SEAFLOOR RELIEF RECONSTRUCTION FROM SIDE SCAN SONAR DATA

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Side scan sonar 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. Although side scan sonar does not provide seafloor bathymetry directly, its records are directly related to seafloor images. In the paper, the method for 3^D seafloor relief reconstruction from side scan sonar data is presented. The method is based on the Shape From Shading technique and for estimation of a bottom depth at a currently processed point, it uses the information from both currently processed and previous ping. The results obtained by several versions of the developed algorithm are presented. The obtained results are promising and also show how the performance of the proposed algorithm might be improved in further work.

INTRODUCTION

3^D visualization of the seabed has become increasingly important for activities such as pipeline tracking, wreck inspection, mine hunting and the study of the terrain and seafloor monitoring. At present acoustic sensors offer the most reliable sight inside underwater environments for these purposes. They offer a longer range compared to video cameras or other sensors and map well the environment in turbid waters.

Side scan sonar is one of the most widely used imaging systems in the underwater environment. Although some limitations, such as its inability to directly recover seafloor depth information, side scan sonar is relatively cheap and easy to deploy, in comparison with more powerful sensors like multibeam systems or synthetic aperture sonar. Many 2^D images acquired by side scan sonar system exist, that could be transformed into 3^D representation in an algorithmic way using intensity information, contained in a grayscale images.

The fundamental principle of imaging sonar systems is based on the signature of the reflection or backscattering of acoustic energy by a target on the seafloor. It is suggested by Jackson [1] that Lambert's Law provides a good fit to seabed backscattering since roughness and volume scattering mechanisms tend to mimic Lambert's Law. Consequently, he has compared

Lambert's Law to his composite roughness backscattering model, therefore Lambert's Law may be considered to provide a good approximation of the bottom backscattering.
Several techniques of 3^D geometry reconstruction for seabed surface or submerged objects using side-scan sonar images has been reported [2, 3]. 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 [4]. In the construction of the seabed elevation map from side-scan data, the SFS technique relays on calculating the local gradient 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 Lambert's Law is often used as a model of the angular dependence of bottom scattering coefficient.
In the previous work [5], simple side-scan data processing method was presented for 3^D wreck and other submerged object shape reconstruction and its imaging. The proposed method utilised two combined techniques: 1) the shape from shading (SFS) algorithm using several types of backscattering coefficient angular dependence function, and 2) the estimation of the elevation change using the dimension of acoustic shadow areas. The applied SFS algorithm operated on each data ping separately and did not use the data from neighbouring pings. The simplifying assumption that the normal of an insonified surface is always perpendicular to the track direction, was utilised. This paper presents the modified version of the algorithm. For estimation of bottom or object depth at a currently processed point in a grid, the information from previous ping is also used, the above assumption is not applied and the normal of an insonified surface is allowed to have two degrees of freedom. The obtained results of algorithm testing and verification are presented for seafloor relief reconstruction and imaging rather than for submerged object shape reconstruction.

1. ALGORITHM DESCRIPTION AND RESULTS

The geometry scheme used in derivation of the seafloor relief reconstruction algorithm is presented in Fig. 1. The beam of a side can sonar covers an angular sector from φ_1 to φ_2. The time position t_i in an echo corresponds to an insonified bottom surface area which middle point has an x co-ordinate of approx. [5]:

