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A REAL-TIME ADAPTIVE BOTTOM TRACKING METHOD FOR BATHYMETRIC SIDE-SCAN SONAR

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Abstract. The performance of the existing bottom tracking method is affected by the seabed model, threshold, computation, etc. The bathymetric side-scan sonar (BSS) cannot accurately detect and extract the seabed in real time, which will cause the problems such as side-scan image distortion, the bathymetric image produces false targets or lost targets, etc. Based on the imaging mechanism of BSS and seabed continuity, a real-time adaptive bottom tracking method for BSS is proposed. Considering the relationship between the relative value, absolute value and maximum value of the seabed echo energy, the real-time bottom tracking of seabed in complex environment is realized by using a sliding window to segment the seabed echo and correcting the seabed abnormal points through the approximate invariance of the physical characteristics of the seabed topography. Theoretical simulations and experiments show that the proposed method can adaptively adjust the threshold parameter compared with the existing method, has less computational complexity, and has better automatic tracking performance.

Key words: bathymetric side-scan sonar, bottom tracking, low computational, real-time.

1. INTRODUCTION

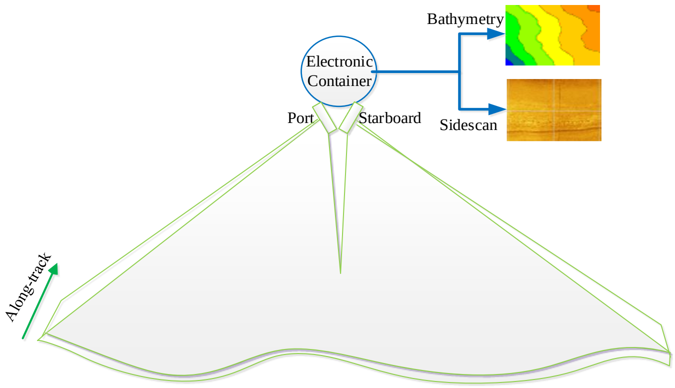
The main task of bathymetric side-scan sonar is to obtain a high-resolution map of the seafloor topography, which is widely used to provide the foundation for marine activities such as explore the seafloor topography, develop marine resources, develop marine scientific research, etc [1–4]. The sea bottom line is the boundary of the water column image and the seabed image, which provides prior information for slope distance correction, automatic gain control, beam angle correction, and direction of arrival (DOA) estimation [5, 6]. Currently, commercial software such as Triton, SonarWeb, and Discovery use threshold control methods which relies on preset parameters such as the amplitude threshold, the starting position, and the number of durations [7, 8]. The disadvantage of this method is that the setting of the amplitude threshold depends on the terrain. Especially when the submarine line is complicated, the threshold needs to be manually set in sections which is inefficient and inaccurate. Zhang uses image edge extraction technology to realize automatic extraction of seabed line, but it is greatly affected by the transmitted pulse, wake, and interference [9, 10]. Zhao proposed a comprehensive detection algorithm, which assumes that the baseline satisfies the hypothesis of symmetry and continuity. At the same time, the seabed line correction depends on third-party sensor information such as tide, height, and depth [11]. Taking into the BSS transducers are installed on both sides of the underwater carrier [12, 13], the carrier has a posture change in the water, which causes the seabed echo may not necessarily meet the symmetry. At the same time, the DOA estimation requires real-time prior knowledge of the seabed line for real-time bathymetry image, resulting in the algorithm to fail to automatically and accurately detect and extract the seabed line in real-time.

Therefore, regarding the issue above, this paper proposes a real-time adaptive bottom tracking method for seabed. The proposed method overcomes the limitations of the amplitude threshold algorithm and comprehensive detection algorithm, which realizes the real-time adaptive extraction of the submarine line and provides real-time effective prior information for DOA estimation for BSS.

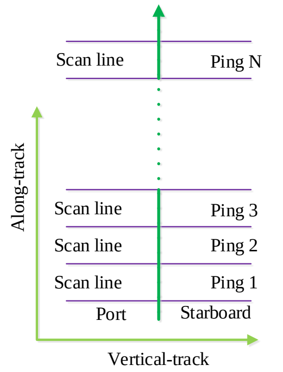
2. METHODS AND MATERIALS

2.1. BSS Imaging Mechanism And Influencing Factors

BSS systems use fan-shaped beampatterns that point sideways to give them a wide field of view in one dimension (across-track) and a narrow field of view in another dimension (along-track). BSS may be mounted on the side of a moving survey vessel or autonomous underwater vehicle (AUV). BSSS are commonly oriented so that they transmit and receive sound from a direction orthogonal to the direction of motion. As the BSSS moves through the water, seabed images are created by repeating the process of a "Ping": transmitting a pulse and receiving the echoes that return from the ensonified portion of the seafloor. After the echoes return from the maximum range of Ping1, the platform has moved forward to a new location, and the process is repeated when Ping2 is transmitted. The intensity of the pulse envelope reflects the information of the ocean floor, i.e. the side-scan image. By estimating the DOA of the echo, the position of the submarine target relative to the sonar, i.e. bathymetry image. Multi-Ping sounding side-scan image stitching to form a seabed sounding side-scan image [14, 15], as shown in Fig. 1.



a) single ping beam pattern



b) multi-Ping scan line timing

Fig. 1 – Principle of BSS.

