Side Scan Sonar Image Geocoding based on Carrier Velocity Coarseness Correction

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Abstract. Gross error may occur in Geocoded side scan sonar image due to complicated water bottom environments and AUV maneuver. This paper presents a side-scan sonar image geocoding method based on carrier speed gross error correction. This method uses the side scan sonar image imaging principle and SIFT feature matching algorithm to calculate the AUV lateral velocity. This lateral velocity is used to detect and eliminate the gross speed error of DVL in underwater integrated navigation, and to perform gross error correction on the side-scan sonar image geocoding. This method can improve the performance of AUV underwater integrated navigation, and significantly improve the accuracy of side-scan sonar image geocoding.

1. Introduction
Side scan sonar image stitching technology (geocoding technology) is currently a worldwide research hotspot [1]. The accuracy of the side-scan sonar image geocoding is mainly related to the accuracy of the underwater integrated navigation algorithm. DVL is an important part of AUV integrated navigation, which can provide AUV with more accurate information about the speed of the carrier relative to the bottom or the water layer [2-3]. However, in actual work, DVL will have a large speed deviation due to various underwater conditions and AUV maneuvers (up, down, steering) and other reasons. The existence of these gross errors can cause faults in the geocoded side-scan sonar image. Therefore, these speed errors must be eliminated in time to make the geocoding of the side-scan sonar image more accurate. If a low-cost inertial navigation system (such as a heading and attitude reference system) is used, the speed information provided by the inertial navigation itself is not accurate and the error increases quickly. Most of the DVL gross errors are often difficult to detect and eliminate.

This paper proposes a side-scan sonar image geocoding based on carrier speed gross error correction. This method calculates the actual lateral velocity of the carrier from the side-scan sonar image based on the SIFT feature matching algorithm. The obtained lateral velocity is used to detect and remove the gross error data in the DVL velocity information. The INS / DVL combined navigation data after removing the gross errors is used to geocode the side-scan sonar data to obtain the stitched image.
2. Obtaining lateral velocity from side scan sonar image data

2.1. Noise reduction of side scan sonar image

The geo coding of side scan sonar image requires a high definition of the image. If the image has serious noise, the effect of geo coding will be very poor. Due to the complexity of the marine environment, the side scan sonar image contains a variety of noise signals and is distorted. And it is difficult to use a noise reduction method for correction, at least 2-3 methods are needed for processing. Gaussian noise and salt and pepper noise are the two most common noises in side scan sonar images. Gaussian noise is usually distributed in the whole area of the image, which will lead to blur of the image target contour and obvious graininess of the pixel. Gauss noise can be eliminated by selecting the appropriate size of template, using mean filter or Gauss filter. Salt and pepper noise is mainly due to the interference of random signal when the transducer receives the echo, which forms the fringe interference image. Generally, it can be filtered by median filter[4].

![Figure 1. Wavelet de-noising and median filtering for strip noise](image)

In this paper, wavelet denoising and median denoising are used, in which Figure 1 (a) represents the image before filtering and Figure 1 (b) represents the image after denoising. The original image mainly contains the upper and middle two bands of noise, and the image after noise reduction basically eliminates the obvious noise signal. The side scan sonar image obtained by noise reduction will be further process.

2.2. Feature point extraction based on SIFT feature matching algorithm

The key to extracting lateral velocity is to find the correlation points between two adjacent frames of data. The related points are not necessarily the same point in practice, and may be adjacent points on the edge line of the same characteristic object. Due to the continuous advancement of the AUV, the same point may not be scanned between adjacent data frames. However, adjacent data frames will scan to the same feature marker edge line. Because the reflection intensity of the sound wave is different from the surrounding environment, there are obvious edge lines between these characteristic markers and the surrounding environment in the sonar image, and the brightness of the pixels on both sides of the edge line shows a significant difference. From this, it can be determined that each frame of data belongs to the feature points of the edge line.

The SIFT feature is a local feature of the image, which maintains invariance to rotation, scaling, and brightness changes, and maintains a certain degree of stability to changes in viewing angle, affine transformation, and noise [5]. Compared with other algorithms, it has better real-time and unique characteristics[6]. Therefore, the SIFT feature matching algorithm is selected as a tool to find the feature points of the side-scan sonar image.

The feature points detected by SIFT feature matching algorithm are not very accurate, and there may be several pixel deviations. In order to get the real image feature points, these deviations need to...
be processed and optimized. The curve fitting method based on least square can be used to fit the feature points in multiple data frames, so as to obtain smooth and continuous feature point curves.

2.3. Carrier lateral speed extraction algorithm

According to the principle of DVL speed measurement, DVL output speed is set as $V(t)$ along the measurement coordinate system.

$$V(t) = \begin{bmatrix} V_x(t) \\ V_y(t) \\ V_z(t) \end{bmatrix}$$ (1)

The $V_x(t)$, $V_y(t)$ and $V_z(t)$ are the velocity components on the X, Y and Z axes of the instrument coordinate system respectively.

