IEEE Second International Conference on Data Stream Mining & Processing
August 21-25, 2018, Lviv, Ukraine

Applying the Neuronetchic Methodology to Text Images for their Recognition

Bohdan Durnyak
Department of Automation and Computer technology
Ukrainian Graphic Arts Academy
Lviv, Ukraine
durnyak@uad.lviv.ua

Oleksandr Tymchenko
Department of Safety Engineering,
University of Warmia and Mazury
Olsztyn, Poland
o_tymch@ukr.net

Oleksandr Tymchenko Jr.
Department of Computer science and Information technology
Ukrainian Academy of Printing
Lviv, Ukraine
bratokokok@gmail.com

Bohdana Havrysh
Department of Preprinting Technology
Ukrainian Academy of Printing
Lviv, Ukraine
dana.havrysh@gmail.com

***Abstract* — There is considered the methodology for recognizing text images based on neural networks, methods and algorithms for building a neuro-fuzzy system for recognizing text images, in particular methods for improving the quality of text images and reducing noise through linear and nonlinear filtration. Features of binarization of such images, fuzzy processing of images to allocate boundaries and segmentation of symbols, and the ability to implement grammar for the structural recognition of text images is shown. The simulation of the developed system is also carried out.**

Keywords — OCR system, fuzzy image processing, neural networks.

I. Introduction

With the development of information technology it has become possible to facilitate, accelerate and improve the quality of recognition of printed or handwritten texts. The first element of the letter recognition system is a scanner or a digital camera that inserts text images into the computer. To create a text document, you need to recognize individual characters in this image. There is a range of software that have virtually automated the process of recognizing texts. However, it is not always possible to ensure a satisfactory result in the case of distortions of printer or handwritted text images of various types (geometric, noise, etc.) [1]. The problem of effective text recognition plays an important role in the areas of informatization of various processes of human activity. The textual presentation of information, in comparison with graphic, allows significantly reduce the costs of storing and transmitting information, and also allows us to implement all methods of using and analyzing electronic documents. Therefore, the greatest interest from a practical point of view is precisely the transformation of information from paper carriers into a text electronic document.

II. General Characteristics of Text Recognition Systems

The OCR system (for example, FineReader, OmniPage, Readlris, etc.) receives a digital image of a scanned or photographed document and forms the text containing this image in one of the formats of electronic text documents (Fig. 1) [2].

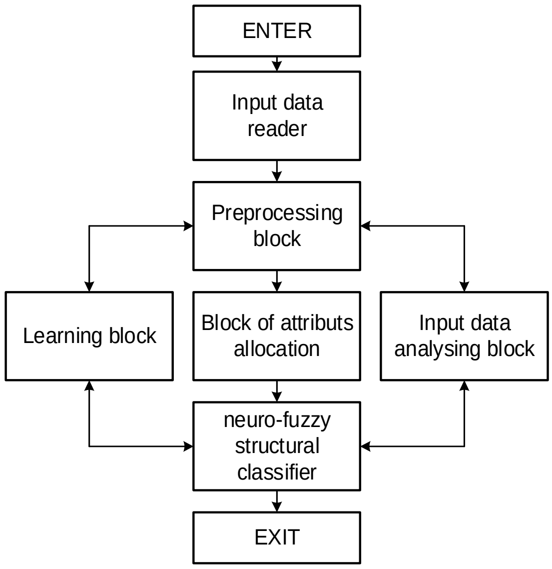

Fig. 1. The generalized structure of the neuro-fuzzy OCR system

Block of attributes allocation has a different complexity depending on the nature of the image being recognized, as well as the methods that are used. Each pre-processed object must be represented in the form of a language-type structure, such as a chain. This process consists of two subprocesses: segmentation and allocation of non-intrusive elements. The main purpose of the segmentation process is to select individual elements from the image to highlight the features or compare the differences with the standard samples in memory. That allow the recognition to obtain a text that is almost identical to the original.

The classification block generates signs of matching elements of the image with reference samples. The classification efficiency is evaluated by the number of features that will be used for this compliance [3].

Preliminary processing of digital images is considered as the result of eliminating the various types of interference and the effects of distortions on which this image was formed. Since methods for improving the quality of images in the frequency domain require a high computational complexity, it is advisable to use spatial in this case.

