Optica Applicata, Vol. XXXI, No. 2, 2001

Optoelectronic module for thresholding and binarisation operation

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The present paper deals with an optoelectronic module for thresholding and binarisation operation. The architecture is suitable for an associative memory, neural network and optical pattern recognition. The article presents both the theoretical description and the real optical setup, as well as their comparison.

1. Introduction

The operations of thresholding and binarisation are among the most important transformations in the present approach to signal processing [1]. A binary signal or image is easier to transform, recognize, compress and transmit than other forms of signal. Thresholding operation is used in neural networks and associative memory [2]. It is also useful for pattern recognition.

The necessity to use both operations paved the way to the design of numerous algorithms and systems for thresholding and binarisation of the input signal. They can be divided into the ones working on 1-D signal (stream of data) and the ones working on 2-D signal (picture). They can also be realized by optoelectronic [3]–[5] and electronic methods.

The basis for the present paper is the thresholding setup proposed by BERGERON [3], [6] and its modification by KASZTELANIC [4], [7]. This is an optoelectronic setup of the winner-take-all type, working in the iterative mode. The main aim of the paper is a comparison of the work of the real setup based on optoelectronic elements with its theoretical model simulated on computer.

In Section 2 of the paper the operations of thresholding and binarisation of the optical signal are described, pointing to the differences between the two, as well as the areas of their usage. Section 3 presents the experimentally measured characteristics of such optoelectronic elements as an SLM (spatial light modulator) and a CCD camera. In Section 4, the possibility of designing a setup for thresholding and binarisation with the use of both these optoelectronic devices is discussed. The following two sections deal with the presentation of the results of an optical experiment and a computer simulation. Section 7 presents the analysis of the results obtained and compares the optical setup with its computer simulated counterpart.

2. Thresholding and binarisation of the optical signal

Both thresholding and binarisation of the input signal are commonly used for image processing. They are used for the preliminary treatment of the input scene, such as noise reduction [8] and finding similar areas, as well as for its change into a binary image, or division into binary layers [8]. In the correlation plane both operations are used to intensify the signal and to get rid of cross-correlations [3], [4], [7]. In neural networks and associative memories they are crucial for the work of each single element of the network structure [2], [7], [9]. On the other hand, in optical massive memories they play the role of an element of error correction [10]. Such a vast range of usage brought about the development of numerous methods for the realization of both the thresholding and the binarising functions.

As for image processing, an interesting option of the realization of the thresholding and binarisation function is a setup of the maximum peak extraction (winner-take-all) type, proposed by BERGERON [3]. Its main advantages are the simultaneous work on all the pixels of the processed image and its simple structure based on the non-linear characteristics of the two optoelectronic elements: an SLM and a CCD camera.

The similar range of the two operations mentioned arises from their mathematical similarity. The thresholding function $T_1(x, t_0)$ realizes the operation in accordance with the equation

$$T_1(x, t_0) = \begin{cases} 0 & \text{for } x < t_0 \\ x & \text{for } x \geqslant t_0 \end{cases} \tag{1}$$

where t_0 is the threshold value and x is the input signal.

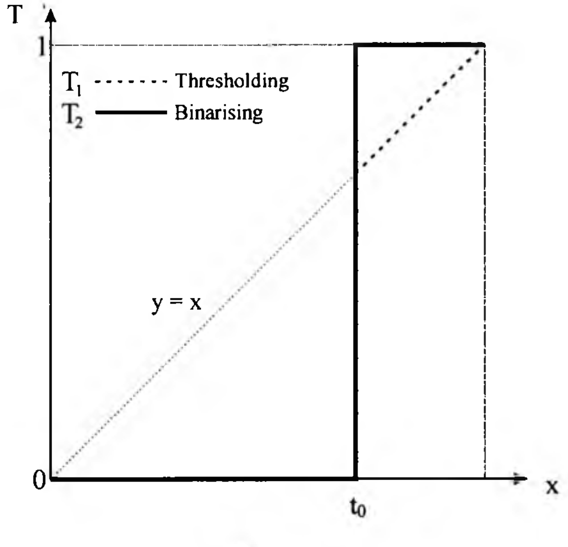


Fig. 1. Thresholding T_1 and binarising T_2 function.

