Chapter 3

Method of Synthesized Phase Objects in the Optical Pattern Recognition Problem

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Abstract

To solve the pattern recognition problem, a method of synthesized phase objects (SPO-method) is suggested. The essence of the suggested method is that synthesized phase objects are used instead of real amplitude objects. The former is object-dependent phase distributions calculated using the iterative Fourier transform algorithm. The method is experimentally studied with an optical-digital Vanderlugt and joint Fourier transform 4F-correlators. The development of the SPO-method for the rotation invariant pattern recognition is considered as well. We present the comparative analysis of recognition results with the use of the conventional and proposed methods, estimate the sensitivity of the latter to distortions of the structure of objects, and determine the applicability limits. It is demonstrated that the SPO-method allows one: (a) to simplify the procedure of choice of recognition signs (criteria); (b) to obtain one-type δ-like recognition signals irrespective of the type of objects; and (c) to improve the signal-to-noise ratio for correlation signals by 20–30 dB on the average. To introduce recognition objects in a correlator, we use SLM LC-R 2500 and SLM HEO 1080 Pluto devices.

Keywords: pattern recognition, method of synthesized phase objects, iterative Fourier transform algorithm, rotation invariant pattern recognition, optical-digital recognition systems, spatial light modulators

1. Introduction

The studies in the fields of Fourier optics, holography, and digital and correlation optics aimed at the solution of the pattern recognition problem remain topical for a long time. This is related to the fact that the recognition problem is object-dependent, i.e., the change in the conditions of recognition or in the type of an object requires, as a rule, the optimization of available methods of solution or the development of new ones [1, 2]. Among the known methods, it is worth to note the following ones: the digital synthesis of Fourier filters [3–6], method of discriminant curve [7, 8], method of stabilizing functional [9], method of projections onto convex sets [10], etc. We emphasize that the mentioned and other available methods lead to a significant number of dedicated solutions, for which the choice of characteristic signs of the object and the subsequent analysis of correlation signals are separate problems. Therefore, topical is the search for the more general solutions of the pattern recognition problem by means of the matched filtering [11] or the joint correlation [12], which are directed to a simplification of the analysis of input data and the main signs of recognition, determination of their connection with the parameters of correlation signals, etc.

Here, we develop a new approach to the solution of the recognition problem. The newness of the proposed approach consists in that we recognize not the object itself, but a certain object-dependent synthesized phase object (SP-object). The latter (its distribution of phases) is calculated with the help of the known iterative Fourier transform (IFT) algorithm [13]. In this case, the problem of recognition of amplitude objects, which belong to arbitrary classes, is reduced to the problem of recognition of phase objects of only one type [14–16].

We also present a development of the SPO-method for the rotation invariant pattern recognition [17]. For the conventional method and the SPO-method, the comparison of the parameters of correlation signals for a number of amplitude objects is executed at the realization of their rotation in an optical-digital joint Fourier transform (JT) correlator. It is shown that not only the invariance relative to a rotation at a realization of the joint correlation for SP-objects but also the main advantage of the SPO-method over the reference one such as the unified δ-like recognition signal with the largest possible signal-to-noise ratio (SNR) independent of the type of an object is attained.

The work is organized as follows: in Section 2, a new approach to the pattern recognition on the basis of SP-objects is presented. The basic results of computational and optical experiments are given. The behavior of cross-correlation signals is studied under the addition of a controlled amount of noises to the structure of objects. In Section 3, a development of the SPO-method for the rotation invariant pattern recognition with an optical-digital JT-correlator is presented.

2. SPO-method: definition, substantiation

We now define an approach, where not the object itself is recognized, but some object-dependent SP-object which is calculated with the help of the known IFT algorithm [13]. In this case, as mentioned above, the problem of recognition of amplitude objects of various classes can be reduced to the problem of recognition of phase objects that belong to the same class. Below, we present the experimental results of recognition of amplitude objects with the use of the conventional and proposed methods, estimate the sensitivity of the latter to changes in the structure of objects, and determine the boundaries of its application. Let us consider the operation of the algorithm (**Figure 1**). For the calculation of SP-objects, we apply IFT algorithm

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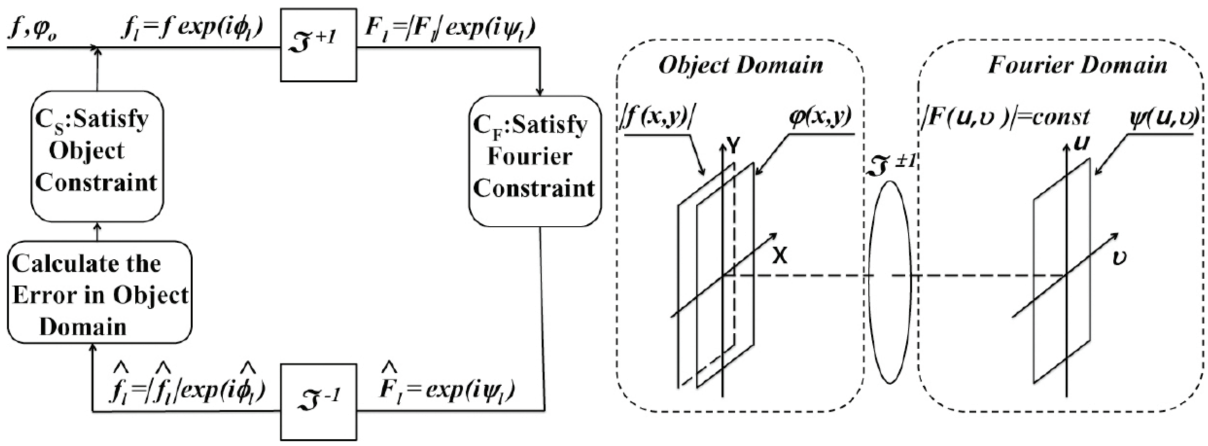
in its kinoform version [18]. In the process of iterations, the phase structure of a kinoform $\psi(u, v)$ is formed in the spectral plane. Simultaneously, one more phase structure, namely $\varphi(x, y)$, appears in the object plane. The function $\phi(x, y) = exp(i\varphi(x, y))$ plays the role of a diffusive scatterer, which is optimized for the object $f(x, y)$ and is necessary for the leveling of the field amplitude in the Fourier plane, i.e., in the plane of a kinoform. However, in the context of the correlation methods of recognition, the phase structures $\varphi(x, y)$ with random distribution of the phase can also be of independent interest not related to the problem of calculation of the kinoform. The matter is as follows. Since the form of $\varphi(x, y)$ for the given number of iterations and the given initial diffuser $\varphi_0(x, y)$ is determined uniquely by the form of the function $f(x, y)$, it is logical to put two questions:

1. While solving the problem of recognition of the object $f(x, y)$, is it possible to replace it by the corresponding SP-object in the form of $\phi(x, y) = exp(i\varphi(x, y))$?

