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Model of Hydroacoustic Signal Synthesis Using Neural Networks

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ABSTRACT Underwater acoustics (also called hydroacoustics), which is associated with the study of the patterns of propagation of sound waves in water, is a driving force in the research and development of systems of hydroacoustic technologies and means of communication, monitoring and detection of surface and underwater objects of biological or artificial origin, study of marine resources and environments, noise measurement, etc. This kind of research requires the analysis of huge amounts of data, revealing non-obvious patterns and creating models for the mathematical description of physical phenomena, such as sound propagation in a medium with random characteristics and radiation from different sources, as well as radiation from sources with different apertures or sound scattering, etc. That is why, in order to create the latest technologies in this area, it is necessary to solve complex specialized problems of a fundamental and applied nature using machine learning algorithms and artificial intelligence. Neural networks are nonlinear systems that allow you to effectively classify data compared to mathematical and statistical methods, which are currently quite widely used. In this paper, the authors propose to use a pre-trained neural network for the analysis and classification of hydroacoustic signals. This procedure for distinguishing acoustic signals has a number of advantages, in particular, individual objects are divided into groups based on information about one or more characteristics inherent in these objects, and on the basis of a training sample of pre-labeled objects. Thus, the proposed model of signal synthesis using neural networks is characterized by increased informativeness of the characteristics of the propagation of hydroacoustic signals, which will have prospects in further practical implementation.

KEYWORDS hydroacoustics, Dirac function, Fourier transform, machine learning.

I. STAGING PROBLEMS

The first studies of digital hydroacoustic communication appeared at the end of the second half of the 20th century. Communication systems with amplitude and phase modulation, where the value of the digital signal was set by the difference between theexact and previous signals, became widespread. Digital signal processing is widely used in radar, hydroacoustics [1], communication systems, geophysics, infocommunication systems, medical diagnostics, seismology, nuclear engineering, etc. Research requires the creation of new mathematical models for describing physical phenomena, such as the propagation of sound in a medium with random characteristics and emissions from different sources, radiation by sources with different apertures or sound scattering, etc.

On the other hand, Practical applications require the creation of devices of extremely high accuracy and technical complexity, which will be used in complex uncertain environments and will process large amounts of data. It is possible to obtain information about objects in the aquatic environment using acoustic methods in many ways.

There are several objects of measurement, such as the underwater noise of the environment, the distribution of the sound field generated by different sources (including a moving object), sound scattering or acoustic parameters of the environment.

II. RESEARCH METHODS

The following have been widely used to classify the received signals: deterministic and stochastic matrix. The deterministic method includes statistical processing and models created using sonar technologies. In the stochastic method, machine learning algorithms and models and artificial intelligence are used to perform classification.

III. STATEMENT OF THE TASK

The objective of this study is to analyze the propagation of an acoustic signal in an aqueous environment in order to build a mathematical model of the hydroacoustic communication channel for distinguishing and classifying targets using machine learning algorithms.

IV. INTRODUCTION

The main purpose of underwater acoustic remote sensing is to obtain information about the target object indirectly, namely with the help of acoustic data. Currently, various types of machine learning methods are widely used to obtain information from acoustic data, followed by the possibility of constructing 3D models of underwater objects and the bottom surface. But at the same time, it is necessary to take into account the peculiarities of the propagation of acoustic waves in the aquatic environment – reflection, refraction, loss, etc. One alternative solution that describes the simulation of sound rays in an aqueous environment is geometric hydroacoustics. Classification of underwater targets to build a three-dimensional image can use both a deterministic method (statistical processing) and a stochastic approach using machine learning. In practice, the classification task requires careful consideration of the mechanisms that can identify and distinguish between the echoes of target and non-target objects, as well as the echoes of objects that are hidden in the background. Simulation of sound rays is an important task in underwater acoustics, because the solution of this issue helps to solve many practical problems of modern hydroacoustic systems by increasing the information content of signal propagation characteristics for both both military and civilian research purposes of countries with access to rivers, seas and oceans.

