SEVERAL REMARKS ON PRACTICAL IMPLEMENTATION OF IMAGE PROCESSING BY CHEMICAL REACTION-DIFFUSION MEDIA.

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Abstract. Belousov-Zhabotinsky chemical reaction-diffusion media represent information processing means fundamentally different from contemporary digital computers. Distributed character and complex nonlinear dynamics of chemical reactions inherent in the medium is the basis for large-scale parallelism and complex logical operations performed by the medium as primitives and equivalent to hundreds of binary fixed-point operations. Photo-sensitive catalysts controlling dynamics (modes of functioning) of the medium enable to easily perform input of initial data and output of computational results. It was shown that the spatio-temporal evolution of an image produced by Belousov-Zhabotinsky medium is adequate to image processing operations carried out using mathematical morphology technique. Conditions necessary to reliable use of Belousov-Zhabotinsky media for image processing are analyzed.

Key words: bimolecular computing, computational complexity, reaction-diffusion media

1. Introduction : von Neumann vs non von Neumann information processing devices and artificial intelligence problems.

The latest decade was remarkable for the development of molecular information processing devices. Important approaches were elaborated that had made practical commercial applications of molecular devices visible. They were:

-engineering style design of hiropticene molecules [1],

- VLSI crossbar architecture based on rotaxane molecules [2]

and some other important suggestions.

However all these attempts used von Neumann principles inherent in contemporary digital computing. And the problem is that these principles do not seem to be efficient for solving artificial intelligence problems which are of the great importance for the modern fields of human activity. According to estimates [3] digital computers will be in striking distance of being powerful enough to match human brainpower in 20^{th} – 40^{th} of our century. However they will be supercomputers composed of tens of thousands of fastest microprocessors and costing tens of millions of dollars. Therefore the elaboration of simple, easy in operation, and cheap information processing devices capable to solve even single artificial intelligence problems is one of the important needs of contemporary computing.

Neural network devices are more efficient in solving problems of artificial intelligence due to their biological background. However practical implementation of these devices faces troubles determined by planar semiconductor technology used. Therefore during the last decade attempts have been made to find another material implementation for neural nets consisting with their biological origin. One of them was based on chemical reaction-diffusion media that have showed real capabilities to solve problems of artificial intelligence, and first of all image processing and recognition [4].

Information processing by distributed reaction-diffusion media was under investigation during the last three decades. Biological origin of these systems was the starting point for different theoretical approaches aimed to solve effectively artificial intelligent problems [5-14]. Important experimental studies in this field were launched in the late eighties [15-19]. It enables to realize basic information capabilities of reaction-diffusion computing.

Primordially concentrations of medium components are spatially uniform. This uniform distribution could be changed by external physical or chemical stimuli. As a result spatio-temporal evolution of the medium composition begins. This situation could be considered as input of information and its following evolution. The character of the evolution is determined by medium specific properties. Media having nonlinear mechanisms of the component interaction are the most promising for information processing. Given high behavioral complexity of these media, modes of the input information evolution could be equivalent to tens or even hundreds binary operations of digital computer.

It has been shown during the last decades that chemical Belousov-Zhabotinsky media could be effectively used for information processing [15-19]. One of the most promising direction of using these media is image processing and recognition. However up to now at least two points are not clear.

Contemporary image processing is an original, practically oriented field of modern informatics. Image processing technique embraces a lot of primitive operations that are based on several approaches, such as cellular logic, prairie fire conception, mathematical morphology[20-24].

So the first point is: are modes of input image evolution in the reaction-diffusion medium adequate to the actual image processing operations?

Specific feature of light-sensitive reaction-diffusion media is high behavioral complexity. Modes of input image evolution in the reaction-diffusion medium are determined not only by the medium composition and temperature, but also by intensity of light illumination.

And the second point is: might modes of image evolution be actual image processing operations or some of them are artifacts that do not reflect real features of the input image?

This work was designed to investigate these problems important for practical implementation based on Belousov-Zhabotinsky reaction-diffusion media and to look for the variety of image processing operations that could be effectively performed by these media.