2. Will the solution of the problem with such replacement of the object be more efficient than that within the known methods?



(a) (b)

Figure 1. IFT algorithm (a), illustrative scheme of the IFT algorithm (b).

The computer-based and optical experiments executed by us give a positive answer to both questions. The method of recognition, where the SP-object $\phi(x, y)$ is recognized instead of a real amplitude object $f(x, y)$, is called the method of synthesized phase objects. We now consider the advantages and limitations of this method in more details. To study its basic characteristics in model and optical experiments, we need to determine a collection of recognition objects, to calculate an SP-object for each of them, and to carry out the recognition.

In view of the circumstance that the iteration method of synthesis of the functions $\varphi(x, y)$ for $f(x, y)$ gives no possibility to get a solution in the analytic form, we study the SPO-method for a finite collection of recognition objects. In order to most completely show the potentialities of the method, we choose objects with essentially different types of Fourier spectra.

For the comparison of the conventional and SPO methods, we need to compare their sensitivities to changes in the structure of objects under recognition. As a parameter for the estimation of the sensitivity, we chose the controlled changes that are introduced in the structure of recognition objects. These changes are carried out by means of the pairwise rearrangements of points of the object taken in an arbitrary order. The number of such rearrangements k varied in the limits from zero to several hundreds.

2.1. SP-objects and their basic properties: model experiments

For model experiments, we chose ten amplitude objects of the binary type 300 × 300 points in size. In **Figure 2**, the reference objects f_n (n = 1, 2, 3, 4) are presented.

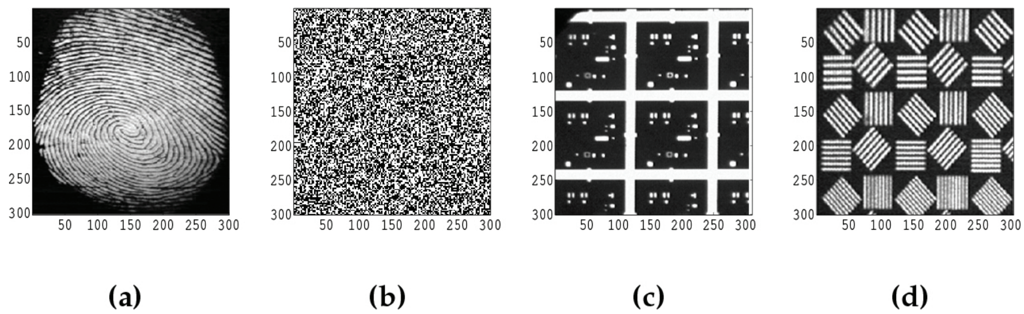


Figure 2. Objects: (a) f_1, (b) f_2, (c) f_3, (d) f_4.

For all of them, we calculated the autocorrelation functions $f_n \otimes f_n$. The SP-objects ϕ_n were calculated by the iteration scheme (**Figure 1a**) with the initial distribution of phases $\varphi_0 = const$. In order to find the degree of connection of ϕ_n with f_n, which determines the degree of suitability of the use of ϕ_n instead of f_n, we obtained ϕ_n for different numbers of iterations N, by gradually increasing N. At a fixed N, we calculated the correlation functions $\phi_{n,N} \otimes \phi_{n,N}$ for the entire totality of $\{\phi_{n,N}\}$. In **Figure 3**, we present object f_4 (1(a)), central fragment of its Fourier spectrum (2(a)), and autocorrelation signal (3(a)). On the right, we show, respectively, a fragment of the phase distribution $\varphi_{4,1}$ of the SP-object (1(b)), shape of its spectrum (2(b)), and a fragment of the autocorrelation signal (3(b)). Analogous results were also obtained for objects $f_1 - f_3$. The presented result is typical and demonstrates the main advantages of SP-objects such as the uniform distribution of the amplitude in the spectral plane and the δ-like autocorrelation signal, which are practically independent of the shapes of Fourier spectra and the type of the autocorrelation signals of real objects, for which they were calculated.

As a result of model experiments, for each f_n, we determined the criterion of choice of ϕ_n from the set $\{\phi_{n,N}\}$ at varying N. The obtained results are demonstrated by the example of object f_4 (**Figure 4a**). Curve (A) shows the behavior of the variance σ^2 of the amplitude of the retrieved image of object f_4 at the calculation of its SP-object relative to the amplitude of the reference object, and curve (B) presents the change in the maximum value of modulus of the Fourier spectrum amplitude of the $\phi_{4,N}$, as N increases. In **Figure 4**(**b–d**), we observe the redistribution of phases of the SP-object in the interval $[0 - 2\pi]$ for various numbers of iterations.