As shown in Fig. 2, the corresponding slope distance is calculated based on the echo time, i.e. $R = ct/2$. c denotes the speed of sound waves in water, t denotes the corresponding propagation time of seabed target echo to sonar array. We can get the horizontal distance L and height H of the target relative to the sonar array based on the geometric relationship:

$$L = R \cdot \cos\theta \quad (1)$$

$$H = R \cdot \sin\theta . \quad (2)$$

The sonar carrier actually works at a certain height from the seabed, DOA needs to acquire real-time accurate seabed line information as a prior knowledge, otherwise it will produce false terrain or lose target, which will reduce the quality of bathymetric image [16, 17]. The real-time seabed line extraction methods in BSS are constrained by transmit pulse, sea surface interference, seabed type and computation load, which will lead to the failure of the traditional seabed line extraction methods.

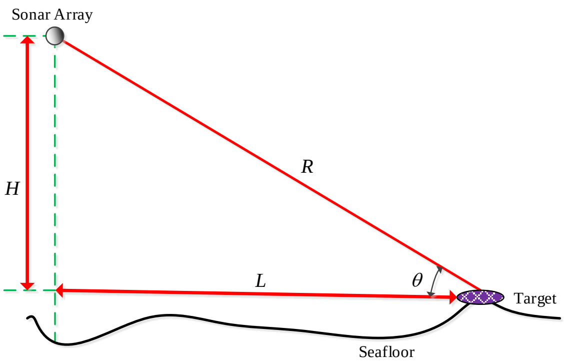


Fig. 2 – Bathymetric schematic diagram.

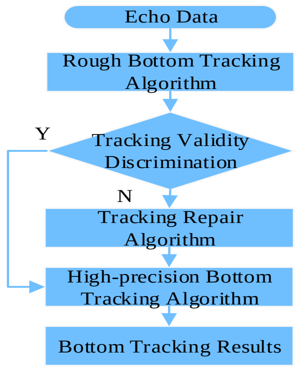


Fig. 3 – Real-time adaptive bottom-tracking method.

2.2. Basic Concept

The real-time adaptive bottom-tracking method uses the sliding window to process seabed echo, i.e. segment processing, calculate the echo energy in the window, i.e. segment energy and then obtain the segment energy sequence $\{x_n\}_{n=1}^{N}$. The methods based on segment energy are defined as follows:

• Energy ratio method

$$B_n = \frac{x_{n+1}}{x_n}, \quad n = 1, \cdots, N-1 \tag{3}$$

$$B_{index} = \max_k \{B_k\}, \quad k = 1, \cdots, N-1. \tag{4}$$

The adjacent elements in the segment energy sequence are ratio-calculated to obtain the ratio sequence B_n, obtain the sequence index number B_{index} corresponding to the maximum value of the ratio sequence.

• Energy difference method

$$C_n = x_{n+1} - x_n, \quad n = 1, \cdots, N-1 \tag{5}$$

$$C_{index} = \max_k \{C_k\}, \quad k = 1, \cdots, N-1. \tag{6}$$

The adjacent elements in the segment energy sequence are difference-calculated to obtain the difference sequence C_n, obtain the sequence index number C_{index} corresponding to the maximum value of the difference sequence.

• Energy maximum method

$$S_{index} = \max_k \{x_k\}, \quad k = 1, \cdots, N. \tag{7}$$

The sequence index number corresponding to the maximum value in the segment energy sequence.

• Energy mean method

$$\bar{x} = \frac{\sum_{k=1}^{N} x_k}{N} \tag{8}$$

$$A_{index} = \min_k \{x_k > \bar{x}, x_{k+1} > \bar{x}\}, \quad k = 1, \cdots, N-1. \tag{9}$$

The sequence index number A_{index} corresponding to the two consecutive elements in the segment energy sequence are greater than the average segment energy $\bar{x}$.

Compared with water scattering, the seabed scattering has strong energy. The acoustic characteristic of different seabeds are quite different. The strong scattering property of the hard seabed make the echo energy have a significant absolute increase, while soft seabed the echo energy of the seabed have a relatively significant increase. Therefore, the four energy methods described above need to be combined to achieve real-time adaptive bottom tracking.

The submarine navigation is affected by many factors in the sea water, which is a slow change process. In order to improve the imaging quality and detection efficiency of the seabed, the BSS generally has a high Ping rate [18-20], the adjacent detection interval is short and the seabed is a continuous change process, so the physical characteristic of the seabed in the two adjacent detections are almost unchanged.