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

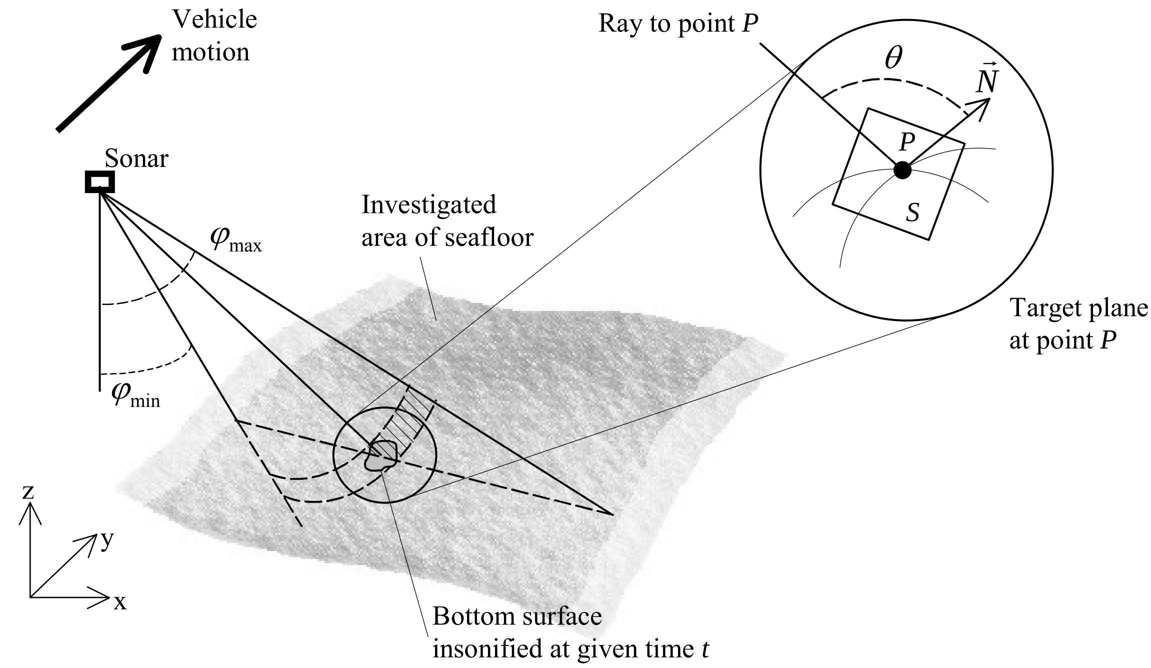


Fig.1 Geometry scheme used in derivation of the seafloor relief reconstruction algorithm

where $t_i \geq \frac{2h}{c}$, H – sensor altitude (the difference between a sonar depth and average bottom depth), c – sound speed in water. The processed images obtained by side scan sonar measurements had been spatially corrected with respect to the above relation prior to further analysis.

The backscattering model was assumed as Lambert-like form of backscattering coefficient angular dependence function:

$$\frac{I_s}{I_{0s}} = \cos^2\theta, \qquad (2)$$

where θ is the angle between ray to point P on seabed surface and normal $\boldsymbol{N}$ to a plane tangent to surface at P. Additionally, it was assumed that the rms height of bottom relief is small in comparison with the tow fish altitude, and that no shading occurs.

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. For the (i, j) iteration (where i – number of processed "line" corresponding to one transmission of sonar signal, j – number of point within 1 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 $P_{i\text{-}1\,j} = (x_j, y_{i\text{-}1}, z(x_j, y_{i\text{-}1}))$ and $P_{i\,j\text{-}1} = (x_{j\text{-}1}, y_i, z(x_{j\text{-}1}, y_i))$, and currently estimated point P_{ij}. Using the applied model, the value chosen for z_{ij} allows for calculation of normal $\boldsymbol{N}_{ij}$ to the surface facet, the angle theta and the local I value, which then many be compared with that from the original sonar image. The analytical form of expression for optimal z_{ij}, i.e. that giving I equal to a given (measured) value, is impossible to obtain in general case. On the other hand, it may be shown that in the applied model, I is a monotonic function of z within the range $[z_{ij\min}, z_{ij\max}]$, where $z_{ij\min}$ corresponds to $\theta_{ij\min} = 0°$ and $z_{ij\max}$ to $\theta_{ij\max} = 90°$ (or vice versa). Therefore, the simple binary algorithm, starting from initial $[z_{ij\min}, z_{ij\max}]$ searched interval, was used for z_{ij} estimation, i.e. the iterated algorithm which in k-th iteration proposes the new z_{ij} as the midpoint of the current [$z_{ijk\min}$, $z_{ijk\max}$] interval, and then appropriately reduces the interval to its left or right half.

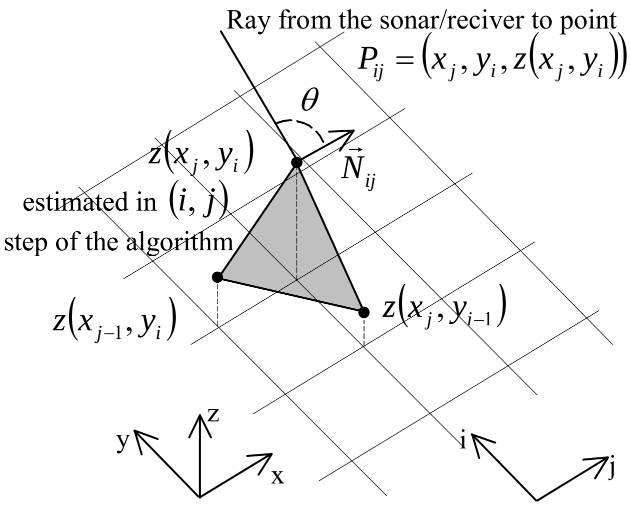


Fig.2 Estimation of the bottom altitude $z(x_j, y_i)$ in (i, j) iteration of the algorithm

The bottom image obtained from original side scan sonar data is presented in Fig. 3, the results obtained using the previous, “1D” version of the bottom relief reconstruction algorithm, i.e. that described in [5], are presented in. Fig. 4a, while the results obtained by algorithm described above, are presented in Fig. 4b.

