p-ISSN 1607-3274
e-ISSN 2313-688X

Радіоелектроніка
Інформатика
Управління

Radio Electronics
Computer Science
Control

Радиоэлектроника
Информатика
Управление

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2023/1

Національний університет «Запорізька політехніка»

Радіоелектроніка, інформатика, управління

Науковий журнал
Виходить чотири рази на рік
№ 1(64) 2023
Заснований у січні 1999 року.
Засновник і видавець – Національний університет «Запорізька політехніка».
ISSN 1607-3274 (друкований), ISSN 2313-688X (електронний).
Запоріжжя
НУ «Запорізька політехніка»
2023

National University «Zaporizhzhia Polytechnic»

Radio Electronics, Computer Science, Control

The scientific journal
Published four times per year
№ 1(64) 2023
Founded in January 1999.
Founder and publisher – National University «Zaporizhzhia Polytechnic».
ISSN 1607-3274 (print), ISSN 2313-688X (on-line).
Zaporizhzhia
NU «Zaporizhzhia Polytechnic»
2023

Национальный университет «Запорожская политехника»

Радиоэлектроника, информатика, управление

Научный журнал
Выходит четыре раза в год
№ 1(64) 2023
Основан в январе 1999 года.
Основатель и издатель – Национальный университет «Запорожская политехника».
ISSN 1607-3274 (печатный), ISSN 2313-688X (электронный).
Запорожье
НУ «Запорожская политехника»
2023

Науковий журнал «Радіоелектроніка, інформатика, управління» (скорочена назва – РІУ) видається Національним університетом «Запорізька політехніка» (НУ «Запорізька політехніка») з 1999 р. періодичністю чотири номери на рік.

Зареєстровано у Міністерстві юстиції України 19.11.2019 р. (Свідоцтво про державну реєстрацію друкованого засобу масової інформації серія КВ № 24220-14060 ПР.)

ISSN 1607-3274 (друкований), **ISSN** 2313-688X (електронний).

Наказом Міністерства освіти і науки України № 409 від 17.03.2020 р. «Про затвердження рішень Атестаційної колегії Міністерства щодо діяльності спеціалізованих вчених рад від 06 березня 2020 року» **журнал включений до переліку наукових фахових видань України в категої «А» (найвищій рівень),** в яких можуть публікуватися результати дисертаційних робіт на здобуття наукових ступенів доктора наук і доктора філософії (кандидата наук).

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Рекомендовано до видання Вченою радою НУ «Запорізька політехніка», протокол № 6 від 16.02.2023.

Журнал зверстаний редакційно-видавничим відділом НУ «Запорізька політехніка».

Веб-сайт журналу: http://ric.zntu.edu.ua.

Адреса редакції: Редакція журналу «РІУ», Національний університет «Запорізька політехніка», вул. Жуковського, 64, м. Запоріжжя, 69063, Україна.

Тел: (061) 769-82-96 – редакційно-видавничий відділ Факс: +38-061-764-46-62

E-mail: rvv@zntu.edu.ua

The scientific journal «Radio Electronics, Computer Science, Control» is published by the National University «Zaporizhzhia Polytechnic» NU «Zaporizhzhia Polytechnic» since 1999 with periodicity four numbers per year.

The journal is registered by the Ministry of Justice of Ukraine in 19.11.2019. (State Registration Certificate of printed mass media series КВ № 24220-14060 ПР).

ISSN 1607-3274 (print), **ISSN** 2313-688X (on-line).

By the Order of the Ministry of Education and Science of Ukraine from 17.03.2020 № 409 "On approval of the decision of the Certifying Collegium of the Ministry on the activities of the specialized scientific councils dated 06 March 2020" **journal is included in the list of scientific specialized periodicals of Ukraine in category "A" (highest level),** where the results of dissertations for Doctor of Science and Doctor of Philosophy may be published.

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Recommended for publication by the Academic Council of NU «Zaporizhzhia Polytechnic», protocol № 6 dated 16.02.2023.

The journal is imposed by the editorial-publishing department of NU «Zaporizhzhia Polytechnic».

The journal web-site is http://ric.zntu.edu.ua.

The address of the editorial office: Editorial office of the journal «Radio Electronics, Computer Science, Control», National University «Zaporizhzhia Polytechnic», Zhukovskiy street, 64, Zaporizhzhia, 69063, Ukraine.

Tel.: +38-061-769-82-96 – the editorial-publishing department. Fax: +38-061-764-46-62

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UDC 621.396.96

METHOD OF SELF-DEFENSE OF GROUND (SURFACE) OBJECTS FROM HIGH-PRECISION RADAR MEANS OF AIR SURVEILLANCE

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ABSTRACT

Context it is caused by the need to search for scientific and technical ways to ensure the effectiveness of protecting ground (surface) objects from high-precision guided missile weapons.

Objective it is a necessity to ensure effective self-defense of objects from radar homing means.

Method. Electrodynamic modeling of Echo signals from spatially distributed objects, taking into account the features of their design and related operational limitations.

Results. Based on the analysis of the shortcomings of the well-known method of protecting stationary objects from radar surveillance and damage, based on the simulation of an effective reflection center outside the physical dimensions of the object, a new method of countering high-precision measurement of coordinates of stationary and mobile ground (surface) objects is proposed. The technique is based on the spatial deformation of the location of the effective target reflection center with dynamics that exceed the inertial capabilities of the auto-observation contour of the attacking missile (projectile). A structural and functional scheme of technical implementation of the methodology based on the first proposed relationship of simple design and technological solutions is proposed and justified.

Conclusions. The analytical model of Echo signals of spatially distributed ground (surface) objects was further developed, which takes into account the specifics of their design, and on its basis, for the first time, a universal method of self-defense of objects from radar home-leading devices was developed, which is implemented in a patented method and complex to exclude damage to protected objects.

KEYWORDS: radar home-leading head, electromagnetic wave scattering model, local reflection section, direction finding characteristic, angular reflector, polarization grating.

ABBREVIATIONS

CU is a control unit;
SGRH is a self-guided radar head;
SP is a scatter plot
LDA is a local display area;
CR is a corner reflector;
MC is a motor controller;
RD is a reduction drive;
RS is a radar station;
RCS is a radar cross-section;
SCS is a scattering cross-section
HLH is a home-leading head;
BSD is a Backscattering diagram
LDA is a local display area;
AR is an angle reflector;
RS is a radar set
RO is a radar objects;
ESS is an effective scattering surface;
ESC is an effective scattering center.

DOI 10.15588/1607-3274-2023-1-1

NOMENCLATURE

α is an angle of view of the target by Yaw;

ε is a Pitch angle of view of the target;

$\vec{\gamma}$ is a vector that characterizes the observation conditions and object orientation;

A_i is an amplitude of the signal reflected from i LDA;

R_i is a radius-vector i LDA;

E is an electromagnetic field strength;

ω is a circular frequency;

λ is a wavelength of the probing signal;

$l_{\alpha,\varepsilon}$ is a geometric size of the target or a fragment of its structure in the "picture" plane;

$\Delta\theta_{\alpha,\varepsilon}$ is a width of the linear section of the direction finding characteristic by Yaw α and Pitch β;

Δf_e is an effective spectral band of the rocket control circuit;

$\sigma_{\alpha,\varepsilon}$ is an error of auto-tracking of the target by Yaw α and Pitch β.

INTRODUCTION

Radar means of air (space) observation is the only effective tool for highly informative remote monitoring of the Earth's surface in the interests of solving various general technical and special tasks in the absence of optical transparency of the surface layer of the atmosphere.

An urgent scientific and applied problem is minimizing the probability of high-precision weapons hitting ground (surface) equipment objects. There is a well-known method of self-defense of an object by installing a simulator outside it, for example, in the form of an angle reflector.

The disadvantages of this approach include:

– use only for stationary objects, since the AR ESS must be guaranteed to exceed the ESS of the protected object;

– a narrow corner protected area, which leads to an increase in the number of AR in conditions of a priori uncertainty in the direction of attack.

Taking into account the above, there is a scientific and technical task-the development of methodological and instrumental bases for electrodynamic simulation of Echo signals of stationary and moving objects in the radar home-leading channel, which exclude the defeat of the protected object regardless of the direction of attack, and optimal according to the criterion "efficiency/cost".

Thus, the topic that involves the search for scientific and technical ways to ensure effective protection of ground (surface) objects (targets) from high-precision missile weapons is relevant.

Object of research there is a process of forming echo signals from ground (surface) targets in the radar home-leading channel.

Subject of research is a analytical model of Echo signals for developing a method of self-defense of targets and a method of its practical implementation.

Purpose of the work is a ensuring effective self-defense of objects from radar home-leading means, for which it is necessary:

– perform an analysis of known approaches to describing echoes from spatially distributed targets;

– to develop and substantiate a model of scattering of electromagnetic waves in the radio range from the forming structure of observed objects in the form of a set of LDA and its analytical description;

– based on the LDA model, develop a methodology and method for self-defense of objects from homing means and perform a model experiment to analyze their effectiveness.

1 PROBLEM STATEMENT

It is known that the energy characteristics of the echo signal, which determine the maximum range of the homing section and potential accuracy, depend on the target'S EER, and the total guidance error is a function of the dynamics of missile-target movement [1–3]. At the same time, the missile's radar homing contour tracks the angular position of the target'S ESC [4–7].

The analytical criterion for stable operation of the homing circuit is the ratio

$$\sigma_{\alpha,\varepsilon} << \Delta\Theta_{\alpha,\varepsilon}. \quad (1)$$

To ensure the failure of auto wiring, artificial provision of the condition is necessary

$$\sigma_{\alpha,\varepsilon} > \Delta\Theta_{\alpha,\varepsilon} \quad (2)$$

per hour $t > \frac{1}{\Delta f_e}$.

For the first time, a complex is proposed as an instrumental basis for implementing this condition, which includes a set of AR that rotate asynchronously and provide a dynamic stochastic change in the BSD of the protected object.

2 REVIEW OF THE LITERATURE

In the radar surveillance channel, two approaches are used to model echoes from spatially distributed targets [8–13].

The phenomenological model is based on direct observations of the scattering process of the probing signal of the forming surface of the target. In practice, two types of phenomenological models are used:

– Radial model, which is the basis of the method of geometric optics and geometric diffraction theory. The radial representation of reflected waves is the main feature of the model. Secondary effects are diffraction and polarization. The model adequately describes the scattering process when the condition is met:

$$l_{\alpha,\varepsilon} > \lambda;$$

– a wave model based on the Huygens-Fresnel principle (physical optics method). The Shape of the object and the angle of the observation point relative to the observed object play a crucial role.

The analog model is based not on direct observations of the process of radio wave scattering, but on the results

DOI 10.15588/1607-3274-2023-1-1

of studies of other phenomena that occur in a similar way to the simulated process. At the same time, as in the phenomenological model, the main features of the process are highlighted:

– the "shiny dots" model. It is based on observations of light reflection from polished target layouts. This model is used to analyze the field reflected from rough surfaces;

– facet model. It is based on the approximation of the target surface in the form of a set of flat reflectors that are normally oriented to the incident wave and on the observation of light reflection from the water surface.

The limited possibilities of applying the above models in practice are due to:

– the need to detail a priori information for a specific phono-target situation accompanying the homing of a missile (projectile);

– analytical complexity of obtaining the resulting expressions describing the echo signal from real objects that are observed;

– weak resistance to changes in observation conditions (in particular, the object's angle).

Therefore, the development of these models in the direction of universality of application while ensuring adequacy should be considered an urgent scientific and applied task.

3 MATERIALS AND METHODS

In order to ensure the adequacy of modeling the scattering process of sensing signals to real physical phenomena accompanying observations of ground (surface) objects in the radar channel, a model is proposed that combines the capabilities of the phenomenological and analog models discussed above – the LDA model [14–16].

The essence of the model is based on the following prerequisites:

– the field scattered by a spatially distributed object is formed by a small number of waves, the source of which is located on the "illuminated" part of its forming surface;

– the distances between LDA exceed the wavelength, and the geometric area that they occupy is small compared to the area of the entire "illuminated" part of the object's surface;

– LDA are partially coherent, but can contain pairs that are either completely coherent or completely incoherent;

– the location of the LDA is clearly related to the design features of the forming surface of the observed object.

Analytically, the field scattered by the LDA aggregate can be represented as

$$E(t,\omega,\vec{\gamma}) = \sum_{i=1}^{l} A_i(\omega\vec{\gamma}) e^{j\omega\frac{2R_i(\vec{\gamma})}{c}}. \qquad (3)$$

The method of self-defense of a ground (surface) object provides for artificial provision of the condition (2). The latter can be achieved by asynchronously changing A_i in expression (3) due to the rotation of angular reflectors located along the perimeter of the protected object.

This leads to a chaotic change in the effective scattering center of the target with dynamics that exceed the capabilities of the missile (projectile) homing contour.

The practical implementation of the methodology is illustrated in Fig. 1 [17].

Structurally, the complex includes a set of an angular reflector with a polarization grating in the aperture to achieve polarization invariance. Asynchronous rotation of the angle reflector is provided by a controlled electric drive through a gearbox by connecting to the control unit.

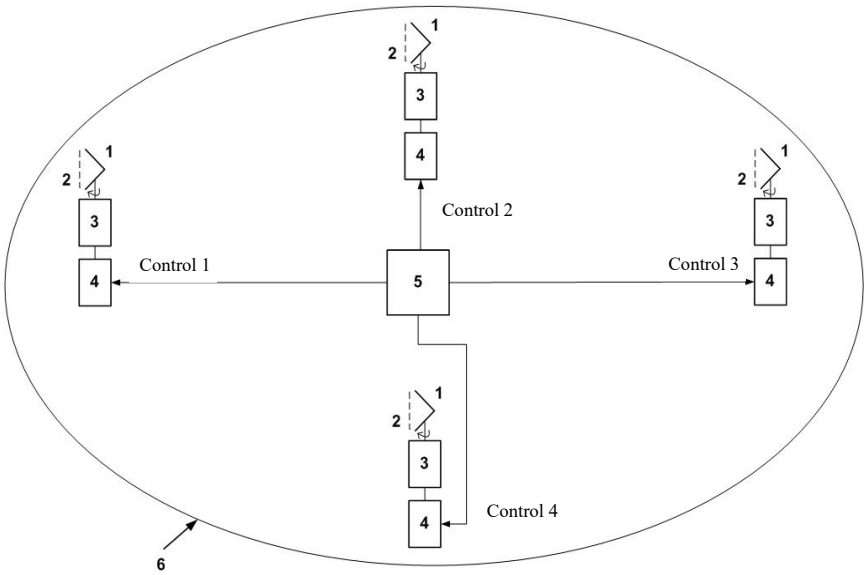


Figure 1 – The structural and functional diagram of a complex for simulating a ground (surface) object in a radar homing channel
1is an angle reflector; 2 is a polarizing grating; 3 is a gearbox; 4 is a controlled electric drive; 5 is a Control Unit;
6 is a geometric contour of the protected object

DOI 10.15588/1607-3274-2023-1-1

4 EXPERIMENTS

A model experiment was performed [18] to prove the adequacy of the proposed LDA model to the real conditions for applying the developed method of self-defense of ground (surface) objects. The essence of the experiment is electrodynamic modeling of Echo signals of complex RO: a railway bridge, a missile system launcher, a helicopter (priority objects of destruction) in a radar home-leading channel. The inclined range was 10 000 m, ε = 75...85 angle degrees and α = 0...180 angle degrees, λ = 8 and 3 mm, and frequencies of 36 and 95 GHz.

To calculate the ratio of the ESS of complex RO when irradiated with an electromagnetic wave with a probing signal wavelength of 8 mm to the ESS of complex RO when irradiated with an electromagnetic wave with λ = 3 mm in the Maple 15 Medium, data arrays were created at Target viewing angles ε = 75...85 angle degrees and α = 0...180 angle degrees in increments of 1 angle degrees.

Polygonal models of the bridge, launcher, and helicopter are shown in Fig. 2–4.

5 RESULTS

The resulting BSD of these objects at wavelengths of 8 and 3 mm are shown in Fig. 5 – 7, respectively.

The obtained patterns allow for a clear physical interpretation.

A graphical representation of the ratio of the ESS of complex RO when irradiated with an electromagnetic wave with λ = 8 mm to the ESS of complex RO when irradiated with an electromagnetic wave with λ = 3 mm in a linear ratio is shown in Fig. 8, respectively.

Plots with a positive value of 10lg ($\sigma_{\lambda=8mm}$ / $\sigma_{\lambda=3mm}$) correspond to the case when the ESS of a complex RO when irradiated with an electromagnetic wave with λ = 8 mm is greater than the ESS of the same object when irradiated with an electromagnetic wave with λ = 3 mm (fig. 8).

Depending on the observation conditions, the value of this ratio can be either greater than 1 or less. Based on the dependence of the detection probability on the signal/noise ratio at the input of the linear detector, the probability of detection in each of these sections is determined with a false alarm probability of 10^{-6} and the fixed probability of detecting a complex RO as a whole is 0.9.

Under such conditions, the value of the signal/noise ratio at the input of the linear detector will be 15 dB, then in the section of the ESS ratio, where the ESS with λ = 8 mm is greater than the ESS with λ = 3 mm, the probability varies in the range of 0.9–1.

In the area where the ESS with λ = 8 mm is 2 times larger than the ESS with λ = 3 mm or less, the signal – to – noise ratio will be 13–15 DB, and the detection probability will be 0.7–0.9.

Figure 2 – Polygonal bridge model

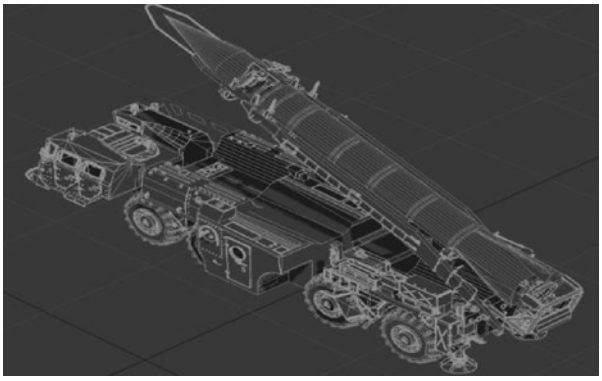
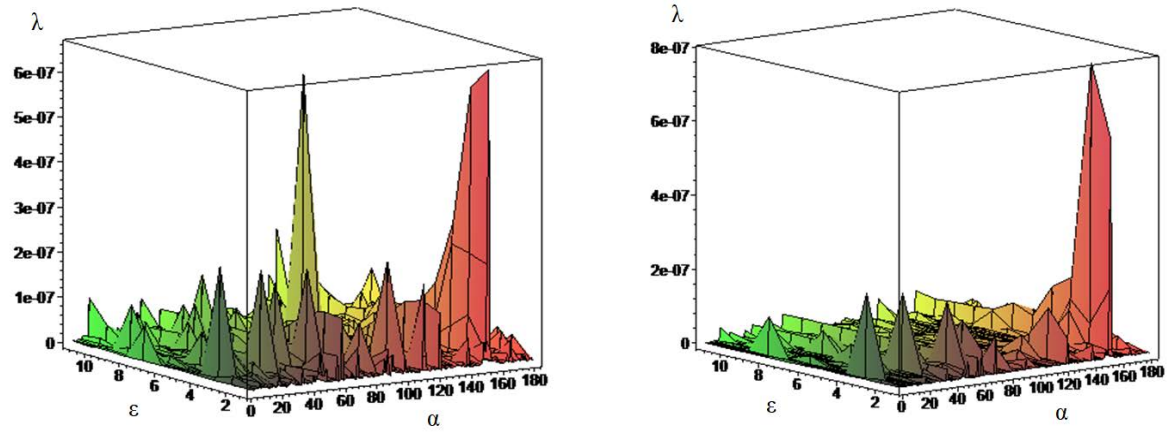


Figure 3 – Polygonal model of a rocket system launcher

Figure 4 – Polygonal helicopter model

DOI 10.15588/1607-3274-2023-1-1



a b

Figure 5 – Bridge backscattering diagram: a – λ = 8 mm; b – λ = 3 mm;

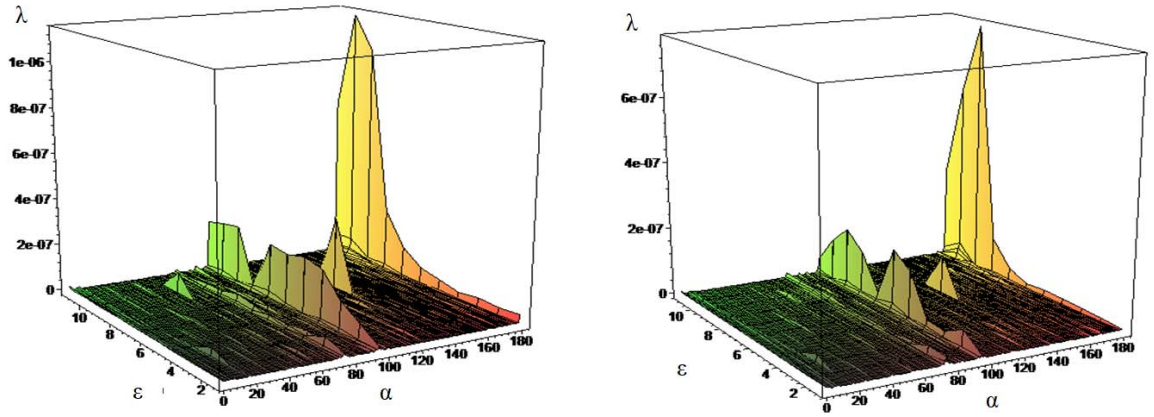


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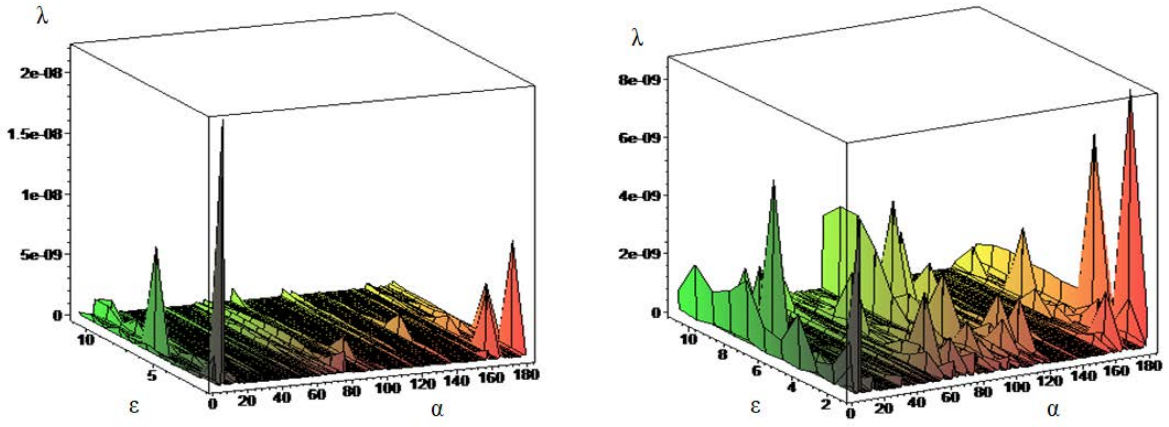
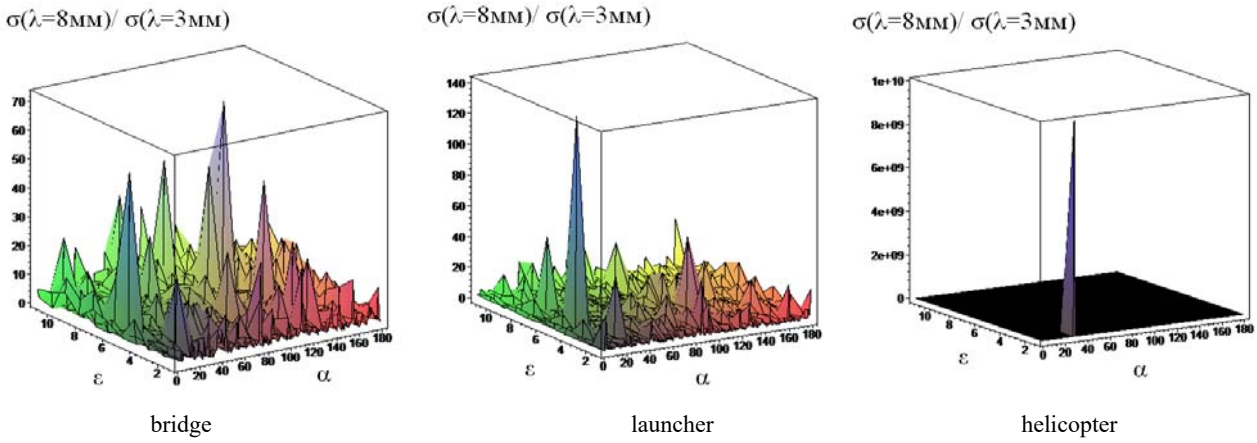
Figure 6 – Backscattering diagram of the launcher: a – λ = 8 mm; b – λ = 3 mm;



a b

Figure 7 – Helicopter backscattering diagram: a – λ = 8 mm; b – λ = 3 mm.

DOI 10.15588/1607-3274-2023-1-1



bridge launcher helicopter

Figure 8 – The ratio of the ESS of complex RO when irradiated with an electromagnetic wave with λ=8 mm to the ESS of complex RO when irradiated with an electromagnetic wave with λ=3 mm in a linear ratio

As can be seen from the nomogram (Fig. 8), Blue shows the area where the ESS with λ = 8 mm is larger, yellow shows the area where the ESS with λ = 8 mm is 2 times larger.

The results of the experiment confirm the initial prerequisites, namely:

– the total energy of target Echo signals is determined by a limited number of BSD extremes associated with the spatial distribution of LDA;

– since the HLH "works" on the ESC, an artificial dynamic change in its location is a universal means of self-defense of an object from self-guided means.

6 DISCUSSION

The method of the experiment provided for:

– approximation of the forming surface of targets observed in the radar channel in the form of an unbroken set of tangent triangles;

– formation of target Echo signals as a superposition of elementary Echo signals from triangles;

– obtaining backscattering diagrams of observed objects at an inclined range of 10,000 m at Target viewing angles of 75...85 angle. degrees in pitch and 0...180 angle. degrees at yaw.

The developed method, in comparison with the known ones, makes it possible to significantly expand the range of practical application conditions, removes restrictions on the type of protected object, its design, and the presence or absence of movement.

The reliability of the results obtained is confirmed by the possibility of their clear physical interpretation and modeling data. The possibility of wide application of the technique for protecting ground (surface) objects from radar home-leading means is based on the simplicity of technical implementation and low cost in comparison with known approaches

For the first time, an analytical description of the echo signal scattered by a complex object (3) was developed, together with the mandatory fulfillment of Condition (2), which gives an adequate description of the processes that accompany the observation of a spatially distributed target and is the basis of the developed method of its self-defense.

The practical implementation of the technique, in contrast to the known approaches, can technically be carried out in accordance with the proposed method for a wide range of external conditions and different dynamics of mutual movement of the protected and attacking objects.

It is important to note that the proposed method and method of self-defense are universal, since:

– invariant to the design and material of the forming surface of the protected object;

– effective for any trajectory and number of attacking objects;

– allow electrodynamic modeling to quantify the effectiveness of self-defense.

CONCLUSIONS

The scientific problem of methodological support of effective self-defense of ground (surface) objects from radar home-leading combat elements by stochastic change in the effective scattering surface of the protected object with dynamics exceeding the speed of the home-leading contour of attacking elements has been solved for that purpose:

– the analysis of the shortcomings of known approaches based on simulating the effective reflection center of the protected object beyond its physical dimensions is performed;

– for the first time, a universal model of a spatially distributed target observed in a radar home-leading channel in the form of a limited set of LDA is proposed and justified;

– based on the new model of a spatially distributed target, a system of self-defense of ground (surface) objects from radar homing means is proposed for the first time. It is based on the deformation of the location of the effective reflection center with dynamics that exceed the

DOI 10.15588/1607-3274-2023-1-1

inertial capabilities of the home-leading contour of attacking means.

Practical significance the obtained results are determined by the proposed method and complex of self-defense of ground (surface) objects, the priority of which is confirmed by the patent for the invention, as well as the data of the model experiment.

Directions for further research there is an optimization of the number of AR based on the "efficiency/cost" criterion with reference to the volume (area) of the protected object.

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Received 18.06.2022.
Accepted 03.02.2023.

УДК 621.396.96

МЕТОДИКА САМОЗАХИСТУ НАЗЕМНИХ (НАДВОДНИХ) ОБ'ЄКТІВ ВІД ВИСОКОТОЧНИХ РАДІОЛОКАЦІЙНИХ ЗАСОБІВ ПОВІТРЯНОГО СПОСТЕРЕЖЕННЯ

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DOI 10.15588/1607-3274-2023-1-1

АНОТАЦІЯ

Актуальність зумовлена необхідністю пошуку науково-технічних шляхів забезпечення ефективності захисту наземних (надводних) об'єктів від високоточного ракетного керованого озброєння.

Метою роботи є забезпечення ефективного самозахисту об'єктів від радіолокаційних самонавідних засобів.

Метод. Електродинамічне моделювання ехо-сигналів від просторово розподілених об'єктів з урахуванням особливостей їх конструкції та супутніх експлуатаційних обмежень.

Результати. На основі аналізу недоліків відомої методики захисту стаціонарних об'єктів від радіолокаційних засобів спостереження і ураження, основаній на імітації ефективного центру відображення за межами фізичних розмірів об'єкту, запропонована нова методика протидії високоточному вимірюванню координат стаціонарних і рухомих наземних (надводних) об'єктів. Методика базується на просторовій деформації місцезнаходження ефективного центру відбиття цілі з динамікою, яка перевищує інерційні можливості контуру авто спостереження атакуючої ракети (снаряду). Запропонована і обґрунтована структурно-функціональна схема технічної реалізації методики на основі вперше запропонованого взаємозв'язку нескладних конструкторсько-технологічних рішень.

Висновки. Отримала подальший розвиток аналітична модель ехо-сигналів просторово розподілених наземних (надводних) об'єктів, яка враховує специфіку їх конструкції, та на її основі вперше розроблена універсальна методика самозахисту об'єктів від радіолокаційних засобів самонаведення, яка реалізована у запатентованому способі та комплексі для виключення ураження захищаємих об'єктів.

КЛЮЧОВІ СЛОВА: радіолокаційна головка самонаведення, модель розсіювання електромагнітних хвиль, ділянка локального відображення, пеленгаційна характеристика, кутовий відбивач, поляризаційна решітка.

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DOI 10.15588/1607-3274-2023-1-1

МАТЕМАТИЧНЕ ТА КОМП'ЮТЕРНЕ МОДЕЛЮВАННЯ

MATHEMATICAL AND COMPUTER MODELING

UDC 004.4:004.032.26

COMPARISON OF SHORT-TERM FORECASTING METHODS OF ELECTRICITY CONSUMPTION IN MICROGRIDS

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ABSTRACT

Context. The current stage of development of the electric power industry is characterized by an intensive process of microgrid development and management. The feasibility of using a microgrid is determined by the fact that it has a number of advantages compared to classical methods of energy generation, transmission, and distribution. It is much easier to ensure the reliability of electricity supply within the microgrid than in large energy systems. Energy consumers in a microgrid can affect the power balancing process by regulating their loads, generating, storing, and releasing electricity. One of the main tasks of the microgrid is to provide consumers with electrical energy in a balance between its generation and consumption. This is achieved thanks to the intelligent management of the microgrid operation, which uses energy consumption forecasting data. This allows to increase the efficiency of energy infrastructure management.

Objective. The purpose of this work is to develop short-term electricity consumption forecasting models for various types of microgrid electricity consumers, which will improve the efficiency of energy infrastructure management and reduce electricity consumption.

Method. The SARIMA autoregressive model and the LSTM machine learning model are used to obtain forecast values of electricity consumption. AIC and BIC information criteria are used to compare autoregressive models. The accuracy of forecasting models is evaluated using MAE, RMSE, MAPE errors.

Results. The experiments that forecast the amount of electricity consumption for the different types of consumers were conducted. Forecasting was carried out for both LSTM and AR models on formed data sets at intervals of 6 hours, 1 day, and 3 days. The forecasting results of the LSTM model met the forecasting requirements, providing better forecasting quality compared to AR models.

Conclusions. The conducted study of electricity consumption forecasting made it possible to find universal forecasting models that meet the requirements of forecasting quality. A comparative analysis of developed time series forecasting models was performed, as a result of which the advantages of ML models over AR models were revealed. The predictive quality of the LSTM model showed the accuracy of the MAPE of forecasting electricity consumption for a private house – 0.1%, a dairy plant – 3.74%, and a gas station – 3.67%. The obtained results will allow to increase the efficiency of microgrid management, the distribution of electricity between electricity consumers to reduce the amount of energy consumption and prevent peak loads on the power grid.

KEYWORDS: Microgrid, machine learning, LSTM model, AR model, forecasting, electricity consumption.

ABBREVIATIONS

AR is an autoregressive;

ARMA is an autoregressive moving average;

ARIMA is an autoregressive integrated moving average;

SARIMAX is a seasonal auto-regressive integrated moving average with exogenous factors;

ML is a machine learning;

LSTM is a long short-term memory;

MAE is a mean absolute error;

RMSE is a root-mean-square error;

MAPE is a mean absolute percentage error.

NOMENCLATURE

y_t is the value of the time series at time t;

$X_{k,t}$ is an exogenous variables;

β_t is aregression parameters;

φ_p is a non-seasonal autoregression;

DOI 10.15588/1607-3274-2023-1-2

Φ_p is a seasonal autoregression;

θ_q is a conditions of non-seasonal moving average;

Θ_q is an average seasonal conditions of movement;

B^s is a lag operator;

z_t is a noise;

x_t is an entrance;

f_t is a forgotten gate;

i_t is an entrance gate;

$\tilde{C}$ is an updating the cell;

C_t is a state of the cell;

o_t is an output gate;

h_t is an output;

$tanh$ is an activation function;

$\hat{\sigma}^2$ is an expected variance;

n is a number of input data;

$\hat{y}_t$ is a predictive value.

INTRODUCTION

The current stage of the power industry development is characterized by the intensive process of microgrid development and its integration with the big centralized electricity grid. The term microgrid is used to refer to an integrated energy system of small power with distributed generators and energy consumers. Such an energy system, as a rule, is located on a small area [1].

The feasibility of using a microgrid is determined by the fact that it has several advantages compared to classical methods of energy generation, transmission, and distribution. In Microgrid, the energy produced is mainly used by local consumers, which ensures a reduction in losses associated with the transmission and distribution of energy by electric networks [2].

