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ЗМІСТ

<i>Олександр Додонов, Олена Горбачик, Марина Кузнєцова</i> Інтелектуальні засоби підтримки Резильєнтності: сучасні підходи для критичних інфраструктур	3
<i>Дмитро Ланде, Юрій Даник</i> Конфліктологічне моделювання через поєднання альтернативного аналізу (Alta) і семантичного нетворкінгу із застосуванням генеративного штучного інтелекту	6
<i>Vitaliy Tsyganok, Viktor Holota, Sergii Kadenko, Pavlo Roik, Ruslan Beselovskyi, Volodymyr Minas</i> Information collection and processing technology for scenario development in uncertain environments	10
<i>Oleksii Novikov, Yuliia Lehoida, Iryna Stopochkina, Mykola Ilin</i> Experimental assessment of cyber-resilience of cloud-based iot architectures in critical water supply infrastructure	15
<i>Oleg Andriichuk, Stanislav Zholobetskyi</i> Semantic fingerprinting of software modules based on tasks description	19
<i>Олег Дмитренко , Антон Астахов, Оксана Власенко , Володимир Циганок, Сергій Патук</i> Аналіз еволюції ключових термінів у наукових публікаціях за тематикою «штучний інтелект»	23
<i>Олександр Додонов, Андрій Бойченко</i> Візуальна аналітика в системах організаційного управління	27
<i>Вікторія Полуциганова, Сергій Смирнов, Дмитро Ланде, Андрій Снарський</i> Методологія аналізу потенціалу співавторства в кібербезпеці через структурно-семантичні гіперграфи на даних ArXiv	30
<i>Поліна Сотнікова, Андрій Родіонов</i> Методи захисту від атак отруєння даних на великі мовні моделі	34
<i>Євген Беляк, Юрій Чегіль, Андрій Крючин, Ле Цзичун, Дмитро Манько</i> Технології зберігання даних і штучний інтелект	38
<i>Vitalii Fesokha, Ihor Subach</i> Reconstruction of the chronology of events in information and communication systems for cyber security purposes based on the coordination of local time spaces	42

Залужний В.Ф.

Напрями подальшого розвитку інформаційного забезпечення автоматизованих систем управління силами та засобами	46
<i>Serhii Smyrnov, Viktoriia Polutsyhanova</i>	
Payoff-based utility swot-assessment of strategic opportunities via Q-analysis	54
<i>Володимир Юзефович, Євгенія Цибульська, Ніколай Стоянов</i>	
Розроблення просторово-часової моделі даних для систем моніторингу навколишнього простору	58
<i>Григорій Гнатієнко, Денис Пастушок</i>	
Математичне забезпечення рейтингування студентів на основі їхньої академічної успішності та соціальної активності	63
<i>Григорій Гнатієнко, Віталій Гнатієнко, Юрій Кравченко, Валентин Собчук</i>	
Математична модель визначення вагових коефіцієнтів сенсорів у системі моніторингу навколишнього середовища	68
<i>Dmytro Kuchеров, Natalia Khalimon</i>	
Data processing to determine the parameters of a mathematical model of dynamic objects	73
<i>Анатолій Гладун, Катерина Хала</i>	
Семантично-прогностична самоорганізація групи бпла на основі динамічних онтологій	77
<i>Володимир Мальчиков</i>	
Визначення нескоротного коефіцієнта масштабування недіадного вейвлет-перетворення	81
<i>Олексій Гайворонський, Василь Горбачук</i>	
Основа на даних економіка та безпека	84
<i>Леонід Гальчинський, Євгенія Тостоган, Антон Снігур</i>	
Оцінювання кібернадійності систем scada енергетичного об'єкта з використанням напівмарківських процесів	88
<i>Храмова Ірина Олександрівна</i>	
Вибір реконструкції як заходу забезпечення живучості розподіленої системи	92
<i>Олексій Шевчук, Наталія Кузнєцова</i>	
Поведінкові стратегії агентів у аналітичній системі оцінювання зелених ризиків	102
<i>Анатолій. Кузьмичов</i>	
Лінійна location-transshipment модель балансування системи постачання	106

