Automatic Rectification of Side-Scan Sonar Images

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AUTOMATIC RECTIFICATION OF SIDE-SCAN SONAR IMAGES

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Abstract: *The authors present a novel procedure for the automated rectification of side-scan sonar images. The traditional assumption of a flat seabed for the computation of the ground projection from the slant-range sonar data can later result in difficult geo-referenciation and registration problems. Proper rectification using actual seabed topography is required for accurate integration of side-scan images into a high-resolution mosaic, which depends on the availability of seabed altitude maps for the area of interest. As an alternative the authors propose a procedure for the estimation of the most probable seabed topography given the acquired side-scan image and a simple scattering model. An Expectation-Maximization framework is constructed to iteratively determine the model parameters that best approximate the observed image.*

Keywords: *Side-scan rectification, bathymetry reconstruction, expectation-maximization.*

1. INTRODUCTION

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 like multi-beam systems or synthetic aperture sonar. It has however, some limitations, such as its inability to directly recover seafloor depth information. This particular drawback means that seafloor mosaics are generally difficult to construct, since the position of features in the seabed is not completely known. Furthermore, modern navigation correction techniques frequently rely on the matching of seabed features between different side-scan runs [1], which makes even more important the correct determination of their position with respect to the sensor location.

In this paper we propose a method for estimating elevation information from the side-scan image, which allows for a more adequate computation of the position of seabed features. Our procedure utilizes an Expectation-Maximization framework to iteratively minimize the difference between the original side-scan and a synthetic image rendered with the current estimation of the seabed parameters. For the construction of the synthetic image, a simple Lambertian scattering model is used, which takes into account the reflectivity and elevation of the seabed, and the sensor's beam-pattern.

2. BACKGROUND

Efforts oriented to the utilization of side-scan sonar for the indirect determination of seabed topography have been scarce [2-7]. The main reasons being the complexity of the full mathematical projection model and the level of pre-processing required. In most cases where acquisition of seabed topography is important, attention is driven to more straightforward solutions such as multi-beam bathymetric systems.

Most existing work on seabed reconstruction from side-scan has been mainly qualitative and oriented to obstacle-avoidance for underwater vehicles [2, 4-6]. Other works focus on seabed texture classification or object recognition [7-9]. In all these situations precise descriptions of the seabed topography are not critical.

In general, the fundamental idea behind most reconstruction methods is to determine a model for the ensonification process that is simple enough for the image formation problem to be inverted, obtaining an approximation to the surface gradients, which can be globally described as shape-from-shading methods [3]. Our goal is to extend these methods using a statistical approach to determine the most probable configuration of the seabed topography compatible with the side-scan image actually observed. To this end we use an expectation-maximization framework [10] in order to iteratively refine the set of parameters defining our model.

3. SCATTERING MODEL

For the side-scan ensonification process we use the traditional Lambertian model [2], which permits to derive the returned intensity from the parameters defining the observed scene. This simple model for diffuse scattering assumes that the returned intensity depends only on the angle of incidence of the illuminating sound pulse, and not on the angle of observation or on the frequency of the pulse. Under this assumptions the intensity I returned from a seabed point $\vec{p}$ can be represented by the following expression:

$$I(\vec{p}) = \Phi(\vec{p})\, R(\vec{p}) \cos(\theta(\vec{p})) \qquad (1)$$

Where Φ represents the intensity of the illuminating sound wave at the point, R is the reflectivity of the seafloor, and θ is the incidence angle of the wave front. Since most logged side-scan images already include a TVG correction for compensation of the intensity decay with distance and gracing angle, no dependence on radial decay has been included in the model (this would otherwise appear as a term on $r(\vec{p})^{-2}$, r being the distance to the sensor). Therefore, in order to simplify the model, all the intensity variations caused by the sensors beam-profile, the radial decay and the corrections are supposed to be grouped under the beam-pattern Φ.

The dependence on the seafloor's elevation is implicit in the incidence angle $\theta(\vec{p})$, which depends on the gracing angle from the sound source and the orientation of the surface normal $\vec{N}(\vec{p})$. This dependence can be made explicit by first expanding the cosine in expression (1) as follows:

曲面法线：surface normal

$$\cos(\theta(\vec{p})) = \frac{\vec{r}(\vec{p}) \cdot \vec{N}(\vec{p})}{\left|\vec{r}(\vec{p})\right| \cdot \left|\vec{N}(\vec{p})\right|} \tag{2}$$

And then by representing N and r on a coordinate system relative to the sensor. Expressing p as $(x, y, Z(x, y))$, with x being the across distance from the sensor and y pointing along its direction of movement, yields:

$$\vec{r}(\vec{p}) = (x, 0, Z(x, y)) \qquad \vec{N}(\vec{p}) = \left(-\frac{\partial Z}{\partial x}(x, y), -\frac{\partial Z}{\partial y}(x, y), 1\right) \tag{3}$$

Combination of expressions (1), (2) and (3) gives a formula that permits the computation of the intensity I at any point p, given the magnitudes that model the seafloor (R and Z) and the illuminating pattern of the sensor (Φ). The inverse problem, however, is severely under-determined, since we only have one observation (of I) at each point to compute the values of the three model parameters.