Assuming that the inertial measurement system coincides with the carrier system B, according to the ins attitude information, the DVL measurement speed is converted to the geographic coordinate system $n$, and the reference speed $V_d^n(t)$ along the geographic coordinate system is obtained.

$$V_d^n(t) = C_n^b(t) \cdot C_n'(t) \cdot C^b$$ (2)

In the formula, $C^b$ is the coordinate transformation matrix from DVL instrument coordinate system $m$ to carrier coordinate system $b$, $C_n'(t)$ is the coordinate transformation matrix from carrier coordinate system to navigation coordinate system, $C_n(t)$ is the coordinate transformation matrix between two parts to the real geographical system. The gross error detection of $V_y(t)$ in the carrier coordinate system will improve the accuracy of $V(t)$. Therefore, according to formula 2, the download speed $V_d^n(t)$ in the inertial coordinate system can be further improved.

If the pixel values of the relevant feature points matched by a pair of adjacent data frames are $n_1$ and $n_2$ respectively, and their corresponding bottom lines are $n_{01}$ and $n_{02}$ respectively, then the lateral velocity $V_y$ of the carrier is:

$$V_y = \frac{\text{Range} \times (\sqrt{n_1^2 - n_{01}^2} - \sqrt{n_2^2 - n_{02}^2})}{N \times \text{Rpetition}}$$ (3)

Where: $d_a$ is the slant distance from the first pixel to the center of AUV, Range is the maximum slant distance, $N$ is the total number of pixels, and Rpetition is the scanning period of each frame of data. The obtained DVL speed is used to remove the gross error of the DVL data in the INS / DVL combination algorithm. The precise INS / GPS integrated navigation data is used to detect the DVL data items after removing the gross errors from the actual data.

The DVL lateral velocity data with big difference from $V_y$ will be eliminated. In this way, not only the gross error of velocity data can be eliminated, but also the image noise can be reduced.

![Figure 2](image.png)

**Figure 2.** Image quality comparison before and after DVL gross error elimination

Figure 2 (a) shows the side scan sonar image processed by wavelet denoising and median denoising, and Figure 2 (b) shows the image after further eliminating gross errors. Comparing the two
images, it can be found that DVL gross error elimination can improve the quality of side scan sonar image and pave the way for geocoding.

3. Side scan sonar image geocoding method

3.1. Slope distance correction based on acoustic ray tracking method

Sound waves are emitted by the transducer from all directions, and they are propagated through the underwater medium until they encounter obstacles that are reflected back and accepted by the transducer. Ideally, the sound waves propagate in a straight line [7]. But in fact, the propagation path of sound waves under water is not a strict straight line, but an approximate straight line consisting of countless polylines. Because the actual water environment is surging undercurrents, and there are various aquatic biological activities, resulting in uneven density under the water surface, which results in multiple media layers. The media interface caused by different media densities can also be a sound velocity profile, because sound waves will change the speed of sound when they pass through different media layers. Refraction occurs when sound waves propagate in different media layers, and the refraction angle is small each time. When the distance of sound wave propagation is long, the actual propagation path of the sound wave will be significantly different from the straight path. The ray tracing technique mainly focuses on the ray trajectory problem under different sound velocity profiles [8]. At the angle of incidence, the sound wave passes through the n + 1 layer of medium under water and undergoes n times of refraction. According to Snell's law, we can get:

\[ p = \frac{\sin \theta_k}{C_k} = \frac{\sin \theta_{k+1}}{C_{k+1}} \]  

(4)

Where \( \theta_k \) and \( \theta_{k+1} \) are the incident and refraction angles at the k-th refraction of the sound wave. The ray tracing method assumes that the velocity of sound traveling through different media layers is a constant gradient.

\[
\begin{align*}
    m_i &= \Delta z_i \tan \theta = \frac{pC_i \Delta z_i}{(1 - (pC_i)^2)^{1/2}} \\
    j_i &= j_i / \sin \theta = \frac{\Delta z_i}{(1 - (pC_i)^2)^{1/2}} \\
    t_i &= \frac{\Delta j_i}{\Delta C_i(z)} = \frac{\Delta z_i}{C_i(1 - (pC_i)^2)^{1/2}}
\end{align*}
\]  

(5)

Among them, \( m_i \), \( j_i \) and \( t_i \) represent the horizontal propagation distance, oblique distance, and propagation time when the sound wave is transmitted to the ith medium layer, and \( \Delta z_i \) represents the depth of the \( i \)th medium layer. From the above formula, it is easy to get the situation after sound waves propagate \( n + 1 \) dielectric layers:

\[
\begin{align*}
    m &= \sum_{i=1}^{n} \frac{pC_i \Delta z_i}{(1 - (pC_i)^2)^{1/2}} \\
    j &= \sum_{i=1}^{n} \frac{\Delta z_i}{(1 - (pC_i)^2)^{1/2}} \\
    t &= \sum_{i=1}^{n} \frac{\Delta z_i}{C_i(1 - (pC_i)^2)^{1/2}}
\end{align*}
\]  

(6)

From the formula 6, combined with the ray tracing method to modify the layered refraction error, the side scan sonar image after the slope distance correction can be obtained.
3.2. Side-scan sonar image stitching based on modified navigation data

It is not enough to correct the slope of the side-scan sonar image only on the horizontal scale. It is necessary to fuse the corresponding navigation information on the vertical scale of the side-scan sonar image, and make corresponding corrections to the possible overlap of pixel information and out-of-file conditions in the fused image to form a complete underwater map [9].