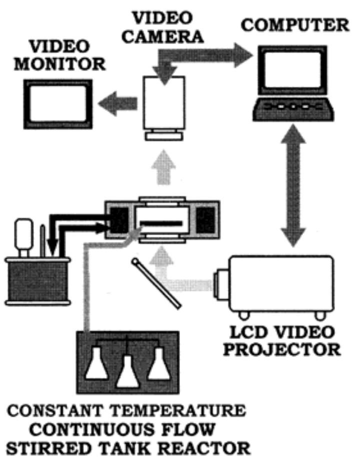

Fig. 1 Principal scheme of the set up

2, Experimental

Experimental investigations discussed below were performed using the set up, that was sufficiently modified in comparison with its previous version [25]. Optical tract of the set up was partly changed to add some additional operational modes and sources of extraneous light were carefully removed. Different designs of reaction-diffusion reactors based on polymeric materials were elaborated.

Principal scheme of the set up is shown in fig.1 The computer-controlled Sanyo PLC-510M LCD video projector (VGA compatible, 270 ANSI lumens) was used for input of initial data.. A Mintron OS-045D video camera was used to record the steps of the image processing by the medium (0.02 lx sensitivity, 600 TV lines resolution). Digitized records of images were saved in the memory of the Pentium III PC. It was possible to write single frames and video clips using VidCap software.

Numerical simulation of the image processing operations performed by the light-sensitive Belousov-Zhabotinsky media was based on modified FKN approximation [26,27]. Euler and Runge-Kutta methods were used to solve sets of differential equations. The software was designed as two independent modules. The first of them was used for the input of initial data and for the visualization of results of computations. The second performed calculations. Such software structure simplified the addition of the new data. Modules were written using C++ programming language and were compilated by Microsoft Visual C++ 6.0. The size of the software is ~ 1 Mb.

Detailed description of the experimental technique was published elsewhere [25].

3. High behavior complexity of light-sensitive Belousov-Zhabotinsky media and some restrictions for the image processing performed by these media.

Detailed description of principles and technique for using Belousov-Zhabotinsky media for image processing were published elsewhere [25]. Let us mention here some points only important for the following discussion.

Belousov-Zhabotinsky type media are the most known chemical nonlinear reaction-diffusion systems [26]. The Belousov-Zhabotinsky reaction is the oxidation of some organic substance (malonic acid) by the inorganic oxidizing agent (sodium or potassium bromate). Ions of transition metals (Fe or Ru mainly) are catalysts of the reaction. The principal scheme of the reaction corresponds to

$$\mathbf{C_3H_4O_4 + NaBrO_3 + H^+ \xrightarrow{Fe} C_3\,H_3BrO_4 + H_2O + CO_2}$$

The process of evolution of initial concentration distribution proceeds in the media due to chemical reactions and diffusion. The catalyst changes its electronic state in the course of reaction when the medium goes from one stable state into another. As a consequence, the reagent changes its color (from red to blue and vice versa) and it is easy to visualize the process and to observe its spatio-temporal evolution. Therefore the catalyst works also as a "micro-macro" interface bringing into correspondence the evolution of the chemical concentration distribution and optical (macro} image of the process evolution.

The important information processing feature of Belousov-Zhabotinsky type media that determine medium processing capabilities is the neural network architecture (see [4]).

Belousov-Zhabotinsky type media based on a light-sensitive catalyst are convenient for the input of initial information. The light-sensitive catalyst initiates a sequence of photochemical reactions under light illumination [28]:

$$\mathbf{Ru^{+2} + h\nu \rightarrow {}^*Ru^{+2}}$$
$$\mathbf{{}^*Ru^{+2} + C_3H_3BrO_4 \rightarrow Ru^{+3} + Br^{-} + \text{ organic products}}$$
$$\mathbf{Ru^{+3} + C_3H_3BrO_4 \rightarrow Ru^{+2} + Br^{-} + \text{ organic products}}$$

that changes the composition of the medium in each its point according to light intensity in the point.