Most of these operations of OCR systems due to the fuzziness and blurriness of the parameters it is expedient to execute methods of fuzzy logic.

Thus, the purpose of this work is to develop methods and algorithms for constructing a neuro-fuzzy recognition system for text images that contain [4]:

1. reduce noise of text images;
2. binarization of images;
3. allocation of boundaries and segmentation of characters;
4. realization of grammar for the structural recognition of text images.
5. Verification of proposed methods.

III. Decrease of digital images noise

To reduce noise, there are used linear and nonlinear filters that store sharp changes and edges of objects while eliminating noise. Most often noise is considered as impulse noise, Gaussian and mixed pulse and Gaussian noises [5].

In the case of mixed noise, linear and nonlinear filters can be used sequentially.

Gauss filter (linear) averages pixels around the point of the image according to Gauss's law $(x, y) \in \mathrm{Z}^2$: $G(x,y) = \frac{1}{2\pi\sigma^2}\exp\left(-\frac{x^2+y^2}{2\sigma^2}\right)$. This filter is separable, filtering can be performed in rows and columns of the image matrix, since it decomposes into two independent filters at different coordinates.

Median filter (nonlinear) best deals with impulse noise. The work of the median filter consists in choosing the median from a set of pixels around: $Im_{i,j} = \mathrm{med}\left[Im_{i+s,j+t}, (s,t) \in W\right]; (i, j) \in \mathrm{Z}^2$. All pixel values around *(s, t)* relative to the pixel of the image $(i, j) \in \mathrm{Z}^2$ are sorted in order of magnitude, then the median value is selected, which replaces the central pixel around.

Note that the processing of images due to fuzziness and blurring of data is today one of the key in the theory and practice of developing information systems. One of the simplest algorithmic methods of image processing is "soft computing" with the use of fuzzy logic. This will improve its visual quality by improving the detail differentiation and increasing detail in general for further classification and image recognition.

Fuzzy image processing is a set of various fuzzy approaches, which are understanding, representation, processing of images, their segmentation and classification. In the process of recognition, the process of pre-fuzzy image processing is extremely important, because a quality of the data that arrives at the inputs of the neural network depends on it. The algorithm of the previous fuzzy processing can be represented in the form of a sequence of steps (Fig. 2): image acquisition; converting the resulting color image into a grayscale image; fuzzy image processing (fuzzyfication, fuzzy output system, defuzzyfication) [6].

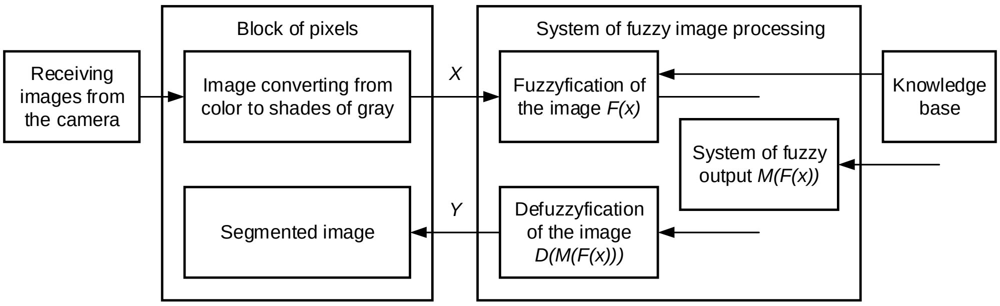

Fig. 2. Algorithm of the previous fuzzy processing of images for their segmentation

A. Binarization of the image

In image binarization the pixel value is conventionally considered equal to zero or one: if its value is above a certain threshold, it corresponds to a white color if it is below the set threshold, that is black. If P(*x*, *y*) > PT(*x*, *y*) then the pixel in the binary image is white, otherwise black.

The threshold surface of the PT is a matrix whose dimension corresponds to the dimension of the original image [7]. All methods of binarization are divided into two groups based on the principle of constructing a threshold surface – these are methods of global and local processing of binarization.

In the methods of global processing, the threshold surface is a plane with a constant brightness value, it means that the threshold value is the same for all pixels of the original image. Global threshold processing has a significant disadvantage – if the original image has non-uniform lighting, the areas that are illuminated worse are classified as black.