Firstly, a large sliding window is used to process the sea bottom echo to get the rough bottom position. Secondly, the effectiveness of rough bottom position can be judged by using the approximately unvarying feature of the seabed between adjacent pings. Finally, on the basis of rough bottom position echo time, a small sliding window is used to process the sea bottom echo to obtain high-precision seabed position. as shown in Fig. 3.

2.3. Real-time Adaptive Bottom Tracking Method

2.3.1. Rough Bottom Tracking Algorithm

The segment processing with a sliding-window indicates superposition of the echo signal energy in a certain area of the sea floor. A larger window indicates superposition of the echo signal energy in a large area of the sea floor. Due to the echo signal near-invariant characteristic of the adjacent pings, the seafloor position of two adjacent pings is approximately constant (the same sequence index number). Based on the above idea, rough bottom tracking uses a large sliding window to process the seabed echo.

As shown in Fig. 4, the rough bottom tracking algorithm uses a large sliding-window function to process the seabed echo. Due to the short-term invariance characteristics of the seafloor and high ping rate, which ensures the rough bottom position will not change greatly. Using the relationship between the energy maximum of seafloor echo, energy jump, energy average, and energy difference, the rough bottom tracking information is obtained, which provides an effective basis for the high-precision bottom tracking algorithm.

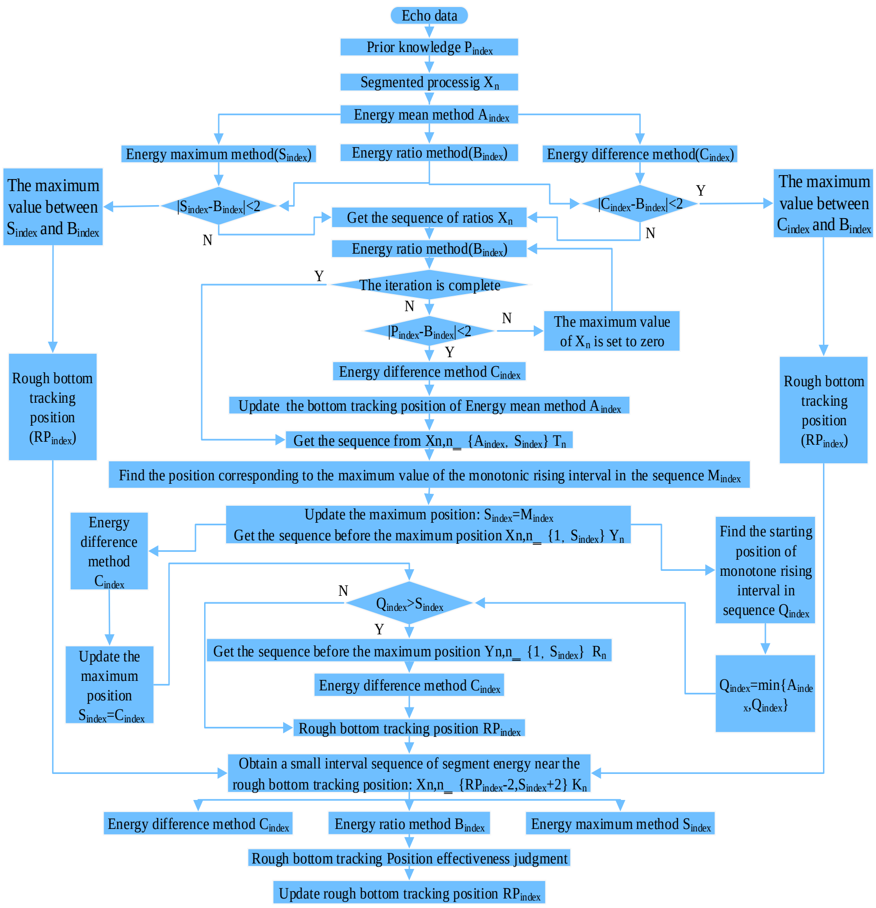


Fig. 4 – Rough bottom tracking algorithm.

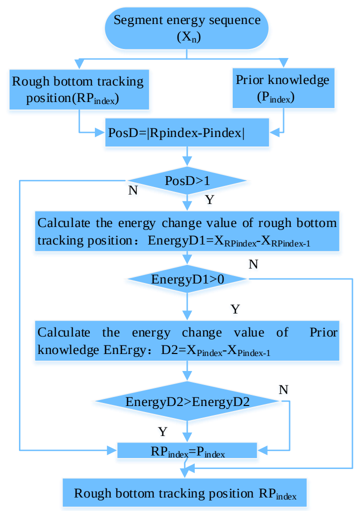


Fig. 5 – Repair of Abnormal Tracking algorithm.