Юлія Наконечна

Оцінювання координатії постингу в інформаційних мережах за мережевими точковими процесами 110

Tetiana Altukhova, Yelyzaveta Yezhova

Mathematical modelling of face detection systems in changing lighting conditions 114

Віктор Зайцев, Анатолій Ланчук

Оптимізація методів розпізнавання таблиць в автономних системах 118

Dmytro Ardashov

Survivability concept in cloud resource allocation 122

Личик Владислав, Гальчинський Леонід

Пошук оптимальної політики забезпечення кіберстійкості енергетичного об'єкта на основі частково спостережуваних процесів 126

Olexandr Kovalenko, Olena Fedusenko

NLP models for semantic analysis of advertising creatives in digital marketing 130

Yevhen Pankratov

Architecture and algorithms of a cyber-physical system for digital automation of technological processes 134

Лабунець В.О., Даник Ю.Г.

Методика формування вимог до засобів протидронової оборони для забезпечення безпеки та живучості критичних інфраструктур 140

Юрій Самохвалов, Олександр Буточнов, Едуард Бовда, Євгеній Науменко

Використання нечітких лінгвістичних оцінок в задачах експертного оцінювання 144

Андрій Линовський, Вадим Мухін

Удосконалена cnn-архітектура для фільтрації кластерного salt-and-pepper шуму в медичних даних 148

Андрій Бойченко, В'ячеслав Сенченко, Олександр Коваль

Моделювання взаємодії критичних інфраструктур під впливом каскадних ефектів 153

Sergii Babiche, Ihor Liak, Yurii Kish, Volodymyr Povkhanyc, Mykhailo Klyap and Myroslava Kulyny

Managing software development risks through decision-making models in uncertain environments 156

<i>Anna Bakurova, Oleh Zaritskyi, Anatoliy Gritskevich, Pavlo Hrynchenko, Andrii Kuznetsov, Elina Tereschenko and Dmytro Shyrokorad</i>	
Methodology for access risk assessment (ACRAM) in information systems	161
<i>Нікіта Бевзюк, Іван Крикун</i>	
Деградація штучного інтелекту через рекурсивне навчання	170
<i>Yana Bielozorova</i>	
Modeling the processes of digital artifact formation in audio and video recording devices	175
<i>Iaroslav Dorohyi, Vladyslav Kravchuk, Vasyl Tsurkan, Iryna Berdychenko</i>	
Application of tensor analysis for cybersecurity tasks in critical infrastructure	179
<i>Yaroslav Dorogyy, Nataliya Maslova, Illia Harbaruk</i>	
Zettelkasten as a semantic framework for decision-support technologies in cybersecurity	183
<i>Dmytro Dotsenko, Maksym Khruslov</i>	
Increasing the efficiency of iot monitoring systems using hybrid fog-cloud architecture	187
<i>Oleh Ilarionov, Hanna Krasovska, Hryhorii Hnatienko, Georgy Gaina</i>	
Categorical framework for formal verification of relational database queries	191
<i>Naïma Illoul, Houda El Bouhissi, Linda Laksari and Olga Pavlova</i>	
A comprehensive review and analysis of artificial intelligence tools usage for the diagnosis and prognosis of gallbladder cancer	196
<i>Андрій Балан</i>	
Система безпеки інформації на об'єкті інформаційної діяльності	200
<i>Dmytro Khoma, Anna Popova</i>	
AKPNET: Attention-based neural network for spatial image steganalysis	204
<i>Вячеслав Корольов, Олексій Куліш, Максим Огурцов</i>	
Оптимізація групового переміщення автономних агентів на основі елементів штучного інтелекту	208
<i>Vladimir Krasilenko, Alexander Lazarev, Diana Nikitovych</i>	
Design and modeling of neuron-equivalentors and their nodes as accelerators of equivalental-convolutional self-learning neural structures	212