The mechanism of the Belousov-Zhabotinsky reaction represents a set of intermediate stages. The real set of these stages is not known exactly till now. The most widely accepted model - Field-Korosh-Noyes (FKN) approximation [26], contains 11 intermediate reactions and could be reduced to two kinetic equations that correspond to temporal evolutions of reaction inhibitor "u" ($HBrO_2$) and activator "v" (Fe^{3+} or Ru^{3+}):

$$\frac{\partial u}{\partial t} = \frac{1}{\varepsilon}\left[\frac{\mu - u}{\mu + u}(qv + \phi) + u - u^2\right] + D_u \Delta u$$

$$\frac{\partial v}{\partial t} = \lambda u - u + D_v \Delta v$$

Here ε , q and λ are constants defined by initial concentrations of the medium components and kinetic of intermediate reactions, μ=0.001, ϕ describes a light illumination of the medium.

These equations are sufficiently simpler in the case of totally mixing media, when the diffusion could be neglected. Null-clines introduced in this case are the convenient basis to classify dynamic states of the medium. Null-clines corresponding to above equations (μ= 0.001, q=0.7) are shown in fig.2 S-type and linear null-clines described inhibitor ($HBrO_2$) and activator (Ru^{+3}) dynamics correspondingly. Here unstable point (λ=1, ϕ/q=0) corresponds to oscillatory mode, whereas stable point (λ=0.05, ϕ/q=0) corresponds to excitable state.

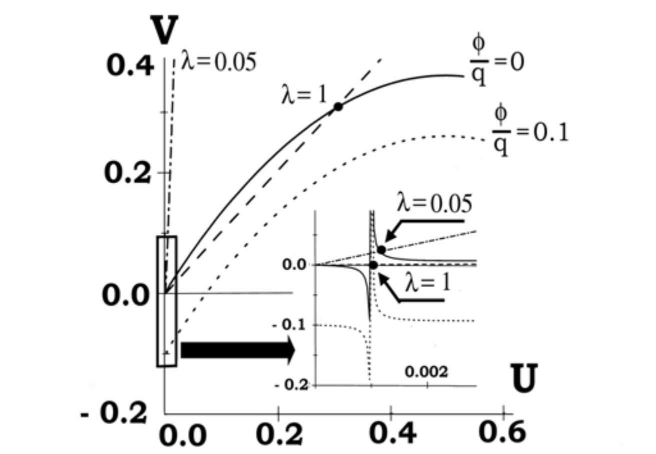

Fig.2 Null clines of Belousov-Zhabotinsky system

The high behavioral complexity of

light-sensitive Belousov-Zhabotinsky media is determined by the two factors responsible for the choice of dynamic state. They are the chemical composition of the medium and intensity of the light radiation. It is easy to see that there are, for instance, two possibilities to get excitable state. If light illumination is neglected ($\phi/q=0$) two states , excitable and oscillatory could be obtained using different medium composition, that are described by different sets of constants ($q=0.7$, $\lambda=1$ for oscillatory state and $q=0.7$, $\lambda=0.05$ for excitable one). At the same time it is possible to move from the oscillatory state ($q=0.7$, $\lambda=1$, $\phi/q=0$) to the excitable state using light illumination of the medium ($q=0.7$, $\lambda=1$, $\phi/q=0.1$). This situation is definable for the understanding of the light-sensitive medium properties.

Considering image processing by light-sensitive media it is necessary to take into account three basic modes of the medium illumination.

The first one is using of the light illumination for the input of initial information into the medium. The exposure of the light illumination determines also the dynamical mode of the medium (see below).

There is another evident illumination mode that isn't usually discussed. It is necessary to illuminate the medium in the process of image evolution to have the possibility to record this process by video camera. It gives additional opportunities to control the medium dynamic mode.

And the third is the continuous illumination of the medium by a chosen non uniform light distribution in the process of the image evolution (see, for instance [29,30]).