The function $T_2(x, t_0)$ which binarizes the input image, cutting off all the values lower than the given threshold t_0, can be described by the following equation:

$$T_2(x, t_0) = \begin{cases} 0 & \text{for} \quad x < t_0 \\ 1 & \text{for} \quad x \geqslant t_0. \end{cases} \tag{2}$$

The difference between the two consists in leaving the original values of the signal above the threshold t_0 in the first case and in equalling the values to 1 in the second case (Fig. 1).

Both operations can also be carried out on a similar optoelectronic setup whose main elements are an SLM and a CCD camera (see Section 4).

3. Nonlinear characteristics of the SLM and CCD camera

The possibility of using an SLM and a CCD camera for image processing described above arises from their nonlinear characteristics.

The present research was carried out on an SLM of 800 by 600 pixels, manufactured by Central Research Laboratories and on a Pulnix TM-765 CCD camera of 765 by 581 pixels and 256 gray levels. What influenced the results obtained was also a frame-grabber steering the work of the CCD camera. We used an Elsat Grafito frame-grabber of 736 by 566 pixels.

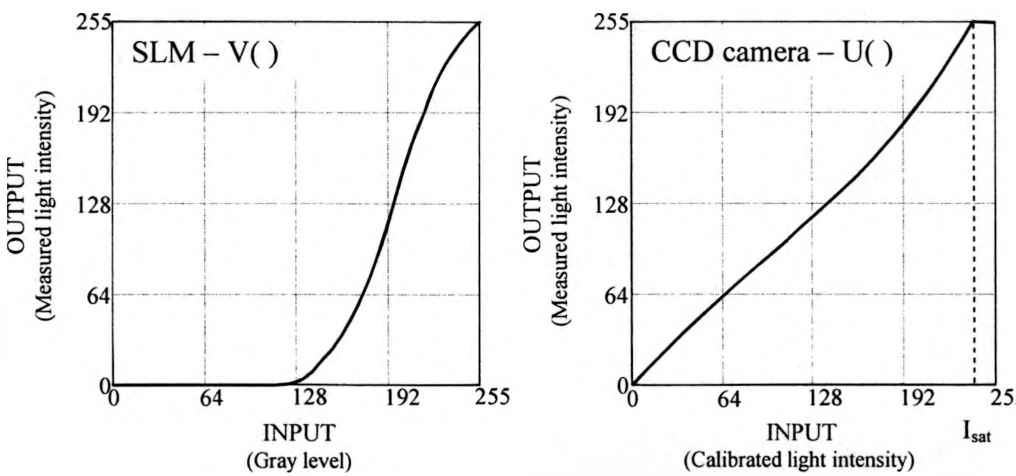


Fig. 2. Nonlinear characteristic $V(\ )$ of the SLM and $U(\ )$ of the CCD camera.

In order to establish the characteristics of the SLM two characteristics were measured. They were the gray level displayed on the SLM and the value of light intensity measured by a calibrated light intensity detector when passing through the SLM. The obtained characteristic $V(\ )$, shown in Fig. 2, is nonlinear. The characteristic is an average of several measurements because the signal on the calibrated light intensity detector changed within the range of ca. 10 per cent. This was due to the non-uniformity of the way all the SLM pixels performed for a given gray level, as well as to the limited number of the gray levels possible to obtain. As a result of measurements, 32 gray levels were established.

When establishing the characteristics $U(\ )$ of the CCD camera, light intensity was measured on the camera and the calibrated light intensity detector as the reference level (Fig. 2). In this case, the light intensity was changed by the location of two linear polarizers. The characteristic was also obtained as an average of several partial results. This was due to the differences, which ranged within several percent for each pixel.

4. Thresholding and binarisation system using an SLM and a CCD camera

The optoelectronic thresholder and binarisation system based on an SLM and CCD cameras is shown in Fig. 3. The main parts of the setup are SLM and CCD2. The CCD1 camera plays the role of the input plane and can be replaced by further elements of the optical setup. Other elements of the setup are a beam splitter and a polarizer, which helps to change the light intensity on the CCD2 camera. The replacement of the polarizer by an additional feedback circuit with optical attenuator allows building a setup which adapts to the character of the signal processed [7]. In the first iteration, the amplitude transmittance t_a^1 of the SLM equals 1, so that the whole undistorted signal is registered on the CCD1 and CCD2 cameras

$$\underset{x,y}{\forall}\, t_a^1(x,y) = 1. \tag{3}$$

The signal from the CCD2 camera is used in the second iteration for the modification of the transmittance of the SLM pixels. The situation repeats until a stable signal is obtained.