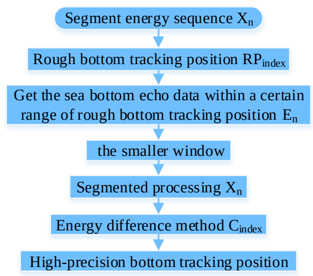


Fig. 6 – High-precision bottom tracking algorithm.

2.3.2. Repair of Abnormal Tracking Algorithm

Due to the physical properties of the water body and the seabed are different, the intensity of backscattering on the seabed is much greater than water, so the acoustic waves will have a large energy jump at the interface between water and seabed. A large sliding-window is used for rough bottom tracking algorithm to ensure it has short-term invariant characteristics. When rough bottom position and prior knowledge(last rough bottom position) are not in the same resolution unit, Calculating the energy change value of the adjacent segment of the energy sequence in the rough bottom position and the prior knowledge respectively, and select the position with large energy change as the rough bottom position. In this way, we can avoid relying on prior knowledge, but only use prior knowledge to judge the effectiveness and repair the abnormal of rough bottom position, as shown in Fig. 5.

2.3.3. High-precision Bottom Tracking Algorithm

Based on the rough bottom information provided by rough bottom tracking algorithm, the high-precision seabed echo information is further processed by using the energy change suddenly characteristics. As shown in Fig. 6, a small sliding-window is used to process the echo data corresponding to the energy of the adjacent section of the rough bottom tracking position. The corresponding energy sequence is calculated and the real-time bottom tracking position is obtained by the using energy difference method. Because the smaller window is used, the higher precision bottom position is obtained.

3. NUMERICAL SIMULATIONS AND EXPERIMENTAL RESULTS

In order to analyse and verify the performance of various bottom tracking algorithms, the simulation of seabed is carried out for flat seabed, symmetric varying seabed and asymmetric varying seabed. The signal parameters are shown in Table 1. For the threshold bottom algorithm, the performance of the algorithm depends on parameters [21], two sets of different parameters are set to compare their effects on the performance of the algorithm. The parameters are shown in Table 2.

Table 1

Simulation signal parameters

Frequency (KHz)	Bandwidth (KHz)	Pulse Width (ms)	Sound Speed (m/s)
200	20	6	1500

Table 2

Threshold bottom tracking algorithm parameters

Name	Amplitude Coefficient	Starting	Duration	Ping Counter
SonarWeb	0.05	3	3	3
SonarWebV1	0.15	3	3	3

In the actual work of the sonar system, there are certain differences between the theoretical model and the actual model [22–24]. In order to verify the performance of the algorithm in the actual situation, the three seabed mentioned are verified by experiments in Zhoushan City, Zhejiang Province, as shown in Fig. 7.

a) system connection b) sonar c) data collection d) control terminal

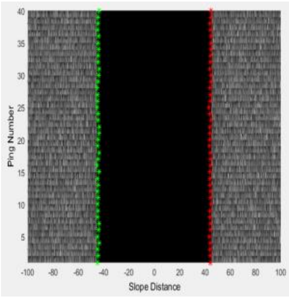
Fig. 7 – Field experiment.

3.1. Flat Seabed

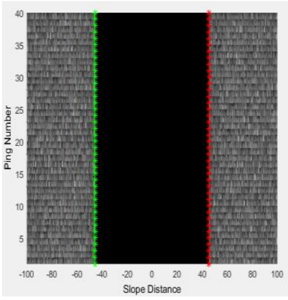
The flat sea floor is mainly used to verify the robustness of the algorithm. When the sea floor height is almost constant, the bottom tracking fluctuation can directly indicate the performance of the bottom tracking algorithm.

Figure 8 shows that the threshold bottom tracking performance depends on parameters, the comprehensive detection algorithm has high performance. The proposed algorithm has some fluctuation which is caused by the real-time change of bottom echo threshold, but it still has good bottom tracking performance. Figure 9 shows that comparing with the SonarWeb algorithm, the proposed algorithm has lower computational load and is more suitable for sonar systems with high ping rates.

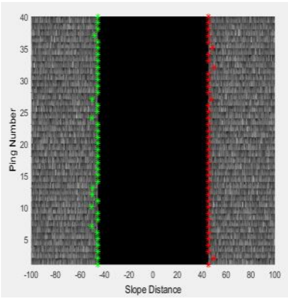
Figure 10 shows that the SonarWeb algorithm has several fluctuations, the SonarWebV1 algorithm, comprehensive detection algorithm, and proposed algorithm have similar bottom tracking performance. The algorithm proposed in this paper has lower complexity, as shown in Fig. 11.