Let us consider some features of the black and white image evolution in a light-sensitive medium. Suppose that exposures of the light illumination used for the input of initial data are low.

Suppose also that medium composition is chosen to initiate oscillatory dynamic mode. It is. possible to observe typical oscillations (fig.3A) if the intensity of the uniform illumination necessary for registration of the image evolution is low (brightness 5%, Photoshop HSB model). At the same time the typical excitable process could be observed (fig.3B) if the intensity of the uniform illumination in the process of the image evolution registration is high enough (brightness 30-40). Here and in all following figures the input of the initial image is shown (black arrows) and its evolution in the medium (grey arrows).

Thus the important feature of the light sensitive Belousov-Zhabotinsky media is that it is possible to observe both oscillatory and excitable modes of the medium dynamics having the same medium composition and different intensities of the light illumination in the process of the medium evolution registration.

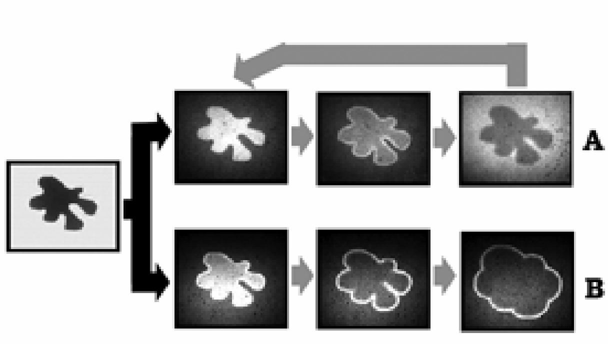

Fig.3 Oscillating (A) and excitable (B) modes of Belousov-Zhabotinsky medium

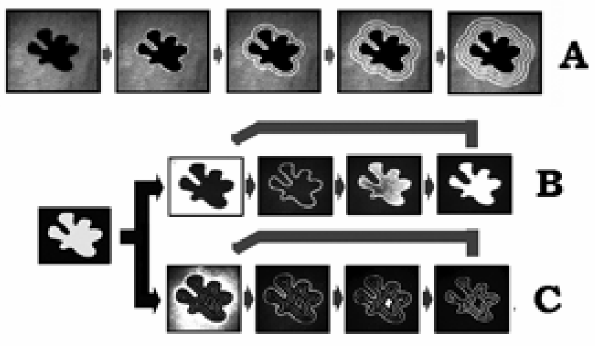

Fig.4 Input of data (A) and oscillating modes (B,C) of Belousov-Zhabotinsky media

The situation dramatically changes if the exposure of the light illumination used for the input of initial data in the medium is high.

The train of the pulses reveals at the borders of images projected at the surface of the medium that spread along the medium (fig.4A). Mention here that this process was observed earlier [31] but under another experimental conditions. The revealing of the pulses stops if the input of the image is switched off, and the mode of the train following evolution can be both oscillatory and excitable depending on intensity of the uniform illumination in the process of the image evolution registration (fig.4B,C).

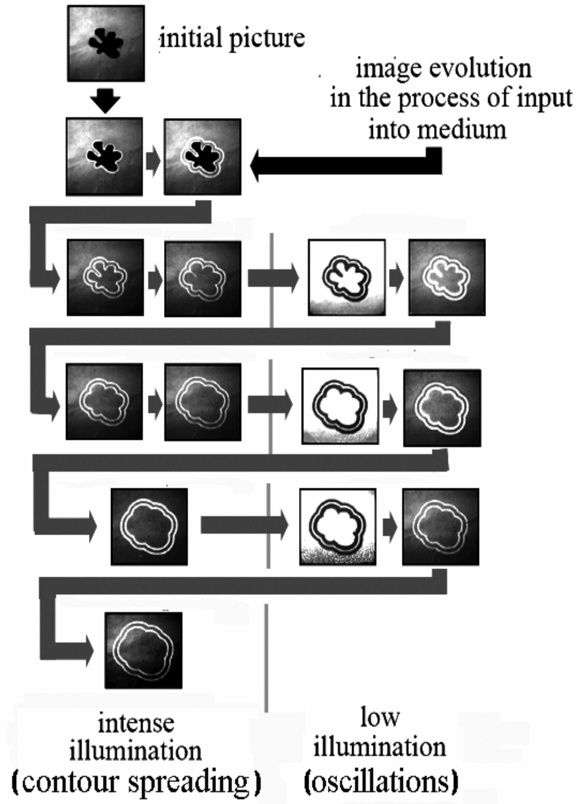

Fig.5 Switrching between oscillating and excitable modes in Belousov-Zhabotinsky medium

