O. K. Kolesnytskiy, Cand. Sc. (Eng.), Assoc. Prof.; I. V. Bokotsey; A. A. Кorinniy

ANALYSIS OF THE CONSTRUCTION PRINCIPLES AND PROPERTIES OF THE DEVICES FOR NEURON SIMULATION

The paper presents classification and comparative analysis of the construction principles and properties of the known devices for neuron simulation, their drawbacks are revealed and the ways for their elimination are proposed.

Key words: *neuron, neuron model, neural network, hardware implementation, pulsed neural network, optoelectronic element base.*

Introduction

At the present stage of the development of engineering and technology human brain performs the following complex tasks much better than computer systems: analysis and recognition of large volumes of information coming from the organs of perception; the problem of finding optimal solutions under multivariable input data conditions; the tasks of planning and forecasting without complete initial information. Computer, on the contrary, is more efficiently used for solving problems involving exact calculations with the use of formulas, laws, arithmetic operations, etc. In order to combine powers of the brain and the computer, it is necessary to create hardware implementations of multi-functional artificial neural networks with large number of neurons.

Problem statement. As it is known [1], to obtain maximum benefits from the use of neural networks for practical tasks of recognition of different-origin images, hardware implementations (as opposed to software or firmware implementations) of neural networks are required with the greatest possible number of neural elements. Ideally, this number should be approaching the number of neurons in the human brain - $(2 \ldots 5)\times10^{11}$. Therefore, the problem of efficient hardware implementation of models of neurons and neural networks in general is very important at present.

The purpose of this article is to perform classification and comparative analysis of the known devices for the neuron simulation, of their properties, shortcomings and to suggest the ways to eliminate these shortcomings.

1. Current importance of the research and development of the devices for neuron simulation

The results of studying neural networks are used to create devices for visual and sound image recognition, for diagnosing states of technical objects, for the development of adaptive control methods, designing reliable and flexible computing machines, teaching robots complex behavior and in many other cases. Current importance of this scientific trend is confirmed by the adopted programs of state research on studying neural systems of information processing. E. g., in EU it is Blue Brain Project on computer modeling of human neocortex. This project is a joint work of IBM and Swiss Federal Technical Institute of Lausanne (Ecole Polytechnique Federale de Lausanne – EPFL). In Ukraine there is a state research program “The Pattern Computer” [2]. “The Pattern Computer” just as one of its components -"Eye Processor" [3] - involves the creation of intelligent systems that model human perception and thinking, including those based on artificial neural networks

Understanding of the mechanisms of information processing in the human brain and practical implementation of these principles using modern element base is a vital research problem. In order to solve it, it is necessary to find out what neural superstructures could simulate elementary acts of intellectual activity and how they could do this. For that it is necessary to have physical and computer models of neural elements and networks that are maximally adequate to biological neurons.

Two main approaches to the construction of neural networks of artificial intellect can be distinguished: the so called "from the top" and "from the bottom" approaches. The first approach – "from the top" – assumes creation of such functional and informational structures that simulate processes occurring in the human brain during information perception. Internal structure of the brain is not taken into account. Therefore, neural elements that employ "from the top" approach are used for studying the principles of brain and so their structure could be more complex to perform large number of operations. The second approach assumes creation of the so called simulation structure, i.e. the systems with the structure similar to that of human brain. For this approach neural elements must be the simplest ones and at the same time sufficiently accurate as they will be used for neural network construction.

2. Classification of the devices for neuron simulation

At present there are many various approaches to the construction of devices for the neuron simulation (DNS). Therefore, a problem arises of their analysis and classification [3, 4].

DNS can be classified according to the following characteristics:

– information representation form (digital or analog);

– the type of element base;

– the character of adjusting synapses (constant or variable);

– signal transfer time (synchronous or asynchronous).

DNS classification according to the form of information representation is shown in fig. 1.

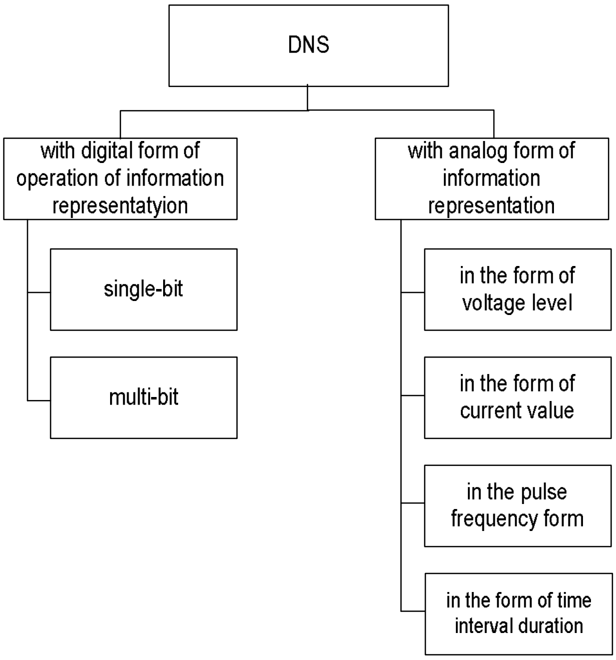

Fig. l. Classification of devices for the neuron simulation according to the form of information representation

