Research on developing an adaptive algorithm for enhancing the quality of underwater positioning based on the sonar USBL principle

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ABSTRACT

The paper proposes an enhanced solution for improving the accuracy of underwater object positioning based on the Ultra-Short Baseline (USBL) sonar principle. In shallow water regions, complex hydrological phenomena affect the quality of underwater acoustic signal transmission and reception, making it essential to enhance the processing of these signal groups. Through the USBL system model, the paper presents a model capable of adaptively selecting accurate signals amidst the noisy underwater environment. The proposed model is implemented and validated in practice using FPGA hardware in Lan Ha Bay. The results demonstrate the effectiveness of the proposed algorithm compared to conventional approaches, as it extends the management range and optimizes the transmission power of the system, even in cases of low signal-to-noise ratio.

Keywords: USBL; Adaptive algorithm; FPGA; Shallow water.

1. SYSTEM OVERVIEW AND RELATED RESEARCH

The management and localization of underwater objects in shallow water represent a significant area of interest in national security and economic development. This topic has drawn the attention of numerous scientists in Vietnam and around the world. Specifically, active sonar systems operating on the principle of Ultra-Short Baseline (USBL) are commonly employed for coastal port monitoring due to their advantages in terms of flexibility (rapid setup time, integration capabilities), performance (real-time signal processing, simultaneous management of multiple objects, and high accuracy) [1]. Based on the principles of hydroacoustic signal transmission and reception, USBL systems can accurately determine the range and direction between objects and a ground station.

However, in practical applications, the complex hydrodynamic phenomena in shallow coastal waters significantly impact the effectiveness of USBL systems. Shallow coastal waters are defined as the spatial region extending from the water surface to a depth of approximately 200 meters [2]. Within this shallow water domain, various phenomena, such as surface and bottom reflections, scattering, and refraction due to currents, as well as temporal and depth-related temperature variations, introduce signal interference, thereby affecting the system's performance and signal quality.

Currently, most research efforts aimed at improving the localization quality of USBL systems primarily focus on addressing noise filtering in the received response signals [3, 4]. Within this group of problems, many scientists have adopted two main approaches: (1) optimizing the signal structure for specific cases and (2) selecting signal processing algorithms for noise filtering with adjustable parameters. These approaches each have their own advantages and disadvantages, and the choice of which approach to adopt depends on the specific characteristics of the sonar system and its intended use.

In approach (1), sonar systems employ various types of modulated frequency waves

[5], frequency-hopping codes [6], or frequency hopping within each transmit pulse sequence [7] to enhance target detection and localization. However, a drawback of this approach is its lack of flexibility in adapting to real-world scenarios when there are variations in signal intensity, source-receiver distances, and other conditions. This can diminish the system's effectiveness in practical deployments in shallow coastal areas with complex hydrodynamic conditions. Therefore, providing adaptive solutions for signal reception in the receiver is of paramount importance rather than directly utilizing complex signals.

In approach (2), advanced signal processing algorithms such as Spectral Subtraction (SS), Principal Component Analysis (PCA), Kalman filtering, and joint filtering are used to separate useful signals from background noise in sonar systems. However, several challenges persist. SS, for example, can remove both noise and useful signals when the signal-to-noise ratio is very low [8]. PCA assumes that noise and signals are uncorrelated, which can be problematic when dealing with real-world signals [9]. Joint filtering lacks adaptability to sound sources with complex time-varying characteristics [10].

Overall, the practical effectiveness of hydroacoustic systems using either approach (1) or (2) faces difficulties due to their limited adaptability to environmental conditions. Therefore, the paper proposes the development of an adaptive model that combines both of these approaches to maximize noise reduction and enhance the performance of USBL-based sonar systems. This combined approach is considered suitable for addressing these challenges.

The previous publications from our research group have primarily focused on building USBL sonar system models using linear frequency-shifted signals [11], and optimizing baseline algorithms for USBL systems while incorporating the structure of Costas frequency-hopping signals [12]. In continuing the development of our previously published research findings, this paper presents the results of constructing and implementing an adaptive algorithm optimized for USBL systems. To achieve this goal, section 2 outlines the system's approach and algorithm flowchart. Section 3 provides the verification results of the algorithm using the Costas frequency-hopping signal structure in real-world conditions in Lan Ha Bay, Vietnam. It evaluates the algorithm's performance and compares it with equivalent published results. Finally, the paper concludes with a general summary and outlines directions for future research.