In local methods, the threshold value varies for each point based on the features of the domain belonging to the vicinity of a given point.

In the developed algorithm, the original half-tone image, given in digital form, is divided into square matrix *S* with size $h \times h$ and elements $S(x,y) \in [0,1]$. Each matrix S is transformed into a binary matrix r of the same size. The transformation $S \rightarrow r$ is carried out under the condition that the matrix is equal to the brightness:

$$Ent \sum_{x,y} S(x,y) = \sum_{x,y} r(x,y) = b \,, \qquad (1)$$

where brightness is the sum of the elements of each matrix. The brightness of the binary matrix is equal to the number of units b. During each $k = \overline{1,b}$ appealing to the elements of the matrix S in it, the position of the element with the maximum value is determined. In place of this position in S zero is written, and in the binary matrix r a unit is written [8].

The criterion for constructing a binary matrix is the minimum of the Euclidean distance between the binary and the halftone matrices.

Then the task is to choose from *2n* matrices. The algorithm searches for the maximal element of the matrix S, so the number of steps in the order of *bn* is required. Unlike pseudo-tone [8] methods, the method of locating zeros and units in the investigated algorithm allows you to convert a semitone unit based on its brightness histogram. Visually this is manifested in a more accurate reproduction of the details and boundaries of objects in a binary image.

B. Algorithm of fuzzy processing for boundaries and segmentation of images allocation

After binarization, the image enters the system of fuzzy image processing (Fig. 3).

Fuzzy image processing consists of three main phases: F-image, fuzzy-output system *(M)* on the values of affiliation, and defuzzifications of the *(D)* images. After transferring the image from the gray-level image to the phase-out, the fuzzy output system is determined by the value of the accessory function.

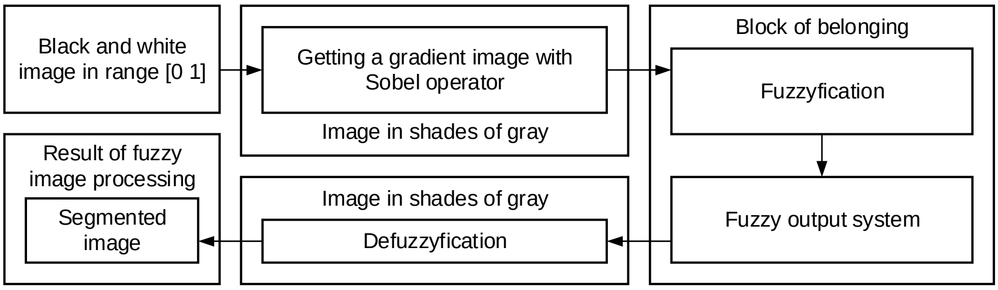

Fig. 3. Algorithm of fuzzy processing of images to allocate boundaries

An image of X-size $M \times N$ with L gray levels g = 0, ..., L-1 can be defined as a fuzzy single-point set that specifies the value of each pixel attribute relative to the image property (for example, brightness, smoothness, etc.).

$$X = \bigcup_{m=1}^{M} \bigcup_{n=1}^{N} \frac{\mu_{mn}}{g_{mn}}, \; \mu_{mn} \in [0.1] \qquad (2)$$

where μ_{mn} and g_{mn} – assignments of the mn pixel in the fuzzy set. Determining the values of affiliation depends on the specific application requirements and knowledge base.

Since the symmetric parts of the bonding site of the membership function are not always effective, attemption in using fuzzy logic to improve the quality of the half-tone images leads to the need to construct S-like fuzzy functions. That have a changed center of symmetry [9]: the function of belonging is described as two glued parabolic links with a continuous derivative in the place of gluing, that is, functions of the second order.

The specific choice of methods of defuzzifications is carried out depending on the desired behavior of the fuzzy output. It is advisable to use the center weighting function of belonging fuzzy set.

$$Y = D(M(F(X))) \,. \qquad (3)$$

C. Construction of grammar for the structural recognition of text images

To justify the method of constructing the grammar of nonstructural image recognition and character classification, consider the following recognition methods.

In the comparison method, the selected element is compared with the database, where each object is represented by different angles, scales, displacements, deformations. For letters in the database, you should also specify the font, font properties, etc.

