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MATHEMATICAL MODEL, ALGORITHM, AND SOFTWARE SUITE FOR ACOUSTIC LOCALIZATION OF UNDERWATER OBJECTS



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ANNOTATSIYA. Suv osti obyektlarini akustik usulda lokalizatsiya qilish uchun yagona matematik model, vaqt farqiga asoslangan (TDOA) lokalizatsiya algoritmi hamda ularni amalga oshiruvchi dasturiy majmua arxitekturasini taklif etilgan. Suv muhitida tovush tezligining harorat, sho'rlanish darajasi va chuqurlikka bog'liqligini hisobga oluvchi model asosida gidrofonlar tarmog'idan olingan signallar o'zaro korrelyatsiya usuli yordamida qayta ishlanadi, obyektning fazoviy koordinatalari esa eng kichik kvadratlar usuli orqali aniqlanadi. Kompyuter simulyatsiyasi natijalari signal-shovqin nisbati hamda sensorlar sonining lokalizatsiya aniqligiga ta'sirini ko'rsatadi. Taklif etilgan yondashuvdan suv osti obyektlarini aniqlash va lokalizatsiya qilish, jumladan, g'arq bo'lgan insonlarni qidirish tizimlarida foydalanish mumkin.

Kalit so'zlar: akustik lokalizatsiya, suv osti obyektlari, TDOA, gidrofon, matematik modellash, dasturiy majmua, sonli usullar.

АННОТАЦИЯ. Представлены единая математическая модель акустической локализации подводных объектов, алгоритм локализации на основе разности времени прихода сигнала (TDOA), а также архитектура программного комплекса для их реализации. Модель учитывает зависимость скорости распространения звука в водной среде от температуры, солёности и глубины. Сигналы, полученные от сети гидрофонов, обрабатываются методом взаимной корреляции, а пространственные координаты объекта определяются методом наименьших квадратов. Результаты компьютерного моделирования демонстрируют влияние отношения сигнал/шум и количества сенсоров на точность локализации. Предложенный подход может применяться для обнаружения и локализации подводных объектов, в том числе в системах поиска утонувших людей.

Ключевые слова: акустическая локализация, подводные объекты, TDOA, гидрофон, математическое моделирование, программный комплекс, численные методы.

ABSTRACT. A unified mathematical model for the acoustic localization of underwater objects, a Time Difference of Arrival (TDOA)-based localization algorithm, and the architecture of a software suite for their implementation are presented. The model accounts for the dependence of sound speed in the underwater environment on temperature, salinity, and depth. Signals received from a hydrophone array are processed using the cross-correlation method, while the spatial coordinates of the object are estimated using the least-squares method. Computer simulation results demonstrate the effects of the signal-to-noise ratio and the number of sensors on localization accuracy. The proposed approach can be applied to the detection and localization of underwater objects, including systems designed to search for drowned persons.

Keywords: acoustic localization, underwater objects, TDOA, hydrophone, mathematical modeling, software suite, numerical methods.

INTRODUCTION

The task of detecting and locating various objects (such as drowning victims, submerged vehicles, remnants of engineering structures, etc.) in bodies of water—rivers, lakes, and reservoirs—is of significant practical importance for rescue services, hydraulic engineering, and environmental monitoring. In a previously published paper by the author titled “Modern Methods for Detecting Underwater Objects: Comparative Analysis and Advantages of the Acoustic Approach,” optical, electromagnetic (radar, GPR), and acoustic (sonar) methods were compared; the study demonstrated the advantages of the acoustic method in terms of propagation range and reliability, taking into account the high density of water and the rapid attenuation of optical and electromagnetic waves within it. A second paper—“Mathematical Model of Acoustic Signal Propagation in an Aquatic Environment”—proposed a model that accounts for the dependence of sound speed on temperature, salinity, and pressure.

However, the modeling and methodological approaches outlined in these studies need to be integrated into a

unified algorithmic and software solution for practical application. While the theoretical foundations of acoustic modeling are well established in international literature [1, 2], and Time Difference of Arrival (TDOA)-based localization methods have been primarily developed for radio signal and GPS systems [4, 5], integrated solutions implemented at the level of numerical methods and software suites and accounting for the specific characteristics of the underwater environment, such as signal attenuation, multipath propagation, and hydrophone synchronization, remain an important area of research.

The objective of this article is to develop, as an integrated system, a mathematical model, a time-difference-based localization algorithm, and the architecture of a software suite for the acoustic localization of underwater objects, as well as to evaluate the system's accuracy through computer simulation.