It is much easier to ensure the reliability of electricity supply within the microgrid than in large energy systems. Energy consumers in a microgrid can participate in the power balancing process by regulating their loads, generating, storing, and releasing electricity. One of the main tasks during microgrid management is to forecast electricity consumption to prevent peak loads on the power grid [3, 4].

The electricity consumption forecasting task is quite relevant due to the necessity to correctly load distribution in electrical networks, ensure their reliable operation and uninterrupted power supply to consumers [5].

Efficiency in forecasting electricity consumption, which is evaluated as the correspondence of the required and actual data, can be achieved by solving the task, formulated as follows: with the minimum number of resources, it is necessary to provide consumers with all the necessary electricity [6]. A similar task often arises for power grid organizations and large industrial enterprises. For enterprises, this problem is caused by the fact that organizations of this type must calculate the demand for electricity when it is generated or purchased on the wholesale market [7, 8]. In addition, such an independent calculation can also be used as a factor in detecting commercial losses of electricity, because currently it is one of the rather serious problems at the stage of electricity transmission to end users.

Electricity consumers face the task of calculating the necessary load on the microgrid, which is influenced by various factors, such as climate, geographical location, time of day, socio-economic and other factors [16]. From the available data, it is necessary to select the most significant ones and make a forecast of energy consumption [17].

Energy sources in a microgrid system may be renewable sources of electricity generation from solar panels and wind turbines, as well as energy stored in large-capacity storage batteries. Microgrids can also combine multiple energy sources to provide consumers with uninterrupted access to electricity. The volume of electricity consumption is not a stable value, therefore, for the normal functioning of the microgrid, short-term forecasting is necessary to determine the future volumes of electricity consumption [7].

The electricity consumption forecast allows to reduce risks when making decisions about balancing the operation of the power system and reducing consumption by end users.

The total energy consumption of the region depends on internal changes for the enterprise, the sector of household consumers and the social sphere [8]. All the changes that occur in the demand for electric energy pose the task of maintaining the balance between production and consumption, because the energy service provider must fully satisfy the needs of electricity. To forecast energy consumption, a few stages must be completed [11]:

– carry out a graphic or descriptive analysis of the available input information about electricity consumption and factors affecting it;

– study the obtained time series;

– choose forecasting methods and make forecast models taking into account the influence of external factors;

– evaluate the received forecast values and choose the best forecasting model.

There is no standard approach to forecasting electricity consumption, as each consumer has its own specific characteristics [5]. Electricity consumption has cyclical, specific, and random components. Approximately 70–80% of all changes have cyclical trends. Also, one of the researched factors is the regularities of a functional nature [6]. These regularities include deviations explained by relatively well-known factors that are specific to each consumer. The third component of the forecast is random variation. When forecasting, these changes are probabilistic in nature [16].

Microgrid control and operation is carried out using specialized software. It is designed to monitor, control and optimize distributed energy for management and support of local IT infrastructure. For the uninterrupted operation of the Microgrid, the monitoring of current

DOI 10.15588/1607-3274-2023-1-2

electricity consumption and the forecasting for future time periods are required, which ensures the energy systems stability[8].

The object of the study is the process of improving the microgrid efficiency by forecasting electricity consumption for different types of electricity consumers.

The subject of the study are the time series forecasting methods that provide electricity consumption forecasting with high accuracy for various types of consumers.

The purpose of the work is the development of electricity consumption forecast models for various types of microgrid consumers', assessment of the forecast quality of forecasting models.

1 PROBLEM STATEMENT

To calculate the values of a time series at future points in time, it is necessary to define a functional dependence that reflects the relationship between the past and future values of this series [16]:

$$Z(\tau) = \Phi(Z(\tau-1), Z(\tau-2), Z(\tau-3), ...) + \varepsilon_t . \quad (1)$$

Dependency (1) is called the forecasting model. It is necessary to create such a forecasting model for which the average absolute deviation of the true value from the forecast tends to the minimum for a given P [17]:

$$\overline{E} = \frac{1}{P} \sum_{t=T+1}^{T+P} |\varepsilon_t| \to \min . \quad (2)$$

The forecasted amount of electricity consumption depends on the values obtained in the previous time intervals of consumption.

Consumers of electricity in microgrid can be enterprises with a permanent or variable work schedule, household consumers, etc. This necessitates the task to create a universal forecasting model that will ensure high forecasting accuracy for all possible users of microgrid systems.

Short-term forecasting is used for decision support on the microgrid operation to choose the optimal mode of operation of the energy supply system, combining different types of renewable energy sources.

2 REVIEW OF THE LITERATURE

Many domestic and foreign scientists were engaged in solving the problem of electricity consumption forecasting as time series forecasting task including using machine learning methods. To generalize their experience, we studied some theoretical, methodological, and applied publications.

The high-precision data on electricity consumption by households were analysed in [9]. The authors separated the average demand profiles from demand fluctuations based solely on time series data and proposed a stochastic model for quantitative coverage of periodic demand fluctuations. The authors used the empirical mode decomposition (EMD) to decompose the data into a finite number of functions based on the local properties of the data.

The authors of the [10] implemented machine learning (ML) models and described the application of machine learning for the development of energy collection (photovoltaics), storage (batteries), conversion (electrocatalysis), and control (smart grids).

In the study [11], a set of machine learning models of electricity consumption of a shoe store was built. As factors were taken: day of the week, day number, week number, holiday/working day, consumption of the previous day. The following machine learning methods were used in [11]: Linear Regression, Random Forest Regressor, Decision Tree Regressor, KNeighbors Regressor, LinearSVR. The model trained by the Random Forest Regressor method showed the best result.

The article [12] analyses the energy consumption of residential buildings. The model proposed by the authors generates a hidden space for demand peaks from the data fed into the long-short-term memory of a convolutional neural network (CNN-LSTM).

The authors of the article [13] used models based on the integration of seasonal autoregressive integrated moving average, Firefly optimization algorithm and support vector regression (SAMFOR). The comparison results showed that the SAMFOR model was more efficient than others such as Seasonal Autoregressive Integrated Moving Average (SARIMA) and Support Vector Regression (SVR) models, SARIMA-SVR and Random Forest (RF) models.

The authors of the article [20–21], on the basis of the future behavior of the microgrid system, predict the generation of electricity from the supply of energy sources. The authors model a system of microgrid with a large number of interchanges and changes for modeling the technology of generation of electricity and physical characteristics. In the article, there is a dynamic structure with mixed logic, to guarantee the future behavior for the microgrid, and also to protect the hour of the work of the accumulative battery. In order to predict inconsistencies in microgrid, a mechanism of reversal linkage is introduced to eliminate the problem of additional control of the horizon. With the help of model predictive control, the minimization of operating costs is achieved for planning the behavior of microgrid components.

The forecasting using artificial neural networks is widely used in modern research in the forecasting of electricity production and consumption [5]. Neural network models allow consideration of a large amount of data that must be processed in real-time and eliminate the uncertainty factor that further complicates the task of electricity consumption forecasting. Adaptation and constant learning makes the use of ML models the most effective for forecasting electricity consumption.

3 MATERIALS AND METHODS

The main factor that determines the power consumption regimes of the object supplied with

DOI 10.15588/1607-3274-2023-1-2

electricity in the microgrid is the nature of the electrical loads, which are generally divided into three types [3]:

– household – the load consumed by the population (residential buildings, dormitories);

– social – the load consumed by social objects (shops, schools, cinemas, etc.)

– industrial – the load consumed by enterprises with a permanent or variable work schedule.

To take into account all possible consumers, predictive models of electricity consumption are built on three data sets:

– household – a residential house;

– social – a gas station;

– industrial – a dairy plant.

Electricity consumption data was collected automatically every hour and entered into a database. Also, additional data such as ambient temperature, wind speed, and daylight length were used.

After a literature review, autoregressive models and machine learning models for electricity consumption forecasting were chosen. Nowadays they are the most popular time series forecasting models because, in most of the analysed articles, they showed better forecasting quality.

Autoregressive models are a statistical method of time series analysis. They use the linear dependence of the future value of the forecast on some number of previous values of the time series [3]. One of the main disadvantages of autoregressive models (AR, ARMA) is the inability to work with non-stationary data [10], therefore, the SARIMAX model was chosen. The SARIMAX model is a seasonal autoregressive integrated moving average model that considers exogenous variables that influence the determination of the forecast value.

$$y_t = \beta_0 + \beta_1 X_{1,t} + \beta_2 X_{2,t} + \cdots + \beta_k X_{k,t} + \frac{(1-\theta_1 B - \theta_2 B^2 - \cdots - \theta_q B^q)(1-\Theta_1 B^S - \Theta_2 B^{2S} - \cdots - \Theta_Q B^{QS})}{(1-\varphi_1 B - \varphi_2 B^2 - \cdots - \varphi_p B^p)(1-\Phi_1 B^S - \Phi_2 B^{2S} - \cdots - \Phi_P B^{PS})} Z_t, \quad (3)$$

A machine learning model such as long-short-term memory (LSTM) network was also chosen for short-term electricity consumption from microgrid (Figure 1). LSTM is a recurrent neural network (RNN) [15] for forecasting time series under conditions where peak values have uncertain periodicity. An advantage over other time series forecasting methods is the insensitivity to noise and outliers.

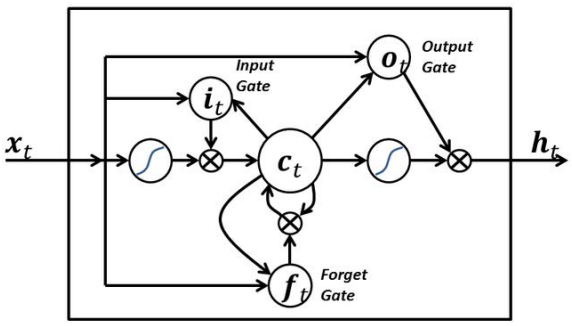

Figure 1 – LSTM Neural Network Architecture [22]

The principle of the model is as follows: first, the level of the forgetting filter determines what information can be forgotten or retained:

$$f_t = \sigma(W_f \cdot [h_{t-1}, x_t] + b_f). \quad (4)$$

Then the new information in the state of the cell is selected. In the next step, the input filter layer (sigmoid layer) updates the data. The tanh layer then creates a vector of new candidate values $\tilde{C}_t$, that can be added to the state of the cell:

$$i_t = \sigma(W_i \cdot [h_{t-1}, x_t] + b_i), \quad (5)$$

$$\tilde{C}_t = than(W_c \cdot [h_{t-1}, x_t] + b_c), \quad (6)$$

The next step is to replace the old state of the cell with a new one:

$$C_t = f_t \cdot C_{t-1} + i_t \cdot \tilde{C}_t, \quad (7)$$

The last step is to select the source information.

$$o_t = \sigma(W_o \cdot [h_{t-1}, x_t] + o), \quad (8)$$

$$h_t = o_t \cdot than(C_t). \quad (9)$$

Information criteria are used to select the best parameters for the autoregression model. They allow you to compare models with each other and cannot test models in the sense of statistical hypotheses checking.

Akaike (AIC) – the criterion for assessing the quality of statistical models, that is defined as follows:

$$AIC = \ln(\hat{\sigma}^2) + \frac{2(p+q+1)}{n}. \quad (10)$$

The Bayesian Information Criterion (BIC) is based on finding the maximum of the likelihood function. BIC is defined as follows:

$$BIC = \ln(\hat{\sigma}^2) + \frac{(p+q+1)\ln(n)}{n}. \quad (11)$$

To compare various forecasting models forecasting accuracy estimates are used.

Mean absolute error (MAE) is the arithmetic mean of absolute errors, calculated as follows:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_l|. \quad (12)$$

The root mean square error (RMSE) is the square root of the root mean square error, calculated as follows:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_l|}. \quad (13)$$

DOI 10.15588/1607-3274-2023-1-2

The mean absolute percentage error (MAPE) is the mean absolute percentage deviation calculated as follows:

$$MAPE = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{y_i - \hat{y}_l}{y_i}\right|,\% \qquad (14)$$

Forecasting errors are used to evaluate the quality of the developed forecasting models. Checking the accuracy of the built models allows to change the input parameters of the models to increase the forecasting accuracy. The forecasting model meets the accepted requirements if the value of the MAPE parameter is less than 5%.

4 EXPERIMENTS

The study was carried out in several stages. First, several types of consumers with various sources of electricity consumption were selected, then different forecasting time intervals were considered. A microgrid system with renewable sources of electricity has been installed at all these consumers. Solar panels have been installed for a residential house and a gas station, and a wind generator for a dairy plant. Renewable sources partially cover the need for electricity.

A data set containing information on electricity consumption in a two-story private house was selected as a household consumer (Table 1).

Table 1 – An example of a data set for a residential house

Date	Value (kWh)	Day of week	notes	Hour	Month	Length of day
01.01.2018 0:00	1.057	2	weekday	0	June	49834
01.01.2018 1:00	1.171	2	weekday	1	June	49834
01.01.2018 2:00	0.560	2	weekday	2	June	49834
01.01.2018 3:00	0.828	2	weekday	3	June	49834
01.01.2018 4:00	0.932	2	weekday	4	June	49834

The level of electricity consumption in the house increases at night and during the hot season (Fig. 2).

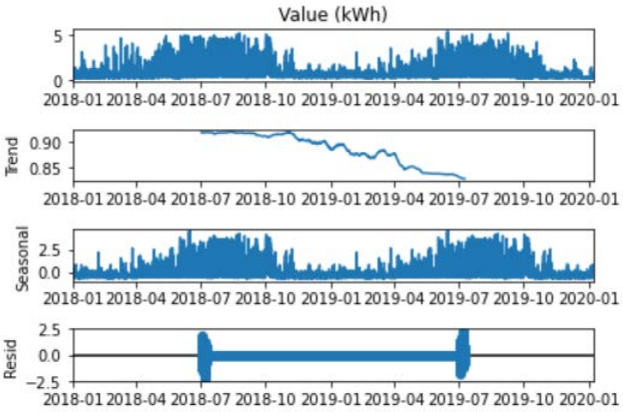

Figure 2 – Time series decomposition for residential consumer

The social electricity consumer is a gas station (Table 2).

Table 2 – An example of a data set for a gas station

Date	Value (kWh)	Indication	Length of day	Month	Week	Hour
01.01.2020 0:00	29.0	68.0	36190	11	44	0
01.01.2020 1:00	60.0	136.0	36190	11	44	1
01.01.2020 2:00	61.0	136.0	36190	11	44	2
01.01.2020 3:00	61.0	136.0	36190	11	44	3
01.01.2020 4:00	61.0	138.0	36190	11	44	4

The volume of electricity consumption at the gas station increases at night and in the cold season (Fig. 3).

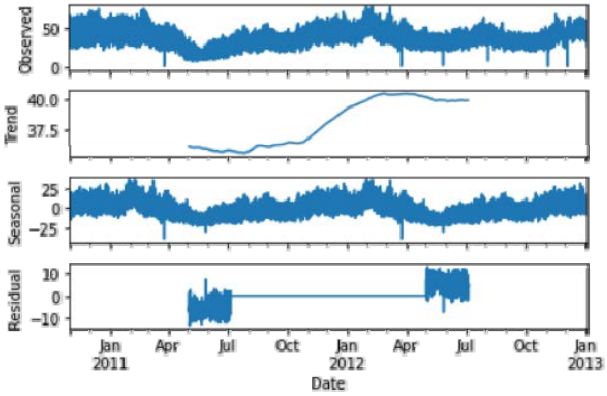

Figure 3 – Time series decomposition for gas station

Industrial electricity consumption data was provided by the dairy plant (Table 3).

Table 3 – An example of a data set for a dairy plant

Date	Value (kWh)	Length of day	T°	Week	Day of week	Hour
01.01.2013 0:00	223	42449	17	39	6	0
01.01.2013 1:00	215	42449	16	39	6	1
01.01.2013 2:00	218	42449	16	39	6	2
01.01.2013 3:00	210	42449	14	39	6	3
01.01.2013 4:00	214	42449	14	39	6	4

The amount of electricity used at the dairy plant increases during the day and during the hot season (Fig. 4).

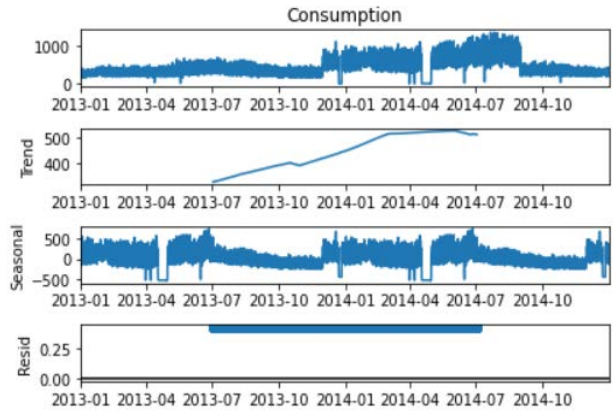

Figure 4 – Time series decomposition for dairy plant

Data from the above sources contained gaps that were filled with the average value of neighbouring indicators. The decomposition of the time series showed a seasonal

DOI 10.15588/1607-3274-2023-1-2

component, a large number of residuals, and the absence of a trend. Weather indicators of the environment, duration of a sunny day were taken as additional data.

The Python programming language and the Google Colab development environment were used to forecast the time series. The SARIMAX model was built for a residential house with the following parameters: p = 0, d = 1, q = 3, P = 1, D = 2, Q = 1, m = 12. The day of the week and the current time are chosen as exogenous parameters. The parameters which are shown in Table 4, provided the best values of the information criteria for a residential house.

Table 4 – Coefficients of the SARIMAX model for a residential house

	coef	std err	z	[0.025	0.975]
Day of week	0.0039	0.004	0.907	–0.004	0.012
Hour	0.0165	0.002	10.606	0.013	0.020
ar.L1	0.6891	0.004	162.102	0.681	0.697
ma.L1	–0.9856	0.001	–836.893	–0.988	–0.983
ar.S.L12	–0.2341	0.006	–40.045	–0.246	–0.223
ma.S.L12	–0.9450	0.002	–568.840	–0.948	–0.942
sigma2	0.2242	0.001	221.779	0.222	0.226

For the gas station, the SARIMAX model was built with the following parameters: p = 1, d = 1, q = 3, P = 1, D = 1, Q = 1, m = 12. The length of the day and the current time are additional data (Table 5).

Table 5 – Coefficients of the SARIMAX model for a gas station

	coef	std err	z	[0.025	0.975]
Length of day	0.0033	0.002	1.365	–0.001	0.008
Hour	0.0285	0.020	1.429	–0.011	0.068
ar.L1	0.7650	0.004	187.115	0.757	0.773
ma.L1	–1.0199	0.002	–616.789	–1.023	–1.017
ar.S.L12	–0.5938	0.004	–132.943	–0.603	–0.585
ma.S.L12	–1.2057	0.005	–251.137	–1.215	–1.196
sigma2	8.4633	0.083	102.044	8.301	8.626

For the dairy factory, the SARIMAX model was built with the following parameters: p = 1, d = 0, q = 1, P = 1, D = 1, Q = 1, m = 12. The length of the day and the ambient temperature serve as auxiliary data (Table 6).

Table 6 – Coefficients of the SARIMAX model for a dairy plant

	coef	std err	z	[0.025	0.975]
Length of day	0.0010	0.003	0.366	–0.004	0.006
T	2.2368	0.156	14.346	1.931	2.542
ar.L1	0.8849	0.004	246.114	0.878	0.892
ma.L1	–1.0000	0.022	–46.128	–1.042	–0.958
ar.S.L12	–0.4206	0.008	–55.627	–0.435	–0.406
ma.S.L12	–0.8688	0.004	–214.637	–0.877	–0.861
sigma2	860.8387	19.769	43.545	822.092	899.585

Another model for forecasting was the LSTM machine learning model. The model was built using the Keras library for Python. The model is built on four layers. First the Sequential class is instantiated, then the LSTM layers and the Dropout and Dense auxiliary layers are added. The number of neurons in the LSTM layer is indicated. Return_sequences parameter is set to “true” to add the following data. The parameter Input_shape indicates the number of time steps, and output_shape shows the number of indicators. A dropout layer is added to avoid retraining. To ensure the reliability of the prediction, a Dense layer with the number of neurons 1 is added. The model for training uses 20 epochs, the data batch size is 100 (Table 7).

Table 7 – Coefficients of the LSTM model

Layer	Shape	Param
LSTM	100	52400
Dropout	100	0
Dense	1	101
Total params	52.501	
Trainable params	52.501	
Epochs	20	
Batch size	100	

Input values of the LSTM model for all types of consumers are indicators of hourly electricity consumption, the length of the day is used as an additional value. The coefficients of the LSTM model were selected in such a way that when the type of electricity consumers changed, the forecasted accuracy remained at a high level.

5 RESULTS

Experiments on forecasting volumes of electricity consumption for selected data sets were conducted. The predictive quality of the models was checked on test data. The selected models forecast hourly electricity consumption for 6 hours, 1 day, 3 days ahead.

The results of testing the forecasting accuracy of the SARIMAX model are in Table 8.

Table 8 – Forecasting accuracy of the SARIMAX model

Forecast period/ Assessment of accuracy		6 hours	1 day	3 days
Dairy Plant	**MAE**	36.6893	49.8139	64.2426
	RMSE	50.7658	110.2718	118.1284
	MAPE (%)	11.4544	13.1783	17.6610
Residential house	**MAE**	0.1145	0.2226	0.2393
	RMSE	0.1066	0.0043	0.3135
	MAPE (%)	0.0021	0.0070	0.0647
Gas Station	**MAE**	4.3309	4.6415	5.1155
	RMSE	11.5534	12.9961	5.9725
	MAPE (%)	5.6638	9.0617	11.5512

DOI 10.15588/1607-3274-2023-1-2

Forecasted by the SARIMAX model and the actual values of electricity consumption by the dairy plant are shown in Fig. 5.

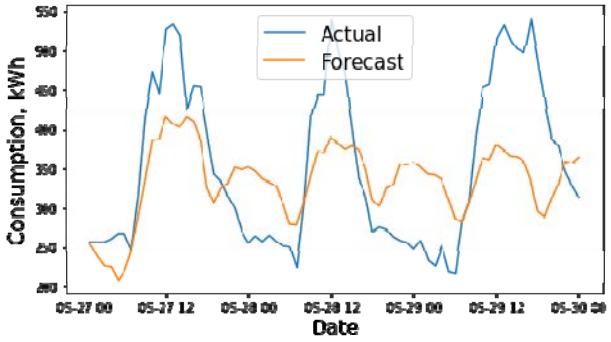

Figure 5 – Actual and forecasted values of electricity consumption by the dairy plant using the SARIMAX model

As a result of using the LSTM model built on parameters (Table 7), forecasting results (Table 9) were obtained for three types of electricity consumers.

Table 9 – LSTM model forecasting quality

Forecast period/ Assessment of accuracy		6 hours	1 day	3 days
Dairy Plant	**MAE**	15.4205	26.3461	24.5023
	RMSE	20.5534	35.6533	32.5615
	MAPE (%)	3.7420	6.7309	6.6436
Residential house	**MAE**	0.0902	0.0596	0.0908
	RMSE	0.1048	0.0784	0.2396
	MAPE (%)	0.1586	0.1631	0.1243
Gas Station	**MAE**	2.2020	3.0619	2.2143
	RMSE	2.4266	3.8967	2.9812
	MAPE (%)	3.6706	6.0989	4.6605

Forecasted by the LSTM model and the actual values of electricity consumption by the dairy plant are shown in Fig. 6.

The loss function (Fig. 7) was used to adjust the model, it is used to adjust the weights during the next evaluation of the model.

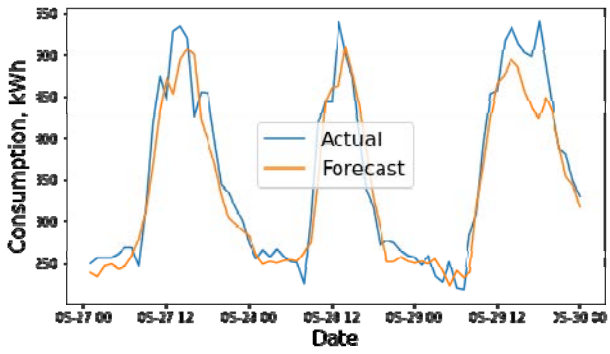

Figure 6 – Actual and forecasted values of electricity consumption by the dairy plant using the LSTM model

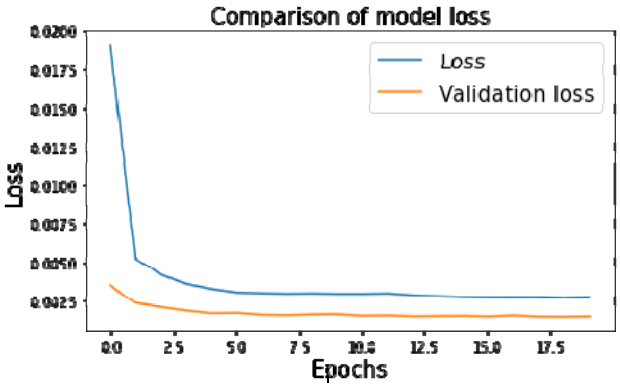

Figure 7 – Dependence of LSTM network loss on the number of training epochs on the dairy plant data set

6 DISCUSSION

The following conclusions can be drawn from the analysis of the results of the forecasting of electric energy in Microgrids. The SARIMAX model does not meet the requirement for forecasting electricity consumption. This model can only be used for short-term forecasting (from 1 hour to 6 hours). Only the prediction of electricity consumption for a private house using the SARIMAX model showed a slight advantage in predictive quality.

The forecasting results of the LSTM model met the forecasting requirements, providing better forecasting quality compared to AR models.

Compared to existing electricity forecasting works [7–12], forecasting results for the private sector have been significantly improved. The quality of forecasting of the LSTM model with the proposed parameters showed better results and forecasts than in the reviewed works. The proposed universal model showed high forecasting results for the considered types of consumers, compared to articles [10] where model parameters need to be constantly adjusted to obtain competitive forecasting results.

CONCLUSIONS

A study of the forecasting of electricity consumption by various types of consumers was conducted, which made it possible to develop universal consumption forecasting models that meet the requirements of forecast quality.

Autoregressive models for selected data sets are built with different values of input parameters. Since the SARIMAX model is sensitive to the input data, there is a need for a large number of values (6–10 seasons) unlike the LTSM model. The parameters of the forecasting models were selected experimentally. The forecasting quality of each model was compared by conducting a series of experiments for each data set and for each time interval.

The comparative analysis of the developed time series forecasting models made it possible to draw a conclusion about the advantages of ML models over AR models. The forecasted quality of the LSTM model showed the accuracy of the MAPE of electricity consumption forecasting: for a residential house – 0.1%, a dairy – 3.74%, and a gas station – 3.67%.

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The scientific novelty consists in building a universal forecasting model that provides high forecasting accuracy for different types of microgrid consumers.

The practical significance is that the developed forecasting models are used in decision support system for microgrid real-time operation. It allows effectively implement microgrid technology to increase the efficiency of energy infrastructure management and reduce electricity consumption.

Prospects for further research include the development of intelligent information technology to support decision-making and a set of software tools for energy infrastructure management, which will increase the efficiency of decision-making at various levels of energy infrastructure management.

ACKNOWLEDGEMENTS

The work was carried out with the support of the state budget research project of the Sumy State University "Intelligent Information-analytical Technologies and Means of Presentation, Assessment, and Management of the Country's Energy Infrastructure" (state registration number 0121U109558).

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Received 10.11.2022.
Accepted 23.12.2022.

УДК 004.4:004.032.26

ПОРІВНЯННЯ МЕТОДІВ КОРОТКОСТРОКОВОГО ПРОГНОЗУВАННЯ СПОЖИВАННЯ ЕЛЕКТРОЕНЕРГІЇ ДЛЯ МІКРОМЕРІЖ

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АНОТАЦІЯ

Актуальність. Сучасний етап розвитку електроенергетики характеризується інтенсивним процесом розвитку та управління мікромережею. Доцільність використання мікромережі визначається тим, що вона має низку переваг порівняно з класичними методами генерації, передачі та розподілу енергії. Забезпечити надійність електропостачання в мікромережі набагато легше, ніж у великих централізованих енергосистемах. Споживачі енергії в мікромережі можуть впливати на процес балансування електроенергії, регулюючи свої навантаження, генеруючи, накопичуючи та відпускаючи електроенергію. Одним із головних завдань Microgrid є забезпечення споживачів електричною енергією в балансі між її генерацією та споживанням. Це досягається завдяки інтелектуальному управлінню роботою Microgrid, яке використовує дані прогнозування енергоспоживання. Це дозволяє підвищити ефективність управління енергетичною інфраструктурою, робить її більш стійкою.

Мета. Метою даної роботи є розробка моделей короткострокового прогнозування споживання електроенергії для різних типів споживачів електроенергії у Microgrid, що дозволить підвищити ефективність управління енергетичною інфраструктурою та загалом зменшити споживання електроенергії.

Метод. Для отримання прогнозних значень споживання електроенергії використовуються авторегресійна модель (AR) SARIMA та модель машинного навчання (ML) LSTM. Інформаційні критерії AIC і BIC використовуються для порівняння авторегресійних моделей. Точність моделей прогнозування оцінюється за допомогою помилок MAE, RMSE, MAPE.

Результати. Проведено експерименти з прогнозування обсягів споживання електроенергії для різних типів споживачів. Прогнозування проводилося як з використанням моделей LSTM, так і моделей AR на сформованих наборах даних з інтервалами кожну годину протягом 6 годин, 1 день і 3 дні. Результати прогнозування з використанням моделі LSTM відповідали вимогам, забезпечуючи кращу якість прогнозування порівняно з авторегресійними моделями.

Висновки. Проведене дослідження прогнозування споживання електроенергії дозволило знайти універсальні моделі прогнозування, які відповідають вимогам якості прогнозування. Проведено порівняльний аналіз розроблених моделей прогнозування часових рядів, у результаті якого виявлено переваги моделей ML перед моделями AR. Прогностична якість моделі LSTM показала точність MAPE прогнозування споживання електроенергії для приватного будинку – 0,1%, молокозаводу – 3,74%, АЗС – 3,67%. Отримані результати дозволять підвищити ефективність управління мікромережею, розподілу електроенергії між споживачами для зменшення загальних обсягів споживання енергії та запобігання виникнення пікових навантажень.

КЛЮЧОВІ СЛОВА: мікромережа, машинне навчання, модель LSTM, модель AR, прогнозування, споживання електроенергії.

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DOI 10.15588/1607-3274-2023-1-2

НЕЙРОІНФОРМАТИКА ТА ІНТЕЛЕКТУАЛЬНІ СИСТЕМИ

NEUROINFORMATICS AND INTELLIGENT SYSTEMS

UDC 519.876.5:681.518.2

COMPUTATIONAL INTELLIGENCE METHODS TO PATIENTS STRATIFICATION IN THE MEDICAL MONITORING SYSTEMS

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ABSTRACT

Context. In modern medical practice the automation and information technologies are increasingly being implemented for diagnosing diseases, monitoring the condition of patients, determining the treatment program, etc. Therefore, the development of new and improvement of existing methods of the patient stratification in the medical monitoring systems is timely and necessary.

Objective. The goal of intelligent diagnostics of patient's state in the medical monitoring systems – reducing the likelihood of adverse states based on the choice of an individual treatment program:

− reducing the probability of incorrectly determining the state of the patients when monitoring patients;

− obtaining stable effective estimates of unknown values of treatment actions for patients (corresponding to the found state);

− the choice of a rational individual treatment program for the patients, identified on the basis of the forecasted state.

Method. Proposed methodology, which includes the following computational intelligence methods to patient's stratification in the medical monitoring systems:

1) method of cluster analysis based on the agent-based approach – the determination of the possible number of patient's states using controlled variables of state;

2) method of robust metamodels development by means artificial neuron networks under a priori data uncertainty (only accuracy of measurements is known) in the monitoring data: a) a multidimensional logistic regression model in the form of analytical dependences of the posterior probabilities of different states of the patients on the control and controlled variables of state; b) a multidimensional diagnostic model in the form of analytical dependences of the objective functions (quality criteria of the patient's state) on the control and controlled variables of state;

3) method of estimating informativeness controlled variables of state at a priori data uncertainty;

DOI 10.15588/1607-3274-2023-1-3

4) method of robust multidimensional models development for the patient's state control under a priori data uncertainty in the monitoring data in the form of analytical dependencies predicted from the measured values of the control and controlled variables of state in the monitoring process;

5) method of reducing the controlled state variables space dimension based on the analysis of the variables informativeness of the robust multidimensional models for the patient's state control;

6) method of patient's states determination based on the classification problem solution with the values of the control and forecasted controlled variables of state with using the probabilistic neural networks;

7) method of synthesis the rational individual patient's treatment program in the medical monitoring system, for the state identified on the basis of the forecast.

Proposed the structure of the model for choosing the rational individual patient's treatment program based on IT Data Stream Mining, which implements the «Big Data for Better Outcomes» concept.

Results. The developed advanced computational intelligence methods for forecast states were used in choosing the tactics of treating patients, to forecast treatment complications and assess the patient's curability before and during special treatment.

Conclusions. Experience in the implementation of "Big Data for Better Outcomes" concept for the solution of the problem of computational models for new patient stratification strategies is presented. Advanced methodology, computational methods for a patient stratification in the medical monitoring systems and applied information technology realizing them have been developed. The developed methods for forecast states can be used in choosing the tactics of treating patients, to forecast treatment complications and assess the patient's curability before and during special treatment.

KEYWORDS: Information Technology Data Stream Mining, Medical Monitoring Systems, Machine Learning Methods, Mathematical Models and Methods for Patient Stratification.

ABBREVIATIONS

ANN is an artificial neural network;

DM is a decision-makers;

CDSS is a computer decision support system;

IDS is an intellectual diagnostics of systems;

MFFN is a multilayer feedforward artificial neural network;

MMS is a medical monitoring system;

RBF is a radial-basis function neural network.