The second approach is an analysis of the characteristics of the image. In the case of optical text recognition, this may be the definition of the geometric parameters of individual characters [10].

Methods, that use artificial neural networks, require a large number of examples in training, but have higher efficiency and productivity. In these methods, the symbol image is reduced to some standard size, for example, 16x16 pixels. The values of brightness in the nodes of the normalized raster are used as input parameters of the neural network. The number of output parameters of the neural network is equal to the number of recognizable characters. The result of the recognition is a symbol that corresponds to the highest value of the source vector of the neural network.

Note that structural description is:

- understandable for a person who solves the problem of object recognition;
- suitable for computer realization;
- free from complexive computing and information loss.

Structural features used in the structural description are non-unique (elementary unique) elements (symbols), primitives of the image. Structural methods store information not about the spontaneous character writing, but about its topology. That is, the standard contains information on the mutual placement of individual components of the symbol [11]. In this case, the size of the distinguished letter and the font that it is printed is not important [12].

The recognizable symbol is given to some sample that has reference dimensions and positions and is smoothed. That means, that an exclusion from the image of all elements that led to its distortion, by replacing the group of image elements (usually adjacent ones) with an element equivalent to them.

The obtained image is subjected to the procedure of skeletonization (reduction) [13]. The contour of the skeletal representation is described in the form of a series of special points of the special points and a circuit code bypassing the circuit clockwise, consisting of an anchor point, a number of codes, and an array of directions from the next point to the next. Special points are end-points and branch points (triodes). These are the points whose neighbors form at least three connected areas. By renumbering special points and changing the path start, there is made the contour identification with one of the main types. Operating a limited number of atomic (non-derivative) elements (primitives), you can get a description of various objects.

As a result of connections from non-derivative elements (structural features) there will be formed an object similar to the way the sentences of the language are constructed by combining words that consist of letters. In this structural methods have an analogy with the syntax of natural language.

For recognition we use sentences, each of which describes the structure of an object from non-derivative (elemental) elements. Structural or linguistic classification of an object in such case is performed by comparing the sentence of an unknown object with standard sentence classes.

D. Characteristics of texts` image

The peculiarity of these images [14] is that they consist of a large number of interconnected parts. Therefore, it is expedient to analyze such images using methods of structural recognition. The result of this recognition is not attribution of the symbol image to the prototype, but the list of characters and relations between them. The complexity of recognizing such images is that the symbol is not defined uniquely by its image. The name of the character image depends not only on the image of this fragment, but also on its place, environment.

Structural recognition of symbols in the conditions of random noises is reduced to finding the optimal image of the characters that are recognized. The function of quality is to search for the most probable set of hidden image parameters. For example, in order to recognize the line of the text, the requirement to find the most to find the most consistent number of letters is the same as requiring the minimization of the number of incorrectly recognized characters.

Images that contain texts, tables, drawings, are created and read in accordance with certain rules, which can be formalized as a grammar. Obviously, algorithms for the recognition of such images should be based on the use of the rules of this grammar.

Methods for creating such grammar are as follows:

- usage of graphs theory. The image of the text is presented in the form of a well-defined graph. The tasks of recognition are presented as the problem of finding an isomorphism of the reference and input graphs, or of the isomorphism of their subgraphs.
- methods of the theory of formal languages and grammar. The image is considered as a word in some formal language, which is given using constructs that are generalizations of the Khomsky grammar. Recognition is to find the best in a certain meaning of the output of an image in a given grammar [15].

The grammar considers the image as an object, consisting of certain rules from a large number of elementary parts. These parts and rules can differ significantly from each other (for example, recognition of notes [16] or recognition of mathematical formulas [17]).

Let T be a certain rectangular subset of a two-dimensional integral lattice: $T = \{(i, j) \mid 0 \le i < H, 0 \le j < W\}$. The set T is called the field of view, the numbers H and W — its height and width, and the elements of the field of view will be called pixels. Pixel colors are selected from a finite Y set. The reflection $x: T \to Y$ is called the image, the value $x(t)$ determines the color of the image x in the pixel $t \in T$.

The two-dimensional context-free grammar will be $G = \langle E, V, P, \varepsilon \rangle$, where E is the set of terminal images containing one-pixel images (images determined by the size of 1 pixel) of all colors from the set Y, V.