The remarkable feature of the light-sensitive Belousov-Zhabotinsky media is the fast switching of the evolution process (from oscillatory to excitable and back) controlled by the intensity of the light illumination (fig.5)

Mentioned here that trains of pulses revealed under high illumination differs from typical excitable mode phenomenon.

The origin of this phenomenon seems to br made clearer taking into consideration that the increasing of the light illumination corresponds to the shift of the inhibitor null-cline and moving of the null-cline intersection point along inhibitor null-cline (from oscillatory to excitable state). Regretfully it was difficult to study this process in experiment because technical difficulties. Therefore an attempt was made to perform numerical simulation.

It was shown earlier [32] that numerical results obtained from an Oregonator model modified to include the photochemical production of Br^- and $HBrO_2$ are in semi quantitative agreement with the experimentally observed behavior. Therefore another possibility was chosen to simulate dynamic modes in the intermediate field between oscillatory and excitable modes.

The inhibitor null-cline was used where $\phi/q = 0$. At the same time λ coefficient of the activator null-cline varied from $\lambda=1$ to $\lambda=0.05$ to describe moving intersection point from oscillatory to excitable state. Results of this simulation are shown in fig.6. It is possible to see the variety of intermediate dynamic modes including trains of pulses.

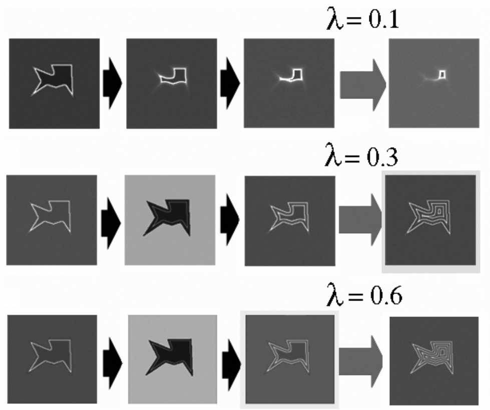

Fig.6 Simulation of Belousov-Zhabotinsky media dynamic modes

It should be concluded as a result of experimental study performed that processing of images by light-sensitive Belousov-Zhabotinsky media could lead to revealing of trains of the image contours. These trains are determined by the intensity and duration of the light illumination , not structural features of image under investigation. It is urgent therefore to choose carefully exposures of the illumination to avoid artifacts in image processing.

4. Mathematical morphology vs image processing by Belousov-Zhabotinsky media.

The methodological basis of image processing by reaction-diffusion media still remains vague enough till now. The process of the image evolution in the medium, not image processing, was considered virtually in the first investigation named “Image processing using light-sensitive

Mathematical morphology	Chemical reaction-diffusion medium
Numerical method of image processing based on nonlinear transformations of images	Processing of images by a chemical medium based on nonlinear dynamic mechanisms
Operational data element is an image represented by a set of pixels	Operational data element is a single image
Consecutive pixel by pixel processing of the image by a numerical computer	Parallel processing of the image in all its points by a chemical reaction-diffusion medium
Multimode processing of images based on different types of structural elements	Only one circular structural element is virtually used
Dilation and erosion are initial image processing operations, two basic operations – opening and closing, could be reduced to initial ones	Contour$^{(+)}$ and contour$^{(-)}$ are initial image processing operations, opening and closing could be performed based on these operations
All practically actual black and white image processing operations could be performed	All practically actual black and white image processing operations could be performed
A variety of the half-tone image processing operations could be carried out	A variety of half-tone image processing operations equivalent to operations performed by mathematical morphology could be carried out

chemical waves" [17] and in the following publications [18]. There were no attempts to understand how complete is the correspondence between modes of the image evolution in the medium and typical image processing operations used in practice. One of the most efficient ways to make clear this problem is to choose generally accepted and practically oriented information processing technique and to compare thoroughly basic principles, image processing operations and the variety of problems which could be solved.