NOMENCLATURE

$\vec{X}^{(0)}$ is an input vector of state parameters values;

$\vec{F}$ is a vector of state's target functions;

P is a number of the elements in the dataset;

H_0 is a dimension of the input vector;

H_{K+1} is a dimension of the output vector;

$\vec{F}^{(K+1)}$ is an output vector of the ANN model;

K is a number of neuron in the hidden layer;

X_j is a set of the elements from j^{th} cluster;

$\vec{x}_{jp}$ is p^{th} vector of the element in the j^{th} cluster;

P_j is a number of elements in the j^{th} cluster;

k^* is a number of clusters;

$d\left(\vec{x}_{jp},\vec{c}_j\right)$ is an intra-cluster distance;

$d_1\left(\vec{x}_{jp},\vec{c}_j\right)$ is Manhattan distance;

MD^2 is Mahalanobis distance;

D_{KL} is Kullback-Leibler entropy;

w_{jp} is a membership matrix;

$\vec{c}_j$ is a vector of cluster's centers;

$M\left(\vec{c}_j\right)$ is an average measure of the intra-cluster distance;

$LF(x)$ is a loss function;

Z is a target set of pairs of cluster's number and number of elements in them;

$\hat{Z}$ is a solution of an optimize problem;

k_j is the cluster's number;

D_X is correctness set;

$\rho\left(\vec{x}_{jp},\vec{c}_j\right)$ is Cauchy distribution;

η is a parameter of Cauchy distribution;

n is an iteration number;

N is total number of iterations;

$k_t^{(n)}$ is estimated number of clusters on the n^{th} iteration;

f_i is selection function's values at the ANN output;

x_h is parameter's value at the input layer;

MV is selection function of the MV-problem;

ξ is significance level;

f_{fit} is a fitness function;

f_i^* is required value of the selection function;

$\sigma^0_{f_i,p}$ is standard deviation of the selection function;

β_f is regularization parameter;

n_α is number of measurements for fixed state;

$\chi^2_{f_i,p}$ is chi-squared test;

d_i is metric of the state's space;

L_{fit} is convergence acceleration factor;

$\mu_i\left(f_i^*\right)$ is membership functions;

$f_i\left(\vec{X}^{(0)}\right)$ is fitness function value;

$\sigma^0_{f_i}$ is standard deviation of variables value f_i;

$f^*_{i,p}$ is required values of the function for p^{th} training set;

f^0 is normalized values of a variables or target functions;

f is current values of a variables or target functions;

$f_{\min}$ is minimum value of a variables or target functions;

$f_{\max}$ is maximum value of a variables or target functions;

l_f is slope factor of the activation function;

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bt is slope factor of the function *th*();

$\sigma^{*}_{X_h^{(0)}}$ is required standard deviation of the input data;

$X^{(0)}_{h.\max}$ is maximum value of the input data variables;

$X^{(0)}_{h.\min}$ is minimum value of the input data variables;

D_L is training dataset;

L is dimension of the training dataset (state's space);

$\hat{M}$ is search variables set;

M is variables subset from D_L set;

D_{F_i} is dispersion of the target function, in decibels;

$D^{(0)}_{F_i}$ is dispersion of the base (linear) model;

$D^{(\mathrm{mod}\,el)}_{F_i}$ is dispersion of the other model;

$D_{M,\lambda}$ is subset of informativeness variables;

Σ_X is the covariance matrix of variables X_l and X_n;

σ_{X_l} is the standard deviation of X_l;

r_{ln} are the correlation coefficients between X_l and X_n (l=1...L, n=1...L);

E_i is a signal energy;

λ_{ih} is the informativeness coefficients;

D_Q is monitoring results;

Q is dimension of monitoring data;

Π^0 is design and regime parameters;

U^0 is control variables;

Φ^0 is phase variables;

t is forecast moment;

T_1 is lower forecast moment;

T_2 is upper forecast moment;

ε_t^0 is relative error;

Ψ is control state model;

Ω is diagnostic model;

W^0 is quality criteria of the patient's condition;

I is dimension of time series q^0;

$\vec{X}^{*}$ is vector of observed symptoms of unidentified precedent;

$X_1^{*},...,X_A^{*}$ are principal components projections of $\vec{X}^{*}$;

A is number of the principal components;

c_{lk} are the classes centers (l, k=1…A);

$\rho(R_{k*})$ is the probability distribution density agreeing to the Student's t-law;

$\left\langle \vec{X}_m \right\rangle$ is average projections value principal components vector of the observed symptoms of layer samples element;

$\Gamma(\,)$ is gamma function;

K_l is number of precedents in l^{th} class, l=1…A;

K_k is number of precedents in k^{th} class, k=1…A;

$\sum_{pooled}$ is the combined correlation matrix for the considered scenarios (for classes);

$P(R_k)$ is a prior probability of the classes realization;

$\hat{X}$ is quasisolution of MV-problem;

t_f is Student's coefficient for considered function f;

Ro_f is Romanovsky's coefficient for considered function f;

$M_\alpha[\ ]$ is mathematical expectation with significance level α;

x_p^{*} is required variables values x_p for prototype;

σ_p^{*} is required mean deviation values of variables x_p for prototype;

σ_{x_p} is mean square deviation of variables $x_p \in X^0$;

$\sigma^{*}_{f_i}$ is the mean deviation values of decision making criterion f_i for prototype;

σ_{f_i} is mean square deviation of decision making criterion $f_i \in F$;

γ is a regularization parameter;

time is the value of the survival time for the patient after undergoing treatment.

INTRODUCTION

The actual problems of modern medicine – the problems of assessing the states, forecasting the outcome of diseases, the effectiveness of treatment methods, assessing the likelihood of complications in patients – can be solved based on the use of advanced machine learning methods and information technologies that implement them. That's why developing an applied information technology for patient stratification in medical monitoring systems based on advanced machine learning methods is an actual scientific and practical task.

An MMS consists of monitoring hardware for the patient's condition, decision makers (physicians) and CDSS. The aim of such systems – to ensure continuous observation, information collecting, data processing and analyzing patient's condition, forming recommendations for treating [1, 2].

National Aerospace University named by N. Zhukovsky "Kharkiv Aviation Institute" for more than 15 years has been developing applied information technology for patient stratification in medical monitoring systems based on machine learning methods. The university has developed its own software to accomplish the assigned problems and has qualified personnel who participate in international projects in the field of applied mathematics, statistics, and machine learning. In cooperation with the Kharkov National Medical University, the developed software is being tested for stratification of patients with prostate cancer, squamous cell carcinoma of the head and neck [3–14]. The developed methods for forecasted states are also planned to be verified on the data obtained in various oncological pathologies and to use them in choosing the tactics of treating patients, to forecast treatment complications and assess the patient's curability before and during special treatment.

The material and technical support and personnel base of the Kharkov National Medical University allows col-

DOI 10.15588/1607-3274-2023-1-3

lecting data on the course of treatment of cancer patients receiving chemoradiation treatment, using the whole range of non-invasive diagnostic methods, a wide range of tumor markers. Working with patients is regulated by the Bioethics and Deontology Committee and complies with international GCP standards.

As part of the implementation of projects, an innovative strategy is proposed for choosing a rational individual tactics for treating patients based on forecasted states identified using robust stratification methods, which will improve clinical results and prevent complications.

It is also planned to collect data on patients with cancer who have undergone COVID-19 before starting treatment and to assess the effect of the latter on the timing of the start of radiation and chemotherapy, depending on the severity of post Covid's syndrome.

This paper shows computational models for processing and research about a patient's condition and his body functioning based on the "Big data for better outcomes" concept for MMS.

The object of study is the processes for predicting the states and choosing individual treatment programs for patients based on monitoring data.

The subject of study is the computational intelligence methods to patient's stratification in the medical monitoring systems.

The purpose of the work is to reduce the likelihood of adverse states for patients in medical monitoring systems based on the choice of an individual treatment program by means of computational intelligence methods.

1 PROBLEM STATEMENT

Reducing material costs and time of forecasting of the patients' states in the medical monitoring systems are possible through the automation forecasting process of the patient's states using information technology Big Data. We define Big Data as an information technology based on the use of approaches series, tools and processing methods of the structured and unstructured data of large volumes and considerable variety to obtain the results for DM that are effective in conditions of continuous increase and distribution by numerous nodes of the computer network data stream.

The goals of intelligent diagnostics of patient's state in the medical monitoring systems:

– reducing the likelihood of adverse states based on the choice of an individual treatment program;

– reducing the probability of incorrectly determining the state of the patients (errors of the third kind in classifying the state of the systems) when monitoring patients;

– obtaining stable effective estimates of unknown values of treatment actions for patients (corresponding to the found state);

– the choice of a rational individual treatment program for the patients, identified on the basis of the forecasted state.

The aim of the investigation is to develop advanced methodology for solving the synthesis problem of patient's individual treatment program in the medical monitoring systems by means of computational intelligence methods for the medical information analysis and applied information technology realizing them by means of new robust estimation methodology (M-estimation) based on the concept of invariance of the theory of optimal control and apply it to solving nonlinear multidisciplinary problem of under uncertainty.

Let us input data $\left(\vec{X}^{(0)}, \vec{F}\right)_p$, $p = 1...P$ are the results of the anamnesis (personal, visual examination, laboratory data), these are statistical data (dataset) from the observed patients, accumulated by medical institutions, as well as the individual results of patient monitoring, considered as training pairs. An input vector and output vector is of dimension H_0 and H_{K+1} respectively.

The data model, such as information from the ambulatory card, formed by experts (physicians).

Statistical data (dataset) from the observed patients had transferred to the database storage Big Data from medical organizations.

Each patient must be able to contribute their own monitoring results to the database.

Data processing and diagnostic results transmission carried out by using Internet resources, which is available to every user, including the use of CDSS on remote servers.

Structuring new mathematical statements and developing computational methods is necessary for solving the synthesis problem of a patient's individual treatment program in the medical monitoring systems by means of computational intelligence methods, in stochastic formulation (MV-problem).

On the result of processing the input data, you need to find the following:

– the required number of controlled state variables for the classification of states (single or multiple diseases, and their corresponding disease stages);

– results of the patient's condition classification (single or multiple cases and their corresponding disease stages);

– estimates of survival rates and clinical effectiveness of the treatment;

– quality of life assessments for patients during treatment and in the follow-up period;

– results of informative monitored condition variables synthesis for patients individually at the current point in the monitoring process;

– results of predicting the time series of monitored state variables (including medical influences);

– justification of the time intervals choice for measuring values of controlled variables during monitoring depending on the disease stage;

– the results of predicting patient conditions that cannot be assessed using current clinical, laboratory and in-

DOI 10.15588/1607-3274-2023-1-3

strumental methods (e.g. hormone resistant prostate cancer);

– selection of an individual treatment regimen (medical interventions) depending on the patient's condition in order to minimize the risk of serious adverse events.

Such developments compared to existing methods will ensure a reduction in the probability of incorrectly determining the state of the systems (errors of the third kind in classifying the state of the patients), as well as obtaining stable effective estimations of the unknown values variables (corresponding to the found state).

2 REVIEW OF THE LITERATURE

Over the past decade, as a result of cooperation, the authors have developed the methods for solving such problems:

– formation of a subset of controlled variables of state, the values of the quantities of which are check in by measuring instruments [3, 9];

– patient's classification of state results [4, 6, 7, 9];

– informativeness evaluations of the variables of for different stages of patients' diseases [4, 5, 9];

– robust metamodels: multidimensional diagnostic model, multidimensional logistic regression [6, 8, 9, 11];

– robust multidimensional models of control the states of the patients, evaluation of forecasted values of the controlled variables of state based on medical monitoring data for patients [11, 5];

– cluster analysis results – the number of recognizable states [5, 9, 12];

– patient's state classification results, using the values of the control and forecasted controlled variables of state [9, 11];

– the results of the synthesis of a rational individual treatment program for the patients for the state, determined on the basis of a forecast (determination of control variables (medical actions), that ensure the implementation of the treatment program) [9, 11, 14].

Numerical research was carried out with the help of the computer program "Non-linear evaluation methods in multicriteria problem of robust optimal designing and diagnostics of systems under parametric a priori uncertainty (methodology, methods, techniques and computer systems of support and decision-making implementing them)" (ROD&IDS) [13] developed by the authors.

The volumes of medical information about various diseases and their course are extremely large, and machine learning methods make it possible to process the accumulated information, take into account millions of different factors, social, territorial, demographic, genomic, etc., and make it possible to identify the unique features of each patient [15, 16]. It has been proven that the automation of the collection processes and further analysis of medical data allows to increase the accuracy of early diagnosis, prediction of the disease's development and the treatment effectiveness assessment [17]. For example, the Frost & Sullivan agency notes that artificial intelligence technologies increase the accuracy of diagnoses by 30–40%, and pathologist Andy Beck from Harvard Medical School believes that the further use of artificial intelligence technologies will reduce the errors rate in diagnosis by 85% [18].

Modern technologies are also used to choose the most effective treatment strategy. Recently, scales (systems) for objectifying the assessment of clinical-physiological and laboratory parameters have been used to choose treatment tactics, the scope of anesthetic support and surgical intervention, predict the frequency of probable postoperative complications, lethality, and the treatment effectiveness [19]. The priority of such a strategy is that after receiving the sum of objective indicators, the doctor converts them into a score, which is ranked into numerical and staging corridors. This makes it possible to comprehensively assess the patient's condition at the moment, monitor his condition and carry out appropriate treatment. The correctness and effectiveness of treatment with this method depends on the qualifications and experience of the doctor treating the patient [20].

The choice of mathematical methods for the description and research of biological and medical objects depends both on the specialist's individual knowledge and on the specifics of the tasks to be solved [21].

The following methods are most often used to solve the classification problem of the medical facilities state:

– binary classification (decision trees and random forests) [22];

– artificial neural networks (ANN) [23];

– multidimensional logistic regression [24];

– naive Bayesian classifier [25];

– support vector machines [23, 26].

Obviously, the use of each of these methods separately does not allow solving the general problem of synthesizing an individual patient treatment program in a medical monitoring system.

So, there is a need to structure the system model of medical decision-making as a sequence of interrelated tasks and the corresponding system model of decision synthesis. In other words, it is necessary to create a methodology for the synthesis of solution to the problem of making medical decisions in general.

The work proposes methodology for solving the synthesis problem of a patient's individual treatment program in the medical monitoring systems by means of computational intelligence methods for the medical information analysis.

3 MATERIALS AND METHODS

Medical Monitoring System is a set of monitoring states hardware, information technology Big Data tools (which contains CDSS), patients and decision-makers (doctors) who are in a communicate relation with each other and united with the purpose of managing and organizing the process of systematic or continuous observation, collection, processing and information investigation about the object state (of patient), its functioning (of various organs) and development for a certain period of time.

DOI 10.15588/1607-3274-2023-1-3

Its system is created and regulated by the monitoring entities (physicians) to ensure full, timely and accurate information and appropriate organization of effective functioning and control of the object of diagnosis (patient).

The Context diagram of "Big Data for Better Outcomes" concept implementation in the medical monitoring systems is shown in Fig. 1.

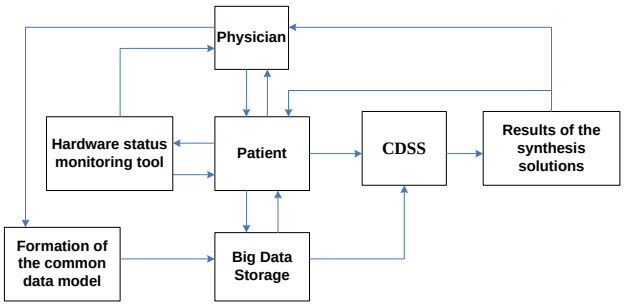

Figure 1 – Context diagram of "Big Data for Better Outcomes" concept implementation in the medical monitoring systems

Generalized methodology for solving the problem of synthesis problem of patient's individual treatment program in the medical monitoring systems by means of computational intelligence methods as a result of its decomposition may be given as a sequence of processing techniques of structured and unstructured data of large volumes and considerable diversity using developed software. The solving result is sequence of steps to obtain mathematical model $\vec{F}^{(K+1)}\left(\vec{X}^{(0)}\right)$ in order to solve diagnosing problems.

Patient stratification is carried out in two steps: Data preprocessing and Monitoring the state of the patients. Each stage is described below.

1. Data Preprocessing (Preliminary data preparation is performed by a doctor):

1.1 Formation of a subset of controlled variables of state $\left(\vec{X}^{(0)},\vec{F}\right)_p, p=1...P$, the values of the quantities of which are checked in by measuring instruments.

1.2 A total dataset of alternatives is generated. Each alternative includes subsets of control variables and controlled variables of state; objective functions. The total dataset includes subsets of alternatives corresponding to different states of the patients, including the healthy state.

1.3 Data cleaning from anomalous values of the quantities (outliers). Normalization of data.

1.4 Cluster analysis – the determination of the possible number of states (states of the patients) using control and controlled variables of state. We are looking for an answer to the question whether there is enough data from medical research to be able to recognize different states and the corresponding stages of diseases with the maximum a posteriori probability? If the number of identified clusters coincides with the specified one and the distances between the clusters are statistically significant, then the subset of monitored variables of state can be considered complete. Otherwise, the diagnostic system, which is used for monitoring of patient's states, should be equipped with new measuring instruments.

Based on the agent-based approach and in accordance with the chosen measures of intra-cluster distance, permissive elite selection rules are proposed for the formation of clusters, the selection of the best of them, and also for the selection of elements into clusters in the process of solution synthesis.

The result of solving such a problem is the number of clusters, as well as the number of elements in them.

The c-means clustering method was chosen as the basis.

Let the sample of data be considered as $X=\{X_j\}; X_j=\{\vec{x}_{jp}\}$ and $P=\sum_{j=1}^{k^*}P_j^*$ is the total number of elements.

It is necessary to find $\{k_j, P_j\}, j=1...k^*$.

Four measures of intra-cluster distance were used as a metric for the clustering data:

$$d\left(\vec{x}_{jp},\vec{c}_j\right)=\begin{cases} d_1\left(\vec{x}_{jp},\vec{c}_j\right), \\ MD^2\left(\vec{x}_{jp},\vec{c}_j\right), \\ w_{jp}^{-1}MD^2\left(\vec{x}_{jp},\vec{c}_j\right), \\ -D_{KL}\left(\vec{x}_{jp},\vec{c}_j\right). \end{cases}$$

Let us define the average measure of the intra-cluster distance:

$$M\left(\vec{c}_j\right)=\frac{1}{P_j}\sum_{p=1}^{P_j}d\left(\vec{x}_{jp},\vec{c}_j\right).$$

Also the loss function is defined as

$$LF(X)=\frac{1}{k^*}\sum_{j=1}^{k^*}M\left(\vec{c}_j\right).$$

Then the research problem statement will take in the form:

$$\begin{cases} Z=\left(k_j,\{P_j\}\right), \\ \hat{Z}=\arg\min\limits_{X\in D_x} LF(X). \end{cases}$$

It is necessary to determine the number of clusters and distribute the data among clusters so that the value of the loss function is minimal.

To correct the centers of clusters, we use the expression

$$\vec{c}_j=\sum_{p=1}^{P_j}w_{jp}\vec{x}_{jp}\Big/\sum_{p=1}^{P_j}w_{jp},$$

DOI 10.15588/1607-3274-2023-1-3

where $w_{jp} = \dfrac{\rho\left(\vec{x}_{jp}, \vec{c}_j\right)}{\sum\limits_{p=1}^{P_j} \rho\left(\vec{x}_{jp}, \vec{c}_j\right)}$ is the membership matrix with the Cauchy distribution

$$\rho\left(\vec{x}_{jp}, \vec{c}_j\right) = \frac{1}{\pi\eta\left[1 + MD^2\left(\vec{x}_{jp}, \vec{c}_j\right) \Big/ \eta^2\right]}.$$

Data clustering algorithm based on agent-based approach:

1) set $k_t^{(n)} > k^*$, $P_j^{(n)} = \text{int}\left(\dfrac{N}{k_t^{(n)}}\right)$ and randomly generate cluster centers $\left\{\vec{c}_j\right\}$;

2) using the selected measure with cluster distance $d_1\left(\vec{x}_{jp}, \vec{c}_j\right)$, choose $P_j^{(n)}$ the nearest neighbors for each j^{th} cluster;

3) for each j^{th} cluster, using the $\left\{w_{jp}\right\}$ and $\left\{\rho\left(\vec{x}_{jp} \middle| P_j\right)\right\}$, the cluster centers $\left\{\vec{c}_j\right\}$ are corrected;

4) for each j$^{\text{th}}$ cluster, using the selected measure within the cluster distance $d\left(\vec{x}_{jp}, \vec{c}_j\right)$ and $P_j^{(n)}$ the nearest neighbors are chosen. Delete the points that are duplicated: $P_j^{(n)} \to P_j$;

5) for each j^{th} cluster the average measure of the intra-cluster distance $M\left(\vec{c}_j\right)$ is calculated, and also $LF(X)$ is calculated;

6) elite selection. Find the cluster with the largest $M\left(\vec{c}_j\right)$ and delete it;

7) $k_t^{(n+1)} = k_t^{(n)} - 1$; $P_j^{(n+1)} = \text{int}\left(\dfrac{N}{k_t^{(n+1)}}\right)$;

8) back to step 2, if $k_t^{(n+1)} > 1$.

1.5 Development of robust metamodels at a priori data uncertainty in the monitoring data (given that the results of measurements of variables of states are random variables – only accuracy of measurements is known):

a) a multidimensional logistic regression in the form of analytical dependences of the posterior probabilities of different states of the patients on the control and controlled variables of state;

b) a multidimensional diagnostic model in the form of analytical dependences of the objective functions (quality criteria of the patient's state) on the control and controlled variables of state.

To development of robust metamodels as initial information used the vector function is given by a training sample $\left(\vec{X}^{(0)}, \vec{F}\right)_p$, $p = 1...P$. We must approximate the given set. The problem can be solved with a resultant mathematical mechanism, which may give any value of the vector function $\vec{F}_p^{(K+1)}\left(\vec{X}_p^{(0)}\right)$, represented by this training set at a fixed input vector within the range, limited by the input data.

A multilayer feedforward artificial neural network (MFFN) and radial basis function network (RBF), used for data approximation, is a parallel distributed processor, which is capable of saving acquired knowledge and processing information between local processor elements (neuro-elements or neurons), bound by special links (synaptic links).

To provide parameter stability (robustness) and informative capability of statistical systems and processes models on the basis of learning ANN at the a priori input data uncertainty and also practically sufficient data approximation, it is reasonable to use advanced deep learning methods – stable (robust) statistical assessment of their parameters with adaptive learning rate as the ANN learning method.

Student and V. I. Romanovsky are used as a smoothing functional when choosing a rational solution, which provides a stable (robust) estimation of the searching values with parametric uncertainty of the input data, as well as sufficient, from a practical point of view, accuracy of data approximation in problems of improving systems.

The function (MV-problem) was used as a scalar convolution of selection functions, considering $f_i \equiv F_i^{(2)}, x_h = X_h^{(0)}$:

$$MV = \frac{1}{2PI} \sum_{p=1}^{P} \xi^{P-p} \sum_{i=1}^{I} \left(\begin{array}{l} f_{fit}\left[\left(\dfrac{\mu_i\left(f_{i,p}^*\right)\Delta_{f_i,p}}{f_i^*\left(1+\sigma_{f_i,p}^0\right)}\right)^2\right] + \\ + \beta_f \cdot f_{fit}\left(\dfrac{\left|\chi_{f_i,p}^2 - n_\alpha\right|}{\sqrt{2n_\alpha}}\right) \end{array} \right),$$

here $I=H_{k+1}$, ξ = [0.95, 0.99],

$$f_{fit}(d_i) = 1 - \exp\left[-\frac{L_{fit}}{4} d_i\right],\ L_{fit} \geq 4,\ (d_i > 0);$$

$$\Delta_{f_i} = F_i^{(K+1)}\left(\vec{X}^{(0)}\right) - f_i\left(\vec{X}^{(0)}\right),\ \sigma_{f_i}^0 = \frac{\sigma_{f_i}}{\sigma_{f_i}^*},$$

$$\frac{\left|\chi_{f_i,p}^2 - n_\alpha + 3\right|}{\sqrt{2(n_\alpha - 3)}} = \frac{n_\alpha}{\sqrt{2(n_\alpha - 3)}}\left|\left(\sigma_{f_i}^*\right)^2 - 1 + \frac{3}{n_\alpha}\right|,\ n_\alpha = 4.$$

For fitness functions $f_i\left(\vec{X}^{(0)}\right)$ in the expression for scalar convolution of selection functions MV the meanings of relative values are calculated by formulas:

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– direct conversation $f^0 = \frac{2l_f\left(f - \langle f \rangle\right)}{f_{\max} - f_{\min}}$, here $\langle f \rangle = \frac{f_{\max} + f_{\min}}{2}$, $f^0 \in [-1,1]$;

– inverse conversation $f = \left[\left(f_{\max} - f_{\min}\right) f^0 / l_f + \left(f_{\max} + f_{\min}\right)\right] / 2$, here $l_f = th(bt)$ for MFFN and $l_f = 1$ for RBF.

The relative mean square deviations of input data are calculated by formula

$$\left(\sigma^0_{f_i}\right)^2 = \left(\frac{2l_f}{f_{i,\max} - f_{i,\min}}\right)^2 \left(\frac{\Delta^0_{f_i}}{300} f_{i,\max}\right)^2 n_\alpha ,$$

$\Delta^0_{f_i} = \frac{\Delta_{f_i}}{f_{i,\max}} 100\%$, here $l_f = th(\beta)$ for MFFN and $l_f = 1$ for RBF;

$$\left(\sigma^*_{X_h^{(0)}}\right)^2 = \left(\frac{2}{X^{(0)}_{h.\max} - X^{(0)}_{h,\min}}\right)^2 \left(\frac{\Delta^0_{X_h^{(0)}}}{300} X^{(0)}_{h.\max}\right)^2 n_\alpha .$$

By known training set D_L the ANN parameters vector $\hat{M}$ will choose according to the principle of maximum aposteriori probability distribution density:

$$\hat{M}_{n+1} = \arg\min_{M \in D_L} MV\left(M \middle| D_L\right).$$

An advanced computational method is proposed for estimating the parameters of structural-parametric models of systems and processes in the form of trained ANNs based on the method of stochastic approximation and the use of a regularizing sequential (adaptive) algorithm for the synthesis of solutions with delayed correction (based on the ravine method of conjugate gradient methods and the method of simulating the movement of bee colonies), which implements adaptive control of calculations in accordance with the principle of minimum disturbance.

Application of the proposed methods avoids the appearance of false ravines or valleys on response surfaces in case of gross errors in the input data.

In the paired comparison of metamodels models changing of the signal variance is evaluating, which defines the robustness of a particular model:

$$D_{F_i}, dB = 10 \lg\left(\frac{D^{(model)}_{F_i}}{D^{(0)}_{F_i}}\right),$$

here *model* = 1 for MFFN and *model* =2 for RBF.

1. Monitoring of the state of the patients (data processing and analysis is performed by the doctor together with the patient):

2.1 The values of the control and controlled variables of state corresponding to the patient's state at a given time are measured.

2.2 Determination of the state for which the maximum a posteriori probability of its realization corresponds with the observed values of the quantities based on the solution of the classification problem, which allows to determine the disease stages that are not recognized by modern biomarkers (e.g., hormone-resistant stage in prostate cancer).

2.3 Estimation informativeness controlled variables of state at a priori data uncertainty, the synthesis of the set of informative controlled variables of state according to the patient's state (disease stage) for the reduction of the variables of state space dimension, using multidimensional diagnostic model, i.e. searching informative subset $D_{M,\lambda}$ of minimal dimension where $D_{M,\lambda} \subset D_L$.

The set of input data $F_i(X)$, where $X = \{x_l\}$, $l = 1 \ldots L$ is presented as a Taylor series, while retaining only the terms of the first infinitesimal order in the expansion. For the dispersion of an arbitrary gotten linear function of several random variables estimate holds:

$$D_{F_i} = \left(grad\, F_i\right)^T \Sigma_X\, grad\, F_i = \ldots = \sum_{l=1}^{L}\left(\frac{\partial F_i}{\partial x_l}\right)^2 \sigma^2_{x_l} +$$

$$+ \sum_{l=1}^{L}\sum_{n=1,n\neq l}^{L} r_{\ln} \frac{\partial F_i}{\partial x_l}\frac{\partial F_i}{\partial x_n}\sigma_{x_l}\sigma_{x_n}.$$

Let us define the signal energy by the expression

$$E_i = \sum_{h=1}^{H_0}\left|D_{F_i^{(2)}\left|X_h^{(0)}\right.}\right|,$$

here

$$D_{F_i^{(2)}\left|X_h^{(0)}\right.} = \left(\frac{\partial F_i^{(2)}}{\partial X_h^{(0)}}\right)^2 \sigma^2_{X_h^{(0)}} +$$

$$+ \left(\sum_{n=1,n\neq h}^{H_0} r_{\ln} \frac{\partial F_i^{(2)}}{\partial X_n^{(0)}}\sigma_{X_n^{(0)}}\right)\frac{\partial F_i^{(2)}}{\partial X_h^{(0)}}\sigma_{X_h^{(0)}}.$$

The informativeness coefficients (contribution weight $X_h^{(0)}$ into $F_i^{(2)}$) are defined by

$$\lambda_{ih} = \frac{\left|D_{F_i^{(2)}\left|X_h^{(0)}\right.}\right|}{E_i}, \sum_{l=1}^{L}\lambda_{ih} = 1.$$

2.4 Development of robust multidimensional models of control the state for the patients at a priori data uncertainty in the monitoring data in the form of analytical dependencies predicted from the measured values of the control and controlled variables of state in the monitoring process.

2.5 Forecasting multidimensional time series of controlled variables of state based on multidimensional models of control of the state for the patients:

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$$D_Q = \{q^0(t+1)\},$$
$$q^0(t+1) = [\Pi^0(t+1), U^0(t+1), \Phi^0(t+1)],$$

where $t=T_1 \ldots T_2$ is a limited set of Π^0, U^0, Φ^0 and creating time series.

It is required to obtain a functional dependence, that will be reflect relationship between the next and previous values of the time series which satisfies the system preferences of DM, for a given forecast horizon:

$$q^0(t+1) = F(q^0(t+T_2-1), \ldots, q^0(t-T_1)) + \varepsilon_t^0 .$$

Controlled process mathematical model:

$$\Delta\Phi^0 = \Psi(\Delta\Phi^0, \Delta U^0),$$
$$\Delta W^0 = \Omega(\Delta\Phi^0, \Delta U^0),$$

where the first expression is recurrent mathematical model for monitoring and the second expression is a diagnostic model:

$$X^0(t+1) = ln\left(\frac{q_i(t+1)}{q_i(t-T_1)}\right), i = 1 \ldots I, t = (-T_1+1) \ldots T_2 .$$

2.6 Reducing the dimension of the space of controlled variables of state based on the analysis of the informativeness of the variables of the robust multidimensional models of control the state for the patients (Sensitivity Analysis). Estimating the rank of time series cointegration.

2.7 Determination of the states of the patients based on the solution of the classification problem and the values of the control and forecasted controlled variables of state is conducted using probabilistic neural networks. An input layer $X_1^*, \ldots, X_A^*$ elements are the principal component vector projections of the monitored state variables $\vec{X}^*$. The layer of samples $c_{1k}, \ldots, c_{Ak}$ are the classes centers of the training samples. The number of exemplars equals the number of classes in the training set. The layer of input and the samples are entirely meshed structure. An element activity of the samples layer was determined by the dependence that related to the probability distribution density agreeing to the Student's t-law (that is proper for the limited samples):

$$c_{lk} = \rho(R_k) = \frac{\Gamma\left(\frac{n+1}{2}\right)}{\sqrt{\pi n}\,\Gamma\left(\frac{n}{2}\right)} \left(1 + \frac{t_{lk}^2}{n}\right)^{-\frac{n+1}{2}},$$

here Γ is gamma function with $n=K_l+K_k-2$;

$$t_{lk} = \sqrt{\frac{MD_{lk}^2}{\frac{1}{K_l} + \frac{1}{K_k}}},$$

here MD_{lk}^2 is Mahalanobis distance from an unidentified precedent (it is supposed that it appropriate to l class) to the k sample:

$$MD_{lk}^2 = \frac{1}{A}\left(\vec{X}^* - \langle \vec{X}_k \rangle\right)^T \Sigma_{pooled}^{-1} \left(\vec{X}^* - \langle \vec{X}_k \rangle\right),$$

here $\sum_{pooled}$ is determined because of belonging of the precedent to one, or another class:

$$\Sigma_{pooled} = \frac{1}{K_l + K_k - 2}\left((K_l - 1)\Sigma_l + (K_k - 1)\Sigma_k\right).$$

The output layer k^*, $\rho(R_{k^*})$ is a discriminator of the threshold value indicating the class to which belongs an unknown precedent.

The values of t-Student statistics depend on the selection of the degree of proximity of the precedent to the samples (when solving the classification problem), as well as between the samples (when analyzing the significance of the distance between classes). Therefore, it is necessary to further forming of supplementary statistical decision rule selecting a single guide basis. According to the maximum likelihood rule as a criterion for the transition from one state to the other state of patients, Bayes formula is used:

$$\forall k = 0 \ldots A-1 : \frac{\rho(\vec{X}_{k+1}^*)}{\rho(\vec{X}_k^*)} \geq 1.$$

Which is true provided that

$$\frac{P(R_k)}{P(R_{k+1})} \cdot \frac{\rho(\vec{X}_{k+1}^*)}{\rho(\vec{X}_k^*)} \approx 1.$$

2.8 Synthesis of a rational individual treatment program for the patients in the medical monitoring system, for the state identified on the basis of the forecast.

The control variables $\hat{X} = (M[X_0], \sigma_x^0)$ estimation problem can be presented like a MV-problem.

The MV-problem provides an efficient stable (robust) estimation of the required quantities under parametric input data uncertainty.

The quasisolution of this problem is

$$\hat{X} = \underset{\hat{X} \in D_X}{\arg\inf}\, MV(\hat{X} | t_f, Ro_f),$$

where the scalar convolution of selection functions MV is

DOI 10.15588/1607-3274-2023-1-3

$$MV = \frac{1}{2I}\sum_{i=1}^{I}\left(\begin{array}{l} f_{fit}\left[\left(\frac{\mu_i\left(f_i^*\right)\Delta_{f_i}}{f_i^*\left(1+\sigma^0_{f_i}\right)}\right)^2\right] + \\ +\beta_f \cdot f_{fit}\left(\frac{\left|\chi^2_{f_i}-(n_\alpha-3)\right|}{\sqrt{2(n_\alpha-3)}}\right) \end{array}\right) +$$

$$+\gamma\frac{1}{2P}\sum_{p=1}^{P}\left(\begin{array}{l} f_{fit}\left[\left(\frac{\mu_p\left(x_p^*\right)\Delta_{x_p}}{x_p^*\left(1+\sigma^0_{x_p}\right)}\right)^2\right] + \\ +\beta_x \cdot f_{fit}\left(\frac{\left|\chi^2_{x_p}-(n_\alpha-3)\right|}{\sqrt{2(n_\alpha-3)}}\right) \end{array}\right).$$

Here $\gamma=10^{-7}\ldots1.0$, $I=H_{k+1}$, $\Delta f_i = M_\alpha[f_i]-f_i^*$, $\Delta x_p = M_\alpha[x_p]-x_p^*$, $\chi^2_{f_i} = n_\alpha\frac{M_\alpha\left[(f_i-M_\alpha[f_i])^2\right]}{\left(\sigma^*_{f_i}\right)^2}$,

$\chi^2_{x_p} = n_\alpha\frac{M_\alpha\left[(x_p-M_\alpha[x_p])^2\right]}{\left(\sigma^*_{x_p}\right)^2}$, $\sigma^0_{f_i}=\frac{\sigma_{f_i}}{\sigma^*_{f_i}}$, $\sigma^*_{x_p}=\left\{\frac{\sigma_{x_p}}{\sigma^*_{x_p}}\right\}$,

$$\frac{\left|\chi^2_{f_i,}-(n_\alpha-3)\right|}{\sqrt{2(n_\alpha-3)}} = \frac{n_\alpha}{\sqrt{2(n_\alpha-3)}}\left|\left(\sigma^*_{f_i}\right)^2-1+\frac{3}{n_\alpha}\right|,$$

$$\frac{\left|\chi^2_{x_p,}-(n_\alpha-3)\right|}{\sqrt{2(n_\alpha-3)}} = \frac{n_\alpha}{\sqrt{2(n_\alpha-3)}}\left|\left(\sigma^*_{x_p}\right)^2-1+\frac{3}{n_\alpha}\right|.$$

For the MV-problem solution the computing method based on the memetic algorithm is applied. In this method the evolutional algorithm was realized with the decremental neighborhood method and the randomize path laying method together. The evolutional algorithm has next parameters, which change from epoch to epoch: real coding operator, fitness function and relaxation function.

