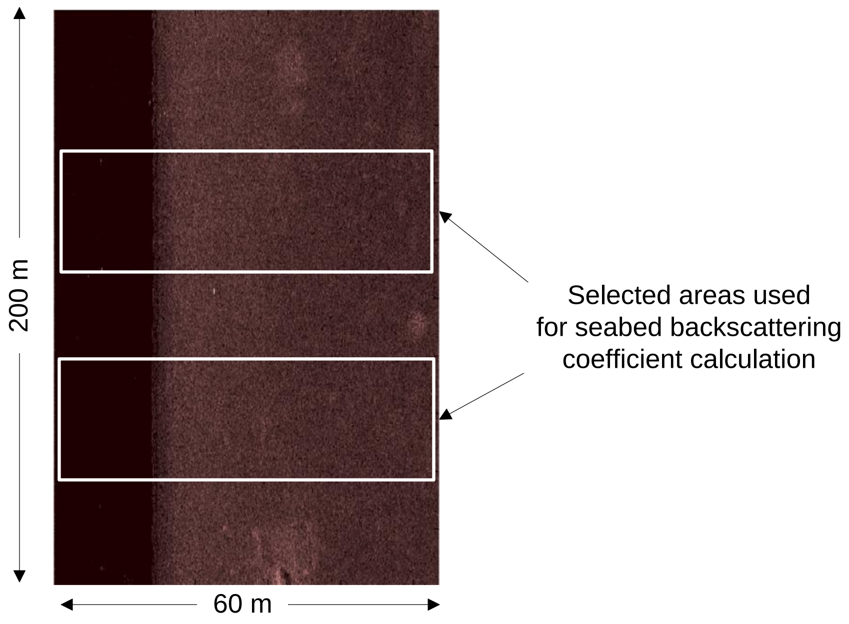

Fig.4. The sample seabed image with selected areas used for seabed backscattering calculation [14].

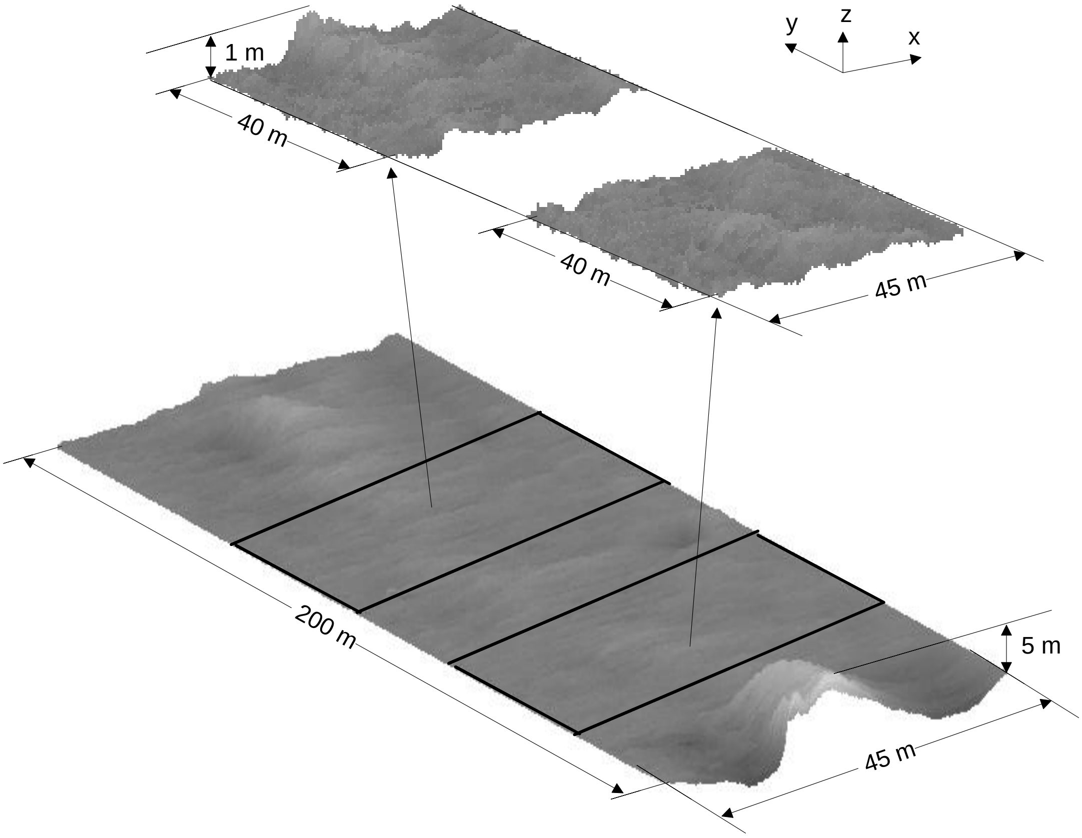

Fig.5. Bottom relief reconstruction results for data in Fig. 4.