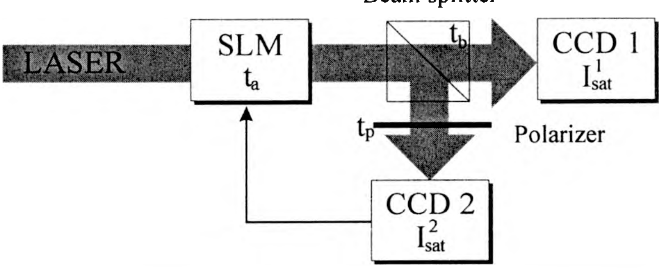


Fig. 3. Optoelectronic thresholder and binarisation system based on a SLM and a CCD.

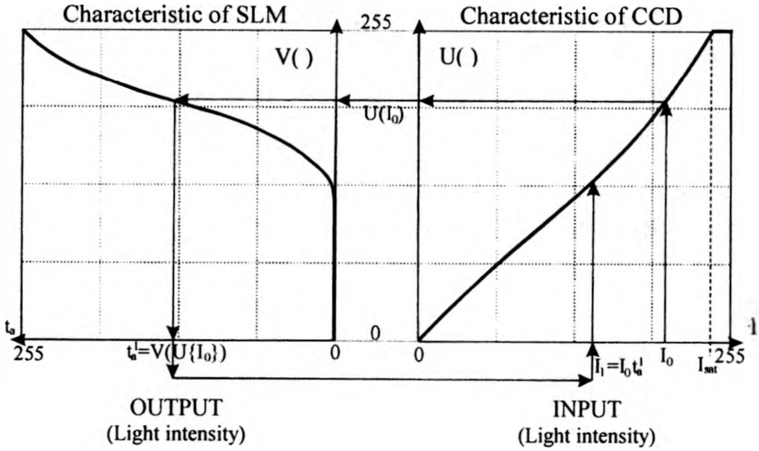


Fig. 4. Idea of work of the thresholder and binarisation system.

Let us examine the two values of the intensity of the input signal (Fig. 4), one of which is above and the other below the saturation intensity I_{sat}. In the first case and in the first iteration, the input signal I_0 is measured on the CCD2 camera. The output signal from CCD2 camera $U(I_0)$ operates the SLM and changes its transmittance to $\{t_a^1 = V(U\{I_0\})$. The input light intensity is not changed, so the input light intensity on the CCD camera in the second iteration is $I_1 = I_0 t_a^1$. The signal I_k on the camera CCD2 diminishes with every iteration k and, as the process continues, will finally reach zero [7]

$$\begin{cases} I_k = I_{k-1} t_a^{k-1} \\ t_a^k = V(U\{I_{k-1}\}) \end{cases} \tag{4}$$

where I_k is the intensity of the signal in the k-th iteration and $V(\ )$ and $U(\ )$ are the characteristics of the SLM and the CCD2 camera, respectively.

In the second case, the transmittance of the respective pixels of the SLM is maximal and does not change the intensity of the passing optical signal. This is due to the fact that the intensity value registered on the camera CCD2 always equals the saturation level I_{sat}. As a result, the intensity transmittance of the SLM pixels equals 1 or 0 after several iterations.

The final result of the work of the setup depends on the place where the signal passing through the SLM is detected. If the result is registered on the camera CCD1 and if the saturation level I_{sat} of the camera is higher than the maximum intensity of the input signal, the result is a threshold system

$$I(x,y)^k_{CCD1} = [A(x,y)^k]^2 = t_b^2\, V\left(U\left\{\left[A(x,y)^{k-1}\, t_p \frac{1-t_b}{t_b}\right]^2\right\}\right)[A^0(x,y)]^2 \tag{5}$$

where $A(x,y)$ is the amplitude of signal in the (x,y) pixel.