The proposed method application gives the stable (robust) estimation of desired values under parametric input data uncertainty and lowers the difficulty of the quasisolution synthesis method.

The structure of the model for the choice of a rational individual treatment program for the patients based on IT Data Stream Mining, which implements the "Big Data for Better Outcomes" concept is shown in Fig. 2.

4 EXPERIMENTS

In that work, as an implementation of the concept "Big Data for Better Outcomes" for stratification of patients, the following tasks were solved:

– formation of a subset of controlled variables of state, the values of the quantities of which are check in by measuring instruments;

– robust metamodels: multidimensional diagnostic model;

– informativeness evaluations of the variables of states for different stages of patients' diseases.

The authors considered the task of assessing the increased survival rate of cancer patients who received chemoradiotherapy.

The multidimensional diagnostic model – model for estimating the survival of patients was built using a data set obtained in the real medical practice of the authors.

The patients with squamous cell carcinomas of the head and cancer (stages III, IVa, IVb) was included in study and did a comprehensive examination, including the collection of anamnestic data, general clinical physical examination, computed tomography of the head, neck and chest organs before the start of radiation therapy and 1 month after its completion, laboratory general clinical and biochemical blood tests. All patient received course of radiation therapy 5 Gy per fraction till 6–7 weeks (32–35

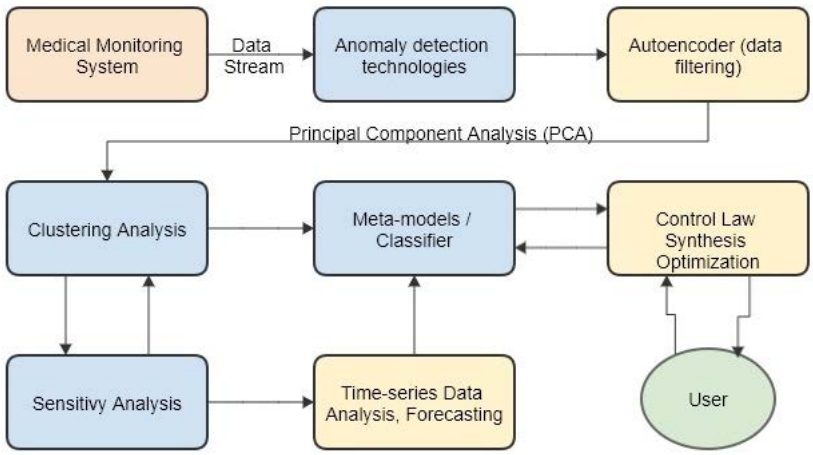

Figure 2 – Context diagram on the implementation of the model of the choice of a rational individual treatment program for the patients, identified on the basis of the forecasted state based on IT Data Stream Mining

DOI 10.15588/1607-3274-2023-1-3

fractions) with chemomodification Cisplatin 100 mg/m^2 at 1, 21, 42 days in SI "Grigoriev Institute for Medical Radiology and Oncology of NAMS of Ukraine". This set contains records of 57 patients on 9 indicators (parameters) that characterize the current state of each patient: age, localization, stage, tumor (T) and lymph (N) nodes status (TNM classification, 8 edition), response (per RECIST 1.1 criteria), tumor marker squamous cell carcinoma's antigen "before" and "after" the course treatment, survival time. All indicators have a numerical type, but some of them are enumerable, for example, the "localization" indicator takes four values from 1 to 4. The objective function for each record is "survival time", the other parameters are attributed to the input data.

First, it is necessary to normalize the data. Since the inputs are different in value and content, the normalization for them will be different. The parameters "localization", "stage", "T" and "response" are normalized according to the formula

$$f_i^0 = \frac{f_i}{f_{\max}},$$

here $f_{\max} = 4$.

The age indicator is normalized as follows:

$$Age_{norm} = \frac{Age_{\max} - Age_{current}}{Age_{\max}},$$

here we take age as the maximum value $Age_{\max} = 85$.

The indicators of tumor markers "before" and "after" are reduced to one parameter of tumor markers as follows:

$$Oncomar\,\mathrm{ker} = \ln\frac{mar\,\mathrm{ker}\_after}{mar\,\mathrm{ker}\_before}.$$

Let's denote the objective function by *Suv_time*, its values are also pre-normalized by the formula

$$Suv\_time = \frac{time}{t\arg et\_time},$$

here $t\,arg\,et\_time = 25$.

The results of the patient survival assessment are a functional relationship between the input data and the survival time. Using a robust meta-model based on a radial-basis neural network, survival time estimation values are calculated that correspond to the input data.

The structure of the simplest radial-basis function neural network includes three types of neuron layers. RBF with one hidden layer (K=1). At the input layer RBF has H_0 =7 neurons, at the hidden layer – H_1 = 44 neurons and H_2 =1 network outputs.

In addition, the task of determining the most influential (informative) parameters for assessing patient survival was solved.

Numerical research was carried out with the help of the computer program "Non-linear evaluation methods in multicriteria problem of robust optimal designing and intelligence diagnostics of systems under parametric a priori uncertainty (methodology, methods, techniques and computer systems of support and decision-making implementing them)" (ROD&IDS) developed by the authors [13].

5 RESULTS

To train the neural network and test its operation, the data set of the patient's survival time was divided into two parts: training (47 records, 82%) and test (10 records, 18%).

As a result of training, the relative error was 1.5%.

The relative error on the test sample was 15.4%. The trained neural network can then be used to provide survival estimates for new patients Table 1).

It was found by means of sensitive analysis of variables of the model for each patient from the training sample that on the average the indicators: T, age of the patient, response and stage of the disease are more likely to be informative (Table 2).

Table 2 – The informativeness evaluations of the indicators

	Age	Local.	Stage	T	N	Response	Tumor marker
Suv. time	0.262	0.0025	0.251	0.185	0.0006	0.289	0.009

Therefore, to assess the survival of patients, it is necessary to pay attention to these indicators.

Table 1 – Result of model for test set

Age	Local.	Stage	T	N	Response	Tumor marker	Suv_time (target)	Suv_time (fact)
0.235294	0.75	0.5	1	0.75	0.25	–0.887762	1	1.112889
0.164705	1	1	0	1	0.75	–0.062609	0.28	0.261637
0.364705	1	0.75	2	1	0.5	–0.243848	0.52	0.682176
0.258823	0.25	0.5	1	0.75	0.75	–0.267833	0.44	0.385309
0.352941	0.5	1	0	1	0.75	0.2626409	0.32	0.259509
0.341176	0.75	1	1	1	0.5	–1.659763	0.44	0.387156
0.305882	0.5	0.25	2	1	0.5	–0.212148	0.6	0.591057
0.188235	0.25	0.5	1	0.75	0.25	–0.472130	1	1.026191
0.258823	0.75	0.75	2	1	0.75	–0.819898	0.36	0.512091

DOI 10.15588/1607-3274-2023-1-3

6 DISCUSSION

Thus, the goal of the study was achieved – developed advanced methodology for solving the synthesis problem of the patient's individual treatment program in the medical monitoring systems by means of computational intelligence methods for the medical information analysis and applied information technology realizing them have been developed.

Its application allows:

– reducing the likelihood of adverse states based on the choice of an individual treatment program;

– reducing the probability of incorrectly determining the state of the patients (errors of the third kind in classifying the state of the systems) when monitoring patients;

– obtaining stable effective estimates of unknown values of treatment actions for patients (corresponding to the found state);

– the choice of a rational individual treatment program for the patients, identified on the basis of the forecasted state.

The developed software, which is described below information technology, is being tested for stratification of patients with prostate cancer, squamous cell carcinoma of the head and neck [3–11]. The developed methods for forecasted states are also planned to be verified on the data obtained in various oncological pathologies and to use them in choosing the tactics of treating patients, to forecast treatment complications and assess the patient's curability before and during special treatment.

The material and technical support and personnel base of the Kharkov National Medical University allows collecting data on the course of treatment of cancer patients receiving chemoradiation treatment, using the whole range of non-invasive diagnostic methods, a wide range of tumor markers. Working with patients is regulated by the Bioethics and Deontology Committee and complies with international GCP standards.

As part of the implementation of projects, an innovative strategy is proposed for choosing a rational individual tactics for treating patients based on forecasted states identified using robust stratification methods, which will improve clinical results and prevent complications.

It is also planned to collect data on patients with cancer who have undergone COVID-19 before starting treatment and to assess the effect of the latter on the timing of the start of radiation and chemotherapy, depending on the severity of post Covid's syndrome.

CONCLUSIONS

The scientific novelty obtained results in the fact that an advanced methodology for solving the synthesis problem of a patient's individual treatment program in the medical monitoring systems by means of computational intelligence methods for the medical information analysis and applied information technology realizing them have been developed.

The practical significance of obtained results is that the advanced computational intelligence methods for forecast states can be used in choosing the tactics of treating patients, to forecast treatment complications and assess the patient's curability before and during special treatment.

Prospects for further research are to study application possibilities of the proposed methodology for the choice of a rational individual treatment program for the patients with various chronic diseases, identified on the basis of the forecasted state by means of IT Data Stream Mining.

ACKNOWLEDGEMENTS

The work is supported by the state budget scientific research project of Karazin Kharkiv National University "Information process modeling in the complex and distributed systems" (state registration number 0121U109183) and research projects of Grigoriev Institute for Medical Radiology and Oncology of the National Academy of Medical Sciences of Ukraine "Development of programs for personalized control of the absorbed dose during radiation therapy of genital, head and neck tumors using in vivo dosimetry" (state registration number 0117U001046, 2017 – 2019) and "Optimizing topometrical preparation for radiation therapy of head and neck cancer patients" (state registration number 0119U103013, 2020 – 2022).

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Received 31.10.2022.
Accepted 22.12.2022.

УДК 519.876.5:681.518.2

ОБЧИСЛЮВАЛЬНІ ІНТЕЛЕКТУАЛЬНІ МЕТОДИ СТРАТИФІКАЦІЇ ПАЦІЄНТІВ У СИСТЕМАХ МЕДИЧНОГО МОНІТОРИНГУ

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DOI 10.15588/1607-3274-2023-1-3

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АНОТАЦІЯ

Актуальність. У сучасній медичній практиці все більше впроваджується автоматизація й інформаційні технології для діагностування захворювань, моніторингу стану пацієнта, визначення програми лікування тощо. Тому розробка нових і удосконалення існуючих методів стратифікації пацієнтів у системах медичного моніторингу є своєчасною і необхідною.

Метод. Розроблено методологію, яка включає такі методи обчислювального інтелекту для стратифікації пацієнтів у системах медичного моніторингу, як:

1) метод кластерного аналізу на основі агентного підходу – визначення можливої кількості станів пацієнтів з використанням контрольованих змінних станів;

2) метод побудови робастних метамоделей за допомогою штучних нейронних мереж при апріорній невизначеності даних (відома лише точність вимірювань) за даними моніторингу стану пацієнтів: а) багатовимірна логістична регресійна модель у вигляді аналітичних залежностей апостеріорних ймовірностей різних станів пацієнтів від контрольованих змінних станів; б) багатовимірна діагностична модель у вигляді аналітичних залежностей цільових функцій (критеріїв якості стану хворого) від контрольованих змінних станів;

3) метод оцінки інформативності контрольованих змінних станів при невизначеності апріорних даних;

4) метод побудови робастних багатовимірних моделей контролю стану пацієнтів при апріорній невизначеності даних у даних моніторингу у вигляді аналітичних залежностей, що прогнозуються за виміряними значеннями контрольованих змінних станів у процесі моніторингу;

5) метод зменшення розмірності простору контрольованих змінних станів на основі аналізу інформативності змінних робастних багатовимірних моделей управління станом пацієнтів (аналіз чутливості);

6) метод визначення станів пацієнтів на основі вирішення задачі класифікації за значеннями контрольних та прогнозованих контрольованих змінних стану з використанням імовірнісних нейронних мереж;

7) метод синтезу раціональної індивідуальної програми лікування хворих у системі медичного моніторингу для стану, виявленого на основі прогнозу.

У роботі запропонована структура моделі вибору раціональної індивідуальної програми лікування пацієнтів на основі IT Data Stream Mining, яка реалізує концепцію « Big Data for Better Outcomes».

Результати. Розроблені передові методи обчислювального інтелекту для прогнозування станів використовувалися при виборі тактики лікування пацієнтів, прогнозуванні ускладнень лікування та оцінці виліковності пацієнта до та під час спеціального лікування.

Висновки. Представлено досвід впровадження концепції «Big Data for Better Outcomes» для вирішення проблеми розробки передових методологій нових стратегій стратифікації пацієнтів. Розроблено передову методологію, методи обчислювального інтелекту для стратифікації пацієнтів у системах медичного моніторингу та прикладну інформаційну технологію, що їх реалізує. Розроблені передові методи прогнозування станів можуть бути використані при виборі тактики лікування хворих, прогнозуванні ускладнень лікування та оцінці виліковності хворого до та під час спеціального лікування.

КЛЮЧОВІ СЛОВА: інформаційна технологія потокового аналізу даних, системи медичного моніторингу, методи машинного навчання, математичні моделі і методи стратифікації пацієнтів.

УДК 519.876.5:681.518.2

ВЫЧИСЛИТЕЛЬНЫЕ ИНТЕЛЛЕКТУАЛЬНЫЕ МЕТОДЫ СТРАТИФИКАЦИИ ПАЦИЕНТОВ В СИСТЕМАХ МЕДИЦИНСКОГО МОНИТОРИНГА

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DOI 10.15588/1607-3274-2023-1-3

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АННОТАЦИЯ

Актуальность. В современной медицинской практике все больше внедряются автоматизированные и информационные технологии для диагностики заболеваний, мониторинга состояния пациентов, выбора программы лечения и др. В связи с этим разработка новых и усовершенствование существующих методов вычислительного интеллекта для стратификации пациентов в системах медицинского мониторинга является своевременной и необходимой задачей.

Метод. Разработана методология, включающая следующие методы вычислительного интеллекта для стратификации пациентов в системах медицинского мониторинга:

1) метод кластерного анализа на основе агентного подхода – определение возможного количества состояний пациентов с использованием контролируемых переменных состояния;

2) метод построения робастных метамоделей с помощью искусственных нейронных сетей при априорной неопределенности данных мониторинга (известна только точность измерений) в данных мониторинга: а) многомерная логистическая регрессионная модель в виде аналитических зависимостей апостериорных вероятностей различных состояний пациентов от контрольных и контролируемых переменных состояния; б) многомерная диагностическая модель в виде аналитических зависимостей целевых функций (критериев качества состояния больного) от контрольных и контролируемых переменных состояния.

3) метод оценки информативности контролируемых переменных состояния при неопределенности априорных данных;

4) метод построения робастных многомерных моделей контроля состояния пациентов при априорной неопределенности данных мониторинга в виде аналитических зависимостей, прогнозируемых по измеренным значениям контрольных и контролируемых переменных состояния в процессе мониторинга;

5) метод уменьшения размерности пространства контролируемых переменных состояния на основе анализа информативности переменных робастных многомерных моделей управления состоянием пациентов;

6) метод определения состояний пациентов на основе решения задачи классификации по значениям контрольных и прогнозируемых контролируемых переменных состояния с использованием вероятностных нейронных сетей;

7) метод синтеза рациональной индивидуальной программы лечения больных в системе медицинского мониторинга, для состояния, выявленного на основе прогноза.

В работе предложена структура модели выбора рациональной индивидуальной программы лечения пациентов на основе IT Data Stream Mining, которая реализует концепцию «Big Data for Better Outcomes».

Результаты. Разработанные усовершенствованные методы вычислительного интеллекта для прогноза состояний использовались при выборе тактики лечения пациентов, для прогнозирования осложнений лечения и оценки излечимости пациента до и во время проведения специального лечения.

Выводы. Представлен опыт реализации концепции «Большие данные для лучших результатов» для решения задачи разработки передовых методологий для новых стратегий стратификации пациентов. Разработаны передовая методология, методы вычислительного интеллекта для стратификации пациентов в системах медицинского мониторинга и реализующие их прикладные информационные технологии. Разработанные усовершенствованные методы прогноза состояний могут быть использованы при выборе тактики лечения больных, для прогнозирования осложнений лечения и оценки излечимости больного до и во время проведения специального лечения.

КЛЮЧЕВЫЕ СЛОВА: информационная технология потокового анализа данных, системы медицинского мониторинга, методы машинного обучения, математические модели и методы стратификации пациентов.

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DOI 10.15588/1607-3274-2023-1-3

UDC 004.896

METHOD AND SOFTWARE COMPONENT MODEL FOR SKIN DISEASE DIAGNOSIS

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ABSTRACT

Context. The problem of skin disease diagnosis was investigated in the paper. Its actuality is caused by the necessity of automation of at least advisory medical decision making. Such decisions are made in telemedicine, for instance, when skin disease diagnostics is performed under specific conditions. These conditions are specified by situations when data for analysis are collected but a qualified doctor has no possibility to process the data and to make a diagnosis decision based on it. The object of the study is a process of skin disease diagnosis.

Objective. The objective of the study is to develop a skin disease diagnosis method to automate making of advisory medical diagnosis decisions and to increase efficiency of such decisions.

Method. The skin disease diagnosis method was proposed in the work. This method applies the modified ResNet50 model. It was proposed to add layers to the ResNet50 model and to train it using transfer learning and fine-tuning techniques. The method also defines image processing in particular through the change of its resolution and uses oversampling technique to prepare a dataset for model training.

Results. Experimental investigation of the proposed method was performed using the HAM10000 dataset which contains images of skin diseases. The images were collected using dermatoscopy method. The dataset contains observations for 7 different skin diseases. The proposed method is characterized by the accuracy of 96.31% on this dataset. It is improved accuracy in comparison with the existing neural network models. Software component model was created to give a possibility to integrate the proposed method into a medical diagnosis system.

Conclusions. The obtained results of the investigation suggest application of the proposed skin disease method in medical diagnostic system to make advisory decisions by the system and to support making final decisions by a doctor.

KEYWORDS: dermatoscopy, medical diagnosis, convolutional neural network, skin disease, ResNet50 model, software component model.

ABBREVIATIONS

AdaBoost is Adaptive Boosting;

AI is Artificial intelligence;

AKIEC is Actinic Keratoses and Intraepithelial Carcinoma;

ANN is Artificial Neural Network;

AUC is Area Under Curve;

BB is Balanced Bagging;

BCC is Basal Cell Carcinoma;

BKL is Benign Keratosis-like Lesions;

BRF is Balanced Random Forest;

CNN is Convolutional Neural Network;

DF is Dermatofibroma;

HAM10000 is Human Against Machine with 10000 training images;

LR is Logistic Regression;

MEL is Melanoma;

NV is Melanocytic Nevi;

ReLU is Rectified Linear Unit;

ResNet is Residual Network;

RF is Random Forest;

SVM is Support Vector Machine;

VASC is Vascular Lesions;

WHO is World Health Organization;

XGBoost is eXtreme Gradient Boosting.

NOMENCLATURE

δ is a standard deviation of pixels;

A is an accurancy;

C is a number of correctly classified observations;

D is a set of diagnoses;

d^A is a skin disease diagnosis for an image of skin area which was not diagnosed by a dermatologist as it was classified by a model;

d_i is an actual skin disease diagnosis for the i-th observation in a dataset;

d_i^C is a skin disease diagnosis for the i-th observation in a dataset as it was classified by a model;

d_i is a class of the i-th observation in a dataset;

f is a functional dependence;

M is a number of misclassified observations;

N is a number of observations in a dataset;

p_i is the i-th image in a dataset;

p_i^{av} is an average pixel intensity value calculated through all values of the i-th image;

$p_i^{q,k}$ is a pixel intensity in all channels for pixel in the q-th row and k-th column of the i-th image;

DOI 10.15588/1607-3274-2023-1-4

$pn_i^{q,k}$ is a normalized pixel intensity in all channels for a pixel in the q-th row and k-th column of the i-th image;

S is a dataset;

S_{tr} is a training dataset;

S_t is a test dataset;

S_v is a validation dataset;

s^A is an image of skin area which was not diagnosed by a dermatologist;

s_i is an image of the i-th observation in a dataset.

INTRODUCTION

Despite active current progress of medicine, skin diseases are one of the most dangerous and widespread types of diseases. At the same time cases of skin diseases increase in number. Such trends are caused by either unfavorable external factors (for instance, environmental degradation, climate change, influence of ultraviolet radiation) or individual factors (chronic stress, heredity, unhealthy lifestyle, bad quality of diagnostics or untimely diagnostics). This year the trends are additionally reinforced in Ukraine by the war. Access of displaced persons or Ukrainian citizens in general to quality medicine (specialists with experience in a specified area) is complicated in some territories.

According to the data presented by WHO, the number of cases with detected nonmelanoma skin cancer increased to the level of 1.2 million and the number of melanoma cases reached more than 0.3 million in 2020 [1]. The percentage of fatal cases in these cases is the following: 5% for nonmelanoma skin cancer and 17% for melanoma skin cancer [1].

Official statistics in Ukraine confirm skin cancer as the cancer type with the biggest number of cases: there were more than 180 thousand of active cases in 2020 [2].

Skin diseases are more easily defined in comparison with the other types of cancer in particular. But people do not always consider its symptoms, paying necessary attention in visiting a doctor. Such a way may not only be the reason for serious health problems but also for a death of a human.

The source [3] states that only 40% of nonmelanoma skin tumors are detected in the early stages (the first and the second stages) in Ukraine. It should be noted that early detection guarantees effective treatment of a patient. At the same time melanoma is detected unfrequently at the initial stage in Ukraine. But in this case a disease is best treated.

The low quality of diagnostics is caused either by low level of patient information awareness regarding these diseases or by low level of procedure quality. The last one is connected with insufficient qualifications of a doctor, lack of necessary equipment, similarity of disease symptoms, analyses collected with procedural violations, human factor.

Diagnostic process includes gathering of data on patient's condition and drawing a conclusion on health issues. The process is realized through the following stages:

– detection of health issues by a patient;

– patient's referring to a medical institution for medical aid;

– collection, integration and interpretation of patient's medical data;

– generation of hypothesis on illness;

– confirmation/update of hypothesis via additional obtained data;

– making final diagnosis [4].

Gathering of patient's medical data for skin diseases requires physical examination of a patient. The examination is traditionally organized using dermatoscopy method. It requires to capture an image of an examined skin area and to estimate the following criteria:

– skin pigmentation change;

– skin color uniformity;

– structure characteristics;

– skin contours and pattern change;

– skin peeling and inflammation;

– skin tightening;

– skin cracks and ulcer areas [5].

Estimations of the presented criteria results in making a diagnosis and determining a treatment.

The object of the study is a process of skin disease diagnosis.

Because these diseases have a great impact on the quality of human life and can be dangerous for human health, timely detection of skin neoplasms with increasing accuracy of classification without doctor participation is actual and important problem which should be solved. This classification is necessary in telemedicine support systems, in systems where advisory decisions are made to decrease working time of a doctor with the necessary qualification.

Dermatologist makes his job in a way similar to image recognition by neural network: it demands input image (skin lesions) processed through neural network (skills and knowledge of dermatologist who analyses an image and synthesizes data) to classify it (to make a diagnosis) [6]. In addition, early diagnostics of a disease is one of necessary conditions for successful treatment of a disease, so modern approaches and methods of diagnosis support based on AI (in particular CNN models) should be applied to increase classification accuracy.

In general, neural network models are widely used in the field of dermatology presently taking into account the described similarity between real process and such models. ANN models are assumed to be efficient diagnosis tool [6, 7]. It can be applied to improve recognition results and to decrease number of misdiagnosed cases.

The subject of the study are ANN models which are applied for diagnostics of skin diseases based on classification of images which present skin state observations collected using dermatoscopy method.

The objective of the study is to develop a skin disease diagnosis method to automate making of advisory medical diagnosis decisions and to increase efficiency of such decisions.

DOI 10.15588/1607-3274-2023-1-4

1 PROBLEM STATEMENT

Skin disease diagnosis problem lies in a recognition of skin area images using appropriate mathematical model. In this work the problem should be specified using CNN as a mathematical model.

Let S be a dataset presenting skin disease cases with known diagnoses.

The dataset $S = \{s_i\}$, $i = 1, 2, ..., N$ consists of N observations s_i. Each i-th observation consists of a pair $s_i = <p_i, d_i>$, where p_i is an object which presents image of skin area and d_i is a diagnosis which was made by dermatologist based on an image p_i.

Object p_i is an array $\{p_i^{q,k}\}$ of elements. Each element $p_i^{q,k}$ is a record of intensity for pixel in the q-th row and k-th column. This record presents pixel intensity for each channel of an image.

Let D be a set of diagnoses. A set D contains the following elements:

– d^0 – Actinic Keratoses and Intraepithelial Carcinoma (to represent investigation results AKIEC is used to mark this diagnosis);

– d^1 – Basal Cell Carcinoma (marked by BCC in investigation results);

– d^2 – Benign Keratosis-like Lesions (marked by BKL in investigation results);

– d^3 – Dermatofibroma (marked by DF in investigation results);

– d^4 – Melanocytic Nevi (marked by NV in investigation results);

– d^5 – Melanoma (marked by MEL in investigation results);

– d^6 – Vascular Lesions (marked by VASC in investigation results).

In this study the diagnoses from d_0 to d_6 are used in a set D. This set could be extended if it is necessary in the medical diagnostic system and there is appropriate dataset.

The skin disease diagnosis problem is to determine a functional dependence $f(s_i) = d_i^C$ which classifies an image s_i into a diagnosis $d_i^C \in D$. This functional dependence should define a model f minimizing accuracy A.

Accuracy A is calculated as a ratio of correctly classified C observations to misclassified M: $A = C / M \cdot 100$. Number C is calculated as a total number of correctly classified observations between N observations of a dataset. Number M is calculated as a total number of misclassified observations between N observations of a dataset.

The defined model f should be used to classify new diagnosis case s^A into a class $d^A \in D$.

2 REVIEW OF THE LITERATURE

AI-based approach to medical diagnostics in general and to diagnostics of skin diseases in particular became widespread recently [8–9]. In a few years a lot of AI-based diagnosis methods were investigated. To develop an own method to support one of the stages of medical diagnostic system according to the objective of the study it is necessary to analyze existing solutions in the beginning.

In the paper [10] different classifiers, including SVM, LR, RF, AdaBoost, BB, BRF, were investigated for melanoma detection using images collected by dermatoscopy method. The best results were obtained by BRF method. SVM, LR and RF were unstable. AdaBoost was a stable classifier but with the lowest AUC value between all the considered methods. AUC was used because the problem in the paper was considered as a binary classification problem. Classification was performed for two classes: melanoma and benign tumor. The main shortcoming of the study is in the binary classification. At the same time this study allowed to compare different classifiers.

The methods investigated in the paper [10] are still applied for images recognition in medical diagnosis but ANN became the most actively used model for solving these problems. ANN popularity is conditioned on its higher productivity, adaptability to different types of objects and its ability to increase classification accuracy [11].

In the paper [12] the method for diagnostics based on the proposed model of ANN was applied for skin disease image recognition. Machine learning methods, including RF, SVM and XGBoost methods, VGG16 and ResNet models, were investigated for the problem solving. As a result of this investigation ANN had significantly better recognition results in comparison with the other considered machine learning methods. The main conclusion of this investigation is in the efficiency and applicability of ANN for the problem solving. The model proposed in the paper [12] was characterized by less estimation results in comparison with VGG16 and ResNet models. The ResNet model had the highest accuracy (90.5%) in the investigation.

The paper [13] was aimed at investigation of different models of CNN, including VGG16, VGG19, MobileNet and InceptionV3 with transfer learning, for recognition of skin disease images. Main feature of the study is in the modification of these models by extended convolution technique, where filter is applied to an area which is bigger than filter length by excluding input values with a step, which is equivalent to a convolution with big filter, created from initial filter by placing zeros in it [14]. The highest value of recognition accuracy was provided by InceptionV3 (90.95%) model. The obtained accuracy value should be increased for practical application in medical diagnostic system.

In the paper [15] efficiency of ANN application for skin disease recognition was investigated in comparison with diagnostics by general practitioners. The dataset was processed for usage of two variants of images: images with high and low resolution. VGG16, VGG19, ResNet34, ResNet50, ResNet101, SEResNet50, EfficientNetB5, MobileNet models were investigated. The highest accuracy (83.88% for images with high resolution and 82.47% for images with low resolution) was obtained using MobileNet model. The main result of this investigation is in the higher recognition accuracy of the worst investigated model in comparison with general practitioners. It means that only decisions made by experienced specialists are valuable. At the same time the

DOI 10.15588/1607-3274-2023-1-4

following decisions could be made using computer systems:

– advisory decisions;

– decisions in situations when there is no possibility of access to a specialist;

– preliminary decisions on what specialist is needed and if this specialist is needed.

The investigated works have such shortcomings as application of outdated methods, classification into less number of classes (for example, the work [10]) and besides low recognition accuracy which is a major indicator for the subject area. These drawbacks are a basis for the next study of skin disease diagnosis methods and models to improve the known results.

3 MATERIALS AND METHODS

To achieve the objective of the study the skin disease diagnosis method was proposed. It consists of the following stages.

At the first stage of the method data presenting images of skin diseases from a set D collected using dermatoscopy method should be processed to prepare it for a dataset S creation. This preparation procedure includes change of image resolution to guarantee higher speed of model training because of the less size of images in dataset (investigated and confirmed in the study [16]). Higher training speed is important for practical application of the method in medical diagnosis system because it decreases time necessary for update when new data presenting new cases are included to the dataset and model retraining is performed.

At the second stage a dataset S ready for training should be created.

During this stage dataset S should be separated into the following subdatasets: training dataset S_{tr} and validation dataset S_v. During this study of the method test dataset S_t should be separated from dataset S. Then these subdatasets should be normalized using a procedure which calculates a value of each pixel. Each pixel $p_i^{q,k}$ should be transformed into $pn_i^{q,k}$ by subtracting average value p_i^{av} calculated through all values and by dividing this result by standard pixel deviation δ: $pn_i^{q,k} = (p_i^{q,k} - p_i^{av}) / \delta$.

A dataset is possibly unbalanced, because a number of observations referred to one class may significantly exceed a number of observations referred to another classes. Such an issue notably impacts on model recognition accuracy, because classes, which observations are in minority, may be ignored by a model. It results in misdiagnosing. Oversampling technique should be used to solve this issue. But oversampling has its own practical drawback. After its application images will be duplicated in training dataset for classes, causing model overtraining. It is explained by image learning without its analysis and detection of specified details of each disease. As a result this model will not be able to highlight structural patterns of tumors and could not be applied for new data observations, which were not used for training. Such methods of image transformation as rotation, horizontal and vertical shift, wheeling and scaling should be used to solve the issue.

At the third stage a model, which defines functional dependence f, should be created by modification of pretrained ResNet50 model. This model was chosen, because it fits the problem solved in the study, using connections with quick access, missing one layer or some layers avoiding model overtraining and increasing diagnosis accuracy [17].

The structure of the full modified model is shown in Fig. 1.

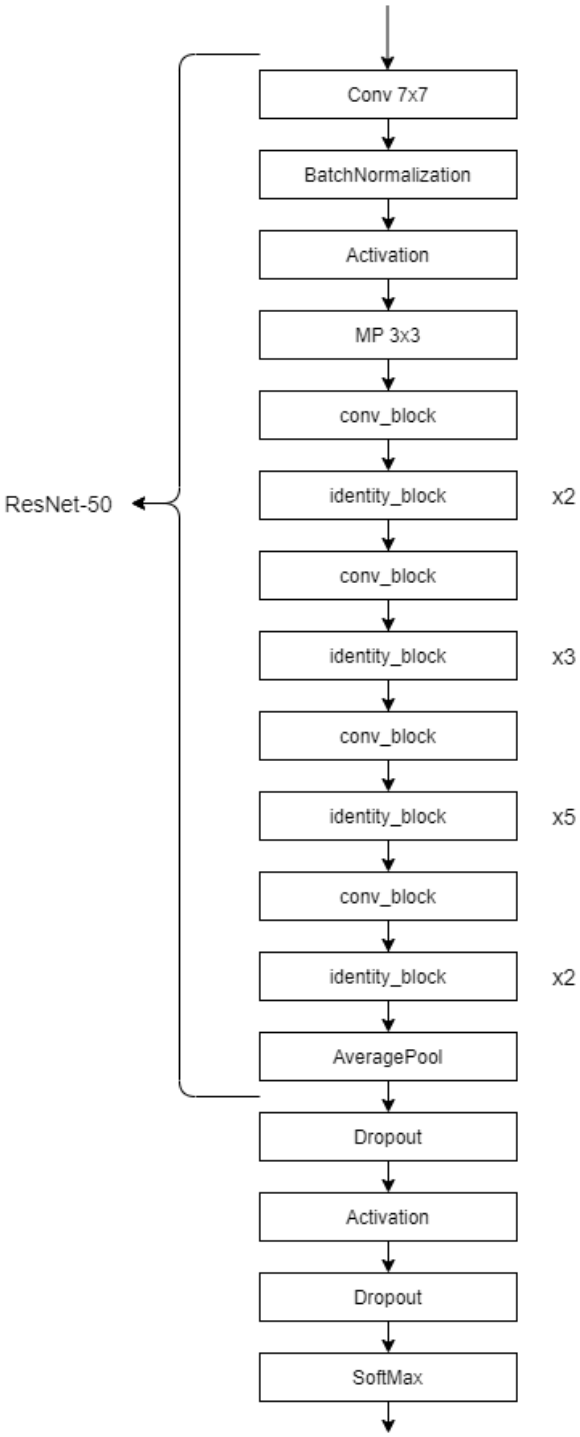

Figure 1 – Structure of the modified model

DOI 10.15588/1607-3274-2023-1-4

The structure of the ResNet50 model was extended by the following additional layers:

− dropout layer;

− layer with 128 neurons and ReLu activation function;

− dropout layer;

− layer with 7 neurons and SoftMax activation function.

