Sonar image reconstruction method based on adaptive compensation of very shallow water acoustic channel features

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Abstract. Aiming at the problem of eliminating the influence of channel interference on the detection results in the process of using sonar to detect very shallow water targets, a sonar image reconstruction method based on adaptive compensation of very shallow water acoustic channel features is proposed. Standard acoustic source and remote server are used to complete the adaptive calibration process of channel characteristic parameters before detection. The calibrated channel characteristic parameters are used in the subsequent beamforming algorithm to compensate the channel interference. The time-of-flight parameters calculated by the compensation algorithm are used in the subsequent point cloud generation and image reconstruction. Simulation and field test show that the proposed compensation method can improve sonar target detection ability by 25% in very shallow water and complex acoustic channel environment, and the quality of sonar image reconstruction is significantly improved.

1. Introduction
The demand of sonar target detection in very shallow water environment is increasing. Acoustic channel in very shallow water presents complex time-varying nonlinear characteristics, and the interference dominated by reverberation makes it difficult to realize beamforming by using the determined sound velocity line model in sonar detection. As a result, the subsequent imaging effect is poor. In order to solve this problem, researchers adopt many parameter compensation algorithms in the modeling of very shallow water sonar. The most typical method is the probability distribution function method based on frequency domain. The channel probability feature is obtained by prior knowledge, and then applied to the subsequent detection, and good results are obtained. However, this method highly depends on prior knowledge of the environment, which is difficult to adapt to the needs of unfamiliar waters[1-3].

In order to solve the problem of acoustic channel parameter compensation in unfamiliar waters and improve the imaging quality of sonar, a channel compensation method based on time-domain random field theory is proposed. In this method, Monte Carlo method is used to generate the value space of channel parameters, standard sound source is used to generate calibration signal and measure the actual received signal of sonar. At the same time, sound line model is used to calculate the theoretical received signal on the remote server, the difference between the two is compared, and the channel parameter value corresponding to the signal with the smallest error is selected as the input of
subsequent calculation to complete the point cloud generation and mapping process. On the basis of simulation calculation, the field experiment is carried out to verify the effectiveness of the method.

2. Modeling of Very Shallow Water Acoustic Channel

Very shallow water acoustic channel is affected by the geographical environment, natural climate and human activities, and presents the nonlinear time-varying characteristics of complex environmental noise and significant multi-path effect. In this section, we will build a general model for analysis based on ray acoustics theory.

2.1. Acoustic Ray Equations

In the classical ray acoustics, the sound energy is transmitted by the ray. The ray from the sound source arrives at the receiver according to different distances, and the received sound field is the superposition result of all the arriving rays. There are two important equations in ray acoustics, one is the eikonomics equation used to determine the ray walking law, and the other is the intensity equation used to determine the intensity of each ray. In the layered ocean medium, the expression of the sound field is as follows:

\[ \psi(x,z) = A(x,z) \exp \left( j \phi(x,z) \right) \]  
\[ \Phi(x,z) = ik_0 x + ik_0 \int_0^z \sqrt{n^2(z) - \xi^2} \, dz \]  
\[ A(x,z) = \sqrt{I} = (W \cos \theta_0)^{0.5} \left[ x (\partial x / \partial \theta)_{\theta_0} \sin \theta_0 \right]^{-0.5} \]

where, \( W \) is the radiation power of unit solid angle, \( \theta_0 \) is the grazing angle of acoustic ray at sound source position, \( \theta_0 \) is the grazing angle of arbitrary depth, \( n(z) \) is the refractive index, \( \xi \) is the acoustic ray constant and \( x \) is the distance.

2.2. Acoustic Channel Models

We use Bellhop sound speed profile to describe the acoustic channel models. In Bellhop, this is called environmental file. Main parameters in environmental file includes: source frequency, attenuation values, bottom depth, depth-soundspeed pairs, bottom boundary, source depths and so on. Some of these parameters can be measured. Moto Carlo method is used to describe the depth-soundspeed pairs, for a certain depth, the speed of sound can be generated according to the distribution characteristic. Thus the uncertainty of the channel can be modeled for the following calculations.

2.3. Generating a Receiver Timeseries using Bellhop

Bellhop can help to calculate the channel impulse response. It produces a file containing a table of the arrivals information (the impulse response). For each source depth, receiver depth, and receiver range it contains the number of echoes or arrivals. Then for each arrival the amplitude, phase, and travel time of the arrival is provided. Once we have the impulse response function, as represented by the arrivals file, we can produce a receiver timeseries by convolving the source timeseries with that impulse response function.