It is visible in Fig. 5 that the preliminary results of applying the proposed approach based on SFS technique to 3^D seafloor relief reconstruction from SSS image are acceptable. However, further verification based on larger amount of experimental data as well as on utilising the reliable reference data (e.g. high resolution bathymetry measurements by multibeam sonar) is needed.

4. CONCLUSION

The method based on Shape from Shading (SFS) approach for 3^D reconstruction of seafloor relief from side scan sonar records was presented. The principle advantage of the presented method is its simplicity and the ability to produce the results within sequential, one-run processing of side scan sonar data. The implementation of more advanced SFS and also the shadow processing algorithms [12] could be required in more complex cases. In particular, the authors expect that presented seafloor reconstruction algorithm performance can be improved by applying procedure similar to Synthetic Aperture Sonar (SAS) principle. It this, instead of taking into account only the current and one proceed previous sonar echo, the current sequence of several consecutive echoes is processed, preferably applying the weighted averaging techniques.

REFERENCES

[1] K. Bikonis, M. Moszynski, A. Stepnowski, Submerged object imaging using virtual reality modeling language, Proceedings of International Congress on the Application of Recent Advances in Underwater Detection and Survey Techniques to Underwater Archeology, 215-220, Bodrum, 2004.

[2] J. Urick, Principles of underwater sound for engineers, McGraw-Hill Book Company, New York, 1975.

[3] J. Bell, D. Lane, E. Dura, Automatic 3^D reconstruction of mine geometric using multiple side scan sonar images, GOATS 2000 Conference, SACLANT-CEN, La Spezia, 2001.

[4] J. M. Cushieri, M. Hebert, Three-dimensional map generation from side-scan sonar images, Journal of Energy Resources Technology, 112, 96-102, 1990.

[5] E. Coiras, Y. Petillot, D. Lane, Automatic rectification of side scan sonar images, Proceedings of the 1st International Conference on Underwater Acoustic Measurements: Technologies & Results (CD-ROM), Heraklion, Greece, 2005.

[6] R. Zhang, P. S. Tsai, J. E. Cryer, M. Shah M, Shape from shading: A survey, IEEE Transactions on Pattern Analysis and Machine Intelligence, 21, 690-705, 1999.

[7] K. Ikeuchi, B. K. P. Horn, Numerical shape from shading and occluding boundaries, Artificial Inteligence, 17(1-3), 141-184, 1981.

[8] M. J. Brooks, B. K. P. Horn, Shape and Source from Shading, Proceedings of International Joint Conference on Artificial Intelligence, 932-936, 1985.

[9] R. T. Frankot, R. Chellappa, A method for enforcing integrability in shape from shading algorithms, IEEE Transactions on Pattern Analysis and Machine Intelligence, 10, 439-451, 1988.

[10] A. P. Pentland, Local shading analysis, IEEE Transactions on Pattern Analysis and Machine Intelligence, 6, 170-187, 1984.

[11] C. H. Lee, A. Rosenfeld, Improved methods of estimating shape from shading using the light source coordinate system, Artificial Intelligence, 26, 125-143, 1985.

[12] K. Bikonis, M. Moszynski, Z. Łubniewski, A. Stepnowski, Three-dimensional Imaging of Submerged Objects by Side-Scan Sonar Data Processing, Proceedings of the 1st International Conference on Underwater Acoustic Measurements: Technologies & Results (CD-ROM), Heraklion, Greece, 2005.

[13] D. R. Jackson, D. P. Winebrenner, A. Ishimaru, Application of the composite roughness model to high-frequency bottom backscattering, J. Acoust. Am, 79(5), 1410-1422, 1986.

[14] Marine Sonic Technology, Ltd., website: http://www.marinesonic.us, 2012.