V. ACOUSTIC WAVE PROPAGATION ANALYSIS

The propagation of acoustic waves is described by an acoustic version of the wave equation [2,3]:

$$\Delta p = \frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = = -\delta(x - x_s, y - y_s, z - z_s)S(t). \quad (1)$$

Where p(x,y,z) is the acoustic pressure. The physical process begins with a normalized acoustic wave signal s(t) emitted by the source, located at a point with coordinates (x_s, y_s, z_s). In equation (1), the source is modelled as a point source delta (Dirac functions of spatial distribution (δ)). The content of the acoustic transfer function is as follows: a tone signal with an amplitude is emitted at a point whose coordinates are determined by the radius vector; so the signal received at time $S_1 t$ at a point defined by the radius vector will have the following form:

$$S_2 = S_1 K\left(\underset{r_1}{\rightarrow}, \underset{r_2}{\rightarrow}, w, t\right) e^{-i\omega t}. \quad (2)$$

Geometric hydroacoustics investigates the propagation of waves according to the following principles [2]:

- refraction of rays when changing the speed of sound according to Snelius' law;
- reflection at the interface of the environment;
- loss of intensity along the rays due to geometric deflection, absorption along the trajectory and reflection at the boundaries of water layers;
- The resulting signal at the receiver point, obtained by summing up the contributions of different beams with their respective frequencies and phases.

To build the trajectory of sound rays in an aqueous medium, it is necessary to have data on the initial values of the speed of sound and the angles of radiation in each of the selected water layers. The aquatic environment is divided into layers of 10 m by parallel horizontal lines, where for the i-th layer the upper limit is denoted i, and the lower limit *is* i+1, *and* i= 0,1,2 ,... The input data is the sound velocity profile, which is given by a set of velocities at a depth of 10 ic_i. For each i-th water layer, the sound velocity gradient is calculated using the formula:

$$k_i = \frac{c_{i-1} - c_i}{10}. \quad (3)$$

Consider a water layer in which the speed of sound is linearly dependent on depth, with velocity increasing with depth. If the speed of sound varies linearly in depth, then a part of the beam in a given water layer has the shape of an arc of a circle with a radius:

$$r = \frac{c_0}{k \sin}, \quad (4)$$

where:
c_0 – muzzle velocity (m/s);
k is the coefficient of change in sound velocity in depth (s–1);
θ – initial emission angle (rad).

The propagation of sound in water depends on many factors: the physical and chemical properties of the water, the type of bottom, the presence of natural or artificial obstacles, the distance between the transmitter and receiver and their relative position, the frequency of signal transmission, etc. [4].

There are two main cases – when the beam moves downwards or upwards. For the case where the beam is moving downwards, the radius of the circle for a part of the arc is calculated using the formula [2]:

$$R = \frac{y_{down_i}}{sin\theta}. \quad (5)$$

And the center of the circle will be at the point with the coordinates:

$$x_n = -\frac{c_i}{k_i \times tg\theta} y_n = y_{down_i - 10i}. \quad (6)$$

In the case when the beam moves upwards, the radius of the circle for the part of the arc is:

$$R = \frac{y_{up_i}}{sin\theta}. \quad (7)$$

And the center of the circle is at the point with the coordinates:

$$x_i = -\frac{c_i + 1}{k_i \times tg\theta} y_i = y_{up_i - 10(i+1)}. \quad (8)$$

Sound is reflected from the boundary of the water area (bottom, water surface, submerged objects). Each reflection attenuates the sound. The amount of attenuation depends on the frequency of the signal and the material from which the object from which the sound is reflected is made. Therefore, the received sound is the emitted sound, which is formed by convolution by the impulse response of the hydroacoustic channel, which can be written as follows:

$$x(n) = s(n) \times h(n, p), \quad (9)$$

where:
$x(n)$ – received signal,
$s(n)$ – a signal has been transmitted,
$h(n, p)$ is the pulse response of the water region measured at point p, and n is the discrete time (sampling) [5].

The signal transmitted is sinusoidal with a given frequency, modulated by a pseudorandom sequence, so it can be written as follows:$s(n) f_c$

$$s(n) = z(n)\sin(2\pi f_c n), \quad (10)$$

where:
$z(n)$– pseudo-random sequence,
f_c – carrier frequency.