The structure of identity block of ResNet50 model is shown in Fig. 2.

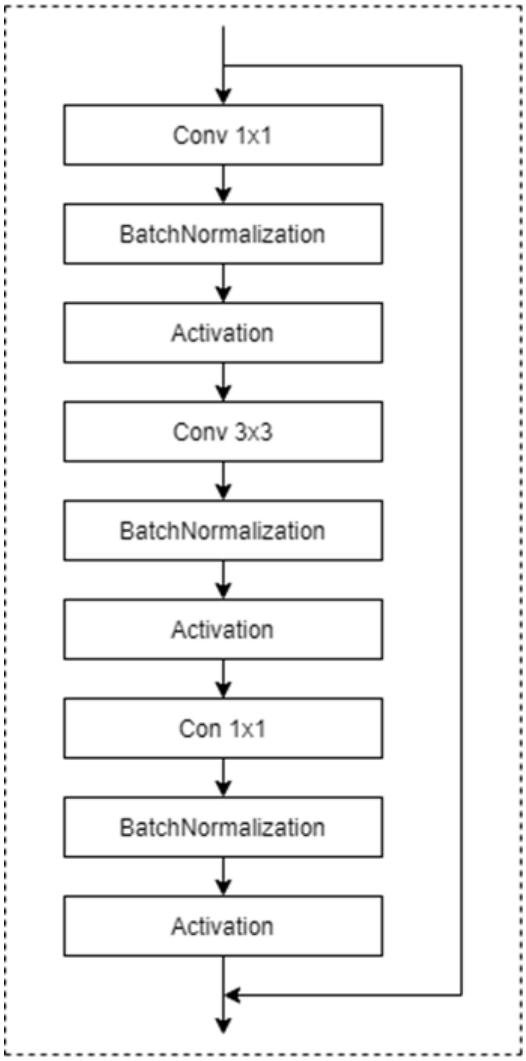

Figure 2 – Structure of identity block of ResNet50 model

The structure of convolutional block of ResNet50 model is shown in Fig. 3.

At the fourth stage the created model is trained. Transfer learning [18] and fine-tuning [19] should be used for training. Transfer learning allows to reuse pre-trained model for new problem. Fine-tuning allows to fix weights of first layers, changing only last layers (aiming at more specific forms and objects on an image) of the model during training.

At the next stages the trained model is applied for new cases when skin diseases should be diagnosed. Each new case should be investigated through the following stages:

− image creation using dermatoscopy method;

− image preprocessing through size change, transformation to a multidimensional array, normalization of its values;

− image recognition, including transfer of preprocessed array to the trained model, classification by the model, return of a class number $d^A \in D$ and of the corresponding diagnosis.

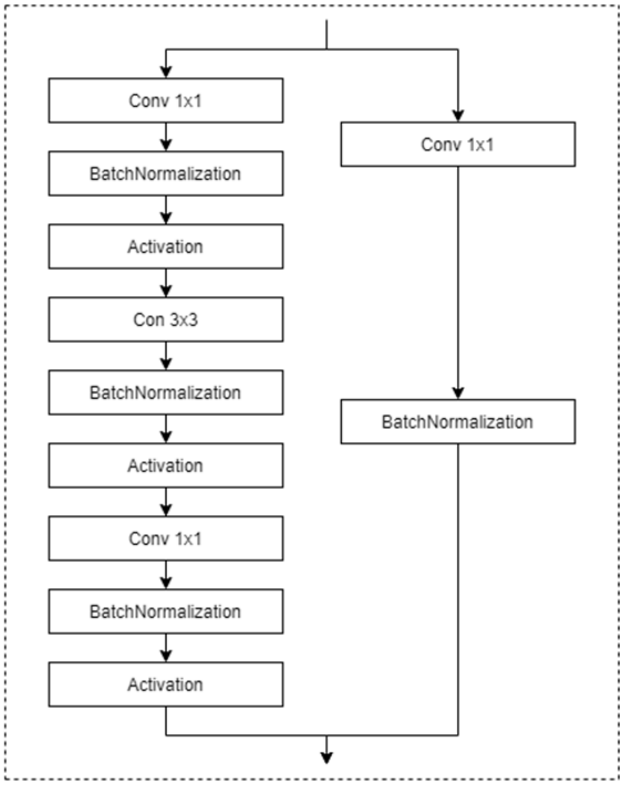

Figure 3 – Structure of convolutional block of ResNet50 model

4 EXPERIMENTS

Experimental investigation was held using the HAM10000 dataset [20]. The dataset contains 10015 images of skin diseases. The images were collected using dermatoscopy method. The dataset contains observations for 7 different skin diseases (AKIEC, BCC, BKL, DF, NV, MEL, VASC).

Histopathology (53% cases), further examination of a patient (37% cases), consensus of experts (9%) and microscopy (1%) were used to detect diagnosis for every case in the dataset. Localization of observations of skin diseases is presented in Fig. 4.

This dataset was separated into subdatasets in the following manner: 60% of data were used as training dataset S_{tr}, 20% were used as validation dataset S_v and 20% were used as test dataset S_t.

Preliminary analysis of the HAM10000 dataset defined that the biggest number of cases in the dataset represents NV (6705). It is 6 times more than number of MEL (1113) and BKL (1099) cases. Four other diagnoses are represented by even less number of cases. Fraction of every diagnosis in the initial dataset is visualized in Fig. 5.

DOI 10.15588/1607-3274-2023-1-4

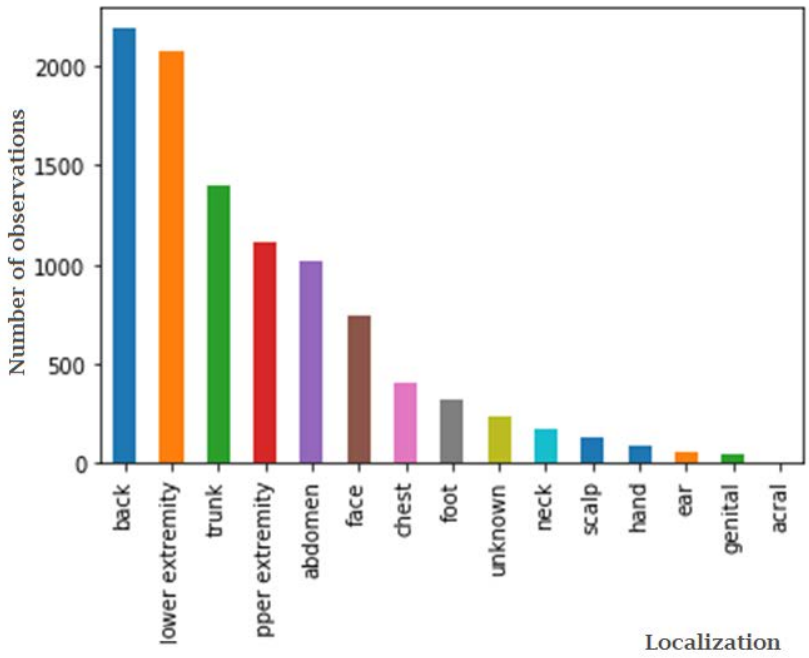

Figure 4 – Graph of localization of observations in the dataset

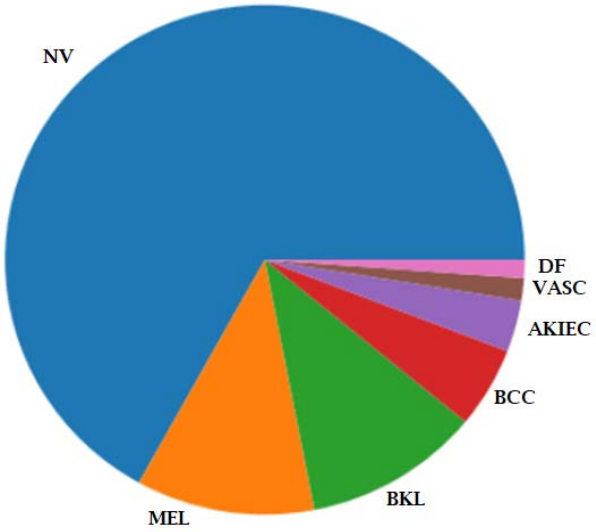

Figure 5 – Part of disease cases in the initial dataset

Oversampling technique was applied to balance number of cases in the processed dataset. Number of cases for each diagnosis is presented in Table 1.

Table 1 – Number of images in the dataset used for investigation after oversampling

Diagnosis	Number of images
AKIEC	4905
BCC	5140
BKL	5495
DF	5750
MEL	5565
NV	6705
VASC	5680

Experimental investigation was performed using the processed dataset. The following models were investigated:

− VGG16 in modifications used in the papers [12], [15], [21];

− VGG19 [15];

− ResNet in modifications used in the papers [12], [21];

– ResNet34 [15];

– ResNet101 [15];

– SEResNet50 [15];

– ResNeXt101 [22];

– AlexNet [21];

– DenseNet [21];

– MobileNet in modifications in the papers [15], [21];

– EfficientNetB5 [15];

– Ensemble [22];

– the proposed model using appropriate method.

The proposed model was trained during 60 epochs with Adam optimizer, which is used instead of stochastic gradient descent algorithm and updates weights in network iteratively, making possible to change learning rate for each parameter and to adapt weight values according to the learning process [23]. Dropout value was set to 0.5. Last 22 layers of the model were used for training, because fine-tuning technique was applied in the method, providing only last layers training.

Experimental investigation was performed using software which was developed to support method practical application. It was developed using the following tools:

– TensorFlow and Keras libraries for model creation and training;

– NumPy, Pandas, scikit learn libraries for data processing;

– Python programming language;

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– Matplotlib library for data visualization.

Additional training parameters included: mini-batch size – 16, minimum learning rate – 0.00001, maximum learning rate – 0.001, reduce learning rate function – ReduceLROnPlateau, loss function – categorical_crossentropy.

Software component model was created to give a possibility to integrate the proposed method into a medical diagnosis system. Software component model provides software interface to communicate with class model. The interface includes methods for the following tasks:

– to create modified model;
– to upload a dataset;
– to preprocess uploaded dataset;
– to train a model;
– to save trained model into a file;
– to upload saved model from a file;
– to upload new case;
– to preprocess new diagnosis case;
– to classify preprocessed diagnosis case using trained model.

This decision allows to integrate this component model into medical diagnosis system in the future. Medical diagnosis system makes decisions for different tasks using accumulated patient data. This approach allows to add necessary components after this system is developed and to create system after separate component models are created if these component models use the same approach.

5 RESULTS

During training of the proposed model values of recognition accuracy (Fig. 6) and error function (Fig. 7) presented by categorical crossentropy were visualized in dynamics.

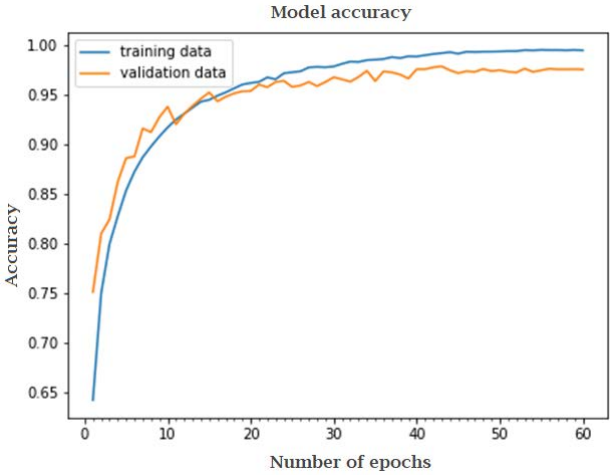

Figure 6 – Graph of accuracy change during model training for training and validation datasets

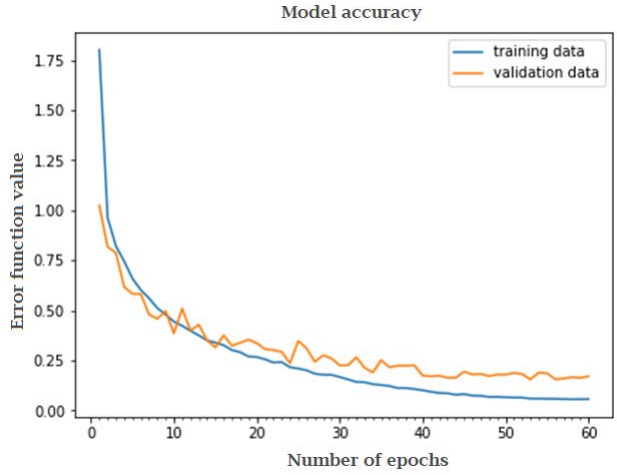

Figure 7 – Graph of error function value change during model training for training and validation datasets

Appropriate values of accuracy and error function were fixed in every epoch for training and validation datasets (Fig. 8).

```
Epoch 1/60
1570/1569 [==============================] - 104s 66ms/step - loss: 1.8020 - acc: 0.6424 - val_loss: 1.0240 - val_acc: 0.7512
Epoch 2/60
1570/1569 [==============================] - 94s 60ms/step - loss: 0.9633 - acc: 0.7502 - val_loss: 0.8172 - val_acc: 0.8102
Epoch 3/60
1570/1569 [==============================] - 95s 60ms/step - loss: 0.8218 - acc: 0.7996 - val_loss: 0.7881 - val_acc: 0.8243
Epoch 4/60
1570/1569 [==============================] - 91s 58ms/step - loss: 0.7460 - acc: 0.8279 - val_loss: 0.6170 - val_acc: 0.8624
Epoch 5/60
1570/1569 [==============================] - 94s 60ms/step - loss: 0.6595 - acc: 0.8535 - val_loss: 0.5827 - val_acc: 0.8861
.....
Epoch 55/60
1570/1569 [==============================] - 87s 55ms/step - loss: 0.0581 - acc: 0.9950 - val_loss: 0.1858 - val_acc: 0.9745
Epoch 56/60
1570/1569 [==============================] - 86s 55ms/step - loss: 0.0581 - acc: 0.9948 - val_loss: 0.1564 - val_acc: 0.9761
Epoch 57/60
1570/1569 [==============================] - 88s 56ms/step - loss: 0.0569 - acc: 0.9949 - val_loss: 0.1593 - val_acc: 0.9755
Epoch 58/60
1570/1569 [==============================] - 88s 56ms/step - loss: 0.0559 - acc: 0.9947 - val_loss: 0.1663 - val_acc: 0.9755
Epoch 59/60
1570/1569 [==============================] - 87s 55ms/step - loss: 0.0563 - acc: 0.9949 - val_loss: 0.1630 - val_acc: 0.9756
Epoch 60/60
1570/1569 [==============================] - 87s 55ms/step - loss: 0.0566 - acc: 0.9946 - val_loss: 0.1706 - val_acc: 0.9753
```

Figure 8 – Model training results

DOI 10.15588/1607-3274-2023-1-4

Confusion matrix (Table 2) was created to assess recognition quality for every skin disease from the set *D*. This matrix represents number of images which were true classified and misclassified by the proposed model. A row in the matrix represents actual values, and a column represents results of classification by the proposed model.

Table 2 – Confusion matrix for skin disease recognition using the proposed method

Diagnosis	AKIEC	BCC	BKL	DF	NV	MEL	VASC
AKIEC	66	0	0	0	0	0	0
BCC	0	105	0	0	1	0	0
BKL	0	0	196	2	1	0	0
DF	0	0	0	22	0	0	0
NV	0	4	22	23	1286	13	1
MEL	0	0	0	1	5	222	0
VASC	0	0	0	1	0	0	32

Fraction of true classified images for the proposed model is presented in Fig. 9. The results are presented for each diagnosis separately.

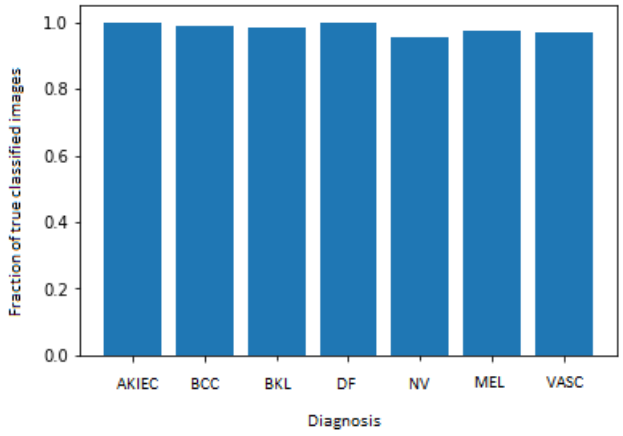

Figure 9 – Chart displaying fraction of true classified images for every diagnosis

Appropriate fraction of misclassified images for the proposed model is presented in Fig. 10.

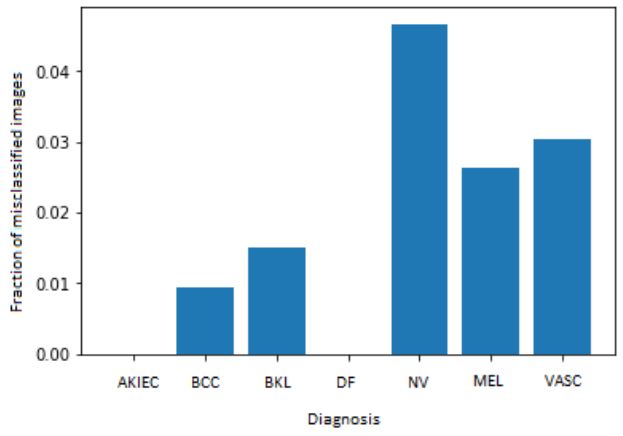

Figure 10 – Chart displaying fraction of misclassified images for every diagnosis

All observations, which actual skin disease diagnosis d_i from the dataset S_t is not equal to a value d_i^C classified by the model, are considered as misclassified.

Accuracy of the proposed and other investigated models was estimated using the test dataset. Results of accuracy comparison are presented in Table 3.

Table 3 – Results of classification by different CNN models

Model	Source	Accuracy *A*, %
VGG16	[12]	78.00
ResNet	[12]	90.50
AlexNet	[21]	88.81
ResNet	[21]	85.20
VGG16	[21]	86.09
DenseNet	[21]	85.25
MobileNet	[21]	82.62
ResNet34	[15]	78.84
ResNet101	[15]	78.96
SEResNet50	[15]	80.72
VGG16	[15]	81.65
VGG19	[15]	79.02
EfficientNetB5	[15]	77.14
MobileNet	[15]	84.73
ResNeXt101	[22]	93.20
Ensemble	[22]	92.83
The modified ResNet50 model of the proposed method	–	96.31

6 DISCUSSION

A wide investigation (Table 3) of different CNN models was conducted to clarify its practical applicability for skin disease diagnosis problem solving. For the purpose HAM10000 dataset was used. The dataset includes cases for 7 skin diseases. Since other investigations were mainly conducted for a smaller number of skin disease such an investigation has practical significance.

The results of experimental investigation confirm that propositions for modification of mathematical model based on ResNet50, presented in the appropriate method, allowed to increase classification accuracy. The modified model has accuracy of 96.31% on test dataset, which is 5.81% higher than base ResNet model and which is 3.11% higher than the best model in a group of other investigated models (ResNeXt101). The best results were obtained by ResNet (90.5%), Ensemble (92.83%), ResNeXt101 (93.2%) and the modified ResNet50 model. Other models had accuracy lower than 90%.

Accuracy of models with less number of layers was lower: VGG16, VGG19, ResNet34, MobileNet models all had accuracy of less than 90% and closer to 80%. It approves that such a number of layers is not enough to learn all patterns necessary to recognize all diseases which were analyzed.

The proposed model allowed to get the number of misclassified observations which was not higher than 5% for all diagnoses (Fig. 10). All AKIEC and DF cases were true classified (Table 2). NV had 1349 observations in test dataset. The proposed model misclassified 63 observations: 4 cases were diagnosed as BCC, 22 cases as BKL, 23 cases as DF, 13 cases as MEL and 1 case as VASC.

DOI 10.15588/1607-3274-2023-1-4

This diagnosis is characterized by the lowest accuracy of 95.33%.

The modified ResNet50 model has additional layers, in such a way having large demands on dataset necessary for model training. Oversampling technique together with transformation methods, applied to dataset images, allowed to get a wider training dataset with sufficient number of observations in it. Images used as input for the model had size of 100x75 pixels. Learning curves (Fig. 6 and Fig. 7) together with model training results (Fig. 8) approve this statement, demonstrating that there was no under- or overtraining. The modified model has accuracy of 97.53% on validation dataset

These experimental results allow to recommend to integrate the proposed method into medical diagnosis system for practical usage as an advisory block [24]. It might have significant effect in countries or territories, where equal and wide access to quality medicine and qualified specialists is impossible or temporarily restricted.

CONCLUSIONS

The problem of skin disease diagnosis was investigated in the paper. It was considered as classification problem. The existing methods for the problem solving are not perfect and may be improved. These methods classify observations into less number of classes and have lower accuracy. The skin disease diagnosis method, based on the modified ResNet50 model, was proposed.

To increase model recognition accuracy it was proposed to perform preliminary data processing to balance dataset, to reduce image size, to normalize values, to transform images inside dataset using different methods to avoid oversampling.

ResNet50 model was modified adding new layers. Dropout layer, layer with 128 neurons and ReLu activation function, dropout layer, and layer with 7 neurons and SoftMax activation function were added to the model. The extended model was trained using transfer learning and fine-tuning techniques Main learning settings were defined. Separate stages were defined in the method to apply the trained model to diagnose new cases.

Experimental investigation was performed using the HAM10000 dataset, which consists of 10015 images of 7 skin diseases (AKIEC, BCC, BKL, DF, NV, MEL, VASC). Accuracy of the proposed model and the existing models was compared during experimental investigation. The proposed method with the modified ResNet50 model applied for classification had an accuracy 96.31 %, which was the highest result between all investigated models. This accuracy level of the method together with learning results confirms possibility of its practical implementation.

Software component model was created to provide an interface for integration of the proposed method into a medical diagnosis system. This interface provides means to manage classification model and to use it for decision making.

The scientific novelty of the obtained results is in the proposed method of skin disease diagnosis.

The practical significance of the obtained results is in classification accuracy of the proposed method and in software, which was developed to support the proposed method, as well as software component model, which allows to integrate the developed software into medical diagnosis system in the future.

Prospects for the further research are to integrate the proposed method and software, which was created based on appropriate software component, for skin disease diagnosis into medical diagnosis system.

ACKNOWLEDGEMENTS

The work was performed as part of the state budget research projects “Development of methods and tools for analysis and prediction of dynamic behavior of nonlinear objects” (state registration number 0121U107499) of Software Tools Department of National University “Zaporizhzhia Polytechnic”.

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Received 20.11.2022.
Accepted 23.01.2023.

УДК 004.896

МЕТОД ТА ПРОГРАМНА КОМПОНЕНТНА МОДЕЛЬ ДІАГНОСТУВАННЯ ШКІРНИХ ЗАХВОРЮВАНЬ

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АНОТАЦІЯ

Актуальність. У даній статті розглянуто проблему діагностування шкірних захворювань. Актуальність проблеми пояснюється необхідністю автоматизації щонайменше дорадчих рішень в медицині, зокрема при підтримці телемедицини під час діагностування шкірних захворювань, коли можливо отримати придатні для аналізу дані, але лікар, здатний прийняти рішення, не може з тих чи інших причин обробити ці дані власноруч. Об'єктом роботи є процес діагностування шкірних захворювань.

Мета робот – розробити метод діагностування шкірних захворювань для автоматизації дорадчих діагностуючих рішень в медицині і підвищення ефективності таких рішень.

Метод. У статті запропоновано метод діагностування шкірних захворювань на основі побудови і навчання моделі ResNet50, модифікованої шляхом додавання нових шарів і використання технік трансферного навчання та fine-tuning. Метод виконує попередню обробку зображень зокрема шляхом зміни їх розміру та використання техніки oversampling для підготовки вибірки даних для навчання моделі.

Результати. Експериментальне дослідження проводилося на наборі даних про шкірні захворювання HAM10000, який складається з 10015 зображень захворювань шкіри, отриманих методом дерматоскопії, для 7 різних діагнозів. У результаті застосування модифікованої моделі на основі запропонованого методу точність розпізнавання склала 96.31%, що перевищує точність розглянутих подібних моделей нейронних мереж. Програмна компонента модель була створена для надання можливості інтегрувати запропонований метод до складу системи медичного діагностування.

Висновки. Отримані в результаті проведеного дослідження результати дозволяють рекомендувати запропонований метод діагностування шкірних захворювань для впровадження у складі системи медичного діагностування задля забезпечення підтримки винесення дорадчих рішень системою з подальшим винесенням остаточних рішень лікарем.

DOI 10.15588/1607-3274-2023-1-4

КЛЮЧОВІ СЛОВА: дерматоскопія, медичне діагностування, згорткова нейронна мережа, шкірне захворювання, модель ResNet50, програмна компонента модель.

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DOI 10.15588/1607-3274-2023-1-4

UDC 004.93

IMAGE SEGMENTATION WITH A CONVOLUTIONAL NEURAL NETWORK WITHOUT POOLING LAYERS IN DERMATOLOGICAL DISEASE DIAGNOSTICS SYSTEMS

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ABSTRACT

Context. The problem of automating of the segmentation of spectral-statistical texture images is considered. The object of research is image processing in dermatological disease diagnostic systems.

Objective. The aim of the research is to improve the segmentation performance of color images of psoriasis lesions by elaboration of a deep learning convolutional neural network without pooling layers.

Method. The convolutional neural network is proposed to process a three-channel psoriasis image with a specified size. The initial color images were scaled to the specified size and then inputed on the neural network. The architecture of the proposed neural network consists of four convolutional layers with batch normalization layers and ReLU activation function. Feature maps from the output of these layers were inputted to the 1×1 convolutional layer with the Softmax activation function. The resulting feature maps were inputted to the image pixel classification layer. When segmenting images, convolutional and pooling layers extract the features of image fragments, and fully connected layers classify the resulting feature vectors, forming a partition of the image into homogeneous segments. The segmentation features are evaluated as a result of network training using ground-truth images which segmented by an expert. Such features are robust to noise and distortion in images. The combination of segmentation results at different scales is determined by the network architecture. Pooling layers were not included in the architecture of the proposed convolutional neural network since they reduce the size of feature maps compared to the size of the original image and can decrease the segmentation performance of small psoriasis lesions and psoriasis lesions of complex shape.

Results. The proposed convolutional neural network has been implemented in software and researched for solving the problem of psoriasis images segmentation.

Conclusions. The use of the proposed convolutional neural network made it possible to enhance the segmentation performance of plaque and guttate psoriasis images, especially at the edges of the lesions. Prospects for further research are to study the performance of the proposed CNN then abrupt changes in color and illumination, blurring, as well as the complex background areas are present on dermatological images, for example, containing clothes or fragments of the interior. It is advisable to use the proposed CNN in other problems of color image processing to segment statistical or spectral-statistical texture regions on a uniform or textured background.

KEYWORDS: psoriasis image, image segmentation, convolutional network, pooling layer, color space, deep learning.

ABBREVIATIONS

BSA is the Body Surface Area;
PASI is the Psoriasis Area and Severity Index;
CNN is a convolutional neural network;
ReLU is a rectified linear unit;
TP is a number of true positive samples in percent;
TN is a number of true negative samples in percent;
FP is a number of false positive samples in percent;
FN is a number of false negative samples in percent;
FOM is a Figure of Merit.

NOMENCLATURE

I_I is the number of pixels of the psoriasis lesion edges, obtained by the proposed CNN;

I_A is the number of pixels of the psoriasis lesion edges on the ground-truth image;

α is a scale factor;

d_i is the distance between the pixel of the psoriasis lesion edge, obtained by the proposed CNN, and the pixel of the psoriasis lesion edge on the ground-thruth image, measured along the normal to this edge.

INTRODUCTION

Medical diagnostic systems are widely used in the field of health care. In particular, such systems can provide information about the pathologies based on medical images. For example, various datasets related to the treatment of dermatological diseases have been collected. A number of datasets include images obtained during the diagnosis of psoriasis. The World Health Organization statistics estimate the number of patients suffering from this disease at 125 million people. According to the International Federation of Psoriasis Associations, the prevalence of this disease depends on the region and ranges from 1.2% to 5%, averaging 3% of the general population [1].

The disease of psoriasis is accompanied by unpleasant sensations such as peeling and itching of the affected areas of the skin, causing discomfort to the patient, and is also a systemic disease, often accompanied by arthritis, diabetes, cardiovascular diseases, etc. To diagnose and monitor the effectiveness of treatment, psoriasis lesions are isolated on photographs of the patient's skin and evaluate their geometric characteristics. The values of these characteristics are used in assessing the clinical severity of psoriasis using the BSA and the PASI [2].

DOI 10.15588/1607-3274-2023-1-5

The identification of psoriasis lesions on skin images by a dermatologist requires a significant time and effort. In addition, since there are other skin diseases similar to psoriasis, then the diagnosis of psoriasis also requires significant experience of a specialist in the field of dermatology. Therefore, medical diagnostic systems are used to perform automated processing of images of psoriasis lesions [3–5].

The object of research is image processing in dermatological disease diagnostic systems.

To assess the clinical severity of psoriasis using the BSA and PASI indexes in dermatological disease diagnostic systems, the results of segmentation of skin images are needed to identify the psoriasis areas [4]. Segmentation of color images of skin affected by psoriasis is a difficult problem due to uneven or insufficient lighting, irregular shape and different sizes of psoriasis lesions, blurred boundaries between lesions and normal skin. In addition, the result of segmentation of images of psoriasis lesions is affected by skin pigmentation and texture that varies from person to person, the presence of hair, as well as the type of skin (dry, oily or combination), which determines its reflectivity.

The subject of the research is the methods of segmentation of color images of psoriasis lesions.

Methods for segmenting color images of psoriasis lesions that do not use convolutional neural networks (CNNs) are generally characterized by low performance [6–8], which is due to the natural variability of human skin and the size of psoriasis lesions. So, plaque psoriasis is often characterized by the lesions of considerable size, while guttate psoriasis is appeared by small lesions. The psoriasis image segmentation is also significantly affected by the experience of the researcher and the segmentation feature selection. Therefore, deep learning CNNs have recently been used to segment color images of psoriasis lesions, providing automatic feature selection [9–10]. The most common architecture of such networks includes convolutional layers, pooling layers and fully connected layers. When segmenting images, convolutional and pooling layers extract the features of image fragments, and fully connected layers classify the resulting feature vectors, forming a partition of the image into homogeneous segments. The pooling layers of the CNN are reduce the size of image feature maps, but negatively affects on the segmentation performance, especially for the images of the small psoriasis lesions and complex-shaped psoriasis lesions.

The aim of the research is to improve the of segmentation performance of color images of psoriasis lesions by elaboration of a deep learning CNN without pooling layers.

1 PROBLEM STATEMENT

The color image of psoriasis lesions is represented by the vector function $\mathbf{I}(x,y)=(I_R(x,y), I_G(x,y), I_B(x,y)\}$, where $x=1, \ldots, n$; $y=1, \ldots, m$; n, m are positive integers, n is the number of rows, m is the number of columns of the image. The intensities of the color components $I_R(x,y)$, $I_G(x,y)$, $I_B(x,y)$ take values from the interval [0, 1]. Then each pixel of the image with coordinates (x,y) is described by three features, namely intensities of color components with values $I_R(x,y)$, $I_G(x,y)$, $I_B(x,y)$. To identify the psoriasis lesions on the image, it is necessary to segment it into non-overlapping regions corresponding to regions of lesions and normal skin. To do this, each pixel of the original image must be associated with the value of the target feature. There is a label of one of two classes, specifically, 0 for normal skin, 1 for psoriasis lesion. The values of the target feature for the psoriasis image should be represented as a binary image which is the result of segmentation.

To segment the color images of psoriasis lesions, a CNN elaboration is needed. The CNN input is a three-dimensional matrix of intensity values of color components for image pixels. At the output of this network, a two-dimensional matrix of target feature values is obtained for each image pixel. To construct a convolutional neural network $CNN = \{struct, param\}$, it is necessary to select its architecture *struct* and evaluate network parameters *param* so as to minimize the cost function on the training set [11, 12]. It is assumed that the training set includes psoriasis images and corresponding ground-truth images for CNN parameters learning.

2 REVIEW OF THE LITERATURE

An analysis of the literature shows that psoriasis image processing implies either classification of such images to determine the severity of the disease [13–15] or psoriasis image segmentation [16–18], since the area of psoriatic lesions is taken into account when determining the severity of the disease and evaluating the effectiveness of treatment [2, 4, 10]. When selecting and evaluating the psoriasis image features it is important to consider that normal skin regions differ from psoriasis lesions both in color and texture. For example these regions can be distinguished by the values of the amplitude and frequency of the components of the spectral texture [19, 20]. Therefore, single-scale and multi-scale methods are presented in the literature for psoriasis image processing.

Single-scale methods use color features and/or spectral features at the dominant frequency. Such methods segmenting psoriasis image into areas of normal skin and psoriasis lesions, based on the feature vectors calculated in the neighborhood of each pixel. The the resulting segmentation performance depends on the parameter values setting. In addition there are difficulties in segmenting objects of different sizes and setting of parameters.

Thus, in [7], two color spaces were used to segment psoriatic plaques on skin images, namely CIE Luv and CIE Lch. In the CIE Luv space, the color feature vectors of the pixels were clustered based on the Gaussian mixture model, and in the CIE Lch color space, a semi-wrapped Gaussian mixture model was proposed to solve this problem. For the localization of plaques on the skin, the von Mises distribution was assumed to determine the

DOI 10.15588/1607-3274-2023-1-5

confidence intervals for the distribution parameters of normal skin and plaque color. This approach showed a higher segmentation performance compared to the fuzzy c-means, the segmentation accuracy was 79.53%.

In [8], a method for texture segmentation of plaque psoriasis images was elaborated for express diagnostic systems in dermatology. Psoriasis lesions on the images were modelled as fragments of a quasi-periodic texture on a complex background with additive Gaussian noise. To segmenting psoriasis lesions, there was used sequentially the localization of spatial frequencies of the image; the amplitude detecting that transforms the texture features into intensity; the edge detection of the resulting image. Then 87% of image pixels were correctly segmented by this method.