The important approach to consider this problem – the theoretical basis and technique of image processing named "mathematical morphology", was elaborated during the last decades [23,24].

Binary mathematical morphology operates complex two-dimensional objects defined in discrete space. Object "A" is a set of pixel satisfied to the specific predetermined conditions:

In spite of numerical presentation of initial data the mathematical morphology operates images as a whole. Primitive operations of the mathematical morphology are dilation - $A \oplus B$ that increases the image, and erosion $A \Theta B$ that decreases it. Here some notion is introduced additionally: together with object A. It is structural element B which determine the character of the shape changes of the object A at its border.

Two basic operations of the mathematical morphology are defined based on these primitives: opening $A \circ B = (A \Theta B) \oplus B$, and closing $A \bullet B = (A \oplus B) \Theta B$.

Detailed consideration shows that combined use of opening and closing enables to perform practically all basic image processing operations: contour enhancement, segmentation and so on.

Information processing features of mathematical morphology approach and image processing by Belousov-Zhabotinsky media are shown in table. There are evident differences between these two approaches. First of all one of them is a numerical method realized by modern digital computers, whereas another is a material realization of reaction-diffusion media capabilities. Nevertheless the information processing origin of these methods is adequate. It based on nonlinear mechanisms and wave character of information processing. Both of these approaches are biologically motivated. At the same time differences in information processing features of them aren't a matter of principle. Therefore all operations inherent in mathematical morphology could be carried out by Belousov-Zhabotinsky media.

Processing of black and white images

There are two operations performed by Belousov-Zhabotinsky media that could be considered as initial primitive ones. They are "contour$^{(+)}$" and "contour$^{(-)}$" operations and represent contour enhancement of the input image following by expanding (contour$^{(+)}$) or shrinking (contour$^{(-)}$) of the contour figure revealed (fig.7). The choice between these operations is determined by the choice of the negative or positive image form.

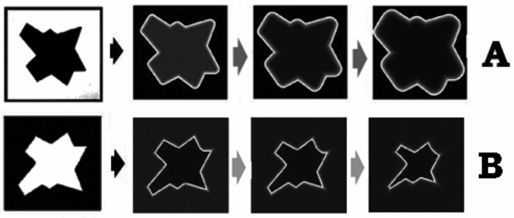

Fig.7 Contour$^{(+)}$ (A) and contour$^{(-)}$ (B) operations of Belousov-Zhabotinsky media

Mention here that considering image processing by Belousov-Zhabotinsky media positive and negative forms of the image should be distinguished.

To avoid vagueness in the following discussion let us define the positive image of a picture as image corresponding to typical picture inherent in human surroundings. If the notion of "typical picture" is uncertain (suppose in the case of geometrical figures, see, for instance, Fig.2, and 6) let us define positive image as dark figure on the light background. Black and white and half-tone pictures will be used below. Images of these pictures could be considered as a set of optical density values D_i corresponding to each point of the picture ($0 < D_i < D_\infty$, where D_∞ is a maximum value of the optical density). The negative image of the picture was defined as a set of inverted density values ($D_i^N = D_\infty - D_i$).

These primitive operations are adequate to dilation and erosion operations of the mathematical morphology. Moreover, it is possible to reproduce also opening and closing operations, using contour$^{(+)}$ and contour$^{(-)}$ primitives performed by Belousov-Zhabotinsky medium (fig.8). Therefore it is possible to conclude that reaction-diffusion medium can perform image processing operations typical for mathematical morphology.