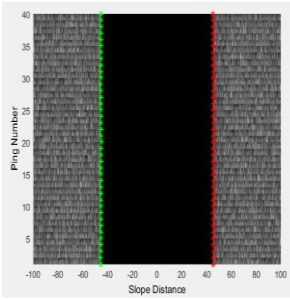
a) SonarWeb



c) Comprehensive detection algorithm

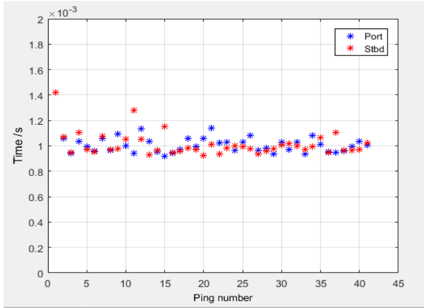


b) Proposed algorithm

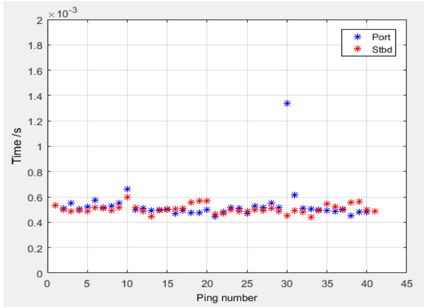


d) SonarWeb1

Fig. 8 – Algorithm performance comparison on the flat seabed simulation.



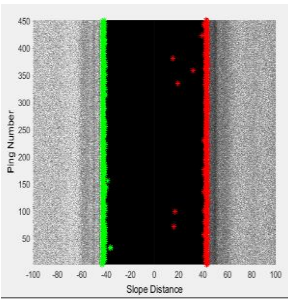
a) SonarWeb



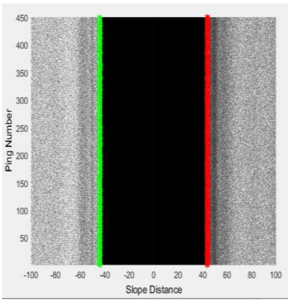
b) Proposed algorithm

Fig. 9 – Time consuming comparison on the flat seabed simulation

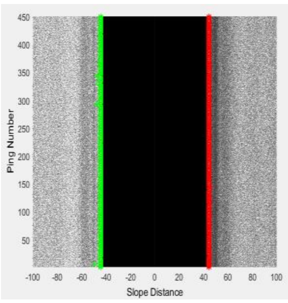
Therefore, it can be seen from the theory and simulation that when the seabed is flat, the sea bottom characteristics can be considered as approximately unchanged, the sea bottom echo characteristics maintain good consistency, and all methods can achieve better bottom tracking performance. However, because the threshold setting of the threshold bottom tracking algorithm is constant, compared with other algorithms, there are a certain amount of abnormal points.



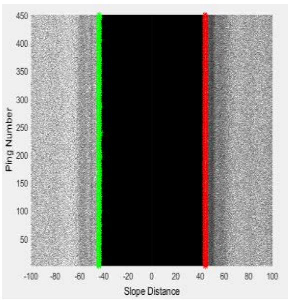
a) SonarWeb



c) Comprehensive detection algorithm

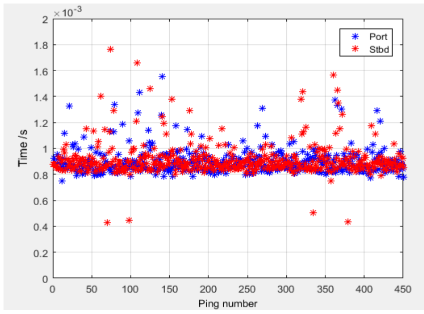


b) Proposed algorithm

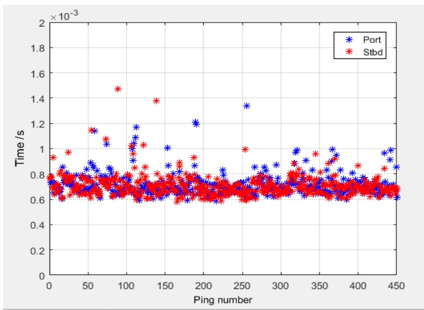


d) SonarWeb1

Fig. 10 – Algorithm performance comparison on the flat seabed experiment.



a) SonarWeb



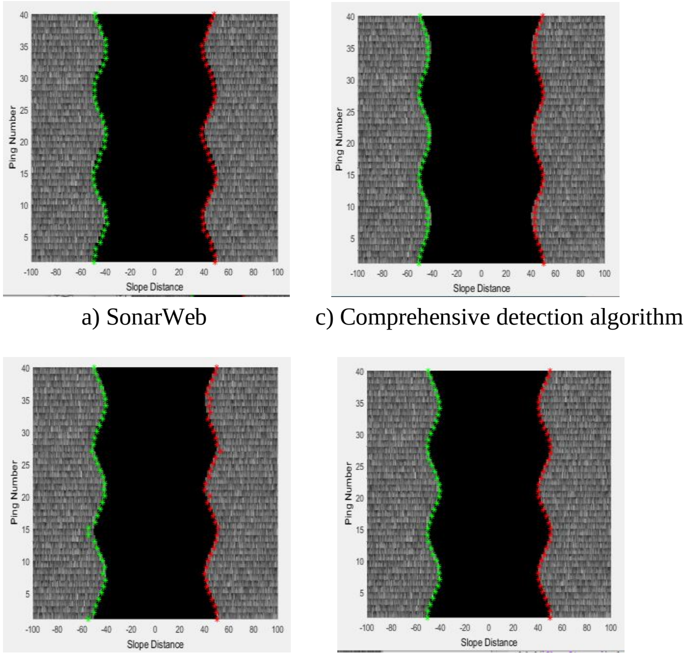
b) Proposed algorithm

Fig. 11 – Time consuming comparison on the flat seabed experiment.