Y, V is the set of nonterminal names (metacharacters) assigned to parts of the image in the process of generating it using grammar, $\varepsilon \in V$ is an axiom, used to name all, completely generated images, P – set of rules of output. It contains the rules of three types: the rules of horizontal concatenation, vertical concatenation (association of image blocks) and the rules of substitution. Each separate set of these rules will be marked *Ph, Pv, Ps* accordingly.

The rules for the substitution of *Ps* have the form $v \to e$, where $v \in V$ –nonterminal name, and $e \in E$ – terminal image.

The set of rules of horizontal concatenation *Ph* contains triples of non-thermal names of the form $v \to vl|vr$. That is, any rectangular image fragment can get the name v if it can be broken up by vertical lines on such two rectangular fragments that the left already has the name *vl*, and the right one is *vr*.. The symbol | is used to divide a pair of nonterminal names in the rules of horizontal concatenation. Similarly, the set of rules for vertical *Pv* concatenation contains triples of nonterminal names of the form $\nu \to \nu t / \nu b$. That is, any rectangular image fragment may get a name *v*, if it can be split by a horizontal line on such two rectangular fragments that the upper one already has the name *vt*, and the lower one is *vb*.

Grammar G is composed of images that can be assigned a name ε. The sequence of rules applied to the image *x*, which results in the assignment of the name *ε* to the entire image, is called the output of the image x in the grammar G. The algorithm [8] for solving the problem is a direct generalization of the Cocke-Younger-Kasami algorithm [18] to determine the relevance of the language of a certain context-free grammar of the Khomsky. t consists in the fact that in the sequential review of all rectangular fragments of an image for each of them it is determined what names can be assigned to him in this grammar. At the same time for reviewing fragments are arranged in size.

The introduction of a two-dimensional context-free grammar and the formulation of a task for exact collision obviously have a number of disadvantages that significantly limit their practical application:

- the formalism of two-dimensional context-free grammar does not always allow you to find a real image that can be split into rectangular fragments, and thus the given fragments do not intersect;
- excessive detailing of the rules of grammar: for each image it is necessary to indicate how it consists of smaller parts up to the level of individual pixels. Obviously it should be used larger fragments of the image, for example, fragments that correspond to individual text lists;
- setting the task for exact collision requires an exact match of the color values of individual pixels of the image with the colors of the terminal images. This condition is not fulfilled if there is a noise characteristic of the recognition.

The basic context-free construct introduced in [19] allows us to eliminate these disadvantages, as it:

- describes the image as being composed of fragments of an arbitrary, not just rectangular shape;
- the process of constructing images is set to the level of a set of term fragments, whose sizes can be much larger than the pixel size;
- a fine is imposed for the assignment of names to fragments of an image, which for a given fragment is equal to the sum of the fines of the fragments from which it was formed;
- the fine for the term fragments is determined by an arbitrary function that is not related to the formalism of context-free grammar. This allows us to use heuristic reasoning in its construction. In the task of recognizing texts, it can have any function that defines the similarity of an arbitrary letter and a fragment of an image.

E. The neural network functioning

To construct a non-structural character recognition system, there is used a neural network of reverse error distribution, which consists of several layers of neurons, and each neuron of the previous layer is associated with each neuron of the next layer. In such networks, after determining the number of layers and the number of elements of each layer, it is necessary to calculate the values of the weights and thresholds of the network in such a way to minimize the forecast error. For network teaching is used an algorithm for reverse error spreading. It calculates a vector gradient surface error. Then it moves to a certain value in the direction of the vector (it will indicate the direction of the fastest descent), where the error value will be less. This gradual progression will gradually lead to a minimization of the error. Denote the matrix of weight coefficients from the inputs to the hidden layer ***W***, and the matrix of weights connecting the hidden and output layer — ***V***. The entries will be numbered only by the index *i*, the elements of the hidden layer — the index *j*, and the outputs — by the index *k*. The number of network inputs is *n*, the number of neurons in the hidden layer is *m*, the number of neurons in the output layer is *p*. If the network is studying on a sample ($\boldsymbol{X}^t$, $\boldsymbol{D}^t$), $t=\overline{1,T}$. Then the learning algorithm for multilayer perceptron will look like [20].