According to the form of information representation all DNS can be divided into two main classes (fig. 1):

– DNS where input and output signals as well as coupling weight coefficients are represented in the form of digital codes (they are usually built on the basis of digital elements – invertors, logic elements, triggers, recorders, digital summators, digital comparators, storage devices, etc.). Digital DNS can be single-bit (e.g. formal neurons) and multi-bit digital devices.

– DNS where input and output signals as well as coupling weight coefficients are represented in the form of analog signals (they are usually built on the basis of analog elements – operational amplifiers and comparators or on the basis of electronic components: diodes, transistors, thyristors, resistors, condensers, etc. Depending on the form of analog signal, DNS with the following forms of information representation are distinguished: 1) voltage level, 2) current value, 3) frequency of pulses, 4) duration of time intervals.

Classification of neuron elements according to the type of element base is presented in fig. 2. Three main groups can be distinguished among electronic element bases: large-scale integrated circuit (VLSI circuit), integrated circuits with medium degree of integration (MIC) and programmable logic integrated circuits (PLD). VLSI circuits contain up to 1 million elements on a chip while MIC – only up to 1000 elements. The main elements of the analog microcircuits are bipolar and field-effect transistors.

PLD (programmable logic device) is an electronic component that is used for creation of digital integrated circuits. Unlike ordinary integrated circuits, logic of PLD operation is not set by a producer but by programming. Main types of PLD include:

– FPGA (field-programmable gate array);
– CPLD (complex programmable logic device);
– PAL (programmable array logic);
– GAL (gate array logic).

PAL and GAL types have simple architecture. PLD have the following alternatives:

– ULA (*Uncommited Logic Array*) – basic matrix crystals, the production of which requires a certain manufacturing process for programming. They are large integrated circuits that are programmed using a mask technology of applying compounds of the final layer of metallization;

– ASIC (*application-specific integrated circuit*) – integrated circuits specially ordered for solving specific tasks;

– specialized processors or microcontrollers (slower than PLD)

In the optoelectronic element base four main groups of components can be distinguished: optoelectronic chips based on photodiodes and operational amplifiers (FD-OA), devices based on optically controllable transparencies (OCT), devices based on optical bistable SEED-devices (Self-Electrooptic Effect Device) and devices based on spatial-temporal light modulators (STLM).

DNS classification according to the character of setting up the synapses:
- With fixed weight coefficients (to be selected at once proceeding from the conditions of the problem);
- With adjustable weight coefficients (weights of synaptic connections are adjusted during the learning process).

In a number of neural elements activation function may depend on the time of the pulse (signal) transmission τ_{ij} through communication channels. Therefore, by the signal transmission time models of neural elements can be divided into synchronous and asynchronous ones. The neuron with transfer time τ_{ij} of each link equal to zero or to a fixed constant τ is called a synchronous neuron. A neuron having its own constant transfer time τ_{ij} for each link is referred to as asynchronous neuron.