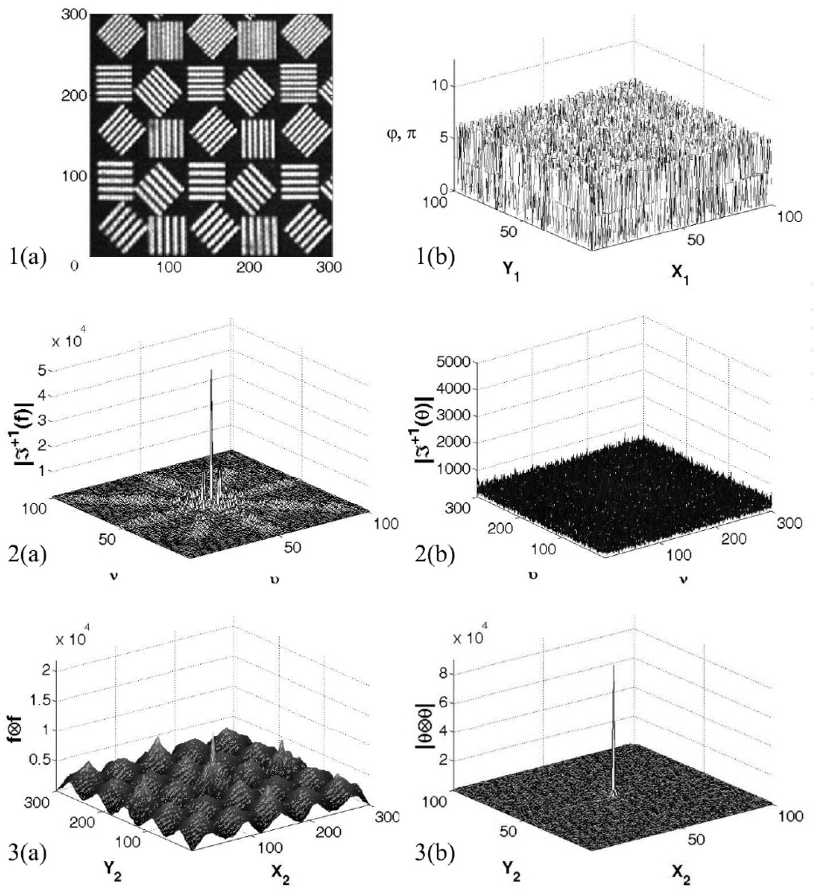


Figure 3. Left (a): distributions for the real object f_4; right (b): for the SP-object $\phi_4 = \exp(i\varphi_4)$: (1) object; (2) Fourier spectrum amplitude modulus; (3) autocorrelation signal.

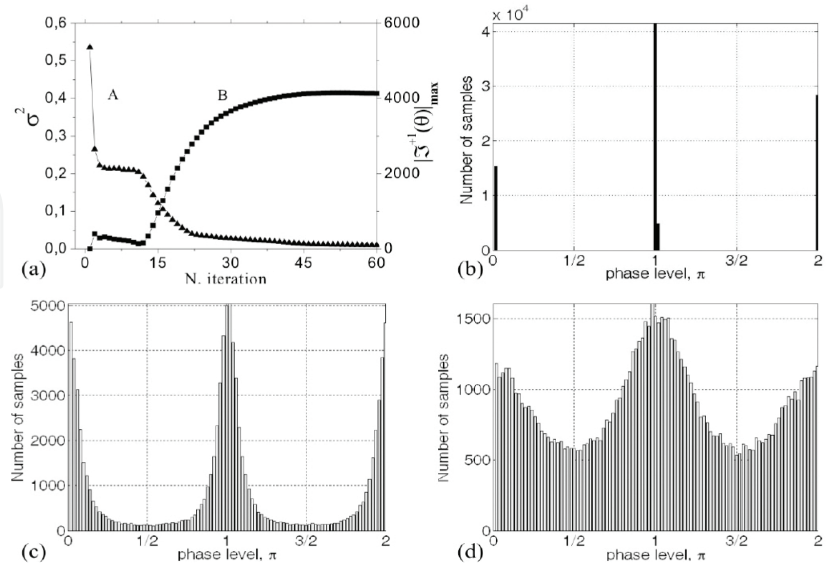


Figure 4. (a) Dependence of σ^2 (A) and $|\mathcal{F}^{+1}(\phi)|_{max}$ (B) on the number of iterations N; histograms for: (b) $\varphi_{4,1}$; (c) $\varphi_{4,13}$; (d) $\varphi_{4,45}$ calculated for 1st, 13th, and 45th iterations.

On the basis of the results of numerical experiments with the whole collection of objects (**Figures 3** and **4**, **Table 1**), we can conclude the following:

- The binary distribution (0 or π) of a phase in the plane of an SP-object obtained on the first iteration is transformed into a continuous one in the interval $[0 - 2\pi]$, as the iteration number increases.
- The distribution of phases in the plane of an SP-object is random.
- The modulus of the amplitude of the Fourier spectrum of an SP-object has a uniform distribution in all cases.

Number of an	**Objects**		**SP-objects**	
object no.	**Frequency[a] $2\xi_{max}$, rel. un.**	**<SNR>[b], dB**	**Frequency $2\xi_{max}$, rel. un.**	**<SNR>, dB**
1	0.30	5.2	0.50	26.2
2	0.25	16.3	0.50	26.2
3	0.20	7.7	0.50	26.2
4	0.37	6.8	0.50	26.2

[a] $2\xi_{max}$, effective band of frequencies.
[b] <SNR>, ratio of the peak value of amplitude of a correlation signal to the mean noise amplitude.

Table 1. Results of recognition of objects and SP-objects in model experiments.

The autocorrelation functions of SP-objects have the δ-like shape and ensure:

1. Maximally possible value of SNR characteristic as for the binary phase masks with a random distribution of elements [19].
2. Possibility to apply a simple threshold criterion to the analysis of the results of recognition.

This is true for both $\varphi_0 = const$ as well as for arbitrary φ_0. We have also established that the SP-objects calculated on the first and all subsequent N-iterations satisfy the following conditions:

1. If there is no correlation between the objects f_n and f_m ($f_n \otimes f_m = 0$), then the correlation is also absent for SP-objects ($\phi_{n,N} \otimes \phi_{m,N} = 0$).
2. If the signal of cross-correlation between the objects f_n and f_m exists ($f_n \otimes f_m \neq 0$), then it exists also for the SP-objects ($\phi_{n,N} \otimes \phi_{m,N} \neq 0$).

The first item indicates that the SP-objects obtained for the uncorrelated real objects are statistically independent of one another. The second shows the possibility to obtain a bijective interrelation between cross-correlation curves for the real and SP-objects.