2. PROPOSED MODEL AND PROPOSED ADAPTIVE ALGORITHM

2.1. Proposed model

The proposed adaptive model is constructed to mitigate the occurrence of false alarm results in signal detection problems, which often happen when setting the decision threshold too low (leading to false alarms) or too high (resulting in the omission of useful signals). Therefore, the model's requirement is to have an environment-adaptive threshold detector that can maximize detection performance while maintaining a constant false alarm rate. This applies to both hydroacoustic signal detection in general and sonar signal detection in particular.

The proposed model is a combination of utilizing Costas frequency-hopping signals and an adaptive joint filter solution, as illustrated in figure 3. In this setup, the Costas frequency-hopping signals s(t) are transmitted into the environment through a transmitting antenna array. The signals received at the receiver antenna array are affected by environmental noise. The received signal at the receiver is passed through a low-pass filter, undergoes analog-to-digital conversion (ADC), and is processed by the adaptive algorithm. Finally, the system makes a decision: whether a signal is present or not.

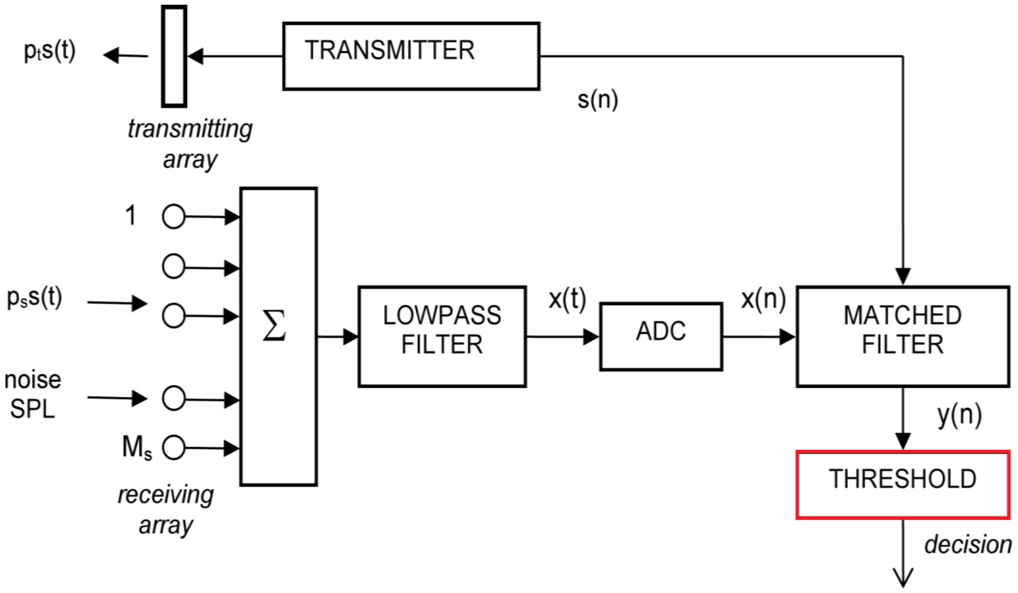

Figure 1. *Proposed adaptive algorithm for USBL system.*

The adaptive algorithm is constructed with the aim of establishing adaptive threshold values that can change according to the environmental conditions. When the received signal has varying signal-to-noise ratios, the adaptive threshold values are computed and adjusted by the proposed model to ensure a fixed false alarm rate. These adaptive thresholds are set at the output of the joint filter to make the decision about the presence or absence of the target signal.

2.2. Adaptive algorithm for model

The Constant False Alarm Rate (CFAR) algorithm is applied in radar-based detection techniques to detect targets [13]. However, in USBL sonar systems, CFAR has limitations, as mentioned in previous research [2, 14].