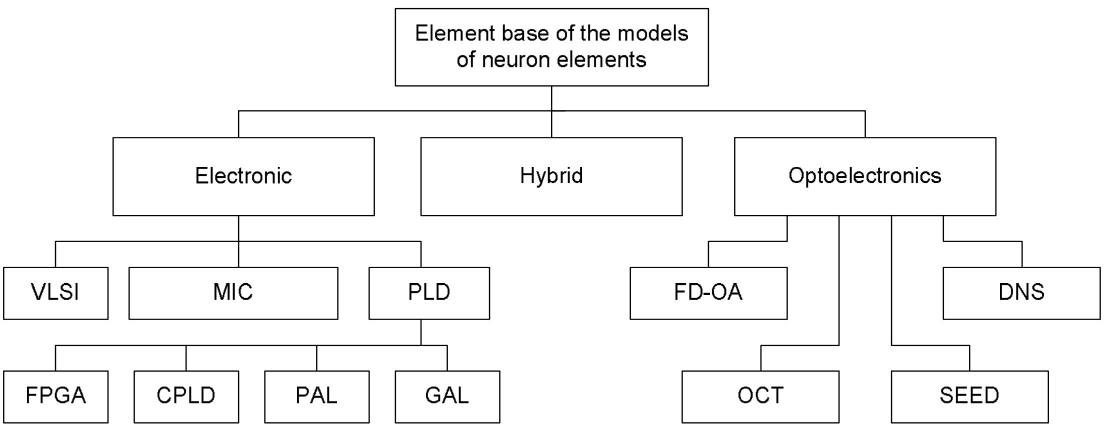

Fig. 2. DNS according to the type of element base

3. Modern devices for the neuron simulation and their shortcomings

In the patent literature of the former USSR (CIS) including that of Ukraine and RF 114 various DNS have been found. Let us discuss DNS of various types presented in fig. 1 in detail.

The conducted review of literature shows that at the territory of the former USSR the following institutions were engaged in the research of DNS: Ufa Aviation Institute, Glushkov Institute of Cybernetics of Ukrainian Academy of Sciences, Rostov State University, Taganrog Radio Engineering Institute, Lviv State Medical Institute, Pavlov Institute of Physiology, Lviv Polytechnic Institute, Vinnitsa National Technical University, Kazan State University, Odessa State University, Dnepropetrovsk State University, higher educational institutions of Moscow (MSU, MEPI, MIREA, BMSTU) and others.

One of the representatives of the digital single-bit DNS is a model of the formal neuron [5], comprising logical elements AND-NO and invertors with Shottki input diodes and transistors. Ordinary R-S trigger forms the basis of the model. Digital logic circuits are often used for the formal neuron construction. At the same time, exotic elements are sometimes also used, e.g. ionotropic transistor (A.C. of the USSSR № 619933) or devices with cylindrical magnetic domains – CMD (A. C. of the USSR № 1013984). Formal neuron models are very simplified as input and output signals in them are binary ones (though weights of the digits could be multi-valued (infinite-valued). That is why they have poor functionality and are seldom used for the construction of neural networks. At present neuron models with multi-value (infinite-value) input and output signals as well as weights of synapses are considered to be more promising [4].

Digital multi-bit DNS is a more numerous class. Their typical representative is a device [6] for the neuron simulation (fig. 3) that contains two groups of information inputs $1_1 \ldots 1_n$ and $2_1 \ldots 2_n$, n blocks $3_1 \ldots 3_n$ of changing weights of synapses, setting inputs $4_1 \ldots 4_n$, summator 5, elements I 6 and 7, recorders 8 and 9, logic unit 10, control inputs 11 – 16, information inputs 17 – 20.

In the units $3_1 \ldots 3_n$ of changing synaptic weights multiplication of input signals $x_{i,1},\ldots,x_{i,n-1}$ by the current values of synaptic weights $\gamma_{i,1},\ldots,\gamma_{i,n-1}$ and of the threshold value $(-\theta)$ by 1 is performed in the modes of gradual and formal neurons; the obtained products are summarized in summator 5 (for the first two modes $P_i = \sum_{j=1}^{n-1} x_{ij} \cdot \gamma_{ij} - \theta$). At the input 20 output signal Y_{output} is formed which for the mode of the graduation neuron will be $Y_{out} = \max\{0; P_i\}$ and for the mode of the formal neuron - $Y_{out} = sign(\sum_{j=1}^{n-1} x_{ij} \cdot \gamma_{ij} - \theta)$. A shortcoming of the given device is its insufficient response due to the sequential principle of processing of n operands in the summator. The main advantage of multi-bit digital DNS is their high (digital) accuracy of simulation and the main disadvantage – high hardware costs.

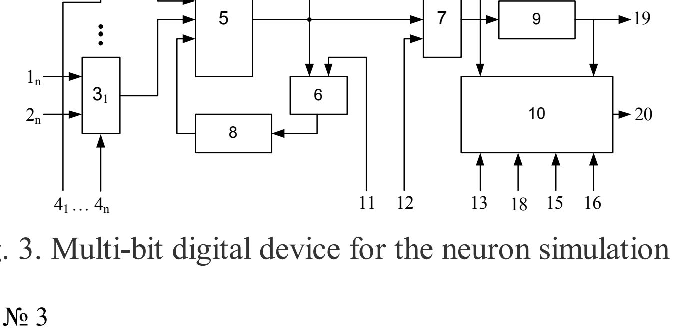

Fig. 3. Multi-bit digital device for the neuron simulation

A typical representative of DNS where information is represented in the form of voltage level is a device for the neural cell transfer function simulation (fig. 4) [7] that includes summator 1, integrators 2 and 3, inverter 4, multiplication unit 5, relay 6 with contact group 7, inputs 8, 9 and the output. As we see, an operational amplifier forms the basis of such DNS and, therefore, they have lower simulation accuracy than multi-bit digital DNS but their hardware is simpler. In spite of this, hardware costs of such DNS do not allow construction of large-scale neural networks on their basis yet.