Thus, we have established that, for SP-objects, the highest degree of uniformity of the amplitudes of their Fourier spectra is ensured already after the first iteration, conditions (1, 2) are satisfied, and the properties of real objects $f(x, y)$ (their significant signs) are integrally represented in the distribution of phase elements in the coordinate plane. Any changes in the

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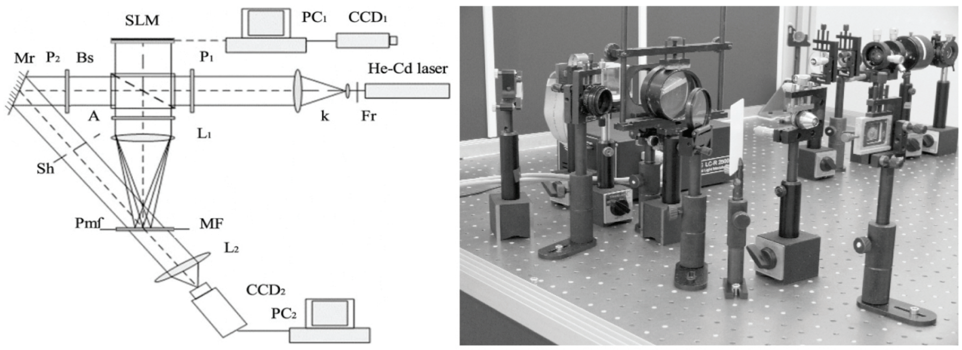
structure of $f(x, y)$ affect directly the distributions of the phase in a plane of the SP-object. This allows one to quantitatively evaluate the indicated variation in the object by a change in the level of a cross-correlation signal from SP-objects calculated for the reference and modified objects, respectively. The following step is the evaluation of the practical value of the proposed method. With this purpose, we will analyze the results of the recognition by the conventional method and the SPO-method executed in a Vanderlugt (VL) correlator.

2.2. Comparison of the SPO and conventional methods of recognition: optical experiment

We studied the matched filtering of amplitude objects. In **Figure 5**, we present scheme (a) and photo (b) of an optical-digital VL-correlator. In order to introduce the images in the object plane of the correlator, we applied spatial light modulator (SLM) LC-R2500. SLM is operated in the mode of phase modulation of the wave front. The amplitude objects were transformed in phase ones [20] and supplied to SLM as standard graphic files with regard to the characteristic curve of SLM. Let us consider the operation of the correlator in the mode of recording of matched filters and the mode of matched filtering.



(a) (b)

Figure 5. Optical-digital VL-correlator: (a) scheme; (b) photo: CCD_1, PC_1, laser, Fr, k, P_1, Bs, SLM, P_2, Mr, Sh, A, L_1, MF, P_{mf}, L_2, CCD_2, PC_2 are, respectively, a camera and a computer in the object plane, He-Cd laser (441.6 nm), Fresnel rhomb; collimator, polarizer, splitting cube, spatial light modulator LC-R2500, polarizer, mirror, gate, analyzer, Fourier lens, matched holographic filter, Fourier plane, lens, CCD camera COHU-4800, controlling computer.

Recording of a matched filter. The beam of a He-Cd laser is split into the reference and object beams, by passing through collimator k and splitter Bs. Fresnel rhomb Fr and analyzer A set the necessary polarization of the object beam, by ensuring the phase mode of operation of SLM. Polarizer P_1 and gate Sh are not used, and polarizer P_2 controls a level of the intensity of the reference beam. With the help of CCD_1 and computer PC_1, the graphic file with the image of the reference object in the grayscale format (1–255) is supplied onto SLM with regard to the characteristic curve of the device. The object beam and the collimated reference beam form a matched filter on a photopolymeric composition [15] in the Fourier plane P_{mf} of the correlator. We optimized the conditions of recording of matched filters in order to get the maximum diffraction efficiency at a minimum level of intrinsic noises and at a maximum SNR.

Matched filtering. The operation of the correlator in the mode of matched filtering consists in the following. At closed gate Sh, the collimated laser beam with the necessary direction of polarization is reflected from the mirror of SLM, to which the image of a recognition object is supplied. After the Fourier transformation executed by lens L_1, the beam enters plane P_{mf}, where a matched filter *MF* for the reference object is placed. Then, camera CCD_2 in the correlation plane registers the signal of mutual correlation, which is obtained as a result of the inverse Fourier transformation of the product of the Fourier transforms of the input and reference images of objects executed by lens L_2.

Define the procedure of recognition by the SPO-method:

- For the reference object f_{ref}, the SP-object ϕ_{ref} is calculated with the help of the IFT algorithm. Into the object plane of the correlator, ϕ_{ref} is introduced instead of f_{ref}, and the recording of the matched filter is realized. For the comparison object f_{in}, the SP-object ϕ_{in} is calculated in the same way.

- Into the object plane of the correlator, ϕ_{in} is introduced instead of f_{in}, and the matched filtering is realized. In the correlation plane, the signal of mutual correlation $I_{corr} = |\phi_{ref} \otimes \phi_{in}|$ is registered.

To obtain the cross-correlation dependences, the same collection of objects $f_1 - f_4$ (**Figure 2**), as in computer experiments, was used. For each of the recognition objects, we calculated the series of $f_n(k)$, $k \in [1 - 800]$ objects obtained by means of the introduction of changes into their structure. As indicated above, the changes are the pairwise permutation of points (pixels) of the object taken in an arbitrary order, *k* being the number of such rearrangements. In **Figure 6**, we present the view of a fragment of the object f_1 for various numbers of rearrangements.

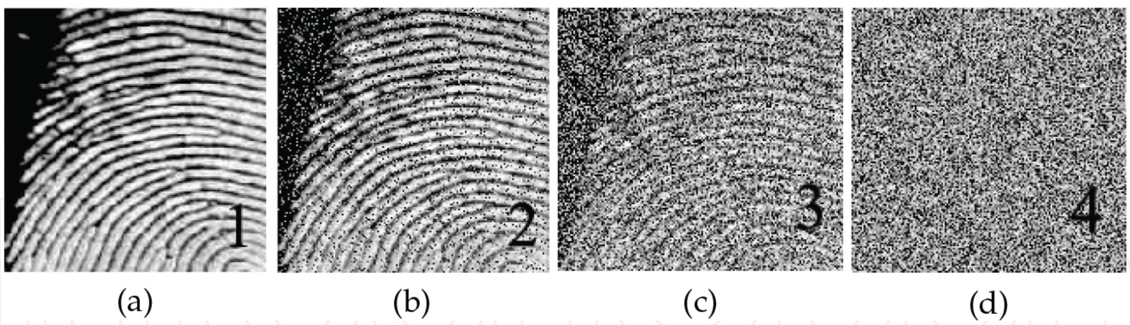


Figure 6. Fragments of object f_1 for: (a) $k = 0$; (b) $k = 200$; (c) $k = 400$; (d) $k = 800$.