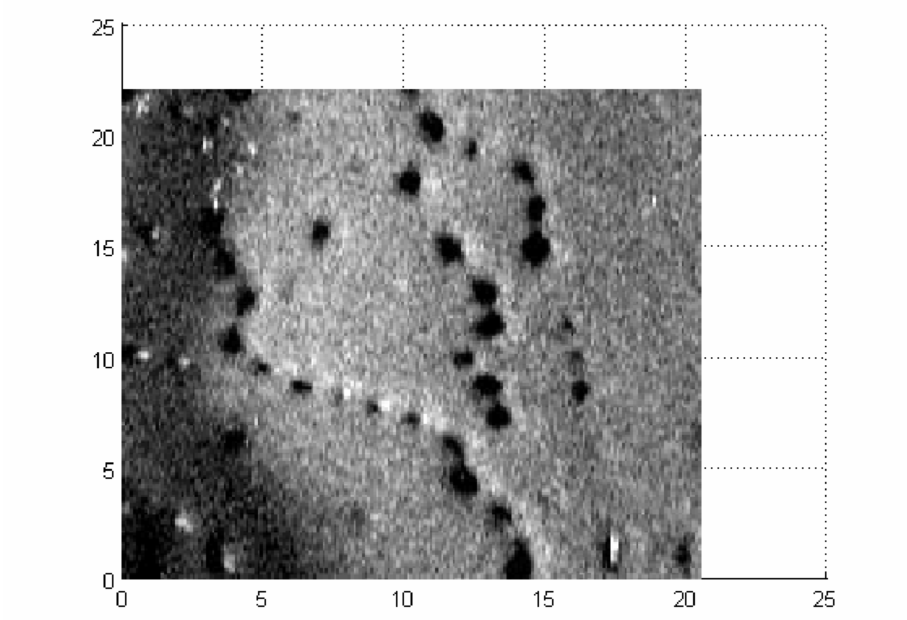


Fig.3 Sample seabed image obtained from side scan sonar data. Axes units in meters

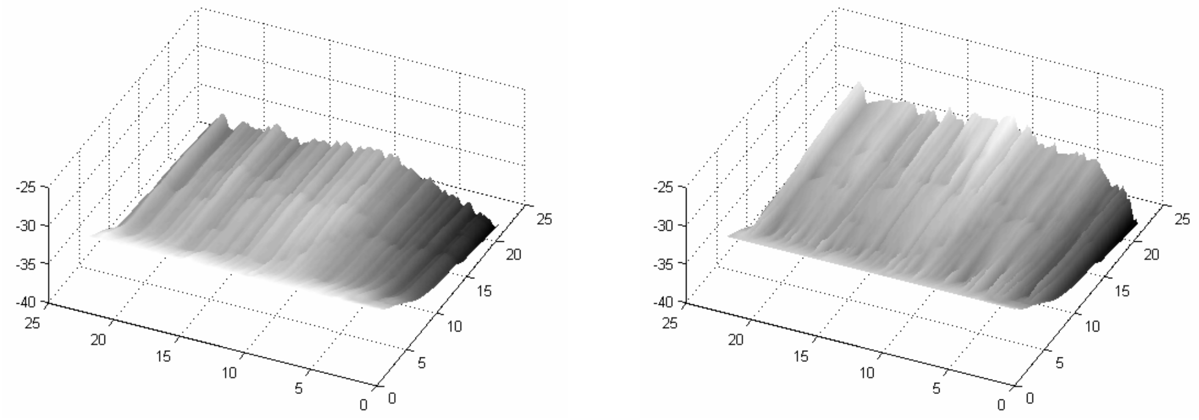
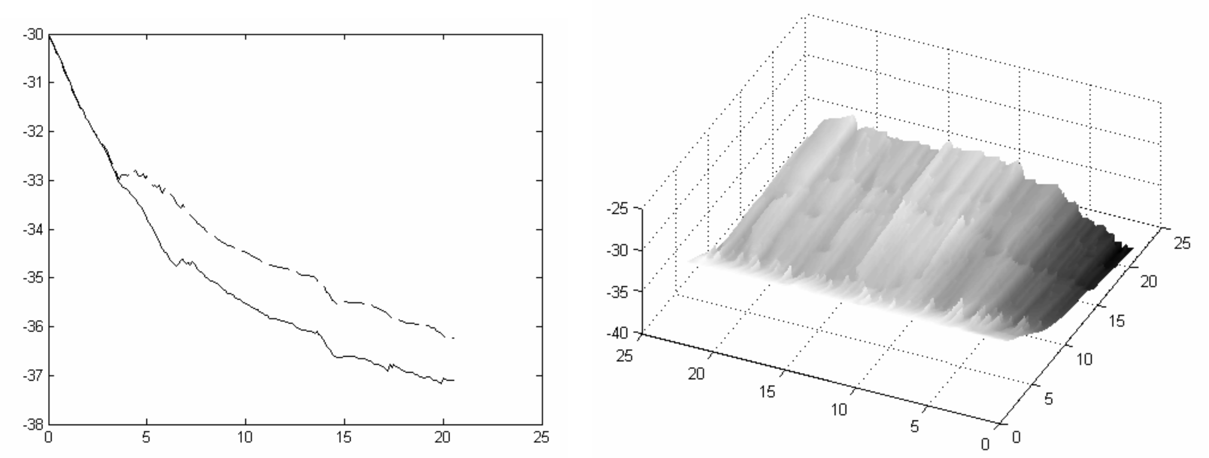