The estimation of the impulse response of a hydroacoustic channel can be determined using a pseudorandom binary sequence Cross-correlation is the dot product of two signals by the oscillation function of one of them. [6,7], which can be calculated using the formula [8]:

$$R_{zy}(k) = \sum_{n=0}^{N-1-|k|} z(n) y^*(n-k), \quad (11)$$

where:
$y(n)$ is the received signal reduced to the baseband.

Based on (11), it is possible to determine the impulse response estimate of the hydroacoustic channel by calculating the modulus as follows [7]:

$$h(k) = \sqrt{\left(\sum_{n=0}^{N-1-|k|} z(n) y_s^*(n-k)\right)^2 + \left(\sum_{n=0}^{N-1-|k|} z(n) y_c^*(n-k)\right)^2}, \quad (12)$$

where:

$y_s(n) = x(n)\sin(2\pi f_c n)$,

$y_c(n) = x(n)\cos(2\pi f_c n)$.

For spectral analysis, it is convenient to use the classical Fourier method. The direct method of periodograms of the spectrum is obtained using the fast Fourier transform. To convert a discrete signal, the sum of harmonics for each sample is used using a fast Fourier transform:

$$F(k) = \sum_{n=0}^{N-1} \left(f(n) \times e^{-i\frac{2\pi}{N}nk} \right), \quad (13)$$

where:

$F(k)$is the value of the discrete Fourier transform, k=0.1....N-1.

VI. MACHINE LEARNING

The simplest structure of a neural network is presented in Fig. 1. Several input data vectors are distributed into nodes (neurons) of the hidden layer, which makes a random selection and evaluates how much it improves or worsens the output result, namely signal discrimination.

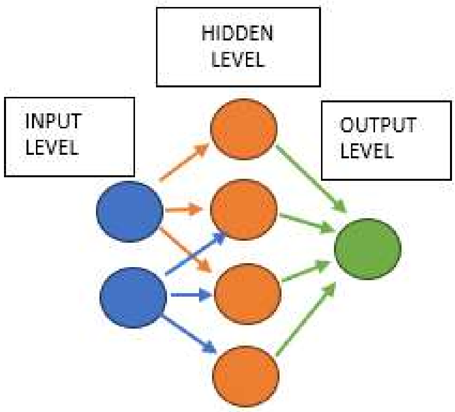

FIG. 1. Structure of the simplest neural network.

With this structure, supervised learning takes place – this is learning through predefined inputs called goals. For each training example, there will be a set of input values and one or more associated defined output values. The purpose of this form of training is to reduce the overall error in the classification of signal models by correctly calculating the initial value of the training sample through training. But this approach has certain disadvantages:

- loss of some useful information due to the conversion of hydroacoustic signals into feature vectors;
- insufficient speed due to the need for additional time after the perception of the hydroacoustic signal to isolate the feature vector from it and the time for processing these features by the neural network.

To use machine learning to classify objects and targets, it is necessary to solve the classification problem according to Fig. 2.

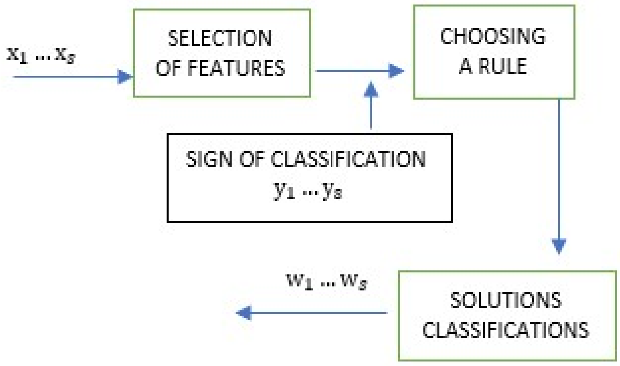

FIG. 2. The Classification Problem.

The number of classification features m must always be less than the number of primary features s, and the greater the difference, the more accurate the classification will be. According to Fig. 2 the quality of solving the classification problem will depend on the type and number of classification features, as well as on the choice of the learning rule. $Y = [y_1 \dots y_s]$

Despite their high accuracy, methods based on machine learning first break down the task into several subtasks and then accumulate the result. In addition, machine learning cannot work with large datasets, as this leads to a decrease in the accuracy of the results obtained. However, these disadvantages can be eliminated by using deep learning approaches, which are end-to-end models that work effectively with huge amounts of data.