<i>Artem Kusakov</i>	
Lightweight cnn architecture for image recognition using dual-path training	220
<i>Illia Kvashuk, Nataliia Kuznietsova</i>	
Modeling green risks with patchwork copula	224
<i>Oksana Mulesa, Iryna Domanetska, Yaroslav Khrolenko, Olha Tsyhanok, Olena Trubitsyna</i>	
Identifying the expert's competence area based on the concepts of the openalex sciometric database: a semantic-statistical approach	228
<i>Maksym Osiponok, Vasyl Tereshchenko</i>	
On incremental construction of polygon subdivisions	232
<i>Oleksandr Palagin, Denys Symonov, Yehor Symonov, Bohdan Zaika</i>	
Entropy–attention integration for anomaly detection in nonlinear and uncertain dynamics	236
<i>Pavlo Pasieka, Svitlana Terenchuk, Natalia Poltorachenko and Bohdan Yeremenko</i>	
Methodology for decision-making by an autonomous system in a complex logistical environment	240
<i>Sergiy Pogorilyy, Bohdan Semonov</i>	
Language-specific fine-tuning of transformer models for commit message generation in version control systems	244
<i>Olexandr Polishchuk, Dmytro Polishchuk</i>	
Vulnerability of multilayer network systems to system-wide disruptions	248
<i>Dmytro Ponzel, Oleh Zaritskyi</i>	
Modern object detection techniques: an overview of challenges and research perspectives	252
<i>Олександр Романюк, Володимир Майданюк, Оксана Романюк</i>	
Мережева взаємодія в системах комп'ютерної графіки	256
<i>Kostiantyn Savchuk, Elena Nyemkova</i>	
Hybrid web security model combining owasp top-10 and artificial intelligence	259
<i>Kostiantyn Tkachenko, Ihor Pylypchuk</i>	
Design and implementation of educational telegram bot with google classroom integration	263
<i>Oleksii Yehorov, Oleksii Komandyrov, Svitlana Terenchuk and Bohdan Yeremenko</i>	
Improving the expertise process by implementing gradient boosted decision trees	267
<i>Oleh Zaritskyi, Dmytro Ponzel</i>	
FOMO models in UAV object detection tasks	271

<i>Vladimír Voral, Pavel Ambruz, Pavel Šimek, Jiří Vaněk</i>	
From isolated lpwan nodes to secure iot data integration: bridging low-power sensing and network segmentation in agricultural infrastructures	275
<i>Quan Trong The, Nguyen Thi Huyen Chau</i>	
Post-Filtering – Based Speech Enhancement by Implementing Microphone Array in Complex Recording Situation	276
<i>Quan Trong The, Nguyen Thi Huyen Chau</i>	
The Real and Imaginary Part – Based Gain Function for GSC Beamformer’s Evaluation	277
<i>Quan Trong The, Nguyen Thi Huyen Chau</i>	
The Maximum Likelihood Approach – Based Robust Microphone Array’s Speech Enhancement	278

DESIGN AND MODELING OF NEURON-EQUIVALENTORS AND THEIR NODES AS ACCELERATORS OF EQUIVALENTAL-CONVOLUTIONAL SELF-LEARNING NEURAL STRUCTURES

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In the paper we consider the urgent need to create highly efficient hardware accelerators for deep convolutional neural networks (CNNs) and machine learning. We show overview of our related works the advantages of the equivalent models (EM) for designing bio-inspired systems. The capacity of neural net on the basis of EM is in several times quantity of neurons. Such EM-paradigms are perspective for clustering, recognition strongly correlated, highly noised images and creating of uncontrolled learning machine. And since the basic functional nodes of EM are vector-matrix procedures with continuous-logical operations as: normalized vector operations "equivalence", "nonequivalence", and etc., we consider in this paper new approaches to the design of arrays of such neuron-equivalentors (NEs) with extended functionality, including activation functions. Our approach is based on the use of analog and mixed methods for implementing the required operations, building NEs (with number of synapsis from 8 up to 128 and more) and their base nodes based on photo-elements and CMOS current mirrors. Simulation results show that the efficiency of NEs relative to the energy intensity is estimated at a value of not less than 10^{12} an. op. / sec on W and can be increased. The results confirm the correctness of the concept of creating NEs and equivalental-convolutional self-learning neural structures (EqCSLNSs) on their basis.