In order to solve this limitation we propose the utilization of an expectation-maximization procedure, which will iteratively converge to an optimal set of modelling parameters given a source side-scan image. The objective then is to minimize the absolute value of the difference between the observed intensity I and the one resulting from the application of the model $\hat{I}$, which we represent by the error quantity E:

$$E(x, y) = \left(I(x, y) - \hat{I}(x, y)\right)^2 \tag{4}$$

In the expectation stage, the current estimates for the model parameters are used to compute an estimation of the intensity $\hat{I}$. Whereas in the maximization a straightforward gradient descent approach [11] is used to minimize E, by updating the model parameters as follows:

$$\begin{aligned} R(x, y) &\leftarrow R(x, y) - \lambda \cdot \frac{\partial E}{\partial R}(x, y) \\ \Phi(x, y) &\leftarrow \Phi(x, y) - \lambda \cdot \frac{\partial E}{\partial \Phi}(x, y) \\ Z(x, y) &\leftarrow Z(x, y) - \lambda \cdot \frac{\partial E}{\partial Z}(x, y) \end{aligned} \tag{5}$$

Where λ is a small constant value used to control the rate of change. The expressions are iterated until the variation in the error E is below a given threshold.

4. RESULTS

A result of the proposed rectification procedure is shown in Fig. 1. The similarity of the rectified ground image and the synthetic render using the estimated parameters can be clearly appreciated. Note that most of the inaccuracies occur in the region right below the sensor, where the utilization of a diffuse scattering model is less appropriate.

Fig. 2 shows in more detail the area surrounding the rock on the top-right, as well as the estimated values for the elevation in that region.

Finally, some shaded-relief renders of the elevation map for the rock area are presented in Fig. 3. Note how the shadowed regions have converged to smooth surface patches parallel to the direction of the sound source, effectively receiving no ensonification whatsoever and therefore appearing dark in the model image.

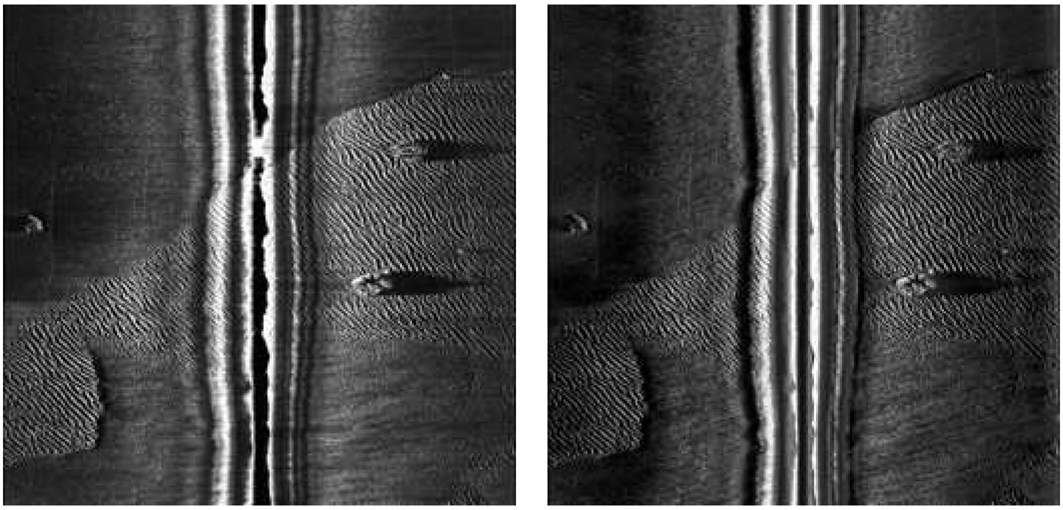

Fig.1: Ground-range image (left) and synthetic model (right) after convergence of the proposed rectification method.

Fig.2: Detail from Fig. 1, showing the area surrounding the rock on the top-right.Ground-range (left), model (centre) and elevation map (right) where brighter areas are closer.