Fig.4 Bottom relief reconstruction results: a) using the "1D" algorithm [5], b) using the algorithm presented above. Axes units in meters

In both cases, although several details of bottom topography shown in Fig. 3 might be recognised in Fig. 4a and 4b, the large inconsistence of consecutive, adjacent cross-sections of $z(x, y)$ parallel to x axis, resulting in large undulations along y axis of the recovered surface, is visible unfortunately. This is because each i-th "line" of $z(x_j, y_i)$ values is estimated sequentially from left to right side and independently (to some extent also in Fig. 4 case) from the adjacent "lines". However, the effect mentioned above is less visible for some parts of bottom surface in Fig. 4b in comparison with Fig. 4a, what proves to some extent the advantage of the proposed algorithm. In Fig. 4b case, the larger average increase of $z(x, y)$ along x axis is visible than in Fig. 4a case. This is in line with the fact, that in general, if the normal of surface facet is allowed to be not parallel to XOZ plane, the $z(x_j, y_i)$ must be chosen more different from $z(x_{j-1}, y_i)$ than in "1D" algorithm case to obtain the same θ angle.

In addition, another improvement of the algorithm was applied. Fig. 5a presents the example of two adjacent "lines" of reconstructed $z(x, y)$ from Fig. 4b (i.e. two adjacent vertical cross-sections of the estimated bottom relief parallel to x axis, corresponding to 2 consecutive sonar transmissions). It is visible that several details of the seabed topography, like a "whole" close to the right side of the picture, are represented quite similarly both in 1st (solid) and 2nd (dashed) line. It may be also noticed, that the local slopes are consistent for large parts of 1st and 2nd line, while on the other hand, from some place along x axis, the altitudes of those lines start to be different in general. It seems that when some shape ("perturbation") is detected (for instance, in the left part of the 2nd line), the algorithm is not able to "come back" to the proper altitude of the surrounding, relatively flat bottom surface. It may be connected with some inconsistency between the assumed $\frac{I_s}{I_{0s}}(\theta)$ model and the reality. Taking this fact into account, the following correction was proposed for the reconstruction algorithm: During processing the current line, if the estimated local slope for the current line becomes back similar to the slope of the previous line after some interval of significant differences between those slopes (using some threshold value and taking the running average values of slope for some number of consecutive points along x axis), the z_{ij} value is set as equal to $z_{i-1\,j}$ value. Then the algorithm continues similarly as previously. The results of application of the algorithm with this modification are presented in Fig. 5b. The improvement with respect to the results presented in Fig. 4 is visible, as the inconsistency of adjacent lines was significantly removed.



a)

Fig.5 a) Example of two adjacent vertical cross-sections of reconstructed $z(x, y)$ from Fig. 4b along x axis, b) results of application of the modified version of seafloor relief reconstruction algorithm. Axes units in meters

2. CONCLUSION

The method for 3^D seafloor relief reconstruction from side scan sonar data based on the SFS technique was proposed and the results obtained by several versions of the developed algorithm were presented. The obtained results are promising. The algorithm performance is expected to be improved after further corrections with taking into account the specific features of the seafloor topography and its image being produced by side scan sonar.

REFERENCES

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

[2] D. Langer, M. Hebert, Building qualitative elevation maps from side scan sonar data from autonomous underwater navigation, International Conference on Robotics and Automation, Sacramento, USA, Vol. 3, 2478-2483, 1991.

[3] E. Dura, D. Lane, J. Bell, Automatic 3^D reconstruction of mine geometric using multiple side scan sonar images, GOATS 2000, La Spezia, Italy, SACLANTCEN CP-46, 2001.

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

[5] K. Bikonis, M. Moszyński, Z. Łubniewski, A. Stepnowski, Three-dimensional imaging of submerged objects by side-scan sonar data processing, 1st International Conference on Underwater Acoustic Measurement: Technologies and Results, Heraklion, Greece, 2005.