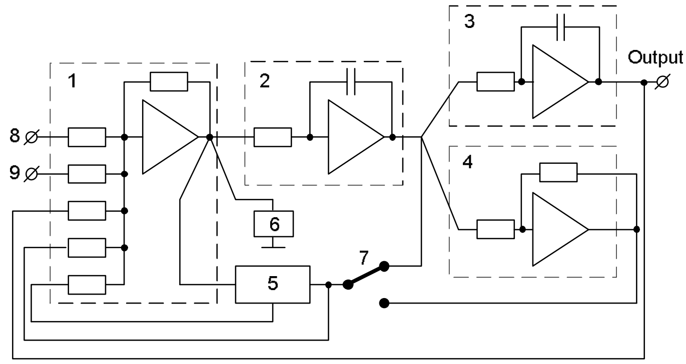

Fig. 4. The device for neural cell transfer function simulation

One of the representative of analog DNS where information is presented in the form of the current value is a device for the neuron simulation [8] built on the basis of logic gates I2L and containing two-collector current inverters-multipliers, four-digit I2L gates and threshold detectors. Functional circuit of the device is shown in fig. 5. It includes a group of excitation channels 1 and inhibition channels 2, summator 3, threshold unit 5 of the output signal formation. Each group of channels 1 and 2 includes units 6 – 9 of weighting input signals as well as threshold units 10 – 13 respectively. The group of excitation channels 1 also contains summator 14 of weighting input signals and inverter 15.

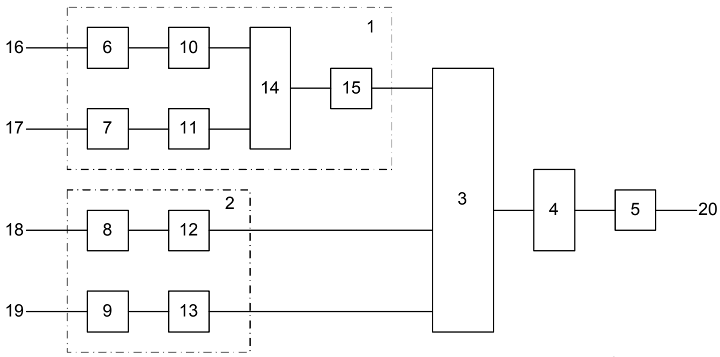

Fig. 5. The neuron simulation device based on I^2 L gates

DNS with pulse-frequency form of information presentation are the most numerous ones. This may be explained the fact that in biological neurons information is also represented by pulses, the frequency of which also depends on the excitation level. According to the complexity of hardware such DNS can be divided into three classes:

1) complex – with the usage of digital element base (counters, triggers, frequency-voltage and voltage-code converters). An example is Patent of Ukraine № 46470;

2) of average complexity – with the usage analog element base (operational amplifiers, analog comparators, frequency-voltage and voltage-frequency converters). An example is A.C. of the USSR № 886016;

3) simple DNS – with the usage of non-linear electronic (optoelectronic) elements (unijunction transistor [9], avalanche transistor [10], thyristor [11], bispin unit [12], Schmitt trigger, based on MDS transistors [13]).

Naturally, in terms of hardware implementation of neural networks with large number of elements simple DNS are the most attractive ones.

As an example (fig. 6) let us consider DNS [9] including unijunction transistor 1, bipolar transistor 2, resistors 3 – 6, load resistor 7, condensers 8 – 10, diodes 11 – 12. The active element is a unijunction transistor 1, resistors 3, 5 and 7 provide the preset mode, excitation 13 and inhibiting 14 inputs contain diodes 11, 12 and time summation circuits, which consist from resistors 6, 4 and condensers 9, 10. A shortcomings of the device [9 – 13] is the presence of electrical inputs and outputs (which does not make it possible to organize a large number of the neuron connections) and low loading capacity (the impossibility to control high currents required to supply the matrices of light diodes or semiconductor lasers for organizing optical outputs of the neuron).