In [6], for the segmentation of color psoriasis images the RGB images convert to the Lab space, and then k-means clustering was applied to the color feature vectors of image pixels. To improve the segmentation performance the merged group of pixels was filtered, as a result of which correctly segmented pixels averaged 95%.

In [19, 20], for systems of express diagnostics of psoriasis, skin images were represented by a spectral-statistical texture. The vector-difference method was applied for image segmentation. This method is based on the calculation of distances between feature vectors of image pixel neighborhoods. Each feature vector is involved the mean value and the standard deviation of the intensities of the neighborhood pixels. For images of plaque psoriasis, the percentage of correct pixel segmentation was 92.7%, and for pixels of lesions of plaque psoriasis, up to 96%, depending on the signal-to-noise ratio.

Multiscale methods are elaborated for segmenting the lesions of different sizes on psoriasis images. However, there are difficulties when combining the results of segmentation at different scales. For example, in [21], a method for segmenting ot the psoriasis images in the Lab color space was proposed. In this space, multi-scale superpixels of images were identified, and superpixels that did not correspond to the skin areas were discarded. Next, at each scale, the superpixels were k-means clustered. The merging of segmentation results at different scales was performed using voting. Correctly segmented pixels in the images were about 90%. The method has shown its effectiveness in the treatment of skin with hair, and with lesions of different sizes and shapes.

A separate group of multiscale methods are CNNs that are used both for segmentation and for classifying of psoriasis images.

In [3], a classification system for skin diseases was developed, implemented as Android application based on the MobilNet. This network alternates convolutional layers and depthwise separable convolutions with depthwise and pointwise layers. Each of these 27 layers was followed by batch normalization and a ReLU activation function. The average percentage of correct recognition of the seven skin diseases reached 94.4% after oversampling to balance the data set and pre-process the researched images.

In [13], images of psoriasis lesions were classified into images of plaque psoriasis and guttate psoriasis. A CNN was used with two convolutional layers, followed by pooling layers, then two fully connected layers were applied. Correct image recognition of plaque and guttate psoriasis was 82.9% and 72.4%.

In [4], psoriasis images were analyzed to automaticall form the severity of the disease. The severity of the psoriasis are assessed on the basis of the erythema or redness level, the degree of scaliness, the thickness or induration of psoriasis plaques on the human skin. The percentage of the body surface area affected by psoriasis also included in PASI estimation. Psoriasis images were classified by a CNN that consisted of a shared subnet followed by three parallel subnets. At the output of these subnets, the level of the disease severity was obtained for each of the three features as an integer from 0 to 4. The shared subnet consisted of 5 convolutional layers with the ReLU activation function and normalization after the 1st and 2nd layers, as well as three pooling layers after the 1st, 2nd, 5th convolutional layers. Subnets for each feature included 2 fully connected layers with the ReLU activation function, after which the SoftMax activation function was applied. The correct recognition of the severity scores based on the each feature was 60%, and about 94% if assuming a maximum deviation ±1 from the actual scores for any of erythema, scaling and induration scores. Under this assumption, the correct recognition of the severity scores is 85.3%.

In [9], a modified U-Net architecture referred as PsLSNet was proposed for the segmentation of psoriasis images. It is a deep learning CNN with 29 layers. By reducing the covariant shift through the implementation of PsLSNet, the training time is reduced compared to U-Net. The PsLSNet network is able to segment psoriasis images even under poor acquisition conditions and in the presence of artifacts. The average percentage of correctly segmented pixels was 94.8% with a sensitivity of 89.6% and a specificity of 97.6%.

In [10], it was assumed that psoriasis images may be blurred or contain areas of a complex background. For the segmentation of such images, a YOLACT CNN has been developed, which includes four consecutive subnets. These are a subnet for evaluating segmentation features, a subnet for generating feature maps at different image scales, a subnet for classifying the obtained feature vectors, and a subnet for generating the result of segmentation and post-processing. Correct segmentation of image pixels was achieved in 96–97% of cases.

The analysis of methods of psoriasis image segmentation showed that the main characteristic of these methods is the segmentation performance, which is affected by the shape and sizes of isolated lesions that differ for plaque and guttate psoriasis. In the case of express diagnostics, the time of image processing is also significant.

DOI 10.15588/1607-3274-2023-1-5

Single-scale methods are characterized by high speed, but the segmentation performance is low, especially when identifying small psoriasis lesions and complex-shaped psoriasis lesions. The results of image segmentation often contain defects in the form of small regions at the boundaries of areas corresponding to psoriasis lesions. In addition, parameters setting are time consuming for single-scale methods.

Multiscale methods are characterized by a higher performance of psoriasis image segmentation due to the better localization of the boundaries of psoriasis lesions. However, these methods are often unable to segment the small lesions or fragments of lesions of complex shape, mistaking them for areas of healthy skin. If the multiscale methods of psoriasis image segmentation don't use the CNN, then it is necessary for the researcher to select segmentation features, the procedure for their evaluation, and a method for combining segmentation results at different scales. The use of CNN allows to avoid these difficulties, since segmentation features are evaluated as a result of network training using ground-truth images which segmented by an expert. Such features are robust to noise and distortion in images. The combination of segmentation results at different scales is determined by the network architecture. However, deep learning CNN contains a large number of layers and, accordingly, is characterized by a significant number of parameters. The training of such CNN requires a large training set, and the complexity of the architecture increases the network training time. In addition, a common drawback of the CNN in solving the problem of psoriasis image segmentation is the low performance if objects of small sizes or complex shapes are processed. This due to the inclusion of pooling layers in the network architecture, which reduce the scale of image feature maps.

3 MATERIALS AND METHODS

The proposed neural network is elaborated to process a three-channel image with a size of 224×224 pixels. Therefore, the initial color images were scaled to the specified size and then giving them as input of the neural network. The architecture of the proposed neural network is shown in Table 1. This CNN contains five convolutional layers, four batch normalization layers, four ReLU activation function layers, one Softmax activation function layer, and one image pixel classification layer. The first convolutional layer uses 18 convolution kernels of size 85×85×3 pixels with a stride of 1 pixel. The feature maps at the output of this layer are batch normalized and then the ReLU activation function is applied. Next, feature maps from the output of the ReLU activation function layer, were inputed to the second convolutional layer, which uses 18 convolution kernels of size 55×55×3 pixels with a stride of 1 pixel. The feature maps at the output of this layer are also batch normalized and then the ReLU activation function is applied again. The resulting feature maps were inputed to the third convolutional layer, which uses 18 convolution kernels of size 35×35×3 pixels with a stride of 1 pixel. The feature maps at the output of this layer are again batch normalized, and then the ReLU activation function is applied again. It is followed by the fourth convolutional layer, which uses 18 convolution kernels of size 15×15×3 pixels with a stride of 1 pixel. The obtained feature maps at the output of this layer are batch normalized, and then the ReLU activation function is applied again. Feature

Table 1 – The proposed CNN architecture

Layer number	Type	Comment	Activations	Learnables
1	Image Input	256×256×3 images with zero center normalization	224×224×3	–
2	Convolution	18 85×85×3 convolutions with stride [1 1] and same padding	224×224×18	Weights: 85×85×3×18 Bias: 1×1×18
3	Batch normalization	Batch normalization with 18 channels	224×224×18	Offset: 1×1×18 Scale: 1×1×18
4	ReLU	Activation function	224×224×18	–
5	Convolution	18 55×55×3 convolutions with stride [1 1] and same padding	224×224×18	Weights: 55×55×3×18 Bias: 1×1×18
6	Batch normalization	Batch normalization with 18 channels	224×224×18	Offset: 1×1×18 Scale: 1×1×18
7	ReLU	Activation function	224×224×18	–
8	Convolution	18 35×35×3 convolutions with stride [1 1] and same padding	224×224×18	Weights: 35×35×3×18 Bias: 1×1×18
9	Batch normalization	Batch normalization with 18 channels	224×224×18	Offset: 1×1×18 Scale: 1×1×18
10	ReLU	Activation function	224×224×18	–
11	Convolution	18 15×15×3 convolutions with stride [1 1] and same padding	224×224×18	Weights: 15×15×3×18 Bias: 1×1×18
12	Batch normalization	Batch normalization with 18 channels	224×224×18	Offset: 1×1×18 Scale: 1×1×18
13	ReLU	Activation function	224×224×18	–
14	Convolution	2 1×1×18 convolutions with stride [1 1] and same padding	224×224×2	Weights: 1×1×18×2 Bias: 1×1×2
15	Softmax	Activation function	224×224×2	–
16	Pixel classification	–	–	–

DOI 10.15588/1607-3274-2023-1-5

maps from the output of this layer were inputted to the fifth convolutional layer, which uses 2 convolution kernels of size 1×1×18 pixels with a stride of 1 pixel, then the Softmax activation function is applied. The resulting feature maps were applied to the image pixel classification layer.

In the convolution layer, the matrix of the convolution kernel moves through a two-dimensional array of image pixels. The values of the corresponding image elements and the convolution kernel are multiplied the results are added up and inputted on the next layer. Usually, several convolution kernels are used in the convolution layer. In addition, it is the stride parameter, which indicates the convolution kernel shift along the image matrix.

Batch normalization layer solves vanishing gradient problem and train deep neural networks consisting of a few dozen layers. It is known that the error backpropagation algorithm converges faster if the input data is normalized (has zero mean and unit variance) [13]. However, when a signal propagates through a neural network, its mean value and variance can change significantly. To avoid this, the standard normalization of the outputs of the convolutional layer is performed by subtracting from each output x_i the average value μ_i of the input packet examples by dimension i and dividing by $(\sigma_i+\varepsilon)^{0.5}$, where σ_i is the standard deviation of the input packet images by dimension i, ε is a constant that ensures the stability of calculations. However, normalizing the output of a neural network convolutional layer can change the representation of the data in the next layer. Therefore, two parameters are introduced: compression γ_i and shift β_i of the normalized value for each output, which are adjusted in the learning process along with the rest of the parameters and transform the normalized output value x_{ni} as $y_i=\gamma_i x_{ni}+\beta_i$. For convolutional neural networks, batch normalization reduces training time and reduces the chance of overfitting.

The ReLU activation function ReLU(y)=max(0,y) returns 0 for a negative argument, and in the case of a positive argument, returns the same. The advantages of this function over the sigmoid are the fast calculation of the derivative (for negative arguments it is 0, for positive ones it is 1), and the sparseness of activation (fewer neurons being activated).

Pooling layers were not included in the architecture of the proposed CNN since they reduce the size of feature maps compared to the size of the original image and can decrease the segmentation performance of small psoriasis lesions and psoriasis lesions of complex shape.

4 EXPERIMENTS

As a result of the experiment, the segmentation performance was estimated for 50 images of psoriasis lesions from the [22]. The researched images contained only areas of healthy skin and psoriasis lesions. Areas corresponding to the background were absent. The image sizes varied as follows. For the images of plaque psoriasis the height varied from 200 to 380 pixels, and the width varied from 180 to 500 pixels. The height of the images of guttate psoriasis varied from 400 to 800 pixels, the width from 300 to 530 pixels. These images were marked by an expert on areas of normal skin and psoriasis lesions. Then the segmentation performance was estimated by confusion matrices [23, 24]. Since psoriasis images were segmented on health skin and psoriasis lesions, then the confusion matrix of size 2×2 consists of the following elements. TP is the percentage of image pixels from the class labeled “Normal skin” that are correctly assigned to the class labeled “Normal skin”; FP is the percentage of image pixels from the class labeled “Psoriasis lesion” that are incorrectly assigned to the class labeled “Normal skin”; FN is the percentage of image pixels from the class labeled “Normal skin” incorrectly assigned to the class labeled “Psoriasis lesion”; TN is the percentage of image pixels from the class labeled “Psoriasis lesion” that are correctly assigned to the class labeled “Psoriasis lesion”.

To characterize the detection of the edges of psoriasis lesions, the FOM value [25] was used:

$$FOM = \frac{1}{I}\sum_{i=1}^{I_A}\frac{1}{1+\alpha d_i^2}.$$

where I=max(I_I, I_A). The FOM value is normalized such that FOM=1 for a well detected edge. The factor 1/I characterizes doubled and split edges.

When training the proposed CNN, a cross-entropy loss function was used, for which the relative frequencies w and 1–w of the appearance of pixels of the “Normal skin” and “Psoriasis lesion” classes were taken into account. For each image pixel, the value of cross-entropy L was calculated by the formula

$$L = -(1/w)\, t_1 \log_2 y_1 - 1/(1-w)\, t_2 \log_2 y_2,$$

where t_i = 1 if the image pixel is assigned to class i on the ground-thruth image, otherwise t_i = 0, with i = 1 for the class “Normal skin” and i = 2 for the class “Psoriasis lesion”. The y_i value is the result of calculating the value of the Softmax function for the image pixel under consideration. It is interpreted as the probability that an image pixel belongs to the class “Normal skin” (i = 1) or “Psoriasis lesion” (i = 2). To calculate the cross-entropy of the image, the values of L were summed over all its pixels.

First, as part of the experiment, RGB, Lab, YCbCr, HSV, YIQ, XYZ color spaces were used to represent images of psoriasis lesions [26]. In this part of experiment the proposed CNN and U-Net [27] consisting of four levels reliazed by 3×3 convolutions are researched. The stochastic gradient descent with a moment of 0.9 and an initial learning rate of 0.01 was used to train the proposed CNN. The Adam method with an initial learning rate of 0.0001 was used to train the U-Net.

Note that the color images of lesions of plaque and guttate psoriasis differ significantly in their properties, primarily in the size of the lesions, as well as their color

DOI 10.15588/1607-3274-2023-1-5

and texture. Plaque psoriasis usually presents by red or light gray lesions of considerable size with coarse grained texture, while guttate psoriasis presents by small reddish lesions of fine texture. Therefore, in this research, segmentation performance was evaluated separately for images of plaque and guttate psoriasis, in contrast to the papers [6–10, 19–21] and others, in which segmentation performance measures were averaged over images of both classes.

Second, as part of the experiment, the Adam method with an initial learning rate of 0.05 and the stochastic gradient descent with a moment of 0.9, and an initial learning rate of 0.01 was used to train the proposed CNN on the researched psoriasis images. To avoid overfitting of the network, training was stopped when the value of the loss function began to increase. The number of training epochs depended on the color space in which the images were presented.

Third, as part of the experiment, the psoriasis image segmentation performance for the proposed CNN was compared with the known segmentation methods [6–10, 19–21]. The accuracy measure is used. It represents the integral characteristic of the segmentation performance calculated by averaging of *TP* and *TN*.

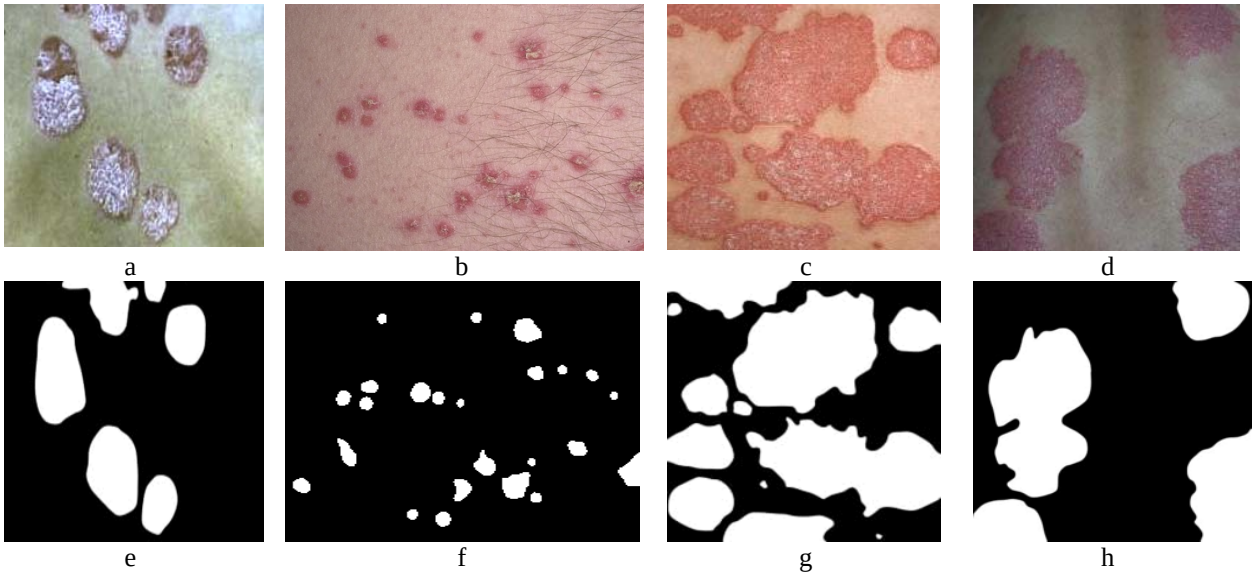
And at last, the comparison of processing time was made for the image segmentation by the proposed CNN and the U-Net [27] for the researched psoriasis images scaled to a size of 224×224 pixels.

5 RESULTS

The elements of confusion matrices for the results of psoriasis image segmentation with representation in different color spaces is shown in Table 2. Values in this table were obtained by averaging the *FOM*, *TP*, and *TN* for the segmentation of plaque psoriasis images, guttate psoriasis images, and all the researched psoriasis images.

Table 2 – The values of TP and TN for the results of segmentation by the proposed CNN and U-Net of psoriasis images represented in different color spaces

Color space	Plaque psoriasis images			Guttate psoriasis images			All researched psoriasis images		
	TR	*TN*	*FOM*	*TR*	*TN*	*FOM*	*TR*	*TN*	*FOM*
Proposed CNN									
RGB	98.48	99.55	0.7844	93.41	91.83	0.7637	95.53	96.78	0.7741
Lab	98.37	99.72	0.7256	91.57	88.01	0.5102	94.42	95.51	0.6179
HSV	97.92	99.56	0.7671	89.75	87.05	0.5996	93.17	95.07	0.6834
YIQ	97.51	99.40	0.7917	93.60	87.98	0.6591	95.24	95.30	0.7254
YCbCr	97.72	99.73	0.6568	93.29	87.33	0.5240	95.14	95.28	0.5904
XYZ	96.04	98.42	0.5854	91.34	80.94	0.5597	93.31	92.15	0.5730
U-Net									
RGB	95.78	99.46	0.4034	88.89	91.70	0.3995	91.77	96.67	0.4014
Lab	95.29	98.77	0.4413	88.91	87.93	0.4524	91.58	94.88	0.4469
HSV	98.00	99.66	0.3689	82.27	90.89	0.3573	86.34	96.51	0.3631
YIQ	94.76	99.67	0.4196	83.52	95.02	0.3821	88.22	98.00	0.4009
YCbCr	96.14	99.61	0.5461	87.91	94.00	0.5167	91.35	97.60	0.5314
XYZ	94.29	97.88	0.3372	87.53	86.21	0.3945	90.36	93.69	0.3658



a b c d

e f g h

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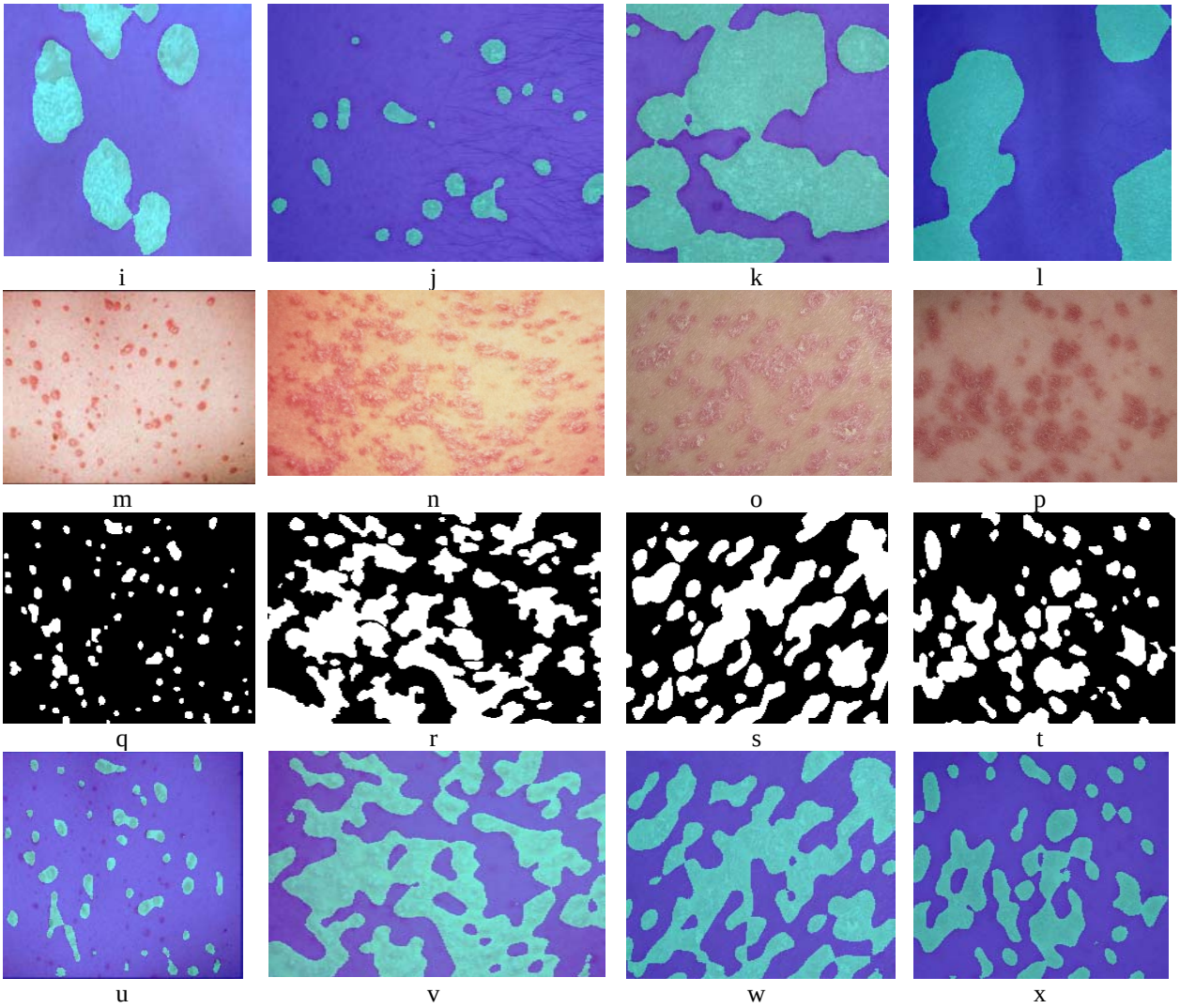

Figure 1 – The segmentation results by proposed CNN:
a–d, m–p – the initial psoriasis images; e–h, q–t – the ground-truth images; i–l, u–x – images, segmented by proposed CNN

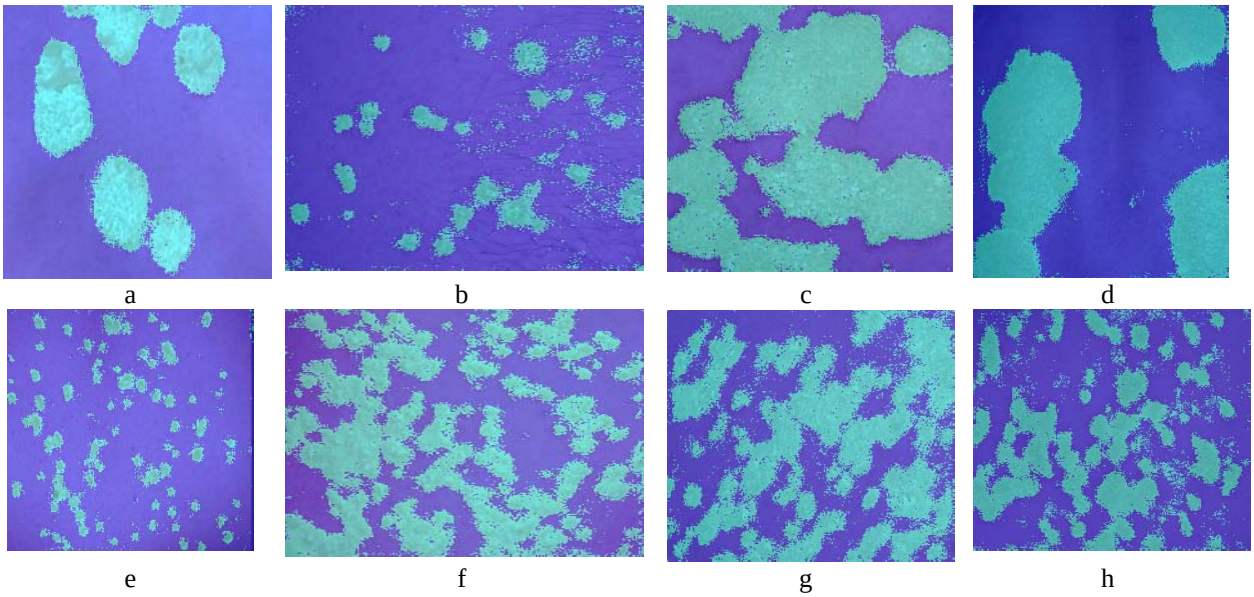

Figure 2 – The segmentation results by U-Net:
a–d – the psoriasis images from Figure 1, a–d, segmented by U-Net; e–h – the images from Figure 1, m–p, segmented by U-Net

DOI 10.15588/1607-3274-2023-1-5

The accuracy of the psoriasis image segmentation by the proposed CNN, the U-Net, and methods known from the literature are given in Table 3.

Table 3 – The segmentation accuracy of the proposed CNN and methods known from the literature

Reference, publication year, network name	Segmentation accuracy, %
Single Scale Methods	
[7], 2015	79.53%
[8], 2019	87.20%
[19], 2022	92.68%
[6], 2017	95%
Multiscale Methods	
[21], 2017	90%
[9], 2019, PsLSNet	94.8%
[10], 2021, YOLACT	96.6–97.3%
Proposed CNN, RGB images of plaque psoriasis	99.02%
Proposed CNN, RGB images of guttate psoriasis	92.62%
Proposed CNN, Lab images of plaque psoriasis	99.05%
Proposed CNN, Lab images of guttate psoriasis	89.79%
Proposed CNN, YIQ images of plaque psoriasis	98.46%
Proposed CNN, YIQ images of guttate psoriasis	90.79%
[27], 2015, U-Net, RGB images of plaque psoriasis	97.62%
[27], 2015, U-Net, RGB images of guttate psoriasis	90.30%
[27], 2015, U-Net, Lab images of plaque psoriasis	97.03%
[27], 2015, U-Net, Lab images of guttate psoriasis	88.42%
[27], 2015, U-Net, YIQ images of plaque psoriasis	97.22%
[27], 2015, U-Net, YIQ images of guttate psoriasis	89.27%

Fig. 1 illustrates the psoriasis images, the ground-truth images, and the segmentation results, obtained by proposed CNN. At Fig. 2 it is shown the segmentation results, obtained by U-Net which consist of four levels reliazed by 3×3 convolutions. It can be seen from the Fig. 1 that image segmentation by the proposed CNN is characterized by high accuracy in detection of the psoriasis lesion edges.

6 DISCUSSIONS

Analysis of the segmentation performance measures given in Table 2 showed the following. It is preferable to segment images of guttate psoriasis lesions in color spaces in which either the red component is isolated separately (RGB), or there is a difference component of red and another color (Lab, YCbCr, YIQ). This is due to the fact that the lesions of guttate psoriasis differ from normal skin mainly by redness level.

Thus, the highest performance of image segmentation of guttate psoriasis lesions by the proposed CNN was obtained using the RGB color space. The Lab, YIQ, YCbCr spaces showed similar results, but compared to the use of the RGB space, TP decreased to 2%, TN decreased by 4%. The presentation of images of guttate psoriasis lesions in xyz and HSV spaces showed the worst results compared to RGB. Specifically, TP is less by 2–4%, TN is less by 4–11%. For images of lesions of plaque psoriasis in the researched color spaces, the segmentation performance mainly differed within the statistical error. Further, for guttate psoriasis images more often image pixels from the class labeled “Psoriasis lesion” were incorrectly assigned to the class labeled “Normal skin”. For plaque psoriasis images, on the contrary, more often the pixels from the class labeled “Normal skin” were incorrectly assigned to the class labeled “Psoriasis lesion”. This result is due to the relative size of lesions of plaque and guttate psoriasis compared to the normal skin areas in the researched images. Plaque psoriasis lesions occupied a significant area on the researched images; guttate psoriasis lesions are much smaller in area.

The use of U-Net for psoriasis image segmentation [27] instead of the proposed CNN did not improve the segmentation performance.

The proposed CNN is shown a particulary significant advantage in detection of the psoriasis lesion edges. For U-Net the FOM values is less by 17–53% with median 40% for plaque psoriasis images, and the FOM values is less by 2–47% with median 40% for guttate psoriasis images, as compared with the proposed CNN. For all researched psoriasis images the FOM values of U-Net segmentation is less by 10–48% with median 40%.

Next, the Adam method is used for training the proposed CNN. In this case the lower segmentation performance is obtained as compared to stochastic gradient descent. For guttate psoriasis images, TP is less by 3–7%, and TN is decreased by 5–11%, for plaque psoriasis images TP is less by 3%.

Analysis of the segmentation performance of the proposed CNN and the known segmentation methods [6–10, 19–21] given in Table 3 showed the following. The percentage of correctly segmented pixels (accuracy, %) of the proposed CNN exceeds the known methods by up to 13% for guttate psoriasis images and by 4–20% for plaque psoriasis images.

A comparison of processing time was made for the image segmentation by the proposed CNN and the U-Net [27]. The researched psoriasis images were scaled to a size of 224×224 pixels. Then the processing time of the proposed CNN was 3.7–3.8 seconds on average per image when training the network using the stochastic gradient descent method. For a 4-level UNet network, when trained by the Adam method, the average processing time for one image with a 3 × 3 filter was 1.9–2 seconds. The research was performed using an Intel Core i5-7400 processor, 3 GHz CPU, 16GB memory, Windows 10 operating system, 64 bit. Thus, the proposed CNN requires on average 2 times more time to process one image than the 4-layer U-Net network. However, the number of training epochs of the 4-layer U-Net for this segmentation problem is, on average, 30–40% more than is required for training the proposed CNN.

CONCLUSIONS

The problem of mathematical support elaboration is solved to automate the image processing in dermatological disease diagnostic systems.

DOI 10.15588/1607-3274-2023-1-5

The scientific novelty of obtained results is that the deep learning convolutional neural network was elaborated to segment color psoriasis images. The improved CNN differs from those known from the literature in that its architecture did not include pooling layers; only convolutional layers, batch normalization, and an activation function were used. The use of the proposed CNN made it possible to enhance the segmentation performance of plaque psoriasis images and, especially, guttate psoriasis images at comparable processing time. There were no abrupt changes in color and illumination, blurring, as well as the complex background, for example, containing clothes or fragments of the interior on the researched psoriasis images. For such images, in cases of slow changes in image illumination, the proposed CNN showed a high segmentation performance, especially at the edges of the lesions.

The practical significance of obtained results is that the software realizing the proposed CNN is developed, as well as experiments to research its image segmentation performance are conducted. The experimental results allow to recommend the proposed CNN for use in practice, as well as to determine effective conditions for the application of the proposed CNN.

Prospects for further research are to study the performance of the proposed CNN then abrupt changes in color and illumination, blurring, as well as the complex background areas are present on dermatological images, for example, containing clothes or fragments of the interior. In addition, it is advisable to use the proposed CNN in other problems of color image processing to segment statistical or spectral-statistical texture regions on a uniform or textured background.

ACKNOWLEDGEMENTS

The author express their deep gratitude to V. N. Krylov, Doctor of Technical Sciences, Professor of the Department of Applied Mathematics and Information Technologies, National University “Odessa Polytechnic” for valuable and constructive advice and comments while working on this paper.

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Received 07.11.2022.
Accepted 21.12.2022.

УДК 004.93

СЕГМЕНТАЦІЯ ЗОБРАЖЕНЬ ЗГОРТКОВОЮ НЕЙРОННОЮ МЕРЕЖЕЮ БЕЗ ПУЛІНГОВИХ ШАРІВ В СИСТЕМАХ ДІАГНОСТИКИ ДЕРМАТОЛОГІЧНИХ ЗАХВОРЮВАНЬ

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АНОТАЦІЯ

Актуальність. Розглянуто задачу автоматизації процесу сегментації спектрально-статистичних текстурних зображень. Об’єктом дослідження є обробка зображень у системах діагностики дерматологічних захворювань. Метою дослідження є покращення якості сегментації кольорових псоріазних зображень шляхом розробки згорткової нейронної мережі глибокого навчання без пулінгових шарів.

Метод. Запропоновано згорткову нейронну мережу для обробки трьохканального псоріазного зображення заданого розміру. Початкові кольорові зображення було масштабовано до заданого розміру, а потім подано на вхідний шар нейронної мережі. Архітектура запропонованої нейронної мережі складається з чотирьох згорткових шарів з пакетною нормалізацією та функцією активації ReLU. Карти ознак із виходу цих шарів передавалися до згорткового шару 1×1 з функцією активації Softmax. Отримані карти ознак подавалися до шару класифікації пікселів зображення. При сегментуванні зображень згорткові та пулінгові шари оцінюють ознаки фрагментів зображення, а повністю зв’язані шари класифікують отримані вектори ознак, виконуючи розбиття зображення на однорідні сегменти. Ознаки сегментації оцінювалися в результаті навчання мережі а допомогою зображень, сегментованих експертом. Отримані ознаки стійкі до завад та спотворень зображень. Об’єднання результатів сегментації в різних масштабах визначається архітектурою мережі. Пулінгові шари включалися в архітектуру запропонованої згорткової нейронної мережі, оскільки вони зменшують розмір карт ознак порівняно з розміром початкового зображення та можуть знизити якість сегментації невеликих псоріазних плям та псоріазних плям складної форми.

Результати. Запропоновану згорткову нейронну мережу реалізовано програмно і досліджено при вирішенні задачі сегментації псоріазних зображень.

Висновки. Використання запропонованої згорткової нейронної мережі дозволило підвищити якість сегментації зображень бляшкового та крапельного псоріазу, особливо на границях плям. Перспективи подальших досліджень можуть полягати у дослідженні якості сегментації зображень запропонованою згортковою нейронною мережею, якщо на дерматологічних зображеннях присутні різкі зміни кольору та освітленості, розмиття, а також фрагменти складного фону, наприклад, що містять одяг або фрагменти інтер’єру. Доцільно. використовувати запропоновану згорткову нейронну мережу в інших задачах обробки кольорових зображень для сегментації статистичних або спектрально-статистичних текстурних областей на однорідному або текстурованому фоні.