Keywords: *accelerator, neural net, convolutional self-learning neural structures, neuron-equivalent, current mirror, vector-matrix procedure, equivalent model.*

Introduction

Solving the problem of object recognition (OR) in images is the basis for creating biometric systems, machine vision systems, and tracking. And comparing two images of the same object, or different ones, or fragments of these images is the basis of most known OR methods and algorithms. The discriminant measure of the mutual combination of the reference fragment with the current, coordinate-shifted image is often the mutual two-dimensional correlation function. In works [1, 2, 3] it was shown that to increase the accuracy and quality of OR images with strong correlation and interference, it is desirable to use OR methods based on neural network models and on mutual equivalent two-dimensional spatial functions, nonlinear transformations, and adaptive-correlation weighting. The equivalence models (EMs) of autoassociative memory (AAM) and heteroassociative memory (HAM) proposed in [2-4], including multiport AAM and HAM, and their studies have shown that these models allow recognizing vectors with $1024 \div 4096$ components and a significant percentage (up to 25-30%) of damage, with a network capacity that is 3-4 times higher than the number of neurons. In our previous article [2], we considered the issues of new possible ways of self-learning in such extended models, explaining some important fundamental concepts of various associative recognition and understanding the principles of functioning of biological NM structures, modeling the processes of processing, learning and extracting patterns in such models, and also proposing their implementation. In article [3], we showed that the concept of self-learning works directly with multi-level images without processing bitmaps. In paper [4] we showed models for the recognition and clustering of images that combine the process of recognition with the learning process. For all known convolutional neural networks, as for our equivalence models, it is necessary to calculate the convolution of the current fragment of the image in each layer with a large number of templates which are used, selected or formed during the learning process. But, as studies show, large images require a large number of filters to process images, and the size of the filters can also be large. For implementation EqCSLNSs [4], we need certain new or modified known devices capable of calculating normalized spatial equivalence

functions (NSEqFs) with the necessary speed and performance. Such specialized devices by authors of papers were previously called "image equivalentor". Since vector-matrix procedures and determination of discriminant functions for comparing two 2D arrays with multiplication and addition-accumulation operations are basic for almost all CNNs, in the last decade, work has been intensified on the creation of specialized neural accelerators. To make the right decisions when determining the winning neurons in CNNs, it is necessary to ensure the accuracy of calculations, especially for large filter sizes and a large dynamic range (8 bits) of halftone images. Therefore, the problem of increasing the computational performance of hardware implementations of CNNs and specialized accelerators is acute. But, as our experiments show, our equivalence-convolutional self-learning neural structures EqCSLNSs also require such accelerators. Therefore, the purpose of this work is to design and simulate an array of equivalent neurons generalized for processing 2D arrays.

Design methodology of the main unit of EqCSLNSs

Fig. 1 shows the new EqCSLNS proposed by us, which forms the required number of equivalent convolutions in the form of matrices $\mathbf{e}$ from the input image matrix $\mathbf{X}$, using a set of certain selected filter templates $\mathbf{W}$, which in our case are also created as a result of self-learning with clustering and are matrices with multi-level pixel values. Comparing each filter in this way with all current (by shifting) fragments in the matrix $\mathbf{X}$, we form the corresponding activation maps. As a measure of similarity of a fragment of the matrix $\mathbf{X}$ and the filter, we propose to use equivalence proximity measures or other measures, such as histograms of the distribution of pixel values of fragments. The proposed structure consists of a micro-display that dynamically displays the current fragments, an optical node in the form of a micro-lens array (MLA) with optical lenses (not shown!) and a two-dimensional array of neuron equivalents (NEq) with optical inputs. Each NEq is implemented in a modular-hierarchical manner and can consist of similar smaller subpixel base nodes, also of two-dimensional type.