Step 1. Initial initialization. For weighted coefficients we give small random values, for example, from the range (-0.3, 0.3); set: ε – learning accuracy parameter, · ≈0.1 – learning speed parameter (may be decreased in the learning process), N_{max} – the maximum number of iterations.

Step 2. Calculation of the current output signal. At the network entrance we submit one of the images of the training sample and determine the values of the outputs of all neurons of the neural network

Step 3. Calculation of the weight change for the source layer of the neural network:

$$V_{jk}^{N+1} = V_{jk}^{N} - \alpha \frac{\partial E}{\partial V_{jk}},$$
$$\text{where } \frac{\partial E}{\partial V_{jk}} = \delta_k y_j^c,\ \delta_k = (y_k - d_k) y_k (1 - y_k) \quad (4)$$

For a hidden layer:

$$W_{ij}^{N+1} = W_{ij}^{N} - \alpha \frac{\partial E}{\partial W_{ij}}, \quad (5)$$

where $\frac{\partial E}{\partial W_{ij}} = \left(\sum_{k=1}^{p} \delta_k V_{jk}^{N+1} \right) y_j^c \left(1 - y_j^c\right) X_i$.

Step 4. Steps 2-3 repeating for all learning vectors. The training ends after achieving for each of the learning images the value of the error function which does not exceed *ε* or after the maximum allowable number of iterations.

Below is a review of the work of the developed neuro-fuzzy system (with a 5x5-pixel window) with the commercial product ABBYY FineReader 11 Corporate

Edition (the image of the page text is 702 characters, the Gaussian noise is 0.03 from the black level). For practical implementation, the Matlab Simulink software environment with built-in Fuzzy Logic Toolbox fuzzy logic elements is selected.

TABLE I. RESULTS

Developed system		**ABBYY FineReader 11**	
Work time	***% errors***	***Work time***	***% errors***
40 s	16	< 2 s	2

Not enough high quality recognition of the developed system compared with the commercial product due to the small size of the selected window.

IV. CONCLUSIONS

The main stages of processing of digital images for the tasks of character segmentation and subsequent recognition of texts are considered. The algorithm of preliminary processing using fuzzy logic and the process of binarization of the image is considered in detail. A fuzzy processing algorithm is constructed to draw the boundaries of characters in the image.

It is shown that the algorithm for solving the problem of syntactic analysis in the chosen grammar is a generalization of the corresponding algorithm for two-dimensional context-free grammars and consists in a sequential calculation for each fragment of a fine for assigning to it each name [19, 20].

The time and spatial complexity in the case of two-dimensional context-free grammars is very height ($O(H^2W^2(H + W))$ and $O(H^2W^2)$). This complexity limits the application of algorithms in practice.

The time and spatial complexity of these algorithms is determined first of all by the number of fragments that are reviewed in the course of their work. Therefore, the reduction of this number is the main way to reduce the complexity of the recognition algorithms.

The methods and algorithms that are considered allow us to approximate the methods of OCR systems to those that are used by people, because despite the great achievements in this area, there are no systems that could equalize the recognition of the text with the person.

ACKNOWLEDGMENT

The authors are appreciative to colleagues for their support and appropriate suggestions, which allowed to improve the materials of the article.

REFERENCES

[1] S. Kumar, S. Chandrakar, A. Panigrahi and S. K. Singh, "Muzzle point pattern recognition system using image pre-processing techniques," 2017 Fourth International Conference on Image Information Processing (ICIIP), Shimla, India, pp. 1-6, 2017.

[2] J. R. Balbin, M. P. Sejera, C. O. A. Martinez, N. A. M. Cataquis, L. M. H. Ontog and J. K. Toribio, "Cloud based color coding scheme violator plate detection through character recognition using image processing," 2017 7th IEEE International Conference on Control System, Computing and Engineering (ICCSCE), Penang, pp. 253-257, 2017.

[3] S. Antoshchuk, "The automatizated systems with the visual information processing design," International Conference Modern Problems of Radio Engineering, Telecommunications and Computer Science, Lviv-Slavsko, Ukraine, 2004, pp. 268, 2004

[4] Y. Cao, T. Zhang, S. Zhang and B. Luo, "Forward scattering bistatic radar imaging method and practice data processing," in Journal of Systems Engineering and Electronics, vol. 22, no. 2, pp. 206-211, April 2011.