3.2. Symmetric Varying Seabed

The symmetrical varying sea bottom means that the seabed is symmetrical and continuously changes. This model is also the most common model of seabed echoes in the actual operation of sonar. This model is used to verify the tracking performance of different bottom tracking algorithms when the seabed characteristics continuously change.

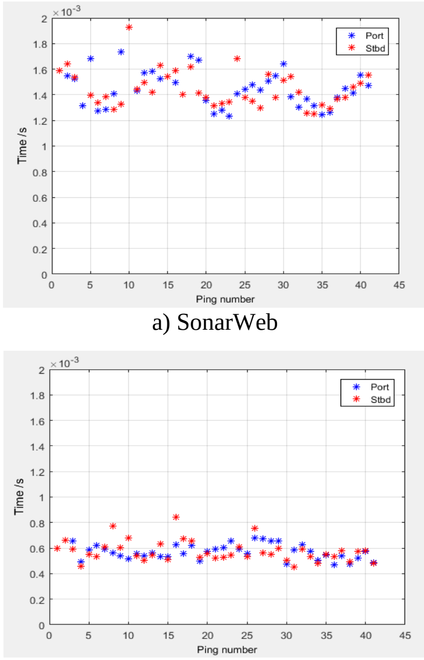
Figure 12 shows that all algorithms have better performance, however, comparing with SonarWeb algorithm, the efficiency of proposed algorithm is improved by nearly 2.5 times, as show in Fig. 13.



a) SonarWeb c) Comprehensive detection algorithm

b) Proposed algorithm d) SonarWeb1

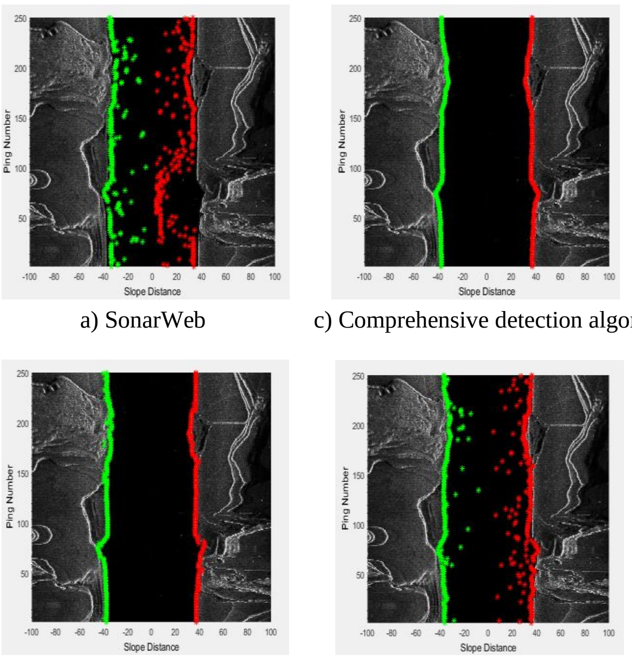
Fig. 12 – Algorithm performance comparison on the symmetry varying seabed simulation.



a) SonarWeb

b) Proposed algorithm

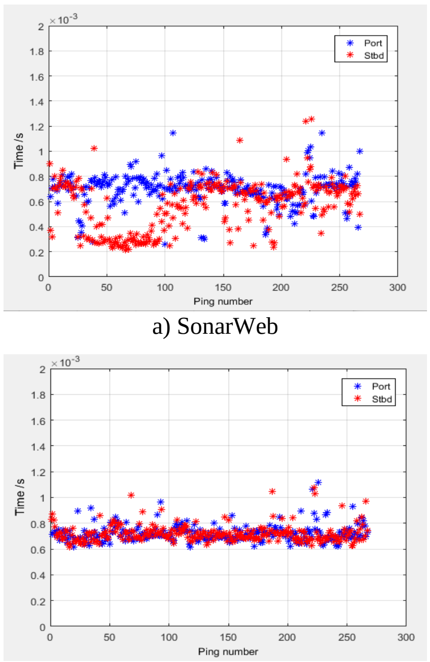
Fig. 13 – Time consuming comparison on the symmetry varying seabed simulation.



a) SonarWeb c) Comprehensive detection algorithm

b) Proposed algorithm d) SonarWeb1

Fig. 14 – Algorithm performance comparison on the symmetry varying seabed experiment.



a) SonarWeb

b) Proposed algorithm

Fig. 15 – Time consuming comparison on the symmetry varying seabed experiment.