LITERATURE REVIEW

Urick, R. J. *Principles of Underwater Sound*. 3rd ed. New York: McGraw-Hill, 1983. Urick's book provides a fundamental theoretical basis for understanding underwater sound propagation. In the article, this source is relevant to the general acoustic approach to underwater object detection and localization. Its importance is reflected in the discussion of acoustic propagation as a practical alternative to optical and electromagnetic methods in aquatic environments. The source supports the physical and acoustic background of the proposed mathematical model and helps establish the scientific basis for using acoustic signals in underwater detection systems.

Etter, P. C. *Underwater Acoustic Modeling and Simulation*. 4th ed. Boca Raton: CRC Press, 2013. Etter's work is directly related to underwater acoustic modeling and simulation and therefore corresponds closely to the mathematical and computational orientation of the article. It supports the modeling perspective used to represent sound propagation in water and the use of computer simulation for evaluating localization performance. The article's emphasis on a unified mathematical model and simulation-based assessment is consistent with the modeling tradition represented by this reference.

Mackenzie, K. V. "Nine-Term Equation for Sound Speed in the Oceans." *Journal of the Acoustical Society of America*, 1981, Vol. 70, No. 3, pp. 807–812. Mackenzie's study is one of the technically significant references used in the article because the nine-term empirical equation for sound speed is explicitly incorporated into the mathematical model. The article states that sound speed depends on temperature, salinity, and depth and employs Mackenzie's formulation for practical calculation. Thus, this source provides a specific physical relationship connecting environmental parameters with the propagation model and contributes to accounting for environmental conditions in the localization algorithm.

Chan, Y. T., Ho, K. C. "A Simple and Efficient Estimator for Hyperbolic Location." *IEEE Transactions on Signal Processing*, 1994, Vol. 42, No. 8, pp. 1905–1915. Chan and Ho's work provides an important methodological foundation for solving the hyperbolic localization problem. In the article, TDOA measurements are transformed into distance differences, producing a system of hyperbolic equations. The article then states that this nonlinear system is linearized using the Chan–Ho approach and solved through the least-squares method. Consequently, this reference is directly connected to the core localization algorithm rather than serving only as general background.

Foy, W. H. "Position-Location Solutions by Taylor-Series Estimation." *IEEE Transactions on Aerospace and Electronic Systems*, 1976, Vol. AES-12, No. 2, pp. 187–194. Foy's work is used to support the iterative refinement stage of the localization procedure. The article first obtains an initial estimate through a linearized least-squares solution and then refines the coordinates using a Gauss–Newton iterative method. The reference therefore contributes to the numerical optimization aspect of the proposed algorithm and supports the refinement of an initial position estimate through iterative estimation.

Knapp, C., Carter, G. "The Generalized Correlation Method for Estimation of Time Delay." *IEEE Transactions on Acoustics, Speech, and Signal Processing*, 1976, Vol. 24, No. 4, pp. 320–327. Knapp and Carter's study provides the signal-processing foundation for estimating time differences between hydrophone signals. The article uses cross-correlation to estimate the delay between pairs of hydrophones, which is then converted into a distance difference for TDOA localization. This reference therefore supports the transition from measured acoustic signals to the numerical TDOA parameters required by the localization solver.

Islomov, D. B. *Suv osti obyektlarini aniqlashning zamonaviy usullari: qiyosiy tahlil va akustik yondashuvning afzalliklari*. Conference Proceedings, 2026. This local source represents the author's previous comparative research on methods for detecting underwater objects. The current article explicitly refers to this work when comparing optical, electromagnetic, and acoustic approaches. Its contribution is therefore contextual and conceptual: it establishes the rationale for selecting acoustic localization and provides continuity between the earlier comparative study and the present integrated mathematical and software solution. As a local reference, it helps adapt the broader international theoretical foundation to the practical research context addressed by the author.

Islomov, D. B. *Suv muhitida akustik signal tarqalishining matematik modeli*. Conference Proceedings, 2026. This source represents the author's earlier work on mathematical modeling of acoustic signal propagation in an aquatic

environment. The present article builds on that direction by incorporating the propagation model into a complete localization framework that includes TDOA estimation, numerical solution, software architecture, and simulation. The local reference therefore serves as a methodological bridge between the earlier propagation model and the current integrated system. It demonstrates the development of the research from a focused mathematical model toward an algorithmic and software implementation.

The foreign and local references perform complementary functions in the article. The foreign literature provides the established scientific foundations of underwater acoustics, environmental sound-speed modeling, time-delay estimation, hyperbolic localization, and numerical position estimation. In particular, References 3–6 are closely integrated into the mathematical and algorithmic parts of the study: Mackenzie's equation is used for sound-speed calculation, Knapp and Carter's correlation approach is used for time-delay estimation, Chan and Ho's method is used for hyperbolic localization, and Foy's approach supports iterative refinement.