The essence of the CFAR algorithm [13] is to calculate the decision threshold value for the detector based on the estimation of noise power from the signal samples obtained within a time interval equal to the processing window width of the detector. The calculation process is performed on each data cell of the data vector, as illustrated in figure 2.

In this context, the processing window comprises the Cell Under Test (CUT) in the center, along with guard cells and reference cells evenly distributed on both sides of the CUT. In each iteration of the calculation, the reference cells are input into the statistical estimation block to compute the Z value. Subsequently, the Z value is multiplied by the scaling factor α, which depends on the estimation method and the desired false alarm probability. Finally, the value $T_{tn} = \alpha.Z$ is used as the threshold for comparison with the value of the CUT to make a decision on the presence or absence of a useful signal.

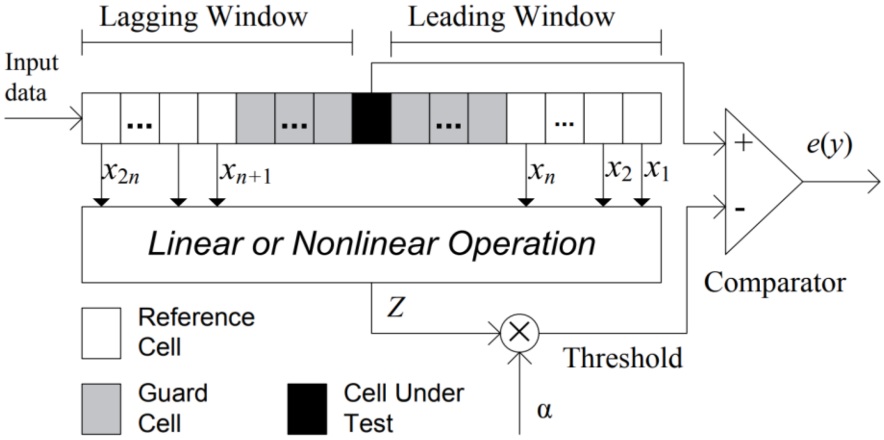

Figure 2. *General principle of implementing CFAR detector [13].*

For the Cell Averaging CFAR (CA-CFAR) algorithm, the statistical estimation block estimates the noise power based on the average value of the reference samples:

$$Z = \frac{1}{2n}\sum_{i=1}^{2n} x_i \tag{1}$$

Under the assumption that the false alarm probability P_{FA} and the size of the reference window 2n are fixed, the scaling factor α_{CA} is a constant determined by the following relationship:

$$\alpha_{CA} = 2n\left(P_{FA}^{-1/2n} - 1\right) \tag{2}$$

3. EXPERIMENT RESULTS OF THE ADAPTIVE MODEL

3.1. System Configuration and Signal Structure Selection

The adaptive model is designed for data processing at the output of the joint filter in the receiving line of the USBL system using a four-hydrophone array, similar to the published results by the author's team [11, 12]. The algorithm's execution results are tested on real data obtained from the USBL system when transmitting Costas frequency-hopping signals as used in [12].

The main technical specifications of the USBL underwater acoustic positioning system are presented in table 1 below:

Table 1. *USBL system configuration.*

Parameter	*Value*
Frequency range	28 – 36 KHz
Modulation signal	Costas hopping
Transmit pulse width	8 ms
Sampling frequency	200 KHz
Speed of sound in water	1500 m/s

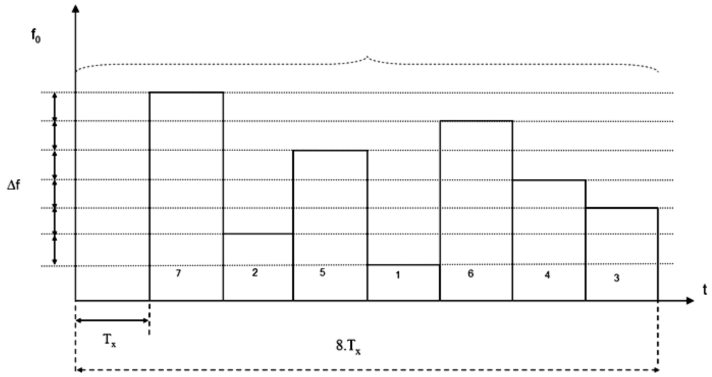

Figure 3. *A sequence of Costas frequency-hopping signal in the 28 - 36 kHz.*

With T_x being the width of an individual pulse within the sequence and Δ_f representing the frequency step size of the Costas signal.