On the other hand, if the result is registered on the camera CCD2, the result is a system which binarises the input signal

$$(x,y)^{k}_{\mathrm{CCD2}} = [A(x,y)^{k}]^{2} - (1-t_b)^{2}\, V\left(U\left\{ \left[A(x,y)^{k-1}\, t_p \frac{1-t_b}{t_b} \right]^{2} \right\} \right). \tag{6}$$

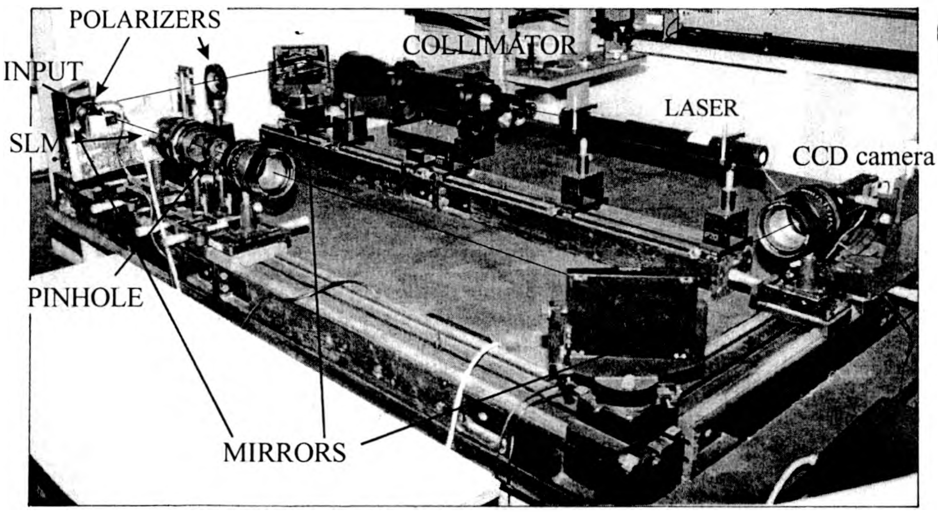
The experiment described below was carried out on the setup with CCD2 camera only. Thanks to that the output signal is always binary.

5. Optical experiment

The theoretical model of an optoelectronic thresholding and binarisation setup described above was built on an optical table [11]. Its scheme and photograph are presented in Fig. 5.

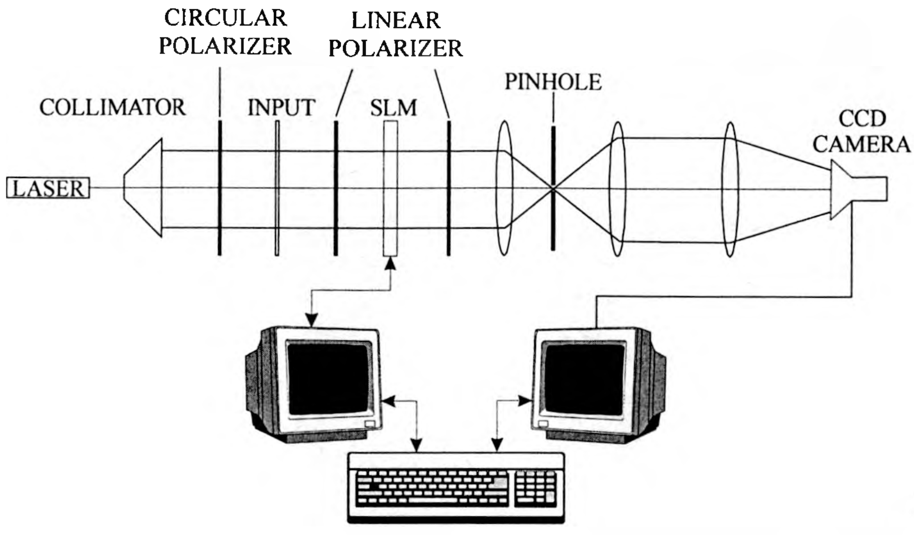
The source of the light beam was a helium-neon laser. The beam was lit onto a pinhole situated in the lens focus (collimator). The aim of these two elements was to obtain homogeneous plain wave lighting onto the input scene and the SLM. Light intensity was regulated with the use of three polarizes: one circular and two linear ones, located on both sides of the SLM. In the theoretical model, the total transmittance of the three polarizes was replaced by a single parameter t_p.