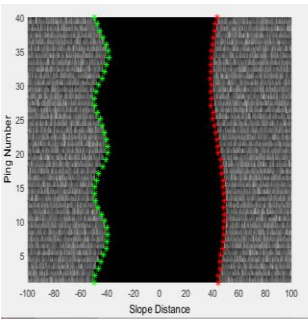
Compared with the flat seabed, the performance of the threshold bottom algorithm has decreased, but SonarWeb has decreased significantly, which is caused by the inconsistency of the bottom tracking parameters. the proposed algorithm has similar performance as the comprehensive bottom tracking algorithm, but has lower computational complexity, as show in Fig. 15.

Compared with the flat seabed, the bottom echo characteristics of symmetry varying seabed are in a slowly changing state. At this time, a certain self-adaptation ability of the bottom tracking algorithm is required to automatically adjust and track this change. Compared with theoretical simulation, actual seabed echoes have more complex acoustic characteristics. Therefore, the threshold bottom tracking algorithm is set to a fixed threshold, which causes the performance of the bottom tracking algorithm to decrease, different bottom thresh-old cause different degrees of divergence. The proposed algorithm and the comprehensive detection algorithm have certain self-adjusting ability, so they have better bottom tracking accuracy and robustness.

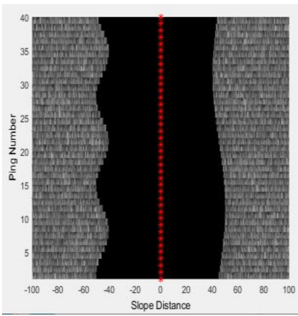
3.3. Asymmetric Varying Seabed

The transducer is installed on the sonar carrier when sonar is actually working, and the sonar carrier changes its attitude in real time, which may cause the inconsistency of the received reflection of the seabed from the port and starboard, i.e., dissatisfaction with symmetry hypothesis.

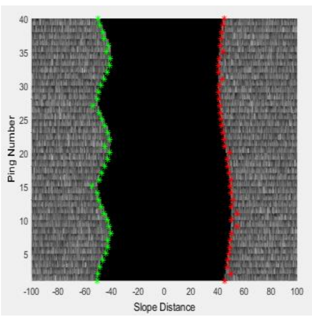
Figure 16 shows that the comprehensive detection algorithm fails when the seabed does not meet the symmetry. However, comparing with SonarWeb algorithm, the efficiency of proposed algorithm is improved by nearly 3 times, as shown in Fig. 17.



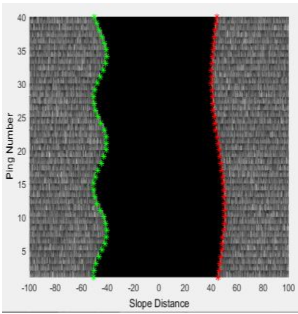
a) SonarWeb



c) Comprehensive detection algorithm

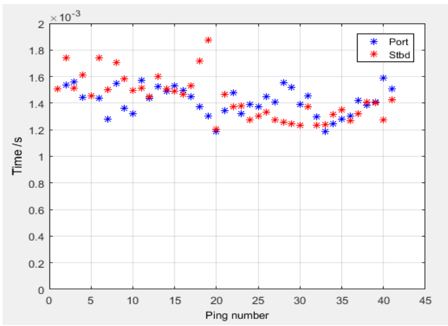


b) Proposed algorithm

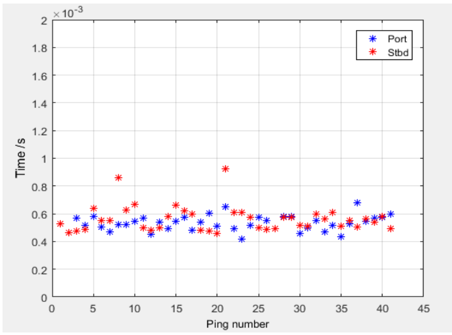


d) SonarWeb1

Fig. 16 – Algorithm performance comparison on the asymmetry varying seabed simulation.