3.2. Flowchart in FPGA

The flowchart of the CA-CFAR algorithm is presented in figure 4.

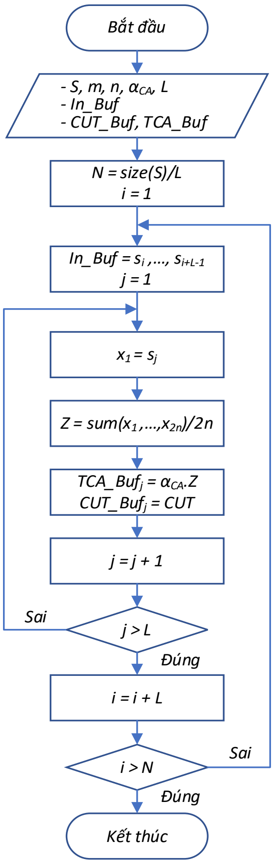

Figure 4. *Flowchart of the CA-CFAR algorithm implementation.*

In this diagram, S represents the input data, In_Buf is a buffer for input data with a size of L samples, CUT_Buf is a buffer for storing samples at the CUT position, and TCA_Buf is a buffer for storing the CA-CFAR algorithm-calculated threshold values. The noise power is the result of averaging over the entire reference window. With a sampling rate of 200 KHz, the corresponding time for processing each input data sample is 5 µs. To ensure real-time processing by the CA-CFAR detector, the total delay introduced by the detector must be less than 5 µs for each processing sample. The CA-CFAR algorithm involves both averaging and multiplication operations. Therefore, in practical hardware implementation, with appropriate design parameters, these operations can be performed using register shifting. This advantage allows the adaptive model to handle real-time processing through FPGA circuits and implementation in the actual USBL system.

3.3. Experiment results

To evaluate the effectiveness of the proposed model, the system is set up and compared in two scenarios: with adaptation (adaptive threshold T_{tn}) and without adaptation (fixed threshold $T_{\text{cđ}}$), with the same transmit power at different ranges (d) at a depth of 20 m; the results were statistically analyzed based on 10 trials.

3.3.1. Case 1: The distance d is 12 meters

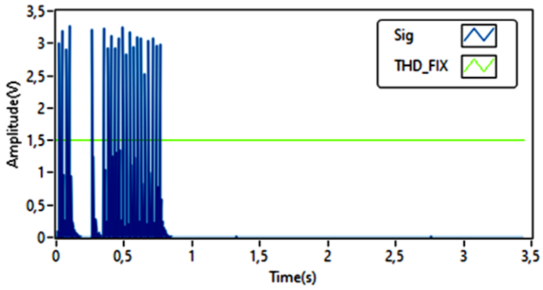

Figure 5. *Signal detection with $T_{\text{cđ}}$ = 1,5 in d =12 m.*

If the fixed threshold value is chosen as $T_{\text{cđ}}$ = 1.5 (figure 5), the receiver will not detect all the useful frequency components, which affects the system's effectiveness. If $T_{\text{cđ}}$ = 0.5 is chosen (figure 6a), there is a significant improvement in the system's performance. The detection results show an effectiveness equivalent to the adaptive threshold (figures 6b, 6c).