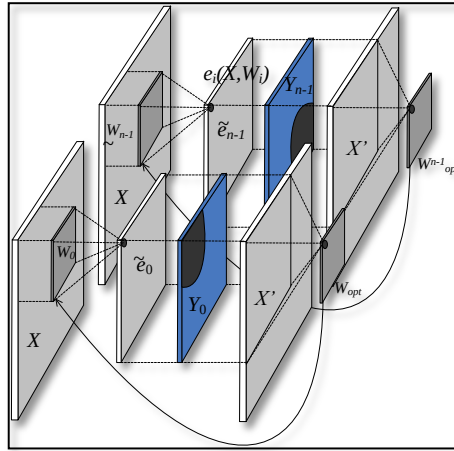


Figure 1. The structure of the basic unit of the EqCSLNS

That is, an array of such NEq allows to calculate in parallel, with a high speed, equal to the speed of selection from the processed image of its displaced current fragment, immediately in one cycle (corresponding to the given displacement coordinates) components (elements) of all activation maps, i.e. equivalent convolutions of the current fragment with the corresponding filters. Each NEq has a matrix of photodetectors, onto which a halftone image of a fragment is projected through a micro-lens array (MLA), and an array of analog (electrical or optical) inputs, the number of which is equal to the number of photodetectors. Filter components are fed to these inputs using any known solutions: either from a sample and store device (SHD) from analog memory, or from a digital processor using a DAC array with the conversion of these components into a set of micro-currents. Each NEq has its own filter mask from a set of filters selected or formed by training. Thus, at the inputs of each NEq we have two arrays of analog currents. These arrays correspond to the compared fragment of the input pattern and the specified reference filter. The output of the NEq is an analog signal in the form of a current, which is first formed by the implementation scheme of the neuron input operator, and then nonlinearly transformed according to the activation function. The signal at the NEq output represents some essentially nonlinear measure of similarity (closeness) of the compared arrays.

Design and Modeling of Neuron-Equivalentors and them of Nodes for EqCSLNS

This measure is a normalized equivalence (**eq**) and nonequivalence (**neq**), we can calculate them by averaging the component maxima and minima currents. Therefore, the base node, see Fig. 2, contains N two input adders of maximum and minimum currents and one normalizer on current mirrors, which forms two output signals corresponding to normalized **eq** and **neq** from two N-component vectors.

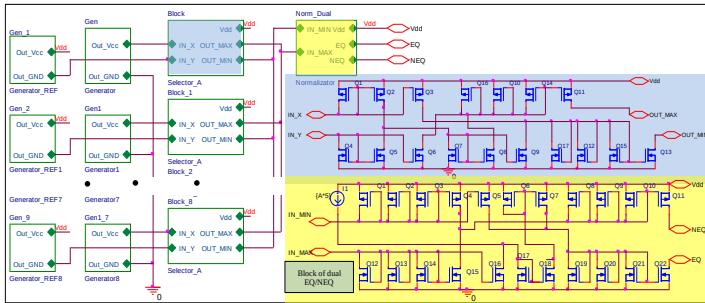


Figure 2. The basic unit for calculating the normalized eq and neq by averaging the maxima and minima of the compared currents based on current mirrors and finite difference circuits

The basic unit for calculating the normalized **Eq** (**NEq**) by averaging the component peak and minima of currents on the basis of current mirrors and the schemes of the limited difference is shown in Fig. 2. Sources of analog currents are shown as current generators for modeling in OrCAD. The dimension of the input vectors is 9, which corresponds to the filter size 3x3. The results of modeling this nonlinear transformation basic node are shown in Fig. 3 On Figure left: a fragment of the successive activity of three neighboring NEs, green - current outputs, blue-additional threshold, red-NE outputs (voltage, potential). On the right: The Mathcad windows on which the module of the program with formulas and results of recognition of fragments on the image are shown, where in 2D and 3D from left to right: the computed NE equivalent, non-linear (after activation) equivalent, linear non-equivalent (part) functions. As can be seen from the diagram, the complete coincidence of the input vectors fed to the input of this node and changing over time is evidenced by the changes