Since an SLM is built of an array of recursive active elements, it plays the role of a diffractive grating. In order to limit the negative effect of this phenomenon, another pinhole was placed behind the SLM. Its role was to cut off the whole information without the zero diffraction order of the processed signal. The pinhole was located in the middle of the light forming system of two identical lenses. Due to the different size of the SLM and the CCD it was necessary also to use the third lens to scale the signal.



a

Fig. 5.a



b

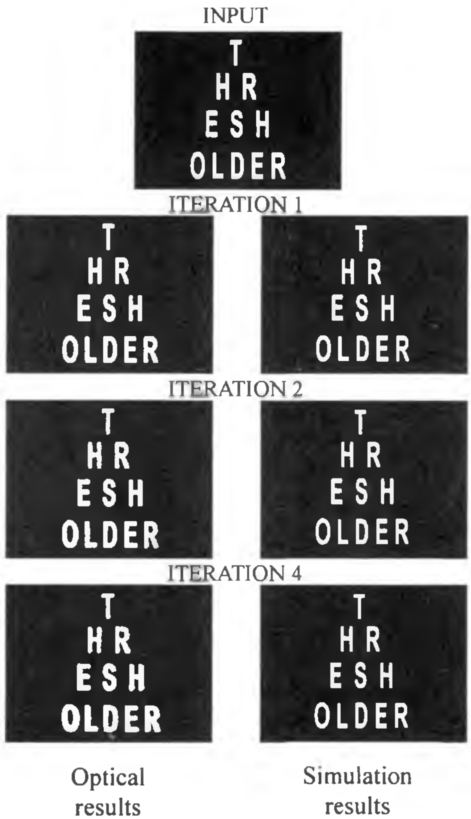
Fig. 5. Photograph (a) and scheme (b) of the binarisation module.

The whole setup was computer controlled [12]. One screen showed the signal simultaneously sent to the SLM, and another screen the signal registered on the CCD. Note that the computer was only the steering element, used to follow the behaviour of the setup, and not to process the signal.

The speed of the system operation depended on the optoelectronic elements used and the frame-grabber [12]. It did not, on the other hand, depend on the speed of the computer. In the experiments conducted the duration of one iteration was roughly 2 seconds.

The experiments were carried out for several input scenes. The results of work of the setup for binary signal are shown in Fig. 6 (left column), for gray level signal in Fig. 7 and correlation signal in Fig. 8. In each case, the proper work of the setup was checked for various saturation levels I_{sat} of the camera CCD2. An example of the work of the binarising setup is presented in Fig. 6 for binary input signal, in Fig. 7 for gray level signal, and in Fig. 8 for correlation signal.

The quantitative analysis of the results obtained results leads us to the conclusion that the first iteration brings about the majority of changes. In the consecutive iterations, however, the changes are diminishing, or they do not occur at all. The proper result of the binarising system operation can be obtained already after three or four iterations. This results from the character of the processed signal and the non-linear characteristics of the optoelectronic elements used. The majority of signals whose intensity value is below I_{sat} are cut off in the first iteration. In the following iterations all the remaining pixels with intensity lower than I_{sat} are lost. The processed image undergoes minor changes also in the consecutive interations, which is due to the size differences of the setup elements, as well as scaling on the optical and electonic route and other distortions.



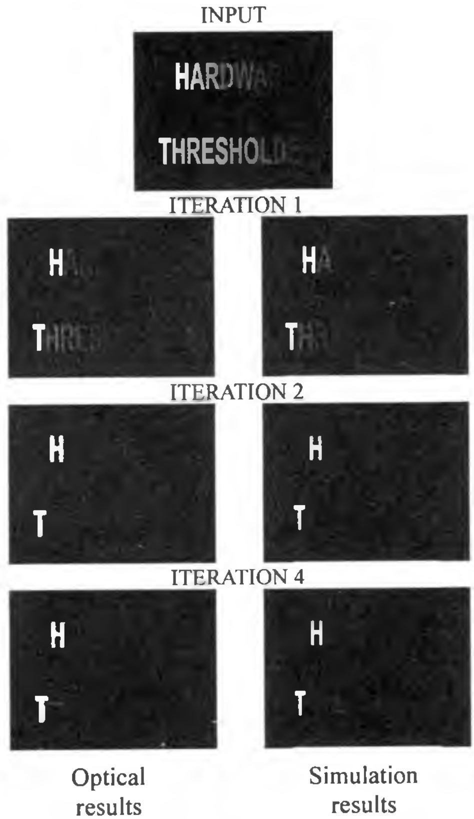


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Fig. 6. Example of the work of the binarising setup for binary signal.
Fig. 7. Example of the work binarising setup for gray level signal.