3. Demarcate System Design based on Standard Acoustic Source

The very shallow water channel calibration system is mainly composed of standard sound source, broadband transducer, receiving hydrophone, 3D imaging sonar, wireless high-speed network, control computer and remote computing server. The received hydrophone measures the signal from the standard sound source, and the measured results and the characteristic data of the standard sound source signal are transmitted to the remote computing server through the wireless high-speed network. The remote computing server calculates the time series of the received signal according to the standard sound source and the model provided in the previous section, and compares the differences between the measurement results and the calculation results. The channel model parameters corresponding to
the calculation results with the smallest difference are sent back to the control computer through the wireless high-speed network to realize the adaptive calibration process of the channel model. The control computer writes the parameters into 3D imaging sonar through serial port, which is the basis of sonar subsequent calculation. At the end of the calibration process, sonar enters the measurement link. The whole system deployment is shown in Fig.1.

![Fig.1 System deployment overview](image)

4. Image Reconstruction for 3D Acoustic Sonar

4.1. Point cloud

Point cloud [4] data is a set of vectors in a three-dimensional coordinate system. Scanning data are recorded in the form of points; each point contains three-dimensional coordinates and reflection intensity information. According to the characteristics of shallow water acoustic channel, a stochastic statistical model is established. For short distance shallow water acoustic channel, a Rician Fading and additive Gaussian white noise channel model can be established; for medium and long distance shallow water acoustic channel, a Rayleigh fading and additive Gaussian white noise channel model can be established. Considering not only the influence of signal multipath propagation, but also the influence of environmental noise, as well as the time-varying and frequency-varying characteristics of underwater acoustic channel, we are concerned about the signal-to-noise ratio of the received signal. Using the above model and the adaptive fitting technology of channel parameters, the received sonar signal can be corrected, so as to compensate the intensity value at each coordinate point and form the point cloud measurement data corresponding to the channel.

4.2. Research on reconstruction algorithm

There are two visualization methods for 3D reconstruction of spatial discrete point clouds: surface rendering and volume rendering. The sonar data of the system meets the characteristics of surface rendering, so surface rendering is selected for 3D image reconstruction.

The single frame reconstruction part of the system is based on the triangle mesh reconstruction method proposed by Castellani [5-7]. By adding dynamic threshold to the reconstruction condition judgment part, the algorithm is improved, which has better performance and makes the image achieve the best effect in different scenes.

The basic principle and steps of the improved triangular mesh reconstruction are as follows:

1. Define the judgment criteria for the connection between adjacent points of sonar arrays:
   \[
   \left| \left( x_1^2 + y_1^2 + z_1^2 \right)^{0.5} - \left( x_2^2 + y_2^2 + z_2^2 \right)^{0.5} \right| < \delta ; \tag{4}
   \]
   (2) For the adjacent points in 2 by 2 grid space, phase matching is performed in turn for the adjacent point connection judgment operation;
(3) Select the 3 by 3 grid space with the center point as the empty point to judge the connection relationship of the points in the space, so as to fill the vacancy and make the reconstruction grid fuller;

(4) In 2 by 3 and 3 by 2 grid space, the connection relationship of points is judged;

(5) Dynamic adjustment $\delta$, repeat the above operation.

Fig. 2 shows the reconstruction results of the improved triangular mesh reconstruction method for spatial discrete points.

![Fig.2 Improved triangular mesh reconstruction](image)

### 4.3. Experimental study

In order to verify the actual performance of the visualization method, laboratory experiments were carried out. The specific environmental parameters of the experiment are as follows: the depth of the sonar system into the water is about 2m; the distance between the sonar system and the target is 3 ~ 4 m; the distance between the sonar system and the poll wall is about 5.3 m; the sonar receiving array is basically vertical to the water surface. The experimental scene is shown in Fig. 3. The experimental target is an irregular ring.

![Fig.3 Test scenario](image)

After processing the data, the scatter display effect is shown in Fig. 4, and the reconstructed result is shown in Fig. 5. The target display coordinate is between 3.39 m and 3.75 m, which is consistent with the actual position.
5. Conclusion
In this paper, the key technology of visualization processing in 3D sonar is studied, and the triangular mesh reconstruction method of spatial point cloud is simulated. According to the characteristics of 3D sonar data, the algorithm with lower complexity is selected, and the algorithm is improved according
to the actual application environment, so that the operator can dynamically adjust the connection judgment threshold, and choose a better observation effect according to the actual scene. The correctness of the visualization results, the reconstruction ability of complex targets in complex environment and the superiority over two-dimensional sonar are verified through three pool and lake experiments, which proves the application value of the visualization method.

Based on the research of this paper, we can do further research on the panoramic mosaic of 3D sonar image.

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