For all objects f_n and series $f_n(k)$, we calculated the corresponding $\phi_{n,1}$ and series $\phi_{n,1}(k)$. Then, we recorded matched filters and carried out the recognition by the conventional and SPO methods. The cross-correlation signals were registered by camera CCD_2, and their SNRs were calculated. We obtained the dependences of the intensities of correlation signals I_{corr} on the level of changes in the structure of compared objects. We also estimated the degree of homogeneity of the intensities of the Fourier spectra of objects and SP-objects. The registration of the corresponding spectra was executed by camera CCD_2 mounted in the plane P_{mf} of the correlator (**Figure 5a**). In **Figure 7**, we show the typical results by the example of object f_1.

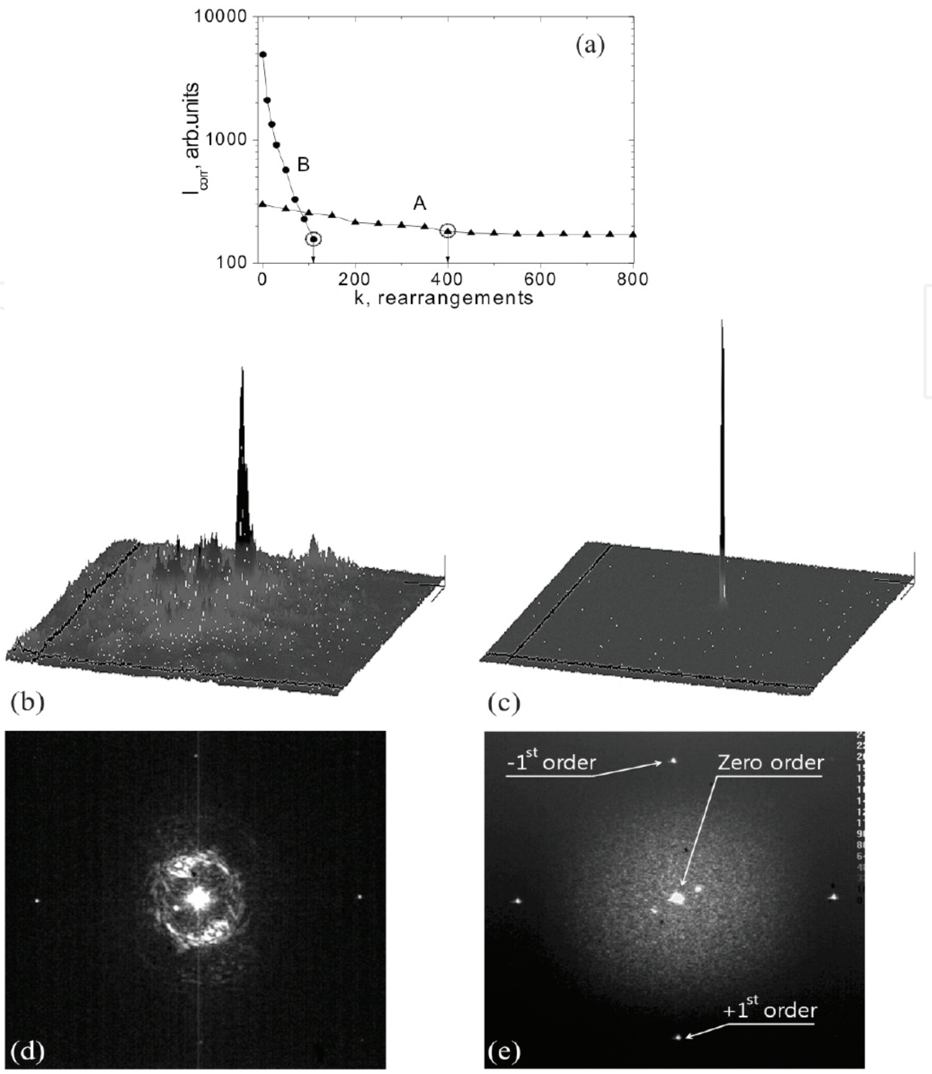


Figure 7. Experimental results for object f_1 (left) and the SP-object $\phi_{1,1}$ (right): (a) dependence of the intensity of a cross-correlation signal on k; (b and c) form of correlation signals at points A, B, respectively; (d and e) the shapes of Fourier spectra.

In **Figure 7a**, curves (A, B), we show changes in the correlation signal I_{corr} for f_1 and $\varphi_{1,1}$, respectively, as the parameter k increases. The autocorrelation signals for $f_1(x, y)$ with SNR of 2.1 dB and $\phi_{1,1}(x, y)$ with SNR of 24.8 dB are shown in **Figure 7b** and **c**, respectively. Fourier spectra of the object and the SP-object are presented in **Figure 7d** and **e**. In the photo of the SP-object Fourier spectrum, we indicate the zero and ± 1 orders of SLM. In the Fourier spectrum of object f_1, the zero order of SLM distorts the real view of the object Fourier spectrum in the zero frequency region. The character of cross-correlation dependences (A, B) (**Figure 7a**) is conserved for the whole collection of objects, which allows us to conclude that the SPO-method has a higher sensitivity to changes in the structure of an object. This can play both positive and negative roles, depending on the character of the recognition problem. On the basis of the results of matched filtering obtained for the whole collection of objects $f_1 - f_{10}$, we can conclude that the characteristic peculiarities and distinctions of the compared methods observed in model experiments are conserved also in optical experiments.

We have established that, in the applied scheme of a VL-correlator (it is true for the schemes with SLM) in the process of recording of matched filters, a part of light that does not diffract on SLM falls in the domain of zero frequencies of the Fourier spectrum of the object. These intense peaks are well noticeable in **Figure 7d** and **e**. The presence of such peaks is the reason for the appearance of a superfluous component in the recognition signals, which masks the real course of a curve in the domain of strong changes in the structure of an object. For example, it is seen in **Figure 7a** (curve A) that, for $k > 400$ where the structure of the object changes quite strongly, the intensity of the correlation signal is practically constant. This effect is observed for both the conventional and SPO methods.