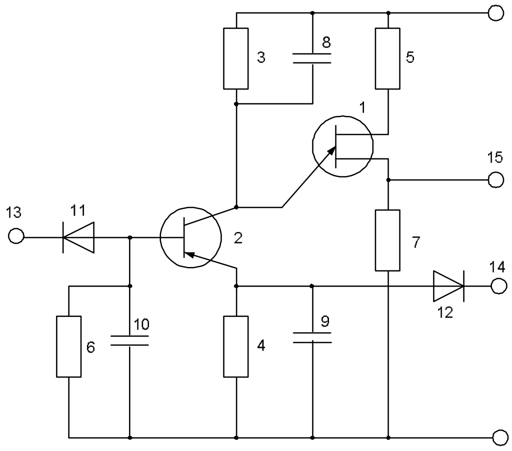

Fig. 6. The neuron simulation device based on a unijunction transistor

DNS where information is represented in the form of time interval duration were not found while conducting the review. However, in the work [14] the authors propose a neuron model of the time-logic type that works with the time interval durations.

4. Recommendations on the hardware realization of neural networks and the ways to improve devices for the neuron simulation

From the above review of typical DNS it is evident that:

1) digital single-bit DNS provide too simplified simulation of the work of biological neuron and therefore they are suitable only for the initial stage of studying artificial neural structures.

2) construction of digital multi-bit DNS requires considerable hardware costs, but at the same time they are quite accurate, multifunctional and, therefore, suitable for detailed study and research of the work of certain biological neurons or small neuron ensembles. The review has shown that their shortcomings include low response and considerable complexity of the hardware, Thus, it is necessary to improve the response of such devices, which is proposed by the authors in works [15 – 17].

3) DNS that work with analog information represented by voltage, current or frequency are usually much simpler than multi-bit digital DNS, but they have limited functional capabilities and low simulation accuracy. Therefore, apart from their application in the research of the biological neuron functioning, they could be also used for the construction of hardware implementation of neural networks with large number of elements.

Undoubtedly, in order to obtain maximum advantage from neural network application for practical tasks of recognizing different-origin images, hardware implementations of neural networks with the maximally possible number of neural elements are required. Ideally, this number must approach the number of neurons in the human brain – $(2…5)\times10^{11}$. Therefore, such neural elements should be the simplest possible ones and suitable for their representation in an integral form.

A pulsed neural network structure is known [18] that is based on the optoelectronic element base of spatially continuous optoelectronic structures (fig.7). It comprises *n* input neural elements $EI_1 ... EI_n$, at the inputs of which input signals x_1 ... x_n are supplied, *N* interneurons $E_1 ... E_N$, two cylindrical lenses CL1 and CL2, transparency T (made, for instance, in the form of a photo plate, with the transparency coefficients of local sections corresponding to the values of the weight coefficients of interneuron connections), optically controlled transparency OCT with the system consisting from 2*m* pairs of strip vertical electrodes, *m* output neuron elements EO_1 ... EO_n, fiber-optic harness with focones of optoelectronic element base of spatially continuous optoelectronic structures F1 and F2. In OCT odd pairs of electrodes correspond to excitatory links and have leads Y^E_i и $Y^E_i{}'$ and even pairs of electrodes correspond to the inhibitory links and have leads Y^I_i and $Y^I_i{}'$ ($i=1...m$). Transparency T and OCT form a common matrix of weights of all INM connections.

The main shortcomings of this hardware realization are poor design-technological parameters and namely:

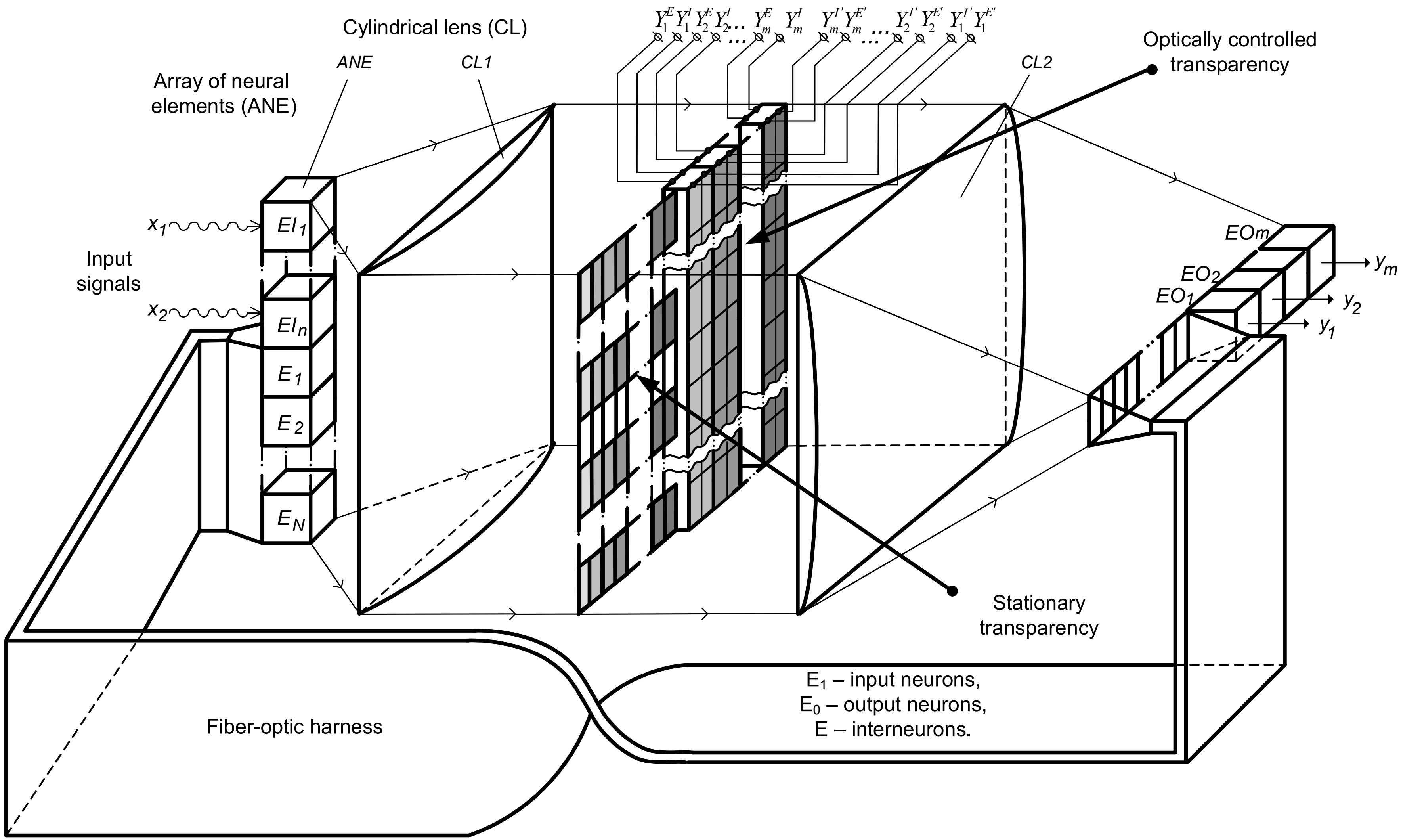

Fig. 7. The structure of pulsed neural network on the basis of optoelectronic element base SCOES

– presence of such optical elements as cylindrical lenses, focones and fiber-optic harness increases the mass of the device;

– as there should be a certain distance (determined by the focal length of cylindrical lenses) from the array of input- and interneurons to the matrix of connections and from the matrix of connections to the output neurons, the device will have considerable length and, therefore, a considerable volume;

– as output optical signal of a neuron is expanded by the cylindrical lens over the whole line of the matrix of connections, it must have considerable power. This requires application of powerful semiconductor lasers as light emitters, which, in its turn, causes the necessity of powerful output cascades of neural elements capable to create high currents while for a large number of neurons in the network optical power per one element of the matrix of connections could still prove to be insufficient.

Thus, the ways to improve multi-bit digital DNS involve improving response and for analog DNS – increasing loading capacity (output loading power) and creating such DNS that would make it possible to build neural networks with improved mass-dimensional characteristics on their basis.

In order to improve the response and to expand functional capabilities of multi-bit digital DNS, the authors created several variants of DNS [15 – 17] where space-time summator operating on the basis of difference slices is used as the main block. The devices operate in the modes of a formal neuron (i.e. comparison of the weighted sum of input signals with the threshold value), digital integrator (i.e. summatrion of input signals), scalar product of the input vectors.