6. Computer simulation

The aim of the computer simulation was the closest approximation of the real optical setup, in order to compare the results of the optical experiment with the theoretical model. The simulations included the nonlinear characteristics of the SLM and the CCD camera measured in the experiment. Apart from that, a limited number of gray levels was taken into account in the case of SLM. Another element which imitated the real optical setup was the scaling of the image between the SLM and the CCD camera on the optical route and scaling it backwards on the electronic route. This was due to the differences in the size of the two elements, as described in Sec. 2.

The simulation did not take into account other elements which could influence the results obtained. These included the difference in the size of the frame-grabber and the CCD camera it worked with, the non-uniformity of the pixels of the SLM and the CCD, whose values varied within the range of a few percent, and the non

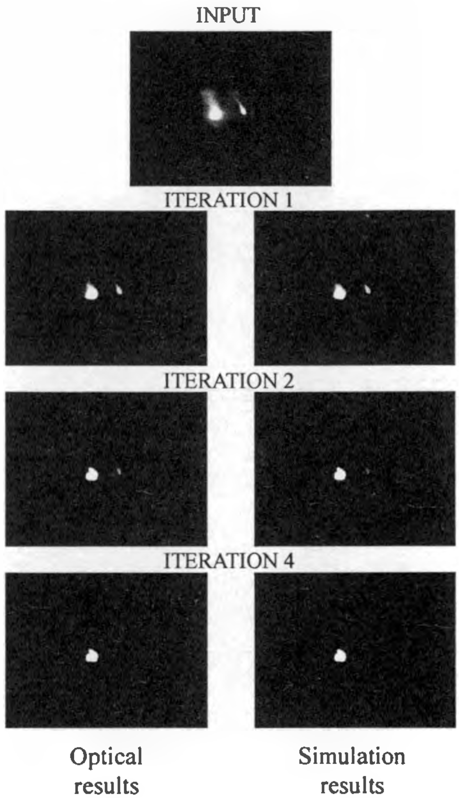

Fig. 8. Exammple of the work of the binarising setup for correlation signal.

-homogeneity of the plain wave lighting the whole setup. Apart from that, the background level for the CCD equalled 0 in the simulation, while in the optical experiment the background equalled 24.

The simulation was carried out for the same input scenes as in the case of the optical setup. Examples of the results for several iterations are shown in Fig. 6 for binary input signal, in Fig. 7 for gray level signal, and in Fig. 8 for correlation signal.

7. Comparison of the results

From the comparison of the figures for the optical experiment and the computer simulation it follows that both setups work in accordance with expectations; however, there are some visible differences. They result form the elements described above which were not included in the simulation.

In order to qualitatively compare both cases another simulation was carried out for the same images, with the absence of any modifications. It was assumed that the model presents an ideal setup, without the necessity to scale the images between the