The local literature has a different but important role. References 7–8 document the author's earlier research and provide a direct connection to the present study. Reference 7 supports the comparative justification of the acoustic approach, while Reference 8 provides a preceding mathematical model of acoustic signal propagation. The current article extends these directions by combining theoretical modeling, TDOA localization, numerical optimization, software architecture, database functionality, visualization, and computer simulation in one proposed software suite.

The local references further support this contribution by showing that the present study continues earlier work on underwater detection and acoustic propagation modeling. The literature analysis therefore indicates a coherent research trajectory: comparative evaluation of detection methods, development of an aquatic acoustic propagation model, and integration of the model with TDOA localization and software implementation.

The references used in the article can be characterized as a combination of international foundational literature and local research publications. The six foreign sources provide the principal theoretical and computational foundations for underwater acoustics, sound-speed modeling, time-delay estimation, hyperbolic localization, and iterative numerical estimation. The two local sources provide continuity with the author's previous studies and contextualize the present integrated solution. Taken together, the literature supports the article's methodological structure and explains how the proposed system develops from established scientific approaches toward an integrated software-oriented solution for underwater object localization.

RESEARCH METHODOLOGY

Mathematical Model of Acoustic Signal Propagation

The propagation of a pressure wave in an aqueous medium is described by the following wave equation:

$$\nabla^2 p(\mathbf{x}, \mathbf{y}, \mathbf{z}, t) - (1/c^2) \partial^2 p(\mathbf{x}, \mathbf{y}, \mathbf{z}, t) / \partial t^2 = 0 \quad (1)$$

Here, p is the acoustic pressure, and c is the speed of sound propagation in the medium. The speed of sound c depends on water temperature T (°C), salinity S (‰), and depth D (m); practical calculations employ the nine-term empirical formula proposed by Mackenzie (1981) [3]:

$$c(T, S, D) = 1448.96 + 4.591T - 5.304 \cdot 10^{-2}T^2 + 2.374 \cdot 10^{-4}T^3 + 1.340(S - 35) + 1.630 \cdot 10^{-2}D + 1.675 \cdot 10^{-7}D^2 - 1.025 \cdot 10^{-2}T(S - 35) - 7.139 \cdot 10^{-13}TD^3 \quad (2)$$

For freshwater bodies ($S \approx 0$), Formula (2) is simplified so that the speed of sound is calculated primarily based on temperature and depth, which facilitates practical application in rivers and lakes.

The signal received by the hydrophone is represented by the following model:

$$s_i(t) = A \cdot s(t - \tau_i) + n_i(t), \quad i = 1, \dots, N \quad (3)$$

Here, $s(t)$ is the source signal, A is the amplitude attenuation coefficient, τ_i is the signal arrival time at the i -th hydrophone, $n_i(t)$ is additive noise, and N is the number of hydrophones. Amplitude attenuation is expressed in logarithmic form as a function of distance r and frequency f :

$$TL(r) = 20 \cdot \log_{10}(r) + \alpha(f) \cdot r \quad (4)$$

Here, $\alpha(f)$ is the medium's absorption coefficient (dB/km), typically estimated using the Thorpe formula.

Time Difference of Arrival (TDOA) Localization Algorithm

To determine the spatial coordinates (x, y, z) of an object, a network consisting of $N \geq 4$ hydrophones with known coordinates is used. The difference in signal arrival times between each pair of hydrophones is estimated using the cross-correlation function [6]:

$$R_{ij}(\tau) = \int s_i(t) \cdot s_j(t + \tau) dt, \quad \hat{\tau}_{ij} = \arg \max R_{ij}(\tau) \quad (5)$$

The estimated time difference $\hat{\tau}_{ij}$ is converted into a distance difference: $d_{ij} = c \cdot \hat{\tau}_{ij} = r_i - r_j$, where $r_i = \sqrt{[(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2]}$ is the distance from the object to the i -th hydrophone. For each pair of hydrophones, the following hyperbolic equation is obtained:

$$\sqrt{[(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2]} - \sqrt{[(x - x_j)^2 + (y - y_j)^2 + (z - z_j)^2]} = d_{ij} \quad (6)$$

This system of nonlinear equations is linearized using the Chan-Ho (1994) method and solved using the least-

squares method [4]:

$$\hat{\mathbf{x}} = (\mathbf{A}^T \mathbf{A})^{-1} \mathbf{A}^T \mathbf{b} \quad (7)$$

Here, $\mathbf{A}$ is the coefficient matrix derived from the hydrophone geometry, and $\mathbf{b}$ is the right-hand-side vector. The initial solution is refined using the Gauss–Newton iterative method to obtain a more accurate result [5].