As shown in Figure 3, the geographic coordinates of the AUV at the end of each sampling period are \( P(X, Y) \), the maximum slope distance of the single-side data frame of the side-scan sonar is \( R \), the sampling rate of the scanning surface is \( N \), and the heading angle is \( \alpha \). Since the scanning line is perpendicular to the track line at each moment, the direction angle of the port side echo is \( \theta = \alpha - \pi / 2 \), and the direction angle of the port side echo is \( \theta = \alpha + \pi / 2 \). Therefore, the coordinate of the \( i \)-th pixel on the scanning line corresponding to point \( P \) is \( (X_i, Y_i) \).

\[
\begin{align*}
X_i &= X_0 + [R \cdot \cos(\alpha \pm \pi / 2) \cdot i]N^{-1} \\
Y_i &= Y_0 + [R \cdot \sin(\alpha \pm \pi / 2) \cdot i]N^{-1}
\end{align*}
\]

(7)

When the geographic coordinates of each echo are determined, the actual geographic range \((X_{\text{min}}, Y_{\text{min}}, X_{\text{max}}, Y_{\text{max}})\) of the strip sonar image is obtained. According to the set pixel size \( \Delta d \), the image resolution and the pixel coordinates \( p_i = (x_i, y_i) \) of the corresponding point are:

\[
\begin{align*}
x_i &= (X_i - X_{\text{min}})\Delta d^{-1} \\
y_i &= (Y_i - Y_{\text{min}})\Delta d^{-1}
\end{align*}
\]

(8)

As shown in Figure 4, a modified side scan sonar image can be obtained according to AUV geographic coordinates and pixel point coordinates. The trajectory is that the curve is no longer a straight line, and the scanning lines are not parallel. This creates a new problem. If the speed is fast, there is usually a gap between the scan lines. If the speed is slow, the scan lines may intersect.

The end point-based filling method is a more practical filling method. It predicts the values of all points in the area based on the limited boundary value of the closed area and the distance from the boundary point to the unknown point in the area [10]. Two adjacent pixel points are taken on two adjacent scan lines, so that the four points form a quadrilateral closed area with the smallest local area.
As shown in Figure 5, \(A_1, A_2\) are two adjacent pixels on one scan line, \(A_3, A_4\) are two adjacent pixels on the other scan line, and \(A_1, A_2, A_3, A_4\) forms a closed connected area. Scanning and filling can be used to calibrate all the pixels in the area. The pixel value of each pixel can be obtained by Equation 5.6. Where \(s_i, i = 1,2,3,4\) is the distance from the unknown point to the four boundary points, and \(I_i, i = 1,2,3,4\) is the brightness value of the four boundary points.

\[
I = \frac{I_1}{s_1} + \frac{I_2}{s_2} + \frac{I_3}{s_3} + \frac{I_4}{s_4} = \frac{1}{s_1 + s_2 + s_3 + s_4}
\]

4. Test verification

The data used for experimental verification are derived from AUV underwater test data in a certain water area of Hubei.

From Figure 6, it can be seen that the side scan sonar image (right side) after the slope distance correction is significantly different from the original image (left side). The side scan sonar image after slope correction is more in line with human's normal thinking, and the approximate outline of the object can be better reflected on the side scan sonar image. Observers can obtain valuable information from the side-scan sonar images more intuitively, which is crucial for the underwater environment detection task with the side scan sonar.
Figure 7 shows the trajectory coordinates estimated by the INS / DVL integrated navigation algorithm. You can see that the actual trajectory is an irregular curve shape.

![Figure 7](image_url)

**Figure 7.** Trajectory coordinates estimated by the INS / DVL integrated navigation algorithm.

Figure 8 (a) is the result of gap filling after the strip images are placed according to the coordinate relationship; Figure 8 (b) is the complete seamless stitching image obtained by the method in this paper. It is concluded that the side-scan sonar image geocoding correction method can greatly improve the quality of image stitching.

![Figure 8](image_url)

**Figure 8.** Image stitching results

5. Summary

The side scan sonar image geocoding method based on carrier speed gross error correction proposed in this paper has high feasibility through actual experimental data verification. It can effectively improve the quality of the side-scan sonar images after stitching, thereby laying a solid foundation for the side-scan sonar image registration. However, there are also some problems that need to be solved, such as the presence of significant noise in the lateral velocity information extracted based on the side-scan sonar image. In the future, research will continue on reducing speed noise.

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