in the complementary output signals of equivalence and non-equivalence (increasing current to a maximum and a corresponding complementary decrease to a minimum!) at the corresponding moments of time (11 - 12 μ s and others). The results of modeling the base unit for the filter size 3x3 (with 9 inputs) showed, that processing time is from 1 μ s to 0.1 μ s for currents $I_{max}=5\mu$ A, consumption power is from 200 μ W to 50 μ W. In addition to simulating the base node on 9 inputs, we additionally synthesized a neuron-equivalent circuit having 8 such nodes, each of which compares 8 input vectors, resulting in a neural element circuit having 2 vector inputs of 64 dimensions. For a non-linear transformation, we used a node of a circuit, which realizes a piecewise linear approximation of the power-law activation function (auto-equivalence). The simulation results of 64 input NE with nonlinear output conversion showed that such a NE comparing the two 64 component vectors from the current signals provides good time characteristics and has a total power consumption of approximately 2mW, a low supply voltage, contains less than 1000 CMOS transistors with which summation circuits are implemented, limited subtraction and multiplication of analog currents on current mirrors.

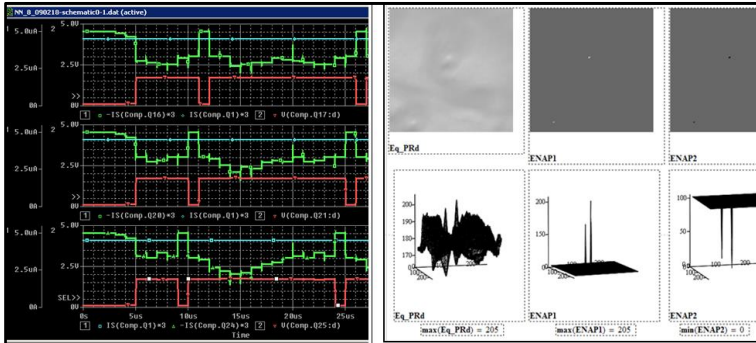


Figure 3. On the left: The result of a network simulation of 8 9-input NEs, On the right: The Mathcad windows on which results of recognition of fragments on the image are shown

The simple build-up of nodes and additional introduction of normalizers for equalization and matching of signal levels in micro-nodes allow to increase the number and dimension of inputs and thus increase the dimension of filters. We designed and modeled a neuron-equivalent for two 81-component input vectors, i.e., to implement

convolution with a filter of dimension 9×9 , by combining nine micro-nodes, namely neuron-equivalentors with two 9-component vector inputs. It has 2 analog input buses. To verify the functioning of the developed neuron-equivalentors in the network, a neural mini-network of eight 9-input micro-nodes neuron-equivalentors was created, the simulation results of which also confirmed its correct functioning. The use of analog current mirrors as basic elements for the construction of all nodes, including the activation function generation node, neuron-equivalentors allowed to achieve the set goal, namely to develop the principles of implementing neuron-equivalentors as accelerators and their basic nodes and to show and experimentally confirm the advantages and prospects of the proposed technical solutions. Technological aspects of implementation for further expansion of the areas of use of the proposed models and their circuit solutions remained unexplored. Therefore, it is desirable to implement physical models and their testing, measure characteristics and indicators for the purpose of their comparative analysis with other concepts.

Conclusions

Neuron-equivalentors have a processing-conversion time of 0.1-1 μ s, low supply voltages of 1.8-3.3V, minor relative computational errors (1-5%), small consumptions of no more than 1-2mW, can operate in low-power modes less than 100 μ W) and high-speed (10-20 MHz) modes. The efficiency of neuron-equivalentors relative to the energy intensity is estimated at a value of not less than 10^{12} an. op. / sec on W and can be increased. The obtained results confirm the correctness of the chosen concept and the possibility of creating hierarchical macro neuron-equivalentors and EqCSLNS based on them. They can become the basis for the implementation of CNN and self-learning biologically inspired devices with the number of such neuron-equivalentors equal to 1000, to realize the parallel calculation of equivalential convolutions with filter sizes up to 32×32 .

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