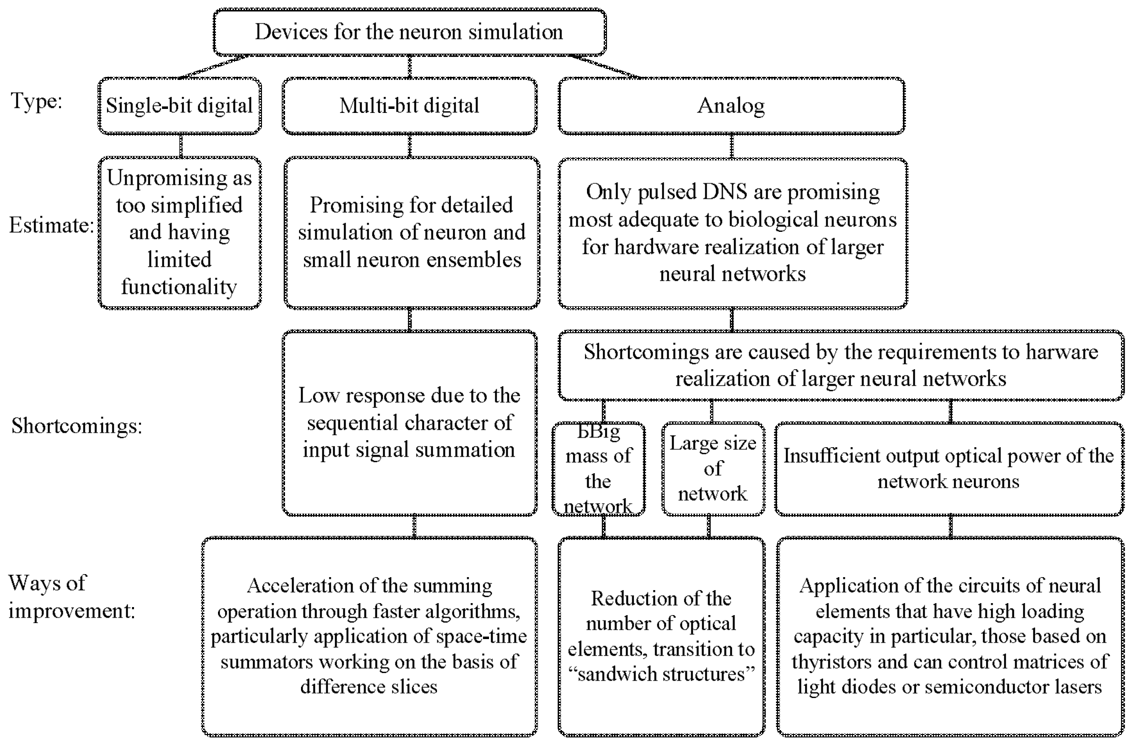

Fig. 8. Shortcomings of the existing DNS and the ways of their elimination

In order to eliminate the shortcomings of the simple analog DNS it is necessary to reduce the hardware complexity of the model and to organize optical inputs and outputs with high output optical power. For this paper [19] proposes DNS on the basis of a thyristor, that can control the matrix of semiconductor lasers, as well as a neural network structure based on such DNS.

Conclusions

The paper proves current importance of the research of devices for the neuron simulation taking into account their application in neural networks of the cognitive problem solution systems (image

recognition, parallel processing, decision making in uncertainty conditions etc. when application of traditional computers becomes ineffective). Fundamental patent search has been performed resulting in finding 91 Authors Certificates of the USSR, 9 patents and 5 patent applications of Russia, 9 patents of Ukraine related to the devices for the neuron simulation. Classification of the known devices for the neuron simulation according to different criteria is created, typical kinds of the neuron elements with different forms of information representation are discussed, different types of the element base are analyzed. Shortcomings of the known devices for the neuron simulation are analyzed and ways for their improvement are suggested: for multi-bit digital DNS it is necessary to improve the response and to expand functional capabilities by using space-time summator, operating on the basis of difference slices, as the main unit, while for simple analog DNS hardware complexity reduction is required as well as organization of optical inputs and outputs with high output optical power.

REFERENCES

1. Галушкин А. И. Нейрокомпьютеры. Кн. 3 : Учебное пособие для вузов / [Общая редакция А. И. Галушкина]. – М.: ИПРЖР, 2000. – 528 с.

2. Вінцюк Т. К. Образний комп'ютер: концепції, методологія, підходи / Т. К. Вінцюк // Оптико-електронні інформаційно-енергетичні технології. – 2001. – № 1. – С. 125 – 138.

3. Кожем’яко В. П. Класифікаційна модель створення прототипу образного комп’ютера / В. П. Кожем’яко, Т. Б. Мартинюк, А. В. Кожем’яко // Оптико-електронні інформаційно-енергетичні технології. – 2006. – № 2 (12). – С. 129 – 138.

4. Бардаченко В. Ф. Таймерні нейронні елементи та структури Монографія // В. Ф. Бардаченко, О. К. Колесницький, С. А. Василецький. – Вінниця: УНІВЕРСУМ-Вінниця, 2005, – 126 с.

5. А. с. 964662 СССР, МКИ[3] G 06 F 7/650. Модель формального нейрона / Фурсин Г. И. (СССР). – №3002819/18-24 ; заявл. 05.11.80 ; опубл. 07.10.82, Бюл. № 37.

6. А. с. 1479944 СССР, МКИ[3] G 06 F 7/650. Устройство для моделирования нейрона / Каляев А. В., Чернухин Ю. В., Брюхомицкий Ю. А., Галуев Г. А. (СССР). – №4296969/31-13 ; заявл. 24.08.87 ; опубл. 15.05.89, Бюл. № 18.