When receiving echo signals from a long distance, it is necessary to filter them before selecting features and classifying them using machine learning in order to reduce noise and increase signal-to-noise levels. Therefore, spectral analysis of tone echoes is carried out first, and then their processing with mutual correlation, which is shown in Figure 3.

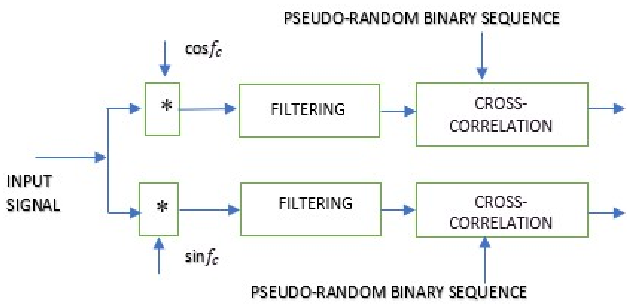

FIG. 3. Lock Circuitsand Signal Processing.

To increase the processing speed of the received hydroacoustic signals, it is advisable to use pulse neural networks, which differ from previous generations of neural networks in that information is transmitted using a sequence of pulses [9-10].

VII. CONCLUSION

The article discusses the problem of interpretation, classification and improvement of the accuracy of the data obtained by the hydroacoustic channel, which are relevant for military and civilian research programs, methods of their solution using machine learning and neural networks. Digital signal processing in hydroacoustics plays a crucial role, it is one of the newest and most powerful technologies for building a 3D model of the bottom surface. The rapid development of information technology makes it possible to conduct research on monitoring of water masses and the bottom of the World Ocean, explore marine objects, as well as transmit information through a hydroacoustic channel. Simulation of sound beams is an important task in underwater acoustics, because the solution of this issue helps to solve many practical problems of modern hydroacoustic systems by increasing the information content of signal propagation characteristics for both military and civilian research work of countries that have access to the seas and oceans.

AUTHOR CONTRIBUTIONS

Y.P. – writing (original draft preparation), conceptualization, methodology, investigation; O.L. – writing (original draft preparation), conceptualization, methodology, investigation;; H.L. – methodology, investigation, writing (review and editing).

COMPETING INTERESTS

The authors declare no competing interests.

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Модель синтезу гідроакустичних сигналів із використанням нейронних мереж

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АНОТАЦІЯ Підводна акустика (ще її називають – гідроакустикою), яка пов’язана із вивченням закономірностей поширення звукових хвиль у воді, є рушієм у дослідженнях та розроблені систем гідроакустичних технологій та засобів зв’язку, моніторингу та виявлення надводних та підводних об’єктів біологічного або штучного походження, вивчення морських ресурсів і середовищ, вимірювання шуму тощо. Такого роду дослідження вимагають проведення аналізу величезних масивів даних, виявляючи неочевидні закономірності та створення моделей для математичного опису фізичних явищ, таких як поширення звуку в середовищі з випадковими характеристиками та випромінюванням від різних джерел, а також випромінювання джерелами з різною апертурою або розсіювання звуку, тощо. Саме тому для створення новітніх технологій в даній сфері необхідно вирішувати складні спеціалізовані задачі фундаментального та прикладного характеру із залученням алгоритмів машинного навчання та штучного інтелекту. Нейронні мережі являють собою нелінійні системи, які дозволяють ефективно класифікувати дані порівняно із математичними та статистичними методами, які наразі мають досить широке застосування. В даній роботі авторами запропоновано для аналізу та класифікації гідроакустичних сигналів застосовувати попередньо навчену нейронну мережу. Така процедура розрізнення акустичних сигналів має ряд переваг, зокрема – окремі об'єкти розподіляються по групах на основі інформації про одну або більше характеристик, притаманних саме цим об'єктам, та на основі навчальної вибірки попередньо промаркованих об'єктів. Таким чином запропонована модель синтезу сигналів із використанням нейронних мереж характеризується підвищеною інформативністю характеристик розповсюдження гідроакустичних сигналів, що матиме перспективу у подальшій практичній реалізації.

КЛЮЧОВІ СЛОВА гідроакустика, функція Дірака, перетворення Фур’є, машинне навчання.