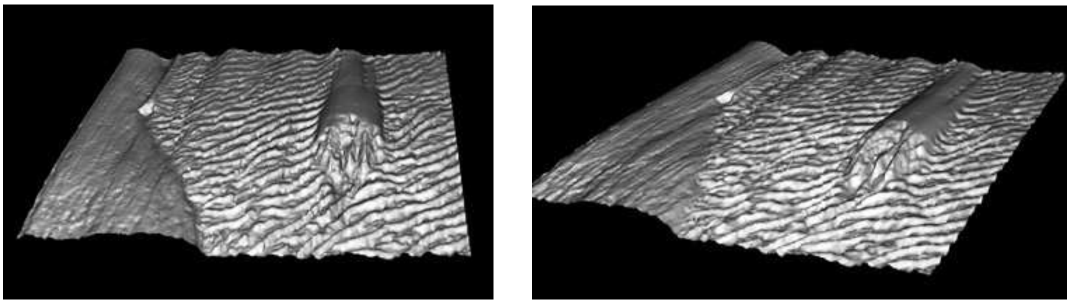

Fig.3: Shaded-relief renders of the elevation map shown in Fig.2.

5. CONCLUSIONS

In this paper we have presented a new method for the estimation of seabed elevation. The method uses a Lambertian model for the sonar scattering process, which is then used by an expectation-maximization procedure to optimally determine the seabed features ultimately responsible for the observed side-scan image. Some examples have been presented, which highlight the type of results that can be expected from this rectification method.

For proper rectification of the full seabed elevation and reflectivity maps, however, a proper calibration procedure is required. Measures against ground-truthed scenes need to be done in order to determine the real accuracy of the method proposed in this paper. And this is one of our next objectives, which we hope will turn the proof of concept presented here into a full-featured side-scan reconstruction application.

Applications of the proposed method are numerous, and include accurate mosaic construction, detail improvement on existing bathymetry maps, generation of three-dimensional models of underwater structures, etc.

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REFERENCES

[1] **I. Tena Ruiz, S. de Racourt, Y. Petillot, D.M. Lane**, “Concurrent Mapping and Localization Using Side-scan Sonar”, *IEEE Journal of Oceanic Engineering*, vol. 29(2), pp. 442-456, 2004.

[2] **D. Langer, M. Hebert**, “Building Qualitative Elevation Maps From Side Scan Sonar Data For Autonomous Underwater Navigation”, In *Proceedings of the 1991 IEEE International Conference on Robotics and Automation*, vol. 3, pages: 2478 -2483.

[3] **R. Li, S. Pai**, “Improvement of Bathymetric Data Bases by Shape from Shading Technique using Side-Scan Sonar Images”. In *Proceedings of the 1991 Oceans Conference*, pages: 320-324.

[4] **S. Tiwari**, “Mosaicking of the Ocean Floor in the Presence of Three-Dimensional Occlusions in Visual and Side-Scan Sonar Images”, In *Proceedings of the 1996 Symposium on Autonomous Underwater Vehicle Technology*, 1996, pages: 308 -314.
[5] **J.M. Cuschieri, M. Hebert**, “Three-Dimensional Map Generation From Side-Scan Sonar Images”, Journal of Energy Resources Technology - Transactions of the ASME, 112(2): 96-102, 1990.
[6] **A.E. Johnson, M. Hebert**, “Seafloor Map Generation for Autonomous Underwater Vehicle Navigation”. Autonomous Robots, 3(2-3): 145-168, 1996.
[7] **V. Murino, A. Trucco**, “Three-Dimensional Image Generation and Processing in Underwater Acoustic Vision”. Proceedings of the IEEE, 88(12): 1903-1948, 2000.
[8] **Y.R. Petillot, S.R. Reed and J.M. Bell**, “Real Time AUV Pipeline Detection and Tracking Using Side Scan Sonar and Multi-Beam Echosounder”, In *Proceedings of the MTS/IEEE Oceans Conference*, 2002.
[9] **J.M. Bell, E. Dura, S. Reed, Y.R. Petillot, D.M. Lane**, “Extraction and Classification of Objects from Sidescan Sonar”, In *Proceedings of the IEE Workshop on Nonlinear and Non-Gaussian Signal Processing*, 2002.
[10] **A.P. Dempster, N.M. Laird, D.B. Rubin**, “Maximum Likelihood from incomplete data via the EM algorithm”, *J. Royal Statistical Soc., Ser. B*, vol. 39(1), pp. 1-38, 1977.
[11] **W.H. Press, S.A. Teukolsky, W.T. Vetterling, B.P. Flannery**, “Numerical Recipes in C. Second Edition”, Cambridge University Press, p. 421, 1994.