7. А. с. 860096 СССР, МКИ[3] G 06 F 7/650. Устройство для воспроизведения передаточной функции нервной клетки / Кирин А. А. (СССР). – №2723778/18-24 ; заявл. 26.01.79 ; опубл. 30.08.81, Бюл. № 32.

8. А.с. 1138813 СССР, МКИ[3] G 06 F 7/650. Устройство для моделирования функций нейрона / Кузнецова В. Л., Раков М. А., Овсяк В. К. – № 3572016/28-13; заявл. 30.03.83; опубл. 07.02.85. Бюл. № 5.

9. А. с. 623215 СССР, МКИ[3] G 06 F 7/650. Устройство для моделирования нейрона / Кряхтунова М. М., Соколов Б. А., Титов Ю. Ф. (СССР). – №2466323/18-24 ; заявл. 24.03.77 ; опубл. 05.09.78, Бюл. № 33.

10. А. с. 482766 СССР, МКИ[3] G 06 F 7/650. Модель нейрона / Иващенко В. Г., Цыбышев Е. Д. (СССР). – №2024002/18-24 ; заявл. 12.05.74 ; опубл. 30.08.75, Бюл. № 32.

11. А.с. 376787 СССР, МКИ[3] G 06 F 7/650. Устройство для моделирования нейрона / Снежко Е. М. (СССР). – №1661157/18-24 ; заявл. 31.05.71 ; опубл. 05.04.73. Бюл. № 17.

12. Пат. 22956А Україна, МПК G 06 F 7/50. Модель нейрона / Колесницький О. К. , Кожем`яко В. П., Нізельський М. Б., Василецький С. А., заявник і власник патенту Вінницьк. нац. технічн. ун-т – №97041757/18-24 ; заявл. 15.04.97 ; опубл. 05.05.98.

13. NASA TECH BRIEFS [Електронний ресурс] : Biomorphic analog pulse - coupled neural circuits – Режим доступу : http://www.techbriefs.com/component/content/article/7354.

14. Кожем’яко В. П. Моделі нейронних елементів логіко-часового типу / В. П. Кожем’яко, Т. Б. Мартинюк, І. В. Мороз, А. А. Яровий // Оптико-електронні інформаційно-енергетичні технології. – 2007. – № 14. – С. 63 – 71.

15. Пат. 27751 Україна, МПК G 06 F 7/50. Пристрій для моделювання нейрона / Кожем`яко В. П., Мартинюк Т. Б., Кожем`яко А. В., Мороз І. В.; заявник і власник патенту Вінницьк. нац. технічн. ун-т – № u200708023; заявл. 16.07.07; опубл. 12.11.07, Бюл. № 18.

16. Пат. 34466 Україна, МПК G 06 F 7/50. Пристрій для моделювання нейрона / Кожем`яко В. П., Мартинюк Т. Б., Колесницький О. К., Мороз І. В., Чечельницький О. І., заявник і власник патенту Вінницьк. нац. технічн. ун-т – № u200803614; заявл. 21.03.08; опубл. 11.08.08, Бюл. № 15.

17. Пат. 38491 Україна, МПК G 06 F 7/50. Пристрій для моделювання нейрона / Мартинюк Т. Б., Куперштейн Л. М., Мороз І. В., Чечельницький О. І., заявник і власник патенту Вінницьк. нац. технічн. ун-т – № 200810096; заявл. 04.08.08; опубл. 12.01.09, Бюл. № 15.

18. Kolesnytskyj O. K. Optoelectronic Implementation of Pulsed Neurons and Neural Networks Using Bispin-

Devices / O. K. Kolesnytskyj, I. V. Bokotsey, S. S. Yaremchuk // Optical Memory & Neural Networks (Information Optics). – 2010, – Vol.19, № 2, P. 154 – 165.

19. Колесницкий О. К. Компактна оптоелектронна реалізація імпульсной нейронної мережі / О. К. Колесницкий, І. В. Бокоцей // Оптико-електронні інформаційно-енергетичні технології. – 2010. – № 2. – С. 54 – 62.

Kolesnytskiy Oleg – Cand. Sc. (Eng.), Assoc Prof. of the Department of Computer Sciences, okk_vin@mail.ru.

Bokcotsey Irina **–** Post Graduate student, Department of Computer Sciences, *leo_19851985@mail.ru.*

Korinniy Anatoliy **–** Senior Lecturer of the Department of Administrative and Informational Management, Chief of the Computer Center.

Vinnytsia National Technical University.