[5] S. Słomiński, "Potential resource of mistakes existing while using the modern methods of measurement and calculation in the glare evaluation," IEEE Lighting Conference of the Visegrad Countries (Lumen V4), Karpacz, pp. 1-5, 2016.

[6] I. Kalaykov and G. Tolt, "Fast fuzzy signal and image processing hardware," 2002 Annual Meeting of the North American Fuzzy Information Processing Society Proceedings. NAFIPS-FLINT 2002 (Cat. No. 02TH8622), pp. 7-12, 2002.

[7] L. Dorosinskiy and F. Myasnikov, "Radarsignal classification algorythms synthesis and analysis," IEEE 2nd Advanced Information Technology, Electronic and Automation Control Conference (IAEAC), Chongqing, pp. 119-122, 2017.

[8] P. Marino, V. Pastoriza, M. Santamarfa and E. Martinez, "Fuzzy image processing in quality control application," Sixth International Conference on Computational Intelligence and Multimedia Applications (ICCIMA'05), pp. 55-60, 2005.

[9] M. I. Chacon, L. Aguilar and A. Delgado, "Definition and applications of a fuzzy image processing scheme," IEEE 10th Digital Signal Processing Workshop, 2002 and the 2nd Signal Processing Education Workshop., pp. 102-107, 2002.

[10] P. Melin, C. I. Gonzalez, J. R. Castro, O. Mendoza and O. Castillo, "Edge-Detection Method for Image Processing Based on Generalized Type-2 Fuzzy Logic," in IEEE Transactions on Fuzzy Systems, vol. 22, no. 6, pp. 1515-1525, Dec. 2014.

[11] R. Chellappa et al., "Towards the design of an end-to-end automated system for image and video-based recognition," 2016 Information Theory and Applications Workshop (ITA), La Jolla, CA, pp. 1-7, 2016.

[12] D. Peleshko, T. Rak, and I. Izonin, "Image Superresolution via Divergence Matrix and Automatic Detection of Crossover," International Journal of Intelligent Systems and Applications (IJISA), vol.8, no.12, pp.1-8, 2016. DOI: 10.5815/ijisa.2016.12.01

[13] N. Ito and M. Hagiwara, "Image description generation without image processing using fuzzy inference," IEEE International Conference on Fuzzy Systems, Brisbane, QLD, pp. 1-8, 2012.

[14] L. Vivona et al., "Unsupervised clustering method for pattern recognition in IIF images," 2016 International Image Processing, Applications and Systems (IPAS), Hammamet, pp. 1-6, 2016.

[15] Z. Qu, G. Xiao, N. Xu, Z. Diao and H. Jia-Zhou, "A novel night vision image color fusion method based on scene recognition," 2016 19th International Conference on Information Fusion (FUSION), Heidelberg, pp. 1236-1243, 2016.

[16] J. Calvo-Zaragoza, A. H. Toselli and E. Vidal, "Handwritten Music Recognition for Mensural Notation: Formulation, Data and Baseline Results," 2017 14th IAPR International Conference on Document Analysis and Recognition (ICDAR), Kyoto, pp. 1081-1086, 2017.

[17] E. Tapia and R. Rojas, "Recognition of on-line handwritten mathematical formulas in the E-chalk system," Seventh International Conference on Document Analysis and Recognition, pp. 980-984, 2003.

[18] F. Rousset, N. Ducros and F. Peyrin, "A Semi Nonnegative Matrix Factorization Method for Pattern Generalization in Single-Pixel Imaging," in IEEE Transactions on Computational Imaging, vol. PP, no. 99, pp. 1-1, 2018.

[19] F. Alvaro, J. A. S´nchez and J. M. Benedi, "Recognition of Printed Mathematical Expressions Using Two-Dimensional Stochastic Context-Free Grammars," 2011 International Conference on Document Analysis and Recognition, Beijing, pp. 1225-1229, 2011.

[20] K. G. Subramanian, M. Geethalakshmi, A. K. Nagar and S. K. Lee, "Two-dimensional Picture Grammar models," 2008 Second UKSIM European Symposium on Computer Modeling and Simulation, Liverpool, pp. 263-267, 2008.