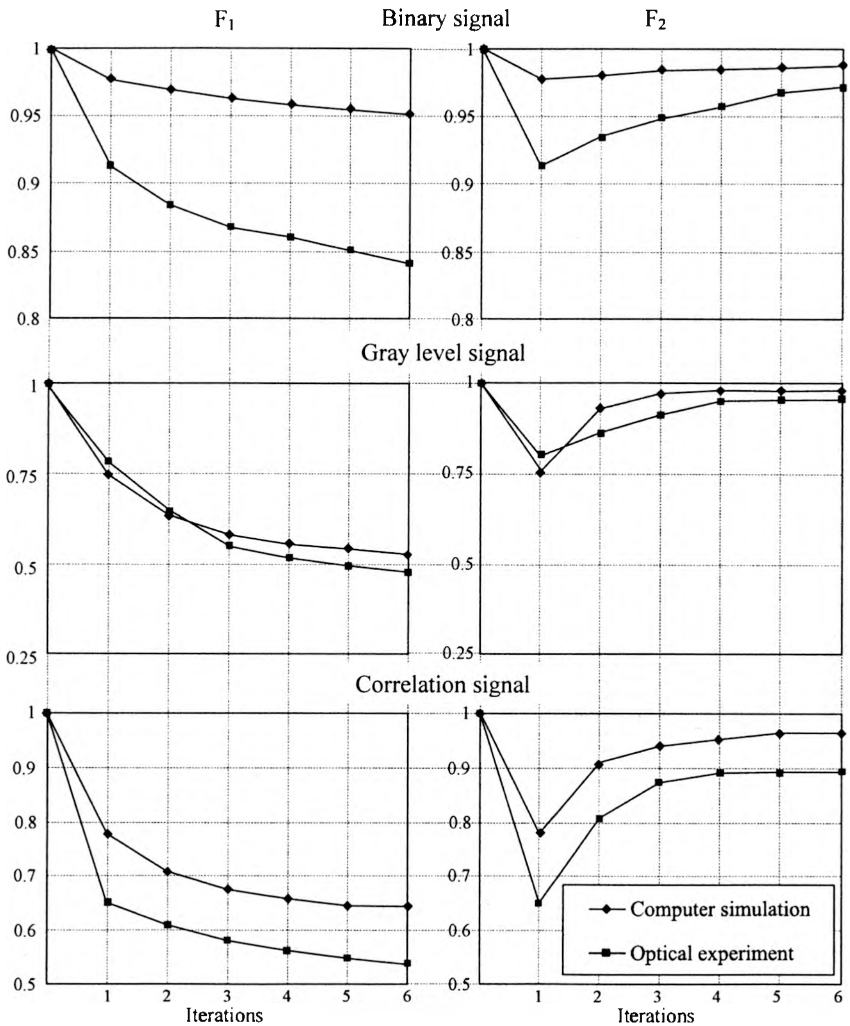

Fig. 9. Image fidelity parameter for binary, gray level and correlation signals.

SLM and the CCD camera, where the SLM performs an unlimited range of gray levels and the CCD background equals 0. This simulation was the reference point for the optical experiment, as well as for the proper simulation which tried to imitate the reality.

The basis for the quantitative analysis was the image fidelity (IF) parameter [13], defined by the following equations:

$$\mathrm{IF}_1^k = \frac{1-\sum\limits_{i}^{M}\sum\limits_{j}^{N}[x(x,j)-y^k(i,j)]^2}{\sum\limits_{i}^{M}\sum\limits_{j}^{N}[x(i,j)]^2} \tag{7}$$

where x is a input signal and y^k is a signal in k-th iteration. In this case, the comparison is done for the first input image and y^k in k-th iteration.

Another possibility is

$$\mathrm{IF}_2^k = \frac{1-\sum_i^M\sum_j^N[y^{k-1}(i,j)-y^k(i,j)]^2}{\sum_i^M\sum_j^N[y^{k-1}(i,j)]^2} \tag{8}$$

where y^k is a signal in the k-th iteration. In this case, two consecutive images of the iterations k and $k+1$ are compared.

The results of the analysis using an IF parameter are shown in Fig. 9.

The quantitative analysis confirms the results obtained on the basis of the qualitative analysis. The image processed in the binarising setup undergoes the greatest changes in the first iteration. In the consecutive iterations the image changes to a lesser extent and the speed of the changes stabilizes on the constant level already after several iterations. This results from the fact that all the elements whose intensity is lower than I_{sat} have already been eliminated from the processed signal. The differences are due to the different sizes of the setup elements. This is also the reason why the signal is completely cut off after fifty to hundred iterations.

The comparison of the results of computer simulation and optical experiment shows that the setup works properly and the results obtained do not differ considerably. In the case of the optical setup the demanded results are obtained in more iterations. It is also in the further iterations that the difference between the two consecutive images is bigger than in the case of the simulation; however, this is due to the size differences described above.

8. Conclusions

The operation and the possibility of building an optoelectronic setup for thresholding and binarisation of an input image have been presented. The proper work of such a setup was confirmed by computer simulations and optical experiments.

The setup can be used wherever there is a need for processing 2-D optical signals. It is possible to increase the effectiveness of the work of the setup and to eliminate the differences in sizes of the elements with the use of optoelectronic devices available. It is also possible to minimize the duration of the work of the setup to roughly one hundred iterations per second.

Acknowledgments — This research was carried out with the financial support of the State Committee for Scientific Research (KBN), Poland, grant No. 8 T11F 028. We also appreciate the help and advice of Prof. K. Chałasińska-Macukow.

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Received May 22, 2000
in revised form September 18, 2000