The general steps of the algorithm are as follows:

Step 1. Digitization and pre-filtering (band-pass filtering and noise suppression) of the signal from each hydrophone.

Step 2. Estimation of the time difference via cross-correlation for pairs of hydrophones (Formula (5)).

Step 3. Calculation of the distance difference ($d_{ij} = c \cdot \hat{\tau}_{ij}$).

Step 4. Estimation of the initial coordinates using Formula (7).

Step 5. Refinement of the result via Gauss–Newton iteration, terminating based on the convergence criterion.

Step 6. Output of the result along with an error estimate based on the covariance matrix.

Software System Architecture

Based on the developed mathematical model and algorithm, a software suite comprising the following modules is proposed:

— **Data acquisition module** — converting analog signals from the hydrophone network into digital format via an ADC and storing them with timestamps;

— **Signal preprocessing module** — band-pass filtering, noise suppression, and normalization (based on the Python libraries NumPy and SciPy);

— **TDOA estimation module** — calculating cross-correlation between hydrophone pairs and determining time delays;

— **Localization solver module** — solving the system of Equations (6)–(7); the algorithm is first verified in the MATLAB environment and then ported to Python;

— **Database module** — storing sensor coordinates, measurement history, and the coordinates of detected objects;

— **Visualization and user interface module** — a web-based dashboard displaying object locations on a map (GIS).

Data exchange between modules is carried out via JSON-formatted messages, which ensures the system's extensibility (for example, the addition of other sensor types or machine-learning-based filters).

ANALYSIS AND RESULTS

A computer simulation was conducted to evaluate the effectiveness of the proposed model and algorithm. The simulation conditions were as follows: $N = 6$ hydrophones were placed at known coordinates within a $100 \times 100 \times 20$ m water basin; an object was positioned at random coordinates; signal propagation times were calculated using Formulas (2)–(4); and additive Gaussian noise of varying levels was added to the signals.

Table 1. Localization Error (RMSE, meters) as a Function of Signal-to-Noise Ratio (SNR)

SNR (dB)	RMSE, $N = 4$ sensors (m)	RMSE, $N = 6$ sensors (m)	RMSE, $N = 8$ sensors (m)
0	4.82	3.15	2.41
10	1.67	0.94	0.68
20	0.53	0.31	0.22
30	0.18	0.11	0.08

The results demonstrate that increasing the number of sensors and improving the signal-to-noise ratio significantly enhance localization accuracy. Specifically, with $N = 6$ and an SNR of 20 dB, the root mean square error (RMSE) is 0.31 meters, which represents a level of accuracy suitable for practical rescue operations. A single iteration of the algorithm took an average of 12 milliseconds on a standard personal computer (Intel Core i5, 8 GB RAM), enabling real-time operation.

Furthermore, when modeling the effect of multipath propagation, it was found that the error increases two- to threefold without filtering, whereas the application of an appropriate median filter significantly reduces this effect.

The results obtained indicate that the acoustic localization method offers several advantages over optical and electromagnetic methods for detecting underwater objects. Firstly, acoustic waves undergo significantly less attenuation in water than light or radio waves, enabling operation over longer distances. Secondly, the acoustic method can remain effective in turbid or deep waters, where the effectiveness of optical methods may be reduced.

At the same time, the method has several aspects that should be considered in its practical application: precise time synchronization between hydrophones is required at the microsecond level, while in shallow and narrow

rivers, multipath propagation and reverberation may affect signal quality. Furthermore, the current model assumes a static water environment; therefore, considering the effects of flow velocity and turbulence on sound propagation represents a prospective direction for further research.

These results form the mathematical and algorithmic basis of a sensor-based method for locating drowning victims—currently being developed as part of the author's doctoral dissertation—and align with Areas 4 and 8 of Specialty 05.01.07: "Mathematical Modeling, Numerical Methods, and Software Packages."

CONCLUSIONS AND SUGGESTIONS

The article presents a unified mathematical model for the acoustic localization of underwater objects, a TDOA-based localization algorithm, and the architecture of a software suite implementing them. Computer simulation results demonstrated that the number of sensors and the signal-to-noise ratio significantly affect localization accuracy and that the proposed algorithm operates at a speed sufficient for real-time performance.

Future research will focus on sensor data fusion, the use of machine learning methods for time-delay estimation, and testing the proposed system on a real hydrophone network.

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