Off-axis matched filtering. We have realized a means to remove a drawback of a VL-correlator with SLM related to the presence of a masking peak of the intensity on zero frequencies, by introducing a phase grating into the structures of input and reference objects. This allows us to spatially separate the Fourier spectra of objects and the zero-order SLM. For functions of the type $\phi(x, y) = exp(i\varphi(x, y))$ that are introduced in the objective plane of a correlator with the help of SLM, such grating is formed by means of the adding of a linear phase $2\pi(xu_0 + y\vartheta_0)$ to the phase $\varphi(x, y)$. The spatial separation of the recognition signal and noise components in the correlation plane by the covering of a synthesized filter in the Fourier plane by a phase grating was demonstrated in [16], but the increase in SNR of the recognition signal by means of the covering of the recognition objects in the objective plane of a VL-correlator by a phase grating is made for the first time by us.

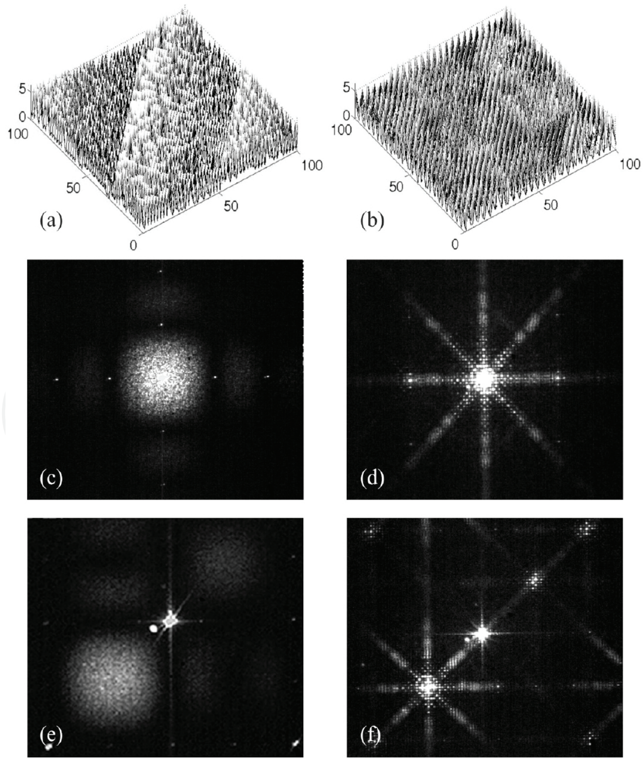


Figure 8. (a and b) Fragment of the phase encoded objects [20] f_2, f_4 with added gratings; (c and d) on-axis Fourier spectra; (e and f) off-axis Fourier spectra.

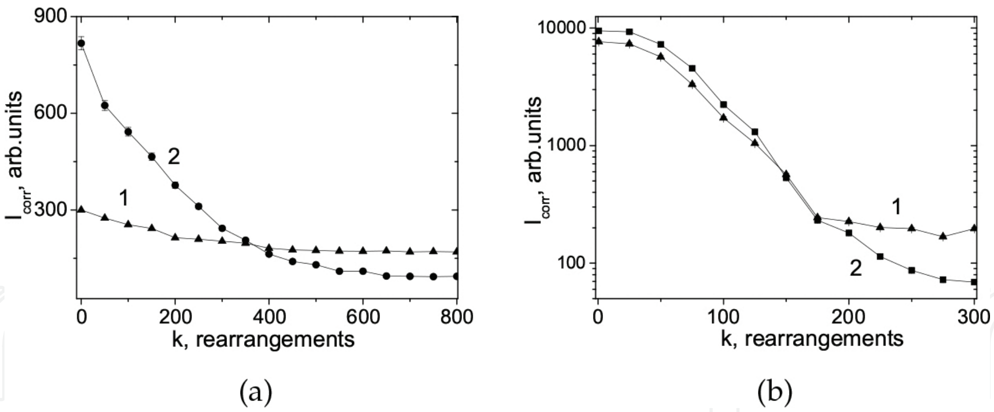


Figure 9. Intensities of cross-correlation signals versus the parameter *k* for object f_1 (a) and SP-object $\phi_{1,1}$ (b) for the on-axis (1) and off-axis (2) matched filtering.

Number of an	Objects SNR[a], dB		SP-objects SNR, dB	
object no.	On-axis	Off-axis	On-axis	Off-axis
1	2.1	9.32	24.8	29.0
2	10.4	18.1	29.1	39.5
3	9.2	19.7	30.0	39.8
4	10.5	20.7	33.9	39.6

[a]SNR, correlation peak intensity relative to the maximal intensity of the correlation noise.

Table 2. Results of matched filtering of objects and SP-objects.

The axis, relative to which the spectrum is shifted, passes through the centers of the objective and Fourier planes. We consider the recording of a filter for the reference object with the added phase grating and the subsequent matched filtering of recognition objects with the added phase grating as an off-axis matched filtering relative to the indicated axis (**Figure 8**). As distinct from the on-axis matched filtering, the implementation of such filtering within the conventional and SPO methods for all objects f_n and series $f_n(k)$, as well as for $\phi_{n,1}$ and series $\phi_{n,1}(k)$, gives the proper behavior of cross-correlation curves for the whole range of variation in the parameter k, including $k > 400$. In **Figure 9a** and **b**, we present the correlation curves for the on-axis (1) and off-axis (2) matched filtering for the object f_1 and SP-object $\phi_{1,1}$, respectively. It is seen that curves (2) are more suitable for the proper comparison of the sensitivities of methods in a wide range of *k*. Hence, the results of model and optical experiments aimed at the study of the SPO-method of recognition of amplitude objects show that the method gives the following possibilities: to simplify the procedure of choice of the criteria (signs) of recognition; to obtain the one-type δ-like signals irrespective of the class, to which the recognition object belongs; and to increase the signal/noise ratio for correlation signals by 2–3 orders. The off-axis matched filtering realized in the experiment increases additionally SNR of correlation signals by one order (**Figures 8** and **9**, **Table 2**).