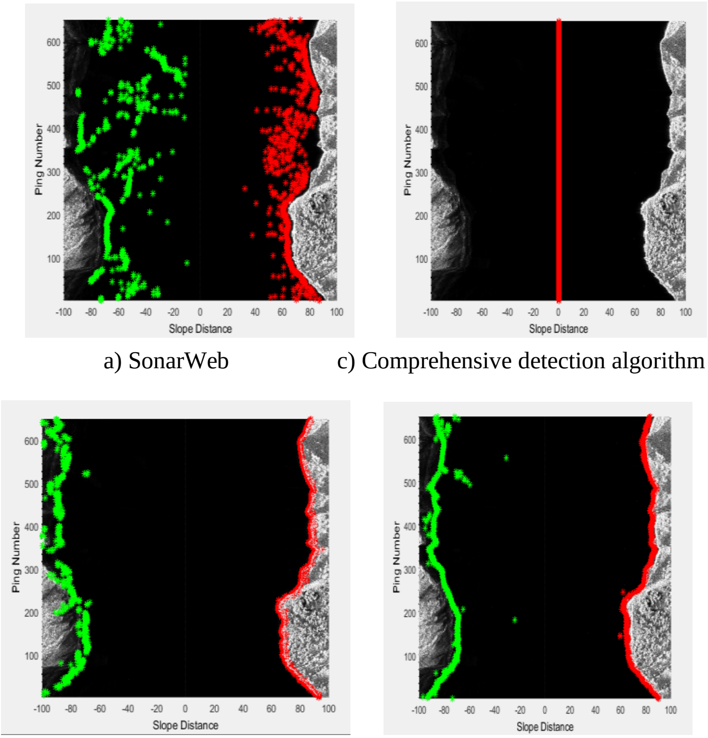
a) SonarWeb



b) Proposed algorithm

Fig. 17 – Time consuming comparison on the asymmetry varying seabed simulation.

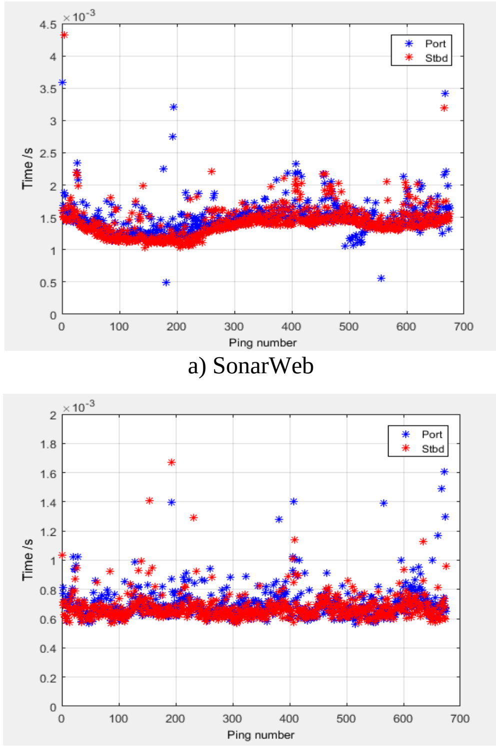
Figure 18 shows that the backscattering intensity of starboard seabed is obviously higher than that of port seabed matter, which does not satisfy the symmetry hypothesis, causing the comprehensive detection algorithm fails. The performance of threshold bottom algorithm depends on parameters. The performance of the proposed algorithm has decreased, but still effectively implements the seabed extraction and has a lower computational complexity, as shown in Fig. 19.



a) SonarWeb c) Comprehensive detection algorithm

b) Proposed algorithm d) SonarWeb1

Fig. 18 – Algorithm performance comparison on the asymmetry varying seabed experiment.



a) SonarWeb

b) Proposed algorithm

Fig. 19 – Time consuming comparison on the asymmetry varying seabed experiment.

When the seabed does not meet the symmetry assumption, the bottom tracking algorithm needs to have strong adaptive ability. The threshold bottom algorithm uses a fixed threshold, its performance depends on the threshold and does not have the ability to adapt. The comprehensive detection algorithm uses the seabed symmetry assumption to realize self-adaptive, when it does not meet the assumption, the performance of the algorithm drops sharply or even fails.

4. CONCLUSIONS

The threshold bottom algorithm uses energy threshold to achieve bottom tracking, its performance depends on the preset threshold, which determines the divergence degree of the bottom tracking abnormal points. Because it uses a fixed threshold and does not have adaptive capabilities, in practice, the threshold needs to be adjusted manually to achieve the optimal state. The comprehensive detection algorithm assumes that the seabed meets symmetry and uses third-party sensor information to repair the seabed anomalies. The algorithm has good performance when satisfying the symmetry assumption, while on an asymmetrical seabed, the performance of the algorithm drops or even fails. This algorithm requires a large amount of calculation and is only suitable for data post-processing, which cannot realize real-time bottom tracking.

To solve the above problem, a real-time adaptive bottom tracking was proposed in this paper, which uses the seabed echo energy characteristics to adjust the threshold in real time. The algorithm has less computation and better tracking ability, which can be applied to sonar systems with high Ping rate. Theoretical simulation and experiment results show that the algorithm has a very small amount of computation and real-time seabed extraction. However, in soft seabed, the seabed has a certain absorption of acoustic waves. To reduce the impact of seabed absorption on the bottom tracking performance, more theoretical analysis and experimental work are still needed, which will be the focus of our future research.

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