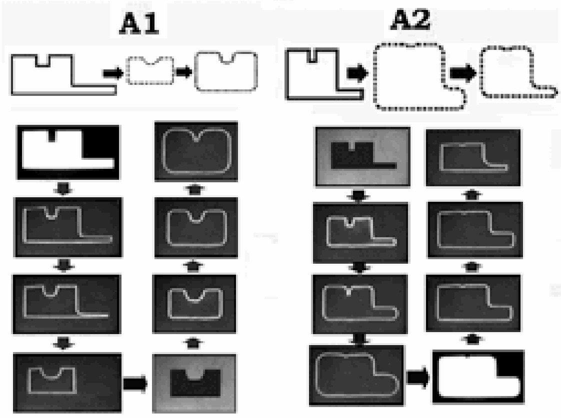

Fig.8 Opening (A1) and closing (A2) operations carried out by Belousov-Zhabotinsky media

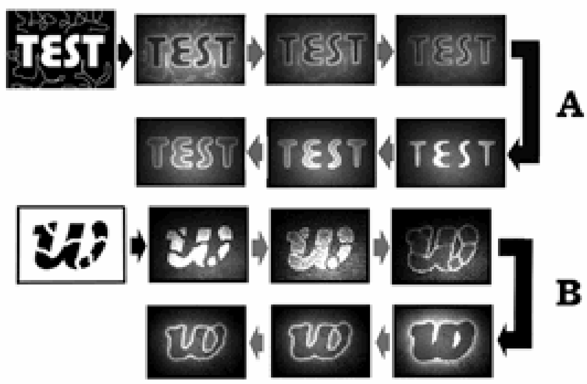

Fig.9 Opening (A) and closing (B) operations performed by Belousov-Zhabotinsky media

All known image processing operation carried out by the mathematical morphology technique could be performed by by Belousov-Zhabotinsky media. Most of them could be carried out using contour (+) and contour(-) operations, equivalent to dilation and erosion. A lot of examples were published elsewhere (see, for instance, [25]). They embrace: smoothing of immaterial features of the figure (enhancement its general shape) and segmentation of the figure, enhancement and removing of small features of the image, thinning, skeleton and Voronoi diagram calculation and so on

Opening and closing operations. performed by Belousov-Zhabotinsky media enable to carry out more complex image processing operations. As example defect repair and removing noises from an image can be mentioned (fig.9). Here consecutive combined use of contour(+) and contour(-) gives the opportunity to reconstruct the initial image.

Half-tone images and images having several levels of brightness

Considerable and notable possibilities of the complex pattern analysis are opened in the case of half-tone images. In this case an image under consideration is first transformed into its negative form. This transformation is the continuous process when the negative image appears step by step beginning from the most dark (or the most bright, depending on positive or negative form of initial image) fields of the image. This capability of Belousov-Zhabotinsky media is one of the most remarkable medium feature.. Namely, Belousov-Zhabotinsky medium is the natural realization of the temporal sequence processor (see, for instance, [33]) that transforms complex spatial distribution of visual information into temporal sequence of its fragments. Because of this feature Belousov-Zhabotinsky media are capable to solve complex practically important problems. Let us give some examples.

The ”hidden image” is a fragment of the picture having brightness very close to the brightness of the background. The example of this situation is shown in fig.10. The difference in brightness between the eagle image and the background is 10 units of Photoshop HSB model (the brightness of the picture was increased greatly to show the content of the picture, fig.10). The evolution of the picture in the Belousov-Zhabotinsky medium enables to enhance the hidden image in spite of a very big difference of its brightness in comparison with the background.

The important part of the image analysis in medicine, material science and some other fields is to reveal consecutively fields of the image having increasing (or decreasing) brightness. Examples of this process performed by Belousov-Zhabotinsky medium are shown in fig.11.

One of the useful tasks of the half-tone image processing is watershed operations. They give the opportunity to enhance the relief of the hill-like image. The example of the watershed operation performed by Belousov-Zhabotinsky medium is shown in fig.12.