КЛЮЧОВІ СЛОВА: псоріазне зображення, сегментація зображення, згорткова нейронна мережа, пулінговий шар, кольоровий простір, глибоке навчання.

DOI 10.15588/1607-3274-2023-1-5

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DOI 10.15588/1607-3274-2023-1-5

UDC 681.518:004.93

MACHINE LEARNING DECISION SUPPORT SYSTEMS FOR ADAPTATION OF EDUCATIONAL CONTENT TO THE LABOR MARKET REQUIREMENTS

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ABSTRACT

Context. The urgent task of increasing the functional efficiency of machine learning of decision support system (DSS) for assessing compliance with content modern requirements of the educational disciplines of the graduation department based on the results of the employer survey has been solved.

Objective. Increasing the functional efficiency of machine learning of DSS for assessing compliance with modern requirements of the educational disciplines content of the first (bachelor's) level specialty educational and professional program based on machine learning and pattern recognition.

Method. The method of machine learning of DSS is proposed for adapting the educational content of the graduation department to the labor market requirements. The idea of the method is to maximize the information capacity of the DSS in the machine learning process, which allows in the monitoring mode to guarantee a high full probability of making the correct classification decisions. The method was developed as part of a functional approach to modeling cognitive processes of natural intelligence, which makes it possible to provide DSS with flexibility when retraining the system due to increasing the power of the recognition classes alphabet. The method is based on the principle of maximizing the amount of information in the machine learning process. The modified Kullback information measure, which is a functional of the accuracy characteristics of classification solutions, is considered as a criterion for optimizing machine learning parameters. According to the proposed functional category model, an information-extreme machine learning algorithm was developed based on the hierarchical data structure in the form of a binary decursive tree. The use of such a data structure allows you to automatically divide a large number of recognition classes into pairs of nearest neighbors, for which optimization of machine learning parameters is carried out according to a linear algorithm of the required depth. The geometric parameters of hyperspherical containers of recognition classes were considered as optimization parameters, which were restored in the radial basis of the binary space of Hamming features in the machine learning process. At the same time, the input traning matrix was transformed into a working binary training matrix, which was changed in the machine learning process through admissible transformations in order to adapt the input information description of the DSS to the maximum reliability of classification decisions.

Results. The informational, algorithmic, and software of the DSS was developed to assess the educational content quality based on the machine analysis results of respondents' answers. Within the framework of the geometric approach, based on the information-extreme machine learning results, highly reliable decisive rules, practically invariant to the multidimensionality of the recognition features space, were constructed based on the hierarchical data structure in the form of a binary decursive tree. The influence of machine learning parameters on the functional effectiveness of machine learning of the DSS was studied on the evaluation example of the educational content of the educational and professional bachelor's program of the specialty 122 Computer Science.

Conclusions. The computer modeling results confirm the high functional efficiency of the proposed method of information-extreme hierarchical machine learning and can be recommended for practical use in institutions of higher education to assess compliance with modern requirements of the educational content of graduation departments.

KEYWORDS: information-extreme machine learning, functional categorical model, information criterion, hierarchical data structure, decursive tree, educational content.

ABBREVIATIONS

IEIT is an information-extreme intellectual technology;

DSS is decision support system;

CNN is convolutional neural network.

NOMENCLATURE

M is a set of recognition classes;

m is a number of the recognition class;

N is a set of recognition features in the structured vector;

i is a number of the recognition feature;

J is a set of structured vectors of recognition features;

J is a number of the structured vector;

H is a set of tiers of decursive tree;

h is a number of the tier of decursive tree;

S is a set of strata of decursive tree;

s is a number of the stratum of decursive tree;

m_s is a serial number of the recognition class in the s-th stratum;

$\delta_{h,s}$ is a parameter that is equal to half of the control tolerances field of the recognition feature.

DOI 10.15588/1607-3274-2023-1-6

$x_{h,s,c}$ is the averaged feature vector of the recognition class neighboring in the stratum

δ_H is the field of normalized tolerances, which specifies the values range of control tolerances

$E_{h\,s,m_s}(d)$ is the informational criterion for optimization of machine learning parameters of DSS to recognize feature vectors of recognition class X^o_{h,s,m_s};

d is a distance measure that is equal to the value of the the recognition class container radius;

G_E is the working area of defining the information criterion;

G_d is the permissible area for changing the radii of the recognition class containers;

P is a set of thematic modules of the educational content, which are evaluated by the respondents;

T is a set of reading information time moments;

Ω is the recognition features space;

A is the recognition classes alphabet;

Y is the input Euclidean training matrix;

$Y^{|S|}$ is the set of input Euclidean traning matrices of recognition classes for all levels of the decursive tree;

$X^{|S|}$ is the set of working binary traning matrices for all strata of the decursive tree;

f_1 is the training matrix formation operator Y;

f_2 is the operator for constructing a decursive binary tree H;

f_3 is the training matrix formation operator $Y^{|S|}$;

f_4 is the training matrix formation operator $X^{|S|}$;

$\{k\}$ is a set of machine learning steps;

$\tilde{\Re}^{|M|}$ is a fuzzy division of the feature space into M recognition classes;

$Y^{|S|}$ is an input training matrix of recognition classes S strata of decursive tree;

$X^{|S|}$ is a binary training matrix of recognition classes S strata of decursive tree;

E is a term set of values of the information criterion;

R is an operator of construction of division $\tilde{\Re}^{|2|}$ of space of signs on recognition classes;

ψ is an operator for testing the basic statistical hypothesis about the affiliation of the vector x_{h,s,m_s} of the recognition class X^o_{h,s,m_s};

γ is an operator of the set formation of exact characteristics for the set system of decisions estimations;

φ is an operator for calculating the information criterion for optimizing the machine learning parameters;

U is an operator that regulates the machine learning process;

$K^{(1)}_{h,s,m_s}(d)$ is the number of events in which "own" feature vectors do not belong to recognition class to the container X^o_{h,s,m_s};

$K^{(2)}_{h,s,m_s}(d)$ is the number of events in which "foreign" feature vectors belong to the recognition class container X^o_{h,s,m_s};

10^{-p} is a sufficiently small number, which is entered to avoid division by zero (in practice, $p=2$ was accepted);

$x^{(j)}$ is a structured feature vector that can be recognized;

μ_{m_S} is the function of belongingness of feature vector $x^{(j)}$ to the recognition class container X^o_{h,s,m_s};

d^*_{h,s,m_s} is the optimal radius of the recognition class container X^o_{h,s,m_s}.

INTRODUCTION

Establishing a stable connection between the graduation department of a higher education institution and employers is a necessary condition for improving the quality of the educational process. The main way to establish such a connection is to survey employers and specialists in the relevant field of knowledge. The development of modern information and communication technologies makes it possible to automate data collection. At the same time, in practice, the results of the respondents survey are processed using the multidimensional statistical analysis methods. Such methods to ensure statistical stability and homogeneity require large volumes of input data, which requires organizers to spend significant time and money on processing and analyzing survey results.

The object of research is the process of sustainable monitoring of the education quality by creation of the DSS for adapting the educational content of the graduation department to the labor market requirements on the machine learning and pattern recognition basis.

The subject of research is the method of hierarchical information-extreme machine learning of DSS for adapting the educational content of the graduation department to the labor market requirements.

The purpose of the work is to increase the functional efficiency of the DSS machine learning during automatically forming an input traning matrix based on the respondents survey results, building decisive rules according to the optimal (here and in the text in the text in the informational sense) machine learning parameters, and in the monitoring mode assessing the compliance of the educational content of the graduation department with modern requirements.

DOI 10.15588/1607-3274-2023-1-6

1 LITERATURE REVIEW

The article considers the method of hierarchical information-extreme machine learning of DSS for adapting the educational content of the graduation department to the labor market requirements. According to European educational standards, the quality of education is determined by the benefits that both employers and graduates of a higher education institution will receive [1, 2]. One of the main ways of organizing sustainable monitoring of the education quality is the creation of the DSS for adapting the educational content of the graduation department to the labor market requirements [3]. A traditional approach to processing and analyzing the stakeholders survey results and specialists in the knowledge relevant fields is the application of decision-making systems existing in social communications using multidimensional statistical analysis methods [4–6]. At the same time, the disadvantages of statistical decision-making methods are the need for large volumes of data, ensuring their statistical stability and homogeneity. A promising direction for increasing the functional efficiency of computerized systems for assessing the quality of education is the use of intelligent information technologies for data analysis [7–9]. Works [10, 11] give examples of creating expert systems for evaluating the quality of the educational process based on fuzzy logic. The main disadvantages of such systems are that they are inflexible and do not provide feedback in the monitoring mode between the graduation department, employers and students of higher education of various forms of education. The further development of computerized systems for assessing the education quality is the development of the scientific and methodological foundations of the information synthesis of DSS, capable of automatically forming an input information description and identifying regularities based on machine learning and pattern recognition [12]. CNN [13, 14] is the most common among known intelligent information technologies for data analysis, but the main drawback of CNN is its sensitivity to the multidimensionality of the feature space and the recognition classes alphabet. Works [15, 16] consider the use of extractors based on artificial neural networks to reduce the impact of input data multidimensionality, but this approach is associated with the information loss possibility.

Works [17–19] consider the use of fuzzy neural networks for functional diagnosis, but at the same time there is also the multidimensionality problem, which significantly limits the capabilities of the fuzzy logic apparatus.

The main scientific and methodological reasons that complicate the use of CNN for the information synthesis of the DSS for the education quality assessment are:

– arbitrary initial conditions of the evaluation process;

– intersection in the recognition classes features space that characterize the corresponding levels of educational content quality;

– multidimensionality of the signs dictionary;

– the impact on the machine assessment of the education quality of uncontrollable disturbing factors, for example, man-made disasters, an unfavorable epidemiological situation or the introduction of martial law.

A promising way to reduce the multidimensionality impact of the recognition features dictionary is the use of machine learning methods, based on the results of which decisive rules are built within the framework of a geometric approach [20]. Among such methods, the information technologies of the support vector method [21, 22] deserve attention, but the functional effectiveness of the algorithms of this method significantly depends on the degree of recognition classes intersection in the feature space. This shortcoming is not present in machine learning methods, which are developed within the framework of the so-called information-extreme intelligent data analysis technology (IEIT) created at Sumy State University (Ukraine) [23–25], the methods of intelligent data analysis proposed within this technology are based on the principle maximizing the information capacity of the system in the process of its machine learning. The work [25] considered information-extreme machine learning based on a hierarchical data structure. But in the case of hierarchical machine learning DSS to assess the educational content quality, it is necessary to take into account such a feature as the presence of an ordered alphabet of recognition classes that characterize different levels of educational content quality when building a hierarchical data structure in the form of a decursive tree.

The purpose of the article is to develop an algorithm of hierarchical information-extreme machine learning of DSS and to verify it on the example of assessing compliance with modern requirements of the educational content of the educational and professional bachelor's degree program of the "Computer Science" specialty.

2 PROBLEM STATEMENT

Let's consider within the framework of IEIT the formalized setting of the information synthesis task of DSS to assess of the educational content quality and professional program of the specialty, which is used to train students of higher education at the graduation department.

It is necessary to build a hierarchical data structure in the form of a decursive binary tree $\{X^o_{h,s,m} \mid h=\overline{1,H}; s=\overline{1,S_h}; m_s=\overline{1,2}\}$ for the given alphabet $\{X^o_m \mid m=\overline{1,M}\}$ of recognition classes that characterize the levels of educational content quality assessment according to the appropriate system.

According to the concept of IEIT, transform the input training matrices of the recognition classes of each layer into the corresponding working binary matrices specified in the Hamming space. At the same time, let the DSS machine learning parameters be set, which, for example,

DOI 10.15588/1607-3274-2023-1-6

for recognition class X^{o}_{h,s,m_s} are represented in the form of a structured vector

$$g_{h,s} =< x^{o}_{h,s,m_s}, d_{h,s,m_s}, \delta_{h,s} > . \quad (1)$$

The number of optimization parameters in expression (1) sets the second depth level of information-extreme machine learning, since vector x_{h,s,m_s} depends on parametera $\delta_{h,s}$ depends on parameter.

Machine learning parameters are limited:

a) $d_{h,s,m_s} \in [0; d(x_{h,s,m_s} \oplus x_{h,s,c})]$;

b) $\delta_{h,s} \in [0; \delta_H / 2]$.

In the machine learning process of DSS, it is necessary to:

1) optimize the parameters of the vector (1) by finding the global maximum of the alphabetically averaged recognition classes of the s-th stratum h-th tier of the information criterion:

$$\overline{E}_{h,s} = \frac{1}{2} \sum_{m_s=1}^{2} \max_{G_E \cap G_d} E_{h,s,m_s}(d), \quad (2)$$

2) in the information-extreme machine learning process, build highly reliable decision rules based on the optimal (here and in the text in the informational sense) geometric parameters of the recognition classes containers;

3) during the operation of the DSS in the monitoring mode, determine whether the recognized feature vector belongs to the corresponding class from the given alphabet.

3 MATERIALS AND METHODS

Information-extreme machine learning of DSS was carried out using a hierarchical data structure in the form of a decursive binary tree [24]. With such a structure, the attribute from the top of the stratum of the higher tier is transferred to one of the vertices of the child stratum s, the lower tier. At the same time, the training matrix of the corresponding recognition class is considered as an attribute of the vertex.

Construction of a decursive binary tree was carried out according to the scheme:

1) alphabet $\{X^{o}_{m} \mid m = \overline{1, M}\}$ of ordered recognition classes is divided into two groups, which define two branches of the decursive tree, respectively;

2) as attributes of the vertices of the upper (first according to dendrographic classification) tier of the decursive tree, the training matrices of the boundaries for each of the recognition classes groups are selected;

3) the attributes of the strata of the upper tier are transferred to the vertices of the corresponding strata of the lower tier;

4) the strata of the lower tiers of each branch of the tree contain, in addition to the traning matrix transported from the upper tier, also the traning matrix of the nearest neighboring recognition class in its group;

5) the construction of the tree continues until the final strata are formed, which contain the training matrices of all recognition classes.

Thus, the binary decursive tree built according to the above scheme divides the given recognition classes alphabet into strata, each of which contains two nearest neighboring classes, which allows applying a linear information-extreme machine learning algorithm for each final stratum. At the same time, the construction of error-free decisive rules based on the training matrix is achieved by optimizing additional parameters of the DSS functioning.

The functional categorical model of the information-extreme machine learning of DSS is considered in the form of a directed graph, the edges of which are the mapping operators of the corresponding sets. At the same time, the input information description of the DSS is given by the structure

$$I =< P, T, \Omega, A, Y, H, Y^{|S|}, X^{|S|}; f_1, f_2, f_3, f_4 > .$$

At the same time, the Cartesian product $P \times T \times \Omega \times Z$ is considered as a source of information.

The functional categorical model of information-extreme machine learning of DSS with optimization of machine learning parameters (1) is shown in Fig. 1.

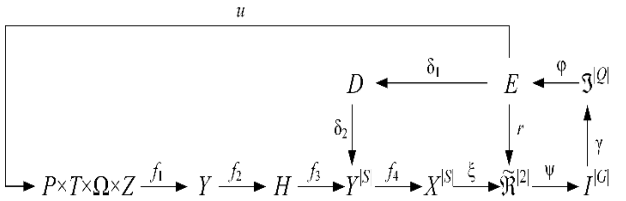

Figure 1 – Functional categorical model of machine learning of DSS

In Figure 1 operator ξ maps the structured binary feature vectors of training matrices $X^{|S|}$ to a fuzzy, in the general case, partition of $\tilde{\Re}^{|2|}_{h,s}$ recognition classes of each stratum of the decursive tree. The classification operator $\psi : \tilde{\Re}^{|2|} \to I^{|G|}$, where $I^{|G|}$ – is a set of G statistical hypotheses, checks the basic statistical hypothesis that the vector $x^{(j)}_{h,s,m_s}$ belongs to the fuzzy recognition class X^{o}_{h,s,m_s}. By evaluating statistical hypotheses, operator γ forms a set of accuracy characteristics $\Im^{|Q|}$, where $Q = G^2$ is the number of accuracy characteristics. Operator φ calculates a set of values of information criterion E, which is a functional of accuracy

DOI 10.15588/1607-3274-2023-1-6

characteristics. The optimization contour of the geometric parameters of partition $\tilde{\Re}^{|M|}$. The optimization contour of the geometric parameters of partition r, which at each step of machine learning restores the recognition classes containers in the radial basis of the Hamming feature space. The optimization contour of parameter $\delta_{h,s}$ of the control tolerances field includes the term set D, the elements of which are the allowable values of control tolerances for recognition features. At the same time, operator δ_1 changes the control tolerances, and operator δ_2 changes the quantization levels of the vector recognition features of the training matrices $Y^{|S|}$. Operator u regulates the machine learning process.

According to the functional category model (Fig. 1). We will present the algorithm of information-extreme machine learning of DSS in the form of a two-cycle iterative procedure for finding the global maximum of an information criterion in the working area of determining its function:

$$\delta^*_{h,s} = \arg\max_{G_\delta}\{\max_{G_E \cap G_d} \overline{E}_{h,s}(d)\}. \qquad (3)$$

The internal loop of the procedure (3) implements the basic machine learning algorithm, the purpose of which is to calculate at each step of learning the optimization information criterion $\overline{E}^{(k)}_{h,s}$ and search for the maximum value in the working area of determining its function.

Since the values of recognition features have the same measurement scale, a machine learning algorithm was implemented with parallel optimization of the control tolerances system, according to which control tolerances are changed for all recognition features simultaneously at each step of machine learning.

The input information for the machine learning algorithm is arrays of training matrices $\{y^{(j)}_{h,s,m_s}\}$ and a system of fields of normalized tolerances $\{\delta_{H,i}\}$ for recognition features, which sets the values range of the corresponding control tolerances.

Consider the optimization scheme of machine learning parameters for the recognition classes of the s-th stratum of the h-th tier of the decursive tree:

1) the recognition class counter of the s-th stratum of the h-th tier of the decursive tree is reset: $m_s := 0$;

2) $m_s := m_s + 1$;

3) the parameter change step counter is reset to zero $\delta_{h,s}: l := 0$;

4) the counter $l := 1+1$ is started and the lower $A_{HK,i}$ and upper $A_{BK,i}$ control tolerances are calculated for all recognition features:

$$\{A_{HK,i}[l] = y_{h,s,i} - l\};\ \{A_{BK,i}[l] = y_{h,s,i} + l\}; i = \overline{1,N},$$

5) the basic algorithm of information-extreme machine learning is implemented, the tasks of which are to calculate at each step of learning the value of the information criterion (2) and search for the maximum value of the criterion in the working area of determining its function;

6) the optimal radius of the recognition class container X^o_{h,s,m_s} is determined

$$d^*_{h,s,m_s} = \arg\max_{G_E \cap G_d} E_{h,s,m_s}(d),$$

7) if $l \le \delta_H / 2$, then point 4 is fulfilled, otherwise – point 8;

8) if $m_s \le 2$, then point 2 is fulfilled, otherwise point 9;

9) the average value of information criterion $\overline{E}_{h,s}$ and the optimal parameter of the control tolerances field $\delta^*_{h,s}$ are calculated;

10) STOP.

Since the machine learning of DSS takes place according to the hierarchical data structure, an algorithm was implemented, the main stages of which are:

1) zeroing of the data structure tiers counter: $h := 0$;

2) initialization of the data structure tier counter: $h := h + 1$;

3) zeroing of the sratum counter: $s := 0$;

4) initialization of the tier counter: $s := s + 1$;

5) for each *s*-th stratum of the *h*-th tier of the decursive tree, an information-extreme algorithm of machine learning with parallel optimization of control tolerances for recognition features is implemented, which calculates:

a) the maximum value of the information criterion $\overline{E}_{h,s}$ averaged for the stratum;

b) averaged for the stratum $\{x^*_{h,s,m_s}\}$ recognition classes of the s-th stratum of the h-th tier;

c) optimal radii of $\{d^*_{h,s,m_s}\}$ recognition classes of the s-th stratum of the h-th tier;

d) optimal paramete $\delta^*_{h,s}$ of the control tolerances field for recognition classes features of the s-th stratum of the h-th tier of the decursive tree;

6) if $s \le S_h$, where S_h is the number of strata on the *h*-th tier, then point 4 is fulfilled, otherwise point 7;

7) if $h \le h_{\max}$, where $h_{\max}$ is the number of the decursive tree levels, then point 2 is fulfilled, otherwise point 8;

8) the maximum value of information criterion $\overline{E}_H$ averaged over all strata of the decursive tree is calculated;

DOI 10.15588/1607-3274-2023-1-6

9) a structured set of decisive rules is formed for all recognition classes;

10) STOP.

As a criterion for optimizing machine learning parameters, the modified Kullback information measure was considered, which for two-alternative solutions and equally likely hypotheses has the form [25]

$$E_{h,s,m_s}(d)=\frac{\left\lfloor n-(K^{(1)}_{h,sw,m_s}(d)+K^{(2)}_{h,s,m_s}(d))\right\rfloor}{n}\times$$
$$\times\log_2\left\{\frac{2n+10^{-p}-\left[(K^{(1)}_{h,sw,m_s}(d)+K^{(2)}_{h,s,m_s}(d)\right]}{\left[K^{(1)}_{h,s,m_s}(d)+K^{(2)}_{h,s,m_s}(d)\right]+10^{-p}}\right\}. \quad (4)$$

Based on the optimal geometric parameters of the recognition classes containers obtained in the machine learning process, decisive rules are constructed, which will be presented in the form

$$(\forall X^{o}_{m,h,s}\in\Re^{|M|})(\forall x^{(j)}\in\Re^{|M|})\{if\ [(\mu_{m_s}>0)\,\&$$
$$\&\,(\mu_m=\max_{\{m\}}\{\mu_{m_s}\mid m_s=\overline{1,2}\}]\ then\ x^{(j)}\in X^{o}_{h,s,m_s} \quad (5)$$
$$else\ x^{(j)}\notin X^{o}_{h,s,m_s}\}.$$

In expression (5), the membership function for the hyperspherical container of recognition class X^{o}_{h,s,m_s} is determined by the formula

$$\mu_{m_s}=1-\frac{d(x^{*}_{h,s,m_s}\oplus x^{(j)})}{d^{*}_{h,s,m_s}}. \quad (6)$$

In expression (6), the code distance between the optimal averaged feature vector x^{*}_{h,s,m_s} and the recognized feature vector $x^{(j)}$, is denoted as $d(x^{*}_{h,s,m_s}\oplus x^{(j)})$.

Thus, the geometric decisive rules (5) built in the information-extreme machine learning process of DSS are characterized by low computational complexity and are practically invariant to the multidimensionality of the recognition features dictionary.

4 EXPERIMENTS

The implementation of the above information-extreme machine learning algorithm of DSS was carried out on the example of assessing the compliance with the labor market requirements of the educational content of the bachelor's level educational and professional program in the specialty "Computer Science", which is taught to students of Sumy State University. The input training matrix was formed by simulating the evaluations of the educational disciplines thematic modules, which were randomly generated according to the normal distribution of probabilities and displayed on a stobal scale. Since the thematic modules were evaluated according to the European rating scale, the stobal scale was previously divided into six fuzzy intervals, which specified the areas of the recognition classes:

1) recognition class X^{o}_{A} included feature vectors that fell within the range from 88 to 100 points;

2) for recognition class X^{o}_{B} – from 81 to 91 points;

3) for recognition class X^{o}_{C} – from 74 to 84 points;

4) for recognition class X^{o}_{D} – from 67 to 77 points;

5) for recognition class X^{o}_{E} – from 59 to 69 points;

6) for recognition class X^{o}_{F} – from 50 to 62 points.

The simulation training matrix for each recognition class consisted of 40 syllabuses of educational disciplines of the educational and professional program structured by thematic modules. Each vector consisted of 144 features, the number of which was equal to the thematic modules number. In addition, according to the educational and professional program of the specialty, educational disciplines were divided into seven blocks, which included: general scientific, fundamental, design, technological organizational, humanitarian and selective educational disciplines.

For a given recognition classes alphabet, a hierarchical data structure in the form of a decursive tree was built according to the above algorithm (Fig. 2).

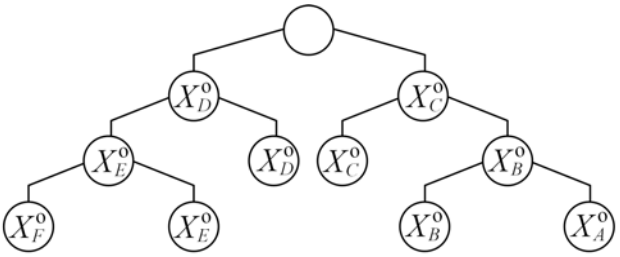

Figure 2 – Hierarchical data structure in the form of a decursive binary tree

According to the decursive tree (Fig. 2), information-extreme machine learning was implemented according to procedure (3). Optimization of machine learning parameters specified by vector (1) was carried out for the two nearest neighboring recognition classes of each stratum. Based on the optimal geometric parameters of the recognition class containers obtained in the machine learning process, decisive rules (5) were constructed. Since each recognition class belongs to two strata, according to the minimum-distance principle of pattern recognition theory, the geometric parameters of the recognition class whose container had the minimum optimal radius were taken as optimal.

According to the machine learning results of DSS, the values of the averaged information criteria (4) were

DOI 10.15588/1607-3274-2023-1-6

analyzed for each stratum in order to determine the need to increase the depth of machine learning by optimizing additional parameters of the DSS operation, including the formation parameters of the input information description.

5 RESULTS

In the programmatic implementation process of information-extreme machine learning of DSS according to the iterative procedure (3), the optimal parameters of the recognition classes for each of the strata of the decursive binary tree were determined (Fig. 2). As an example, Figure 3 shows the dependency graph of the averaged information criterion (4) for the stratum of the first (upper according to dendrographic classification) tier of the decursive tree, obtained by the machine learning results.

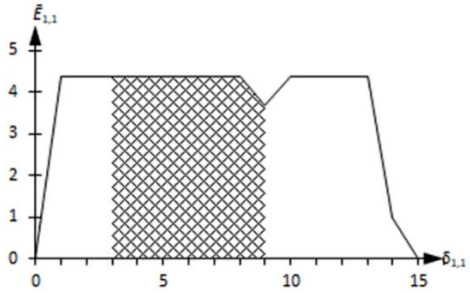

Figure 3 – Dependency graph of the information criterion on the parameter of the control tolerances field for the strata of the first tier

In Fig. 3 double hatching indicates the working area of the definition of the criterion function (4), in which the errors of the first and second kind are less than the first and second reliabilities, respectively. The analysis of Figure 3 shows that the global maximum of the optimization criterion is reached in the area of the plateau-type graph. In this case, the optimal parameter is determined under the condition of the minimum value of the so-called coefficient of recognition classes intersection [23]

$$\eta = \frac{d^*_{h,s,m_s}}{d(x^*_{h,s,1} \oplus x^*_{h,s,2})} \to \min_{\{m_s\}}. \qquad (7)$$

In expression (7), the intercenter code distance between the recognition classes and the $X^o_{h,s,1}$ and $X^o_{h,s,2}$ s-th stratum of the h-th tier of the decursive tree is denoted as $d(x^*_{h,s,1} \oplus x^*_{h,s,2})$.

After checking the fulfillment of condition (7), the optimal values interval of the control tolerance field parameter $\delta^*_{1,1} = 5$ was determined, from which the value $\overline{E}^*_{1,1} = 4.50$ was selected. At the same time, the averaged information optimization criterion reaches its maximum value at parameters $n = 40$ and $p = 2$ specified in formula (4).

Since decisive rules (5) are built within the framework of a geometric approach, they require knowledge of the optimal geometric parameters of recognition class containers obtained in the machine learning process. Figure 4 shows dependency graphs of criterion (4) on the radii of the recognition classes containers of the first tier of the decursive tree (Fig. 2).

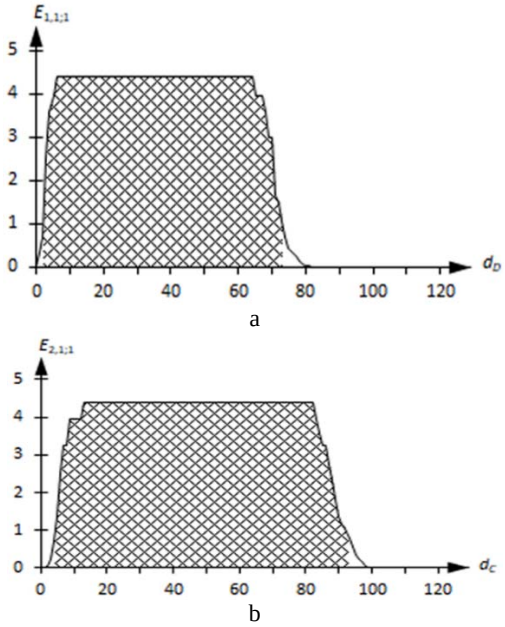

Figure 4 – Dependency graphs of the information criterion (4) on the radii of the recognition classes containers of the first stratum of the second tier: a – class X^o_D; b – class X^o_C

The optimal radii of the recognition classes containers of the first stratum according to the condition (7) are equal to any number from the intervals: $d^*_D \in [38,39]$ (hereafter in code units) for class X^o_D and $d^*_C \in \overline{[24,27]}$ for class X^o_C. According to the minimum-distance principle of the pattern recognition theory, the minimum radii were chosen: $d^*_D = 38$ and $d^*_C = 24$.

Fig. 5 shows dependency graph of the averaged information criterion (4) on parameter δ, obtained during machine learning based on the training matrix of recognition classes of the first stratum of the second tier of the decursive tree (Fig. 2).

DOI 10.15588/1607-3274-2023-1-6

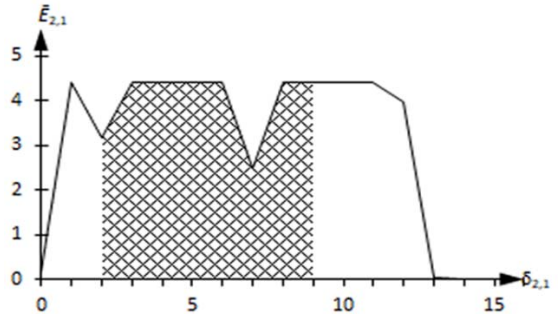

Figure 5 – Dependency graph of the information optimal parameter of machine learning of the criterion on the parameter of the control tolerances field for the first stratum of the second tier

When condition (7) is fulfilled, the optimal parameter of the control tolerances field for recognition classes of the first stratum of the second tier of the decursive tree (Fig. 2) is equal to $\delta^*_{2,1} = 4$ at the maximum value of the criterion $\overline{E}^*_{2,1} = 4.50$.

Figure 6 shows dependency graphs of criterion (4) on the radii of the recognition classes containers of the first stratum of the second tier of the decursive tree (Fig. 2).

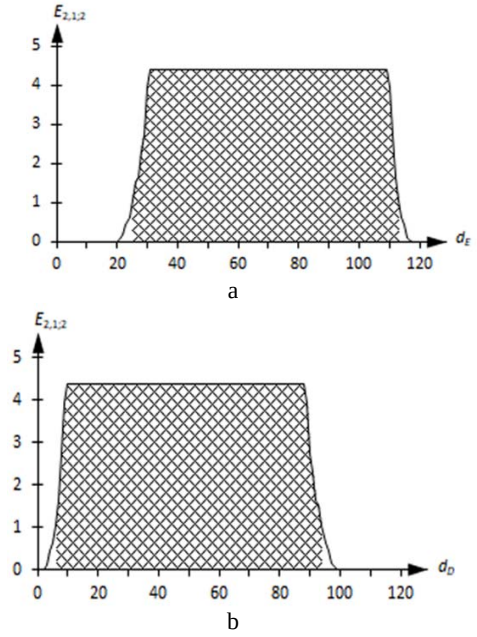

Figure 6 – Dependency graphs of the information criterion (4) on the radii of the recognition classes containers of the first stratum of the second tier: a – class $X^o_{2,1,1}$ (X^o_E); b – class $X^o_{2,1,2}(X^o_C)$

The optimal radii of the recognition classes containers of the first stratum of the second tier according to condition (7) are equal to $d^*_{2,1,1} = 46$ for class X^o_E and $d^*_{2,1,2} = 32$ for class X^o_D. Similarly, the optimal machine learning parameters for other recognition classes were determined. Table 1 shows the results of information-extreme machine learning of DSS according to the hierarchical structure (Fig. 2).

Table 1 – Optimal machine learning parameters

Strate number (h,s)	$\delta^*_{h,s}$	$d^*_{h,s,,1}$	$d^*_{h,s,,2}$
1,1	$\delta^*_{1,1} = 5$	$d^*_{1,1,1} = d^*_D = 38$	$d^*_{1,1,,2} = d^*_C = 24$
2,1	$\delta^*_{2,1} = 4$	$d^*_{h,s,,1} = d^*_E = 46$	$d^*_{2,1,2} = d^*_D = 32$
2,2	$\delta^*_{2,2} = 5$	$d^*_{2,2,1} = d^*_C = 52$	$d^*_{2,2,2} = d^*_B = 16$
3,1	$\delta^*_{3,1} = 5$	$d^*_{3,1,1} = d^*_F = 64$	$d^*_{3,2,2} = d^*_E = 12$
3,2	$\delta^*_{3,2} = 4$	$d^*_{3,2,1} = d^*_B = 57$	$d^*_{3,2,2} = d^*_A = 16$

Comparing in Table 1 the radii of the recognition classes containers X^o_D for the strata of the upper and lower tiers, a smaller value of $d^*_D = 32$, should be taken as the optimal one, since class X^o_E is the nearest neighbor for it. Similarly, for recognition class X^o_C the permissible optimal radius is equal to $d^*_C = 24$, for class X^o_B – $d^*_B = 16$ and for class X^o_E – $d^*_E = 12$.

When calculating the membership function (6), vectors x^*_{h,s,m_s} were determined by optimal control tolerances for recognition features.

6 DISCUSSION

The advantages of building a hierarchical data structure in the form of a decursive binary tree are shown on the example of information-extreme machine learning of DSS for adapting the educational content of the educational and professional program of the second (bachelor) level to the labor market requirements. Thanks to the proposed structure, it was possible to automatically divide a set of recognition classes into pairs of nearest neighbors. In addition, the a priori structuring of the recognition classes due to the corresponding knowledge level assessment system is taken into account. As a result, there is no need to form a variational series of recognition classes, which is an advantage of the training required to build a decursive binary tree. The use of a hierarchical data structure in the form of a decursive binary tree, in addition, allows for each stratum to implement information-extreme machine learning according to a linear algorithm with the required level of depth. Unlike neuro-like structures in IEIT methods, the depth level of information-extreme machine learning is determined by the number of optimization parameters that affect the functional efficiency of the intelligent system. This approach corresponds to a greater extent to the mechanism of making classification decisions by natural intelligence. It is also justified to use information criterion (4) in classification tasks as an optimization criterion,

DOI 10.15588/1607-3274-2023-1-6

which in the logical and epistemological aspect is considered as a measure of the diversity of recognition classes.