3. SPO-method for pattern recognition with rotation invariance

As is known, one of the basic problems hampering the application of optical methods of recognition in practice is a fast degradation of the correlation signal under a variation in the scale of the object and its rotation around the coordinate origin. This problem is solved by means of the use of the integral Fourier-Mellin transformation instead of the pure Fourier transformation for the recognition. For the first time, the possibility of a realization of the Fourier-Mellin transformation in a hybrid electron-optical or optical-digital Fourier system was indicated by Kuzmenko [21]. Casasent used successfully this idea for the recognition of objects, which is invariant to the scaling, rotation, and shift, in a hybrid optical-digital 4F-system [22, 23]. In the subsequent years, a lot of works [24–35] were devoted to the invariant methods of recognition. In what follows, we will demonstrate a possibility to use the SPO-method for the pattern recognition with rotation invariance.

3.1. Computational experiment

Consider the rotation invariant recognition of objects realized by the conventional method and the SPO-method. Of interest is the comparison of the cross-correlation curves obtained with the help of both methods to recognition objects for various angles of its rotation.

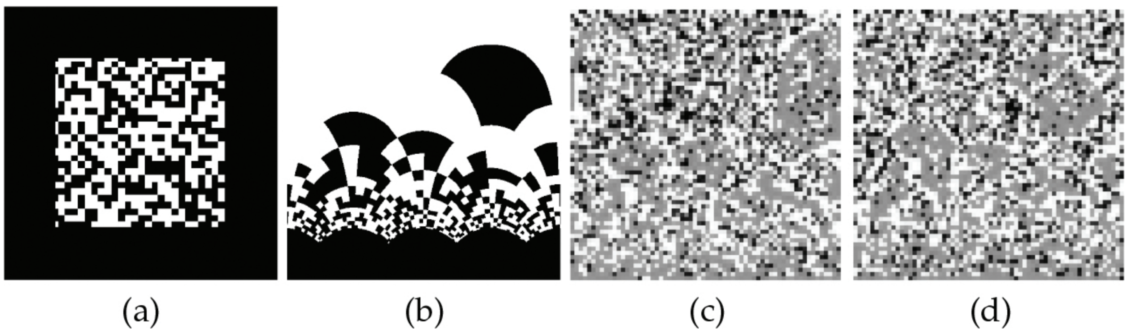


Figure 10. Reference objects: $f_1(x, y)$ (a); $g_1(exp(\rho), \theta)$ (b); $\phi_1(x, y)$ (c); $\chi_1(exp(\rho), \theta)$ (d).

As the reference objects for numerical experiments, we took a set of objects of the amplitude and half-tone types $f_i(x, y)$, $i = 1, 2, \ldots, 10$. For each of them, we define the sets of comparison objects $f_{i,\alpha_j}(x, y)$, $j = 1, 2, \ldots, 41$, which are obtained by the rotation of corresponding reference objects around the optical axis by an angle α with the step $\Delta\alpha = 0.5°$ in the limits [0°–20°]. In addition, for all reference objects and comparison objects, we define the sets $g_{i,}$ $(exp(\rho), \theta)$, $i = 1, 2, \ldots, 10$, of reference objects and $g_{i,\alpha_j}(exp(\rho), \theta)$, $j = 1, 2, \ldots, 41$, of comparison objects after a logarithmic polar transformation of coordinates [26]. For the comparison of cross-correlation dependences, we define the correlation functions for the SPO conventional recognition: $I_\phi(\alpha_j) = \left|\phi_i \otimes \phi_{i,\alpha_j}\right|_{max}$; by Fourier–Mellin rotation invariant recognition: $I_g\left(\alpha_j\right) = \left| g_i \otimes g_{i,\alpha_j} \right|_{max}$. For the SPO-method for the above-defined sets by the iteration scheme (**Figure 1**) at the initial $\varphi_0 = 0$ we calculate the SP-objects ϕ_i, $i = 1, 2, \ldots, 10$ for each reference object and for each comparison object $\chi_{i,\alpha_j}(x, y)$, $j = 1, 2, \ldots, 41$. All SP-objects were taken on the first iteration. Analogously, we define the correlation functions for the SPO conventional recognition: $I_\phi\left(\alpha_j\right) = \left| \phi_i \otimes \phi_{i,\alpha_j} \right|_{max}$; by SPO Fourier–Mellin rotation invariant recognition: $I_\phi\left(\alpha_j\right) = \left| \phi_i \otimes \chi_{i,\alpha_j} \right|_{max}$.

Below in **Figure 10**, we present an amplitude reference object of the binary type $f_1(x, y)$ (a), the object obtained for it after the logarithmic polar transformation of coordinates $g_1(exp(\rho), \theta)$ (b), and the SP-objects $\phi_{1,0}(x, y)$ (c) and $\chi_{1,0}(exp(\rho), \theta)$ (d) calculated for them.

To increase the peak values of correlation signal for recognition objects and the SNR, all amplitude objects f_i, g_i were transformed in phase ones by the Kallman method [20]. The results were obtained for ten objects with a dimension of 512 × 512 elements by the conventional and SPO methods. We analyzed the parameters of correlation signals and compared the correlation curves defined above. By the examples of **Figures 11–13**, we show the typical results of numerical experiments.

In **Figure 11a**, we show the dependence of the SNR of a recognition signal on the rotation angle of the object f_{1,α_j} at the subsequent calculation of the correlation of this object with the reference one f_1 (**Figure 10a**)— the curve formed by white squares.