Very important is processing patterns taken from aircrafts or satellites, and, particularly, urban roads detection [34]. Evolution of the test pattern similar to multi-view aerial imagery is sown in fig. Given both positive and negative forms of the pattern, fragments of the pattern having different brightness are revealed consecutively depending on the brightness of the fragments (fig.13).

An attempt to use mathematical morphology technique for urban road detection was performed lately [34]. The urban map and results of the preliminary detection of the road network by the mathematical morphology technique are shown in fig.14A,B1. The detection of the road network by Belousov-Zhabotinsky type medium using the same urban map is shown in fig.14B2. Easy to see, that these two road networks are in a good correspondence.

Some of the examples considered above were discussed in publications devoting to the mathematical morphology technique. The correspondence between these mathematical morphology operations and results obtained here using Belousov-Zhabotinsky media is satisfactory.

5. Some concluding remarks.

In the nineties of the last century Lee A. Rubel, one of the fathers in the field of unconventional computing, said to J.W. Mills [35]:

Fig.10 Enhancement of the hidden image by Belousov-Zhabotinsky media

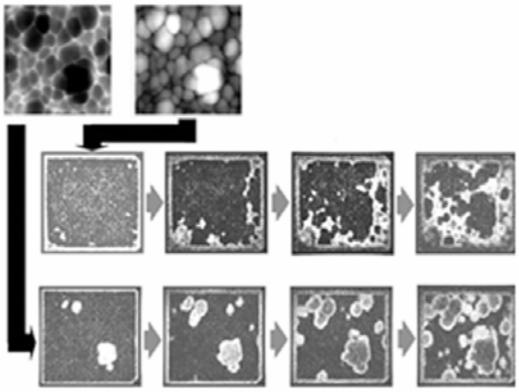

Fig.11 Processing of half-tone images by Belousov-Zhabotinsky media

Fig.12 Watershed operation carried out by Belousov-Zhabotinsky media

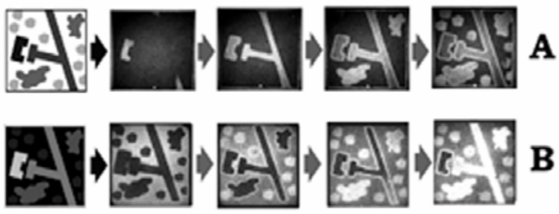

Fig.13 Processing of multi-view aerial imagery by Belousov-Zhabotinsky media

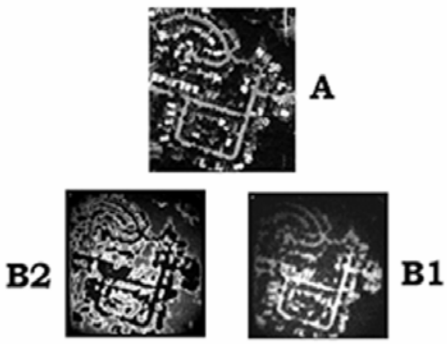

Fig.14 Urban road detection by mathematical morphology technique (B1) and Belousov-Zhabotrinsky medium (B2) using the same urban map (A)

"The future of analog computing is unlimited. As a visionary, I see it eventually displaying digital computing, especially in the beginning, in partial differential equations and as a model in neurobiology. It will take some decades for this to be done. In the meantime, it is my belief, it is a very rich and challenging field of investigations, although (or may be because) it is not in the current fashion."

Nowadays, a decade later, problems that could be solved by reaction-diffusion media are more and more complicated and practically purposeful.

Information processing by reaction-diffusion media is virtually the analog computation process which due to neural net medium architecture simulate some functions of the cerebral cortex activity. The basic problem is that the mechanisms of problem solution by the cerebral cortex are yet far from detailed understanding. If they are known, it would enable to create powerful means solving single artificial intelligence problems based on reaction-diffusion systems. However lack of knowledge along with von Neumann principles that are obvious in our thinking leads nowadays to ineffective use of these unique means. At the same time, algorithms guessed rightly enable not only to elaborate powerful information devices but to make clearer to some extent mechanisms of the cerebral cortex activity [25].

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