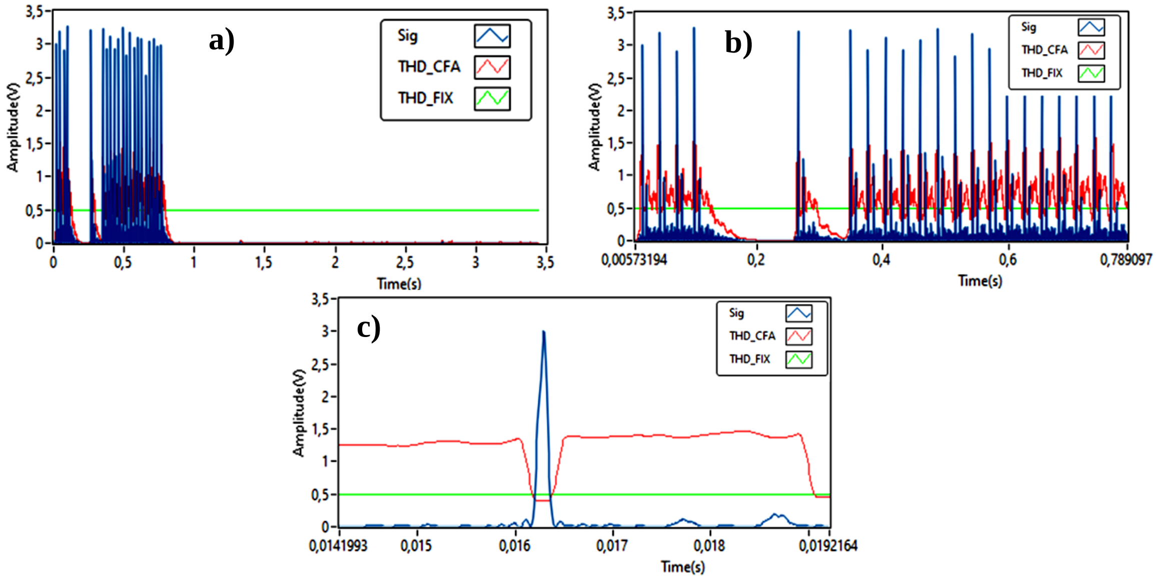

Figure 6. *Signal detection with $T_{\text{cđ}}$ = 0,5 and T_{tn} in d =12 m.*

3.3.2. Case 2: The distance d is 300 meters

When changing the range from 12 m to 300 m, the results show that with a fixed threshold $T_{cđ}$ = 0.5, the system cannot detect useful signals (figure 7). The system only detects useful signals when the $T_{cđ}$ = 0.1. In contrast, with the adaptive algorithm, where the T_{tn} coefficient changes based on the quality of the received signal, the system was able to detect the useful frequency components (figure 8).

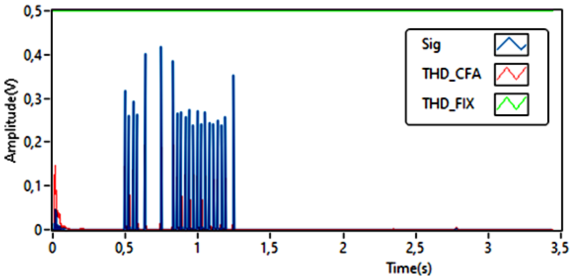

Figure 7. *Signal detection with $T_{cđ}$ =0,5 in d = 300 m.*

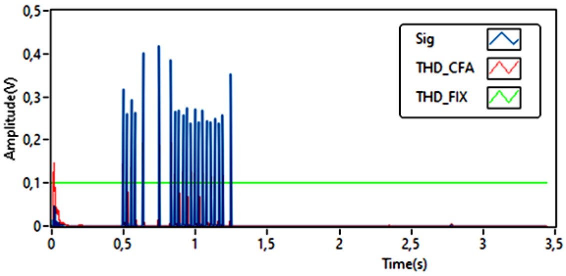

Figure 8. *Signal detection with $T_{cđ}$ =0,1 and T_{tn} in d=300 m.*

3.3.3. Case 3: The distance d is 1100 meters

At a distance of d = 1100 m, to detect a signal with a fixed threshold $T_{cđ}$ = 0,01 (figure 8), it is impractical to manually adjust threshold coefficients for USBL sonar systems. With the adaptive algorithm, the results show that at 1100 m, the proposed model still operates effectively. The test results at a 1km range provide performance equivalent to existing foreign products with the same input parameters of the system [14].