The analysis of the obtained results of the information-extreme machine learning of DSS for adapting the educational content to the labor market requirements shows that for each layer of the decursive tree it was possible to build error-free decisive rules according to the training matrix. At the same time, in accordance with the minimum-distance principle of pattern recognition theory, the radii of the recognition classes containers determined relative to the nearest neighboring class were considered optimal.

The specifics of the development of algorithmic and software of the DSS for adapting educational content to the labor market requirements is the use of simulation modeling for the formation of the input traning matrix. Such an approach is due to the large material and time costs of obtaining the results of the respondents survey in the absence of the DSS. However in the future, when the DSS is functioning in the monitoring mode, as archival representative data accumulates, it becomes possible to retrain the system based on real data. Further research will be aimed at expanding the functional capabilities of the DSS in order to evaluate blocks and individual academic disciplines. As a result, graduation departments will be able to quickly adjust the educational content to modern requirements.

CONCLUSIONS

The actual problem of improving the quality of education is being solved by building an information and communication system for adapting the educational content of the graduation department of the university to the requirements of the labor market.

The scientific novelty of the obtained results is that the method of information-extreme machine learning based on the hierarchical data structure in the form of a decursive binary tree is proposed for the first time. The method automatically divides the alphabet of high-power recognition classes into pairs of nearest neighbors. It performs two-class machine learning of DSS, ensuring high reliability with a minimum depth of machine learning. As a result, error-free decision rules based on the training sample were built in the monitoring mode of DSS. It allows the total probability of correct classification decisions to be close to the maximum limit.

The practical significance of the obtained results is that the developed DSS software allows for quickly adjusting the educational content of the graduation department of the university, taking into account the requirements of the labor market, with minimal material and time costs.

Prospects for further research consist in simplifying the formation of the input information description of the DSS by automatically reading the thematic modules from the syllabuses of the educational disciplines of the specialty of the corresponding level of training of higher education applicants.

ACKNOWLEDGEMENTS

The work was carried out in the laboratory of intelligent systems of the Department of Computer Sciences of Sumy State University with the funds of the state budget scientific research theme “Information technology of autonomous navigation of unmanned aerial vehicles by terrestrial natural and infrastructural landmarks” (№ DR 0122U000786).

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Received 25.11.2022.
Accepted 22.01.2023.

УДК 681.518:004.93

ІНФОРМАЦІЙНО-ЕКСТРЕМАЛЬНЕ МАШИННЕ НАВЧАННЯ СИСТЕМИ ПІДТРИМКИ ПРИЙНЯТТЯ РІШЕНЬ ДЛЯ АДАПТАЦІЇ НАВЧАЛЬНОГО КОНТЕНТУ ДО ВИМОГ РИНКУ ПРАЦІ

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АНОТАЦІЯ

Актуальність. Розв'язана актуальна задача підвищення функціональної ефективності машинного навчання системи підтримки прийняття рішень (СППР) для оцінки відповідності сучасним вимогам контенту навчальних дисциплін випускової кафедри за результатами опитування роботодавців.

Мета. Підвищення функціональної ефективності машинного навчання СППР для оцінки відповідності сучасним вимогам контенту навчальних дисциплін освітньо-професійної програми спеціальності першого (бакалаврського) рівня на основі машинного навчання та розпізнавання образів.

Метод. Запропоновано метод інформаційно-екстремального машинного навчання СППР для адаптації навчального контенту випускової кафедри до вимог ринку праці. Ідея методу полягає у максимізації інформаційної спроможності СППР в процесі машинного навчання, що дозволяє в режимі моніторингу гарантувати високу повну ймовірність прийняття правильних класифікаційних рішень. Метод розроблено в рамках функціонального підходу до моделювання когнітивних процесів природнього інтелекту, що дозволяє надати СППР гнучкість при перенавчанні системи через збільшення потужності алфавіту класів розпізнавання. В основу методу покладено принцип максимізації кількості інформації в процесі машинного навчання. Як критерій оптимізації параметрів машинного навчання розглядається модифікована інформаційна міра Кульбака, яка є функціоналом від точнісних характеристик класифікаційних рішень. Згідно із запропонованою функціональною категорійною моделлю розроблено алгоритм інформаційно-екстремального машинного навчання за ієрархічною структурою даних у вигляді бінарного декурсивного дерева. Застосування такої структури даних дозволяє автоматично розбивати велику кількість класів розпізнавання на пари найближчих сусідів, для яких оптимізація параметрів машинного навчання здійснюється за лінійним алгоритмом необхідної глибини. Як параметри оптимізації розглядалися геометричні параметри гіперсферичних контейнерів класів розпізнавання, які в процесі машинного навчання відновлювалися в радіальному базисі бінарного простору ознак Геммінга. При цьому вхідна навчальна матриця трансформувалася в робочу бінарну навчальну матрицю, яка змінювалася в процесі машинного навчання шляхом допустимих перетворень з метою адаптації вхідного інформаційного опису СППР до максимальної достовірності класифікаційних рішень.

Результати. Розроблено інформаційне, алгоритмічне і програмне забезпечення СППР для оцінки якості навчального контенту за результатами машинного аналізу відповідей респондентів. В рамках геометричного підходу за результатами інформаційно-екстремального машинного навчання за ієрархічною структурою даних у вигляді бінарного декурсивного дерева побудовано високо достовірні вирішальні правила, практично інваріантні до багато вимірності простору ознак розпізнавання. Досліджено вплив параметрів машинного навчання на функціональну ефективність машинного навчання СППР на прикладі оцінки навчального контенту освітньо-професійної програми бакалаврського рівня спеціальності «Комп'ютерні науки».

Висновки. Результати комп'ютерного моделювання підтверджують високу функціональну ефективність запропонованого методу інформаційно-екстремального ієрархічного машинного навчання і можуть бути рекомендовані до

DOI 10.15588/1607-3274-2023-1-6

практичного використання у закладах вищої освіти для оцінки відповідності сучасним вимогам навчального контенту випускових кафедр

КЛЮЧОВІ СЛОВА: інформаційно-екстремальне машинне навчання, функціональна категорійна модель, інформаційний критерій, ієрархічна структура даних, декурсивне дерево, навчальний контент.

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DOI 10.15588/1607-3274-2023-1-6

УДК 004.8:004.032.26

КЛАСТЕРИЗАЦІЯ МАСИВІВ ДАНИХ НА ОСНОВІ МОДИФІКОВАНОГО АЛГОРИТМУ СІРОГО ВОВКА

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АНОТАЦІЯ

Актуальність. Задача кластеризації масивів багатовимірних даних, основною метою якої є знаходження однорідних у сенсі прийнятої метрики класів спостережень, є важливою частиною інтелектуального аналізу даних Data Mining. З обчислювальної точки зору задача кластеризації перетворюється у проблему пошуку локальних екстремумів багатоекстремальної функції, які багатократно запускаються з різних точок вихідного масиву даних. Пришвидшити процес пошуку цих екстремумів можна, скориставшись ідеями еволюційної оптимізації, що включає в себе алгоритми, інспіровані природою, ройові алгоритми, популяційні алгоритми, тощо.

Мета. Мета роботи полягає у запровадженні процедури кластеризації масивів даних на основі покращеного алгоритму сірого вовка.

Метод. Введено метод кластеризації масивів даних на основі модифікованого алгоритму сірого вовка. Перевагою запропонованого підходу є скорочення часу вирішення оптимізаційних задач в умовах коли кластери перетинаються. Особливістю запропонованого методу є обчислювальна простота і висока швидкість, пов'язана з тим, що весь масив обробляється тільки один раз, тобто виключається необхідність в багатоепоховому самонавчанні, що реалізується в традиційних алгоритмах нечіткої кластеризації.

Результати. Результати експериментів підтверджують ефективність запропонованого підходу в задачах кластеризації за умов перетинних кластерів та дозволяють рекомендувати запропонований метод для використання на практиці для вирішення проблем автоматичної кластеризації великих даних.

Висновки. Введено метод кластеризації масивів даних на основі покращеного алгоритму сірого вовка. Перевагою запропонованого підходу є скорочення часу вирішення оптимізаційних задач. Результати експериментів підтверджують ефективність запропонованого підходу в задачах кластеризації за умов перетинних кластерів.

КЛЮЧОВІ СЛОВА: нечітка кластеризація, багатоекстремальна оптимізація, еволюційний метод.

АБРЕВІАТУРИ

FCM – метод нечітких с-середніх;

HSCI – гібридні системи обчислювального інтелекту;

PCO – алгоритм «рій частинок»;

CSO – алгоритм зграї котів;

NIC – природньо – інспіровані обчислення;

GWO – алгоритм сірого вовка.

НОМЕНКЛАТУРА

X – матриця набору даних;

E – цільова функція;

N – кількість спостережень;

R – вектор атрибутів;

n – кількість атрибутів;

k – номер вектору-спостереження;

$x(k)$ – вектор-спостереження;

$x_i(k)$ – значення вектора-спостереження за i-м атрибутом;

$x_{i,i2}(k)$ – значення вектора-спостереження за i-м та $i2$-м атрибутами при нормуванні даних в гіперкуб;

i – номер атрибуту вектора-спостереження;

j – номер кластеру;

m – кількість неперетинних класів;

w – вага вовка;

c – центроїд кластера;

c_j – центроїд j-го кластеру;

t – ітерація пошуку;

T – максимальна кількість ітерацій, що задана;

φ – фаззіфікатор;

α – контрольний параметр;

r – випадкове число;

U – рівень належності спостереження до кластеру;

U_j – рівень належності спостереження до j кластеру;

$U_j(k)$ – рівень належності k-го вектора – спостереження до j-го кластера;

$U_j^{\varphi}(k)$ – рівень належності k-го вектора-спостереження до j-го кластера при заданому рівні розмитості (фаззіфікатора) φ кластерів, що перетинаються;

A, B, C – коефіцієнти поведінки оточення;

GW – вектор позиції сірого вовка;

DOI 10.15588/1607-3274-2023-1-7

$GW(t)$ – вектор позиції сірого вовка в поточній ітерації t;

α - , β - та δ – вовки-домінанти.

ВСТУП

Задача кластеризації масивів багатовимірних даних, основною метою якої є знаходження однорідних у сенсі прийнятої метрики класів спостережень, є важливою частиною інтелектуального аналізу даних Data Mining [1–3]. В рамках традиційного кластерного аналізу апріорі передбачається, що кожен вектор спостереження може належати тільки одному класу-кластеру, хоча в реальних даних досить часто виникає ситуація, коли це спостереження з різними рівнями належності (можливості, ймовірності) відноситься відразу до кількох кластерів, що взаємно перетинаються. Подібна ситуація є предметом розгляду нечіткого (фаззі -) кластерного аналізу [4–5], в рамках якого необхідно оцінити не тільки факт належності кожного спостереження до конкретних класів, але і дати кількісну оцінку рівня цієї належності. З обчислювальної точки зору можна відзначити, що найбільш адекватним математичним апаратом для вирішення задач кластеризації є методи штучного інтелекту [6–8] і, перш за все, нейронні мережі, нечіткі системи, еволюційна оптимізація та, так звані, гібридні системи обчислювального інтелекту.

Об'єкт дослідження кластеризація даних на основі покращеного алгоритму сірого вовка.

Предмет дослідження процедура онлайн кластеризації даних в умовах кластерів що перетинаються на основі модернізованої еволюційної оптимізації.

Мета роботи полягає у запровадженні процедури кластеризації масивів даних на основі покращеного алгоритму сірого вовка.

1 ПОСТАНОВКА ЗАВДАННЯ

Вихідною інформацією для вирішення задачі кластеризації традиційно є матриця спостережень

$$X = \{x(1), x(2), ..., x(k), ..., x(N)\},$$

$x(k) = \{x_i(k)\} \in R^n$, при цьому дані попередньо відцентровано на гіперкуб так, що $x(k) = \{x_{i,i_2}(k)\} \in R^{n_1 \times n_2}$. Така ситуація може виникати у випадку обробки масивів зображень.

2 ОГЛЯД ЛІТЕРАТУРИ

На сьогодні крім методів нечіткої кластеризації таких як FCM, розроблено безліч методів і алгоритмів нечіткої класифікації зі своїми достоїнствами і недоліками, всі вони дозволяють відшукати тільки локальний екстремум прийнятої цільової функції [5, 9], що веде до того, що використання процедур оптимізації (нелінійного програмування) на основі похідних прийнятого критерію в загальному випадку не дозволяє отримати найкраще шукане рішення. Подолати цю проблему можна, багаторазово вирішуючи задачу за різних початкових умов і вибираючи найкращий варіант із безлічі отриманих. Зрозуміло, що подібний підхід суттєво збільшує час вирішення задачі.

Подолати зазначені труднощі можна, скориставшись апаратом гібридних систем обчислювального інтелекту (HSCI) [7, 9–11], що поєднують в собі навчання штучних нейронних мереж, інтерпретованість результатів і можливість роботи в умовах класів, що перетинаються, систем непарного виведення і високу швидкість відшукання глобального екстремуму, що забезпечується еволюційними алгоритмами оптимізації, заснованими на «роях частинок» (PCO).

Традиційно алгоритми оптимізації поділяються на дві частини: детерміновані алгоритми та стохастичні алгоритми [13]. Доведено, що детерміновані алгоритми легко потрапляють в локальні оптимуми, в той час як стохастичні алгоритми здатні уникати локальних розв'язків випадковим чином. Таким чином стохастичні алгоритми набули широкого розвитку, зокрема презентацій, удосконалень і застосувань природньо-інспірованих обчислень (NIC).

Однією з найважливіших частин алгоритмів NIC є так звані біонічні алгоритми, і більшість яких є метаевристичними [13–15]. Вони можуть вирішувати проблеми з паралельними обчисленнями та глобальним пошуком. Метаевристичні алгоритми поділяють рої на глобальний і локальний пошук за допомогою деяких методів. NIC алгоритми не можуть гарантувати глобальні оптимальні рішення; таким чином, більшість метаевристичних алгоритмів вводять випадковість, щоб уникнути локальних оптимумів. Індивідуумами в зграях керують, щоб розділяти, вирівнювати та об'єднувати за допомогою випадковості; їх поточні швидкості складаються з попередніх швидкостей, випадкових множників частоти [16] або евклідових відстаней положень конкретних індивідів [17–21]. Деякі покращення зроблено за допомогою модифікації ваг інерції, хаосу та бінарних векторів, тощо. Більшість із цих удосконалень призводить до трохи кращої продуктивності конкретних алгоритмів, але загальні структури залишаються незмінними.

Більшість метаевристичних алгоритмів та їх удосконалення наразі базуються безпосередньо на поведінці організмів, таких як пошук, полювання [18], запилення [19] та спалах [20].

Метаевристичні алгоритми працюють за схожими цільовими функціями, та досягають кращої продуктивності та зменшення ймовірності потрапити в пастку локальних оптимумів, уникнути випадкових блукань або польотів за допомогою введення додаткових умов для індивідів. Здебільшого це означає, що зграї поводитимуться більш неконтрольованими способами. Крім того, як організми, що живуть у зграях в природі, більшість із них мають соціальну ієрархію. Наприклад, у мурашиній колонії королева є командиром, незважаючи на її репродуктивну роль; динергати – це солдати, які займаються садівництвом колонії, тоді як

DOI 10.15588/1607-3274-2023-1-7

ергати займаються будівництвом, збиранням і розведенням.

3 МАТЕРІАЛИ І МЕТОДИ

В основі поширеного алгоритму ймовірної нечіткої кластеризації лежить процедура мінімізації цільової функції

$$E\left(U_j(k), c_j\right) = \sum_{k=1}^{N}\sum_{j=1}^{m} U_j^{\varphi}(k)\left\|x(k) - c_j\right\|^2 \qquad (1)$$

при обмеженнях

$$\sum_{j=1}^{m} U_j(k) = 1, \quad 0 \le \sum_{j=1}^{m} U_j(k) \le N, \qquad (2)$$

(тут φ – невід'ємний параметр фазифікації (фаззифікатор), що задає розмитість границь між кластерами), в основі якого лежать стандартні методи нелінійного (при $\varphi = 2$ – квадратичного) програмування.

Вирішуючи задачу нелінійного програмування, отримуємо імовірнісний алгоритм нечіткої кластеризації

$$\begin{cases} U_j(k) = \dfrac{\left(\left\|x(k) - c_j\right\|^2\right)^{-1}}{\sum\limits_{l=1}^{m}\left(\left\|x(k) - c_j\right\|^2\right)^{-1}}, \\ c_j = \dfrac{\sum\limits_{k=1}^{N} U_j^2(k)\, x(k)}{\sum\limits_{k=1}^{N} U_j^2(k)}. \end{cases} \qquad (3)$$

В [5] була показана збіжність процесу (3) до локального мінімуму, при цьому досягнення глобального екстремуму в загальному випадку не гарантується.

В роботах [22–23] задача умовної оптимізації (1), (2) була переформульована в задачу безумовної оптимізації цільової функції виду

$$E\left(c_j\right) = \sum_{k=1}^{N}\left(\sum_{j=1}^{m}\left\|x(k) - c_j\right\|^{2(1-\varphi)}\right)^{1-\varphi}, \qquad (4)$$

при $\varphi = 2$

$$E\left(c_j\right) = \sum_{k=1}^{N}\left(\sum_{j=1}^{m}\left\|x(k) - c_j\right\|^{-2}\right)^{-1}. \qquad (5)$$

Таким чином, задача нечіткої кластеризації може бути зведена до пошуку глобального екстремуму цільових функцій (4), (5).

Для вирішення задачі можуть бути використані еволюційні біоінспіровані «роєві» процедури оптимізації [9–11], серед яких в якості одного з найбільш швидкодіючих можна відзначити, так званий, алгоритм сірого вовка (GWO) [24].

За даними Мірджалілі [24], сірі вовки живуть разом і полюють групами. Процес пошуку та полювання можна описати так: (6) якщо видобуток знайдено, вони спочатку вистежують, переслідують і наближаються до неї; (7) якщо здобич біжить, тоді сірі вовки переслідують, оточують і спостерігають за здобиччю, поки вона не перестане рухатися; (8) нарешті починається атака.

Стандартний алгоритм GWO. Алгоритм імітує поведінку пошуку і полювання на здобич сірих вовків в зграї. В математичній моделі найкращій результат вовка в зграї називається альфа (α), а другий найкращий є бета (β), і, отже, третій найкращій називається дельта (δ). Інші рішення кандидатів зграї омегами (ω). Всі омеги будуть керуватися цими трьома сірими вовками під час пошуку (оптимізації) та полювання.

Коли жертва знайдена, починається ітерація (t=1). Згодом α- , β- та δ-вовки керуватимуть ω, щоб переслідувати здобич і, зрештою, оточити її. Три коефіцієнти A, B і C пропонуються для опису поведінки оточення:

$$\begin{aligned} C_\alpha &= \left|B_1 * GW_\alpha - X(t)\right|, \\ C_\beta &= \left|B_2 * GW_\beta - X(t)\right|, \\ C_\delta &= \left|B_3 * GW_\delta - X(t)\right|, \end{aligned} \qquad (6)$$

де t вказує на поточну ітерацію, GW вектор позиції сірого вовка, GW_1, GW_2 і GW_3 – є векторами положення α- , β- та δ-вовків, що обчислюється наступним чином:

$$\begin{aligned} GW_1 &= GW_\alpha - A_1 * C_\alpha, \\ GW_2 &= GW_\beta - A_2 * C_\beta, \\ GW_3 &= GW_\delta - A_3 * C_\delta, \end{aligned} \qquad (7)$$

$$GW(t) = \frac{GW_1 + GW_2 + GW_3}{3}. \qquad (8)$$

Параметри A та B є комбінаціями керуючого параметра α та випадкових чисел r_1 та r_2 [24]:

$$\begin{aligned} A &= 2\alpha r_1 - \alpha, \\ B &= 2r_2. \end{aligned} \qquad (9)$$

Контрольний параметр α замінюється значенням параметра A і, нарешті, змушує омега-вовків наближатися або тікати від домінуючих вовків, таких як альфа, бета та дельта. Якщо $|A| > 1$, сірі вовки втікають від домінантів, а це означає, що омега-вовки вте-

DOI 10.15588/1607-3274-2023-1-7

чуть від здобичі та досліджуватимуть більше простору, що в оптимізації називається глобальним пошуком. Та якщо $|A|<1$ вони наближаються до домінант, а значить δ-вовки будуть слідувати за домінантами, які наближаються до здобичі, і це називається локальним пошуком в оптимізації.

Контрольний параметр α визначається як лінійне зниження від максимального значення 2 до 0 під час ітерацій:

$$\alpha = 2\left(1-\frac{t}{T}\right),$$

де t – номер ітерації, T – максимальна кількість ітерацій, що задана.

Схематично представити роботу алгоритму можна наступним чином (рис. 1).

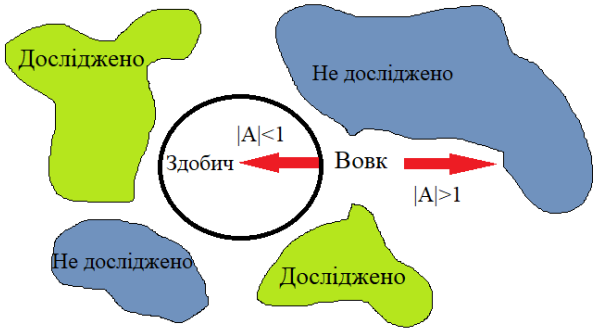

Рисунок 1 – Схема роботи алгоритму GWO

Блок-схема алгоритму сірих вовків наведена на рис. 2.

Багато алгоритмів ройового інтелекту імітують поведінку полювання та пошуку деяких тварин. Однак GWO моделює внутрішню ієрархію керівництва вовків, таким чином, в процесі пошуку позиція найкращого рішення може бути комплексно оцінена-тьрьома рішеннями. Але для інших алгоритмів ройового інтелекту, найкраще рішення шукається лише на основі одного рішення – локального оптимума.

Отже, GWO може значно зменшити ймовірність передчасного потрапляння в локальний оптимум. Щоб досягти належного компромісу між розвідкою та полюванням, пропонується покращений GWO.

Розглядаючи рівняння (8) видно, що в процесі пошуку, однакову роль відіграють домінанти. Кожен із сірих вовків зграї наближається або тікає в пошуку здобичі. Однак, слід зауважити, що найближче до здобичі домінанти із середньою вагою альфа, ніж бета і дельта. Таким чином, на початку процедури пошуку в рівнянні (8) слід враховувати лише положення альфа, або його вага має бути набагато більшою, ніж ваги інших домінант. Таким чином, рівняння (8) можна переписати у вигляді:

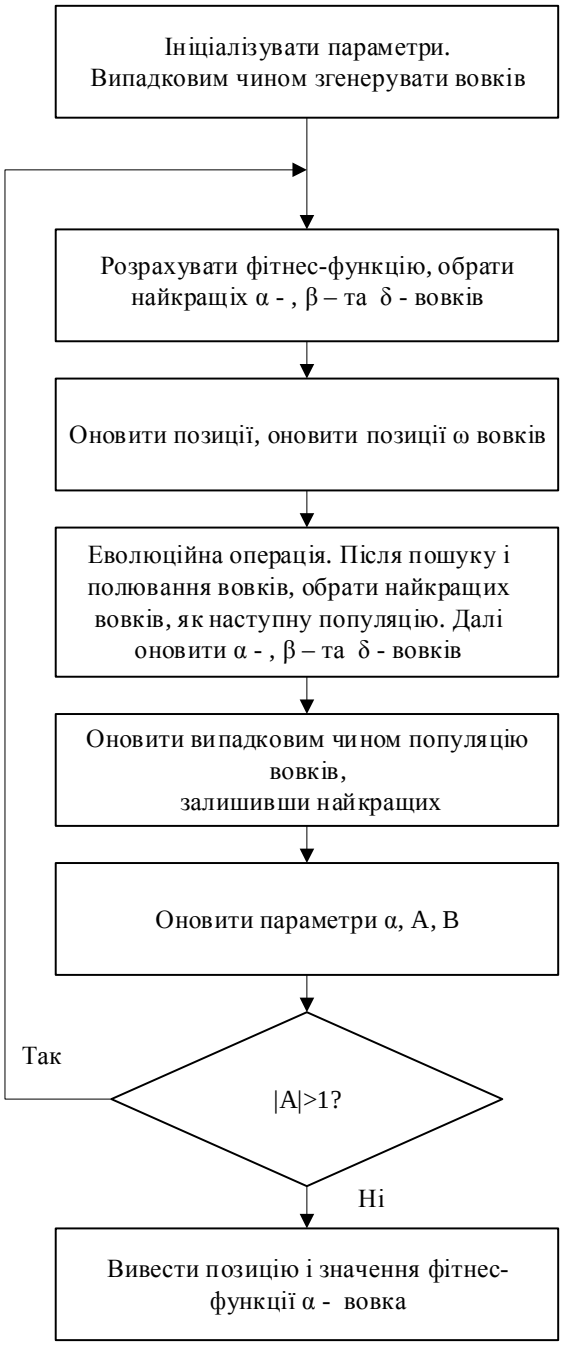

Рисунок 2 – Блок-схема алгоритму GWO

$$GW(t+1)=\frac{w_1GW_1+w_2GW_2+w_3GW_3}{3}, \qquad (10)$$

де $w_1+w_2+w_3=1$, при w_1 – вага α – вовка, w_2 – вага β-вовка, w_3 – вага δ-вовка, при цьому $w_1\geq w_2\geq w_3$. На першій (або $t=0$) ітерації пропонується задати ваги результатами алгоритму кластеризації за рівнянням (3), де:

$$\begin{aligned} c_1 &= w_\alpha; \\ c_2 &= w_\beta; \text{ при } t=0 \\ c_3 &= w_\delta; \end{aligned} \qquad (11)$$

DOI 10.15588/1607-3274-2023-1-7

Тоді ми можемо визначити, що ваги змінних задовольняють гіпотезі про соціальну ієрархію функцій сірих вовків та їх пошукову поведінку.

4 ЕКСПЕРИМЕНТИ

Дослідження методу кластеризації масивів даних на основі покращеного алгоритму сірого вовка (FGWO) проводились на двох багатоекстремальних функціях, наведених в табл. 1.

Таблиця 1 – Тестові функції

Назва функції	Формула	Інтервал
Растрігін	$f(x) = 20 + x^2 + y^2 - -10\cos(2\pi x) + \cos(2\pi y)$	[−5.12;5.12]
Гріванг	$f(x) = \frac{1}{4000}x + \frac{1}{4000}y - -\cos\left(\frac{x}{\sqrt{1}}\right)\cos\left(\frac{x}{\sqrt{2}}\right) + 1$	[−30;30]

Якість роботи запропонованого метода (FGWO) порівнювалось із декількома класичними алгоритмами кластеризації, еволюційними процедурами, а також модифікованими методами кластеризації на основі оптимізаційних процедур, а саме алгоритм оптимізації рою частинок (PSO), алгоритм зграї котів (CSO), класичний алгоритм сірого вовка (GWO) та модифікованого алгоритму кластеризації на основі зграї котів (FCSO) [25–26]. Для кожного метода, задано 30 агентів, що шукають оптимум в багатоекстремальній функції.

5 РЕЗУЛЬТАТИ

Перш за все перевіримо роботу запропонованого метода з його модифікацією, тобто використання вагів для кожного вовка. Результат зміни ваг продемонстровано на Рисунку 3. Аналізуючи отриманий графік залежності зміни ваг кожного вовка від кількості ітерацій, можна зробити висновок, що запропонований підхід є сприятливим для подальшого аналізу методу кластеризації масивів даних на основі покращеного алгоритму сірого вовка.

На рис. 4 та рис. 5 показане графічне порівняння методів та їх збіжності за функціями Растригіна та Грінварга відповідно.

6 ОБГОВОРЕННЯ

Аналізуючи результати отриманих експериментальних досліджень та порівняльного аналізу роботи методу кластеризації масивів даних на основі покращеного алгоритму сірого вовка із методами кластеризації, що базуються як на класичному підході до кластеризації даних, так і більш екзотичних, запропонований метод демонструє достатньо високі результати.

Основними перевагами запропонованого методу полягає в простоті математичних розрахунків, швидкості роботи з даними, незалежно від виду, розміру та якості вибірки, що аналізується. Слід відзначити точність роботи метода кластеризації даних на основі покращеного алгоритму сірого та отриманих результатів кластеризації, що досягається за допомогою оптимізаційної процедури еволюційного алгоритму.

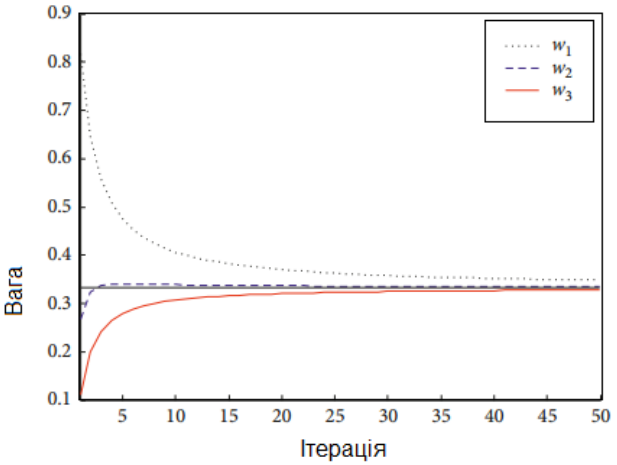

Рисунок 3 – Залежність зміни ваги вовків від кількості ітерацій

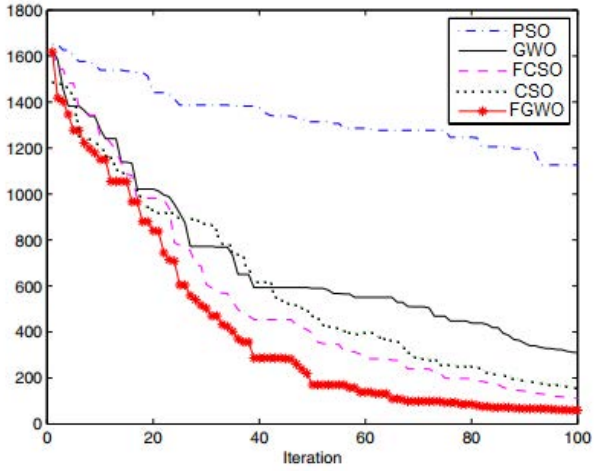

Рисунок 4 – Криві збіжності функції Растригіна

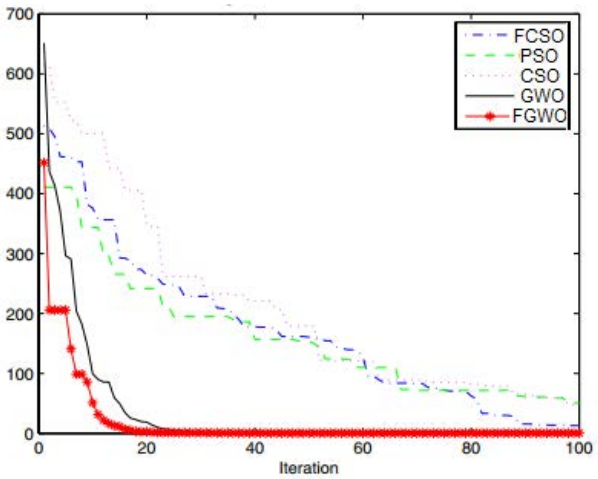

Рисунок 5 – Криві збіжності функції Грінванга

DOI 10.15588/1607-3274-2023-1-7

ВИСНОВКИ

Введено метод кластеризації масивів даних на основі покращеного алгоритму сірого вовка. Перевагою запропонованого підходу є скорочення часу вирішення оптимізаційних задач. Результати експериментів підтверджують ефективність запропонованого підходу в задачах кластеризації за умов перетинних кластерів.

Наукова новизна: вперше запропонований метод кластеризації масивів даних на основі покращеного алгоритму сірого вовка.

Практичне значення: результати експерименту дозволяють рекомендувати запропонований метод для використання на практиці для вирішення проблем автоматичної кластеризації багатоекстремальних даних різної природи.

Перспективи подальших досліджень методи нечіткої кластеризації даних для широкого класу практичних проблем.

ПОДЯКА

Робота виконана в рамках науково-дослідного проєкту державного бюджету Харківського національного університету радіоелектроніки «Розробка методів та алгоритмів комбінованого навчання глибинних нейро-нео-фаззі систем за умов короткої навчальної вибірки».

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Стаття надійшла до редакції 09.01.2023.
Після доробки 13.02.2023.

UDC 004.8:004.032.26

CLUSTERIZATION OF DATA ARRAYS BASED ON THE MODIFIED GRAY WOLF ALGORITHM

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DOI 10.15588/1607-3274-2023-1-7

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ABSTRACT

Context. The task of clustering arrays of multidimensional data, the main goal of which is to find classes of observations that are homogeneous in the sense of the accepted metric, is an important part of the intelligent data analysis of Data Mining. From a computational point of view, the problem of clustering turns into the problem of finding local extrema of a multiextreme function, which are repeatedly started from different points of the original data array. To speed up the process of finding these extrema using the ideas of evolutionary optimization, which includes algorithms inspired by nature, swarm algorithms, population algorithms, etc.

Objective. The purpose of the work is to introduce a procedure for clustering data arrays based on the improved gray wolf algorithm.

Method. A method of clustering data arrays based on the modified gray wolf algorithm is introduced. The advantage of the proposed approach is a reduction in the time of solving optimization problems in conditions where clusters are overlap. A feature of the proposed method is computational simplicity and high speed, due to the fact that the entire array is processed only once, that is, eliminates the need for multi-era self-learning, implemented in traditional fuzzy clustering algorithms.

Results. The results of the experiments confirm the effectiveness of the proposed approach in clustering problems under the condition of classes that overlap and allow us to recommend the proposed method for use in practice to solve problems of automatic clustering big data.

Conclusions. A method of clustering data arrays based on the modified gray wolf algorithm is introduced. The advantage of the proposed approach is the reduction of time for solving optimization problems. The results of the experiments confirm the effectiveness of the proposed approach in clustering problems under the conditions of overlapping clusters.

KEYWORDS: fuzzy clustering, multi-extremal optimization, evolutionary method.

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DOI 10.15588/1607-3274-2023-1-7