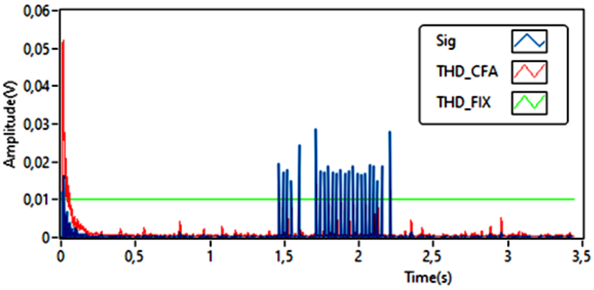

Figure 9. *Signal detection with $T_{cđ}$ = 0,1 and T_{tn} in d = 1100 m.*

3.3.4. Case 4: The distance d is 1565 meters

The adaptive model continues to be tested at a distance of d = 1565 m, which is farther than the operational limit of some foreign products [14]. The results show that with $T_{cđ}$ = 0.01, the system cannot detect the reflected signal (figure 9a), while the proposed model can still detect the signal with a very low signal-to-noise ratio (figure 9b).

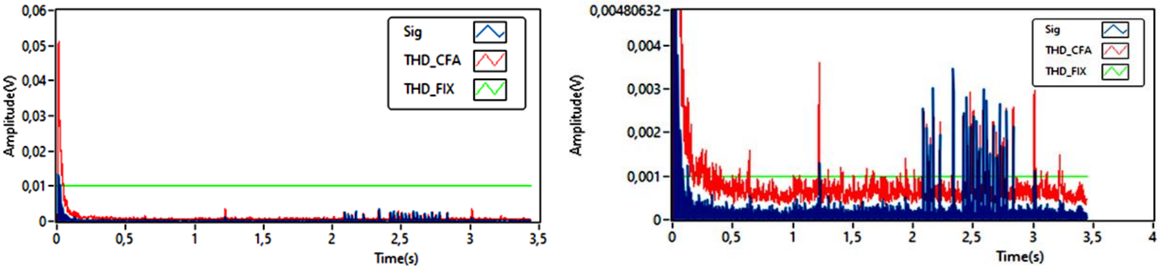

Figure 9. *Signal detection with $T_{cđ}$ = 0,01 and T_{tn} in d = 1565 m.*

The test results at distances of 12 m, 300 m, 1100 m, and 1565 m demonstrate that the adaptive algorithm is more effective than choosing a fixed detection threshold. The adaptive model enhances the system's ability to detect signals in real-world conditions, improving the operational range and accuracy of the system in complex hydrological environments.

4. CONCLUSIONS

The paper is rooted in theoretical research on signal structure and modern hydroacoustic signal processing algorithms. It progresses to propose and develop adaptive algorithm models, followed by their implementation and validation in real-world systems. The results are then compared with equivalent published findings. The effectiveness of the adaptive model is demonstrated in the detection range of signals under complex hydrodynamic conditions in the shallow coastal waters of Vietnam, thereby enhancing the accuracy and flexibility of the system.

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TÓM TẮT

Nghiên cứu phát triển thuật toán thích nghi nhằm nâng cao chất lượng định vị dưới nước dựa trên kỹ thuật sonar USBL

Bài báo đề xuất một giải pháp nhằm nâng cao độ chính xác trong kỹ thuật định vị dưới nước sử dụng đường cơ sở cực ngắn (USBL) dựa trên nguyên lý sonar. Ở vùng nước nông, các hiện tượng thủy văn phức tạp ảnh hưởng đến chất lượng truyền và nhận tín hiệu âm, do đó việc xử lý các tín hiệu này trở nên rất quan trọng. Thông qua mô hình hệ thống USBL, bài báo trình bày một mô hình có khả năng lựa chọn thích nghi các tín hiệu chính xác trong môi trường phức tạp dưới nước. Mô hình đề xuất được triển khai và kiểm nghiệm trong thực tế trên phần cứng FPGA tại Vịnh Lan Ha. Kết quả cho thấy hiệu quả của thuật toán đề xuất so với các phương pháp thông thường, giải pháp này cho phép mở rộng phạm vi quản lý và tối ưu hóa công suất truyền của hệ thống, ngay cả trong trường hợp tỷ lệ tín trên tạp thấp.

Từ khóa: USBL; Thuật toán thích nghi; FPGA; Vùng nước nông.