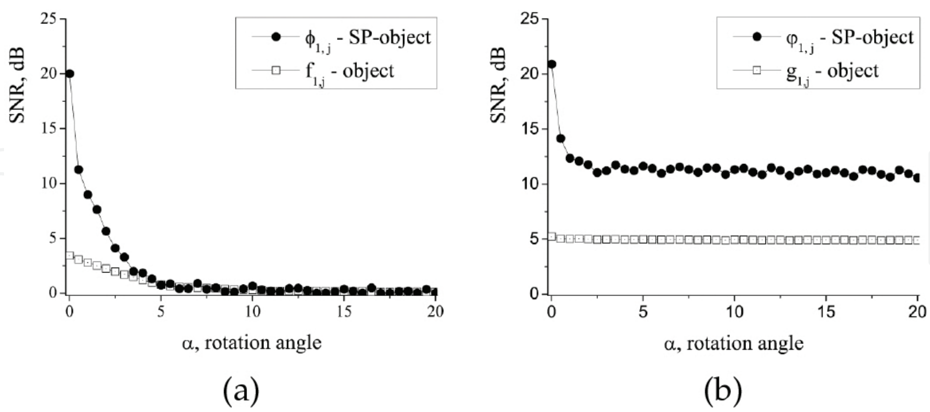


Figure 11. Dependence of the SNR for cross-correlation signals I_{corr} on the rotation angle α for: $\left| f_1 \otimes f_{1,\alpha_j} \right|$ (a), $\left| \phi_1 \otimes \phi_{1,\alpha_j} \right|$ (b) the conventional recognition; $\left| g_1 \otimes g_{1,\alpha_j} \right|$ (c), $\left| \chi_1 \otimes \chi_{1,\alpha_j} \right|$ (d) the recognition with the use of the Fourier-Mellin transformation.

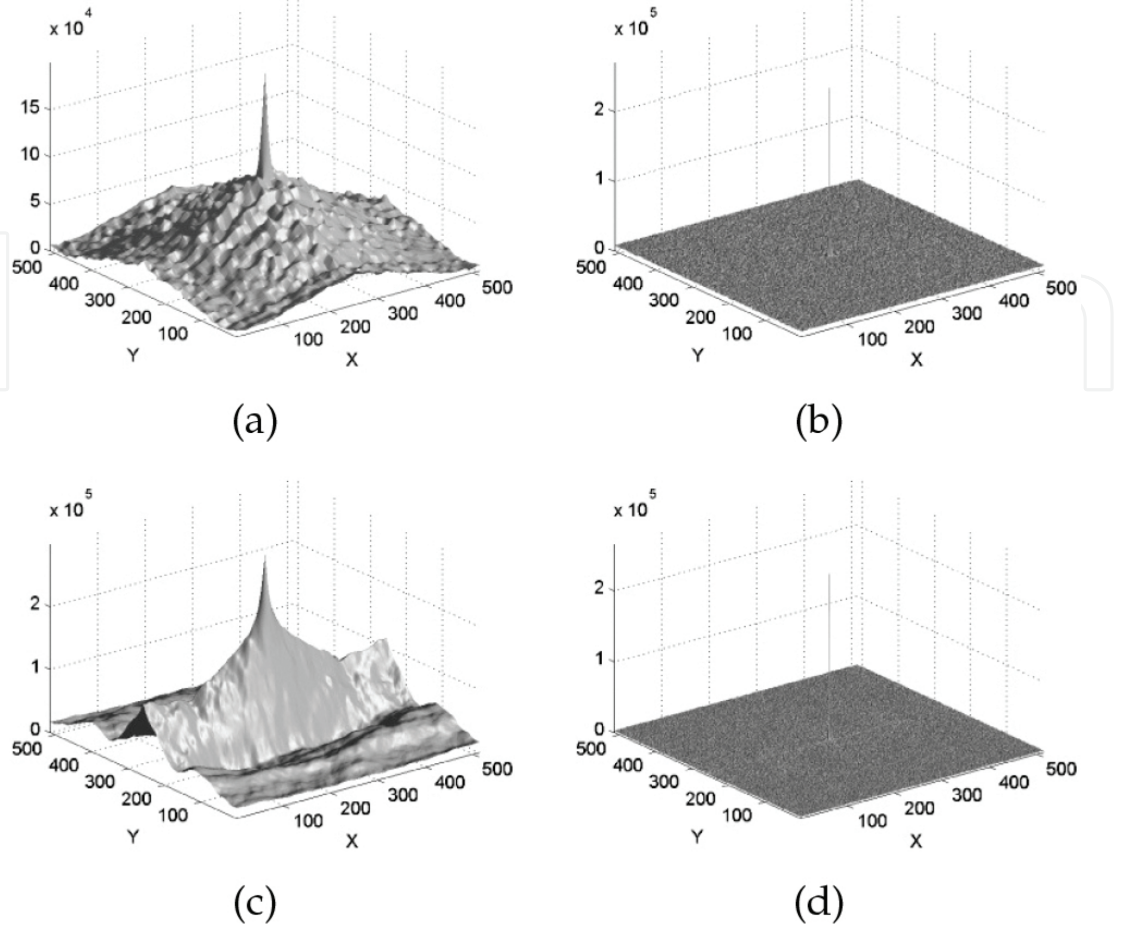


Figure 12. Autocorrelation signal: $|f_1 \otimes f_1|$ (a), $|\phi_1 \otimes \phi_1|$ (b) the conventional recognition; $|g_1 \otimes g_1|$ (c), $|\chi_1 \otimes \chi_1|$ (d) the recognition with the use of the Fourier-Mellin transformation; $\alpha = 0^0$.

The curve demonstrates the typical behavior [22, 23], namely the strong degradation of the correlation function under a rotation of the comparison object around the optical axis, while comparing it with the reference object. The correlation signal with SNR = 3.4 dB (**Figure 12a**) from the reference object under a rotation of the comparison object already at angles $\alpha > 5°$ is transformed into noise components of the cross-correlation signal, which change insignificantly their shapes at a subsequent rotation (**Figure 13a**). Curves (**Figure 11a**) demonstrate the above-written method for both conventional and SPO methods. As shown in [16], the SPO-method demonstrates a faster diminution of the curve with increase in distortions (in the given case, with increase in the rotation angle), δ-like shape of a recognition signal, and higher values of SNR about 20.2 dB for the autocorrelation (**Figure 12b**); for the angle $\alpha = 5°$, the signal is absent (**Figure 13b**). The curves in **Figure 11b** show variations in SNRs of the correlation functions with increase in the rotation angle for comparison objects for the conventional (light circles) and SPO (dark circles) methods at the Fourier-Mellin rotation invariant recognition. For g-objects, SNR of the signal is about 5 dB in the whole interval of change of the angles. For the SPO-method, we observe a change in SNR of the δ-like signal from 20 dB (**Figure 12d**) for autocorrelation to 11 dB; further, SNR of the cross-correlation signal is also independent of the angle of rotation of objects of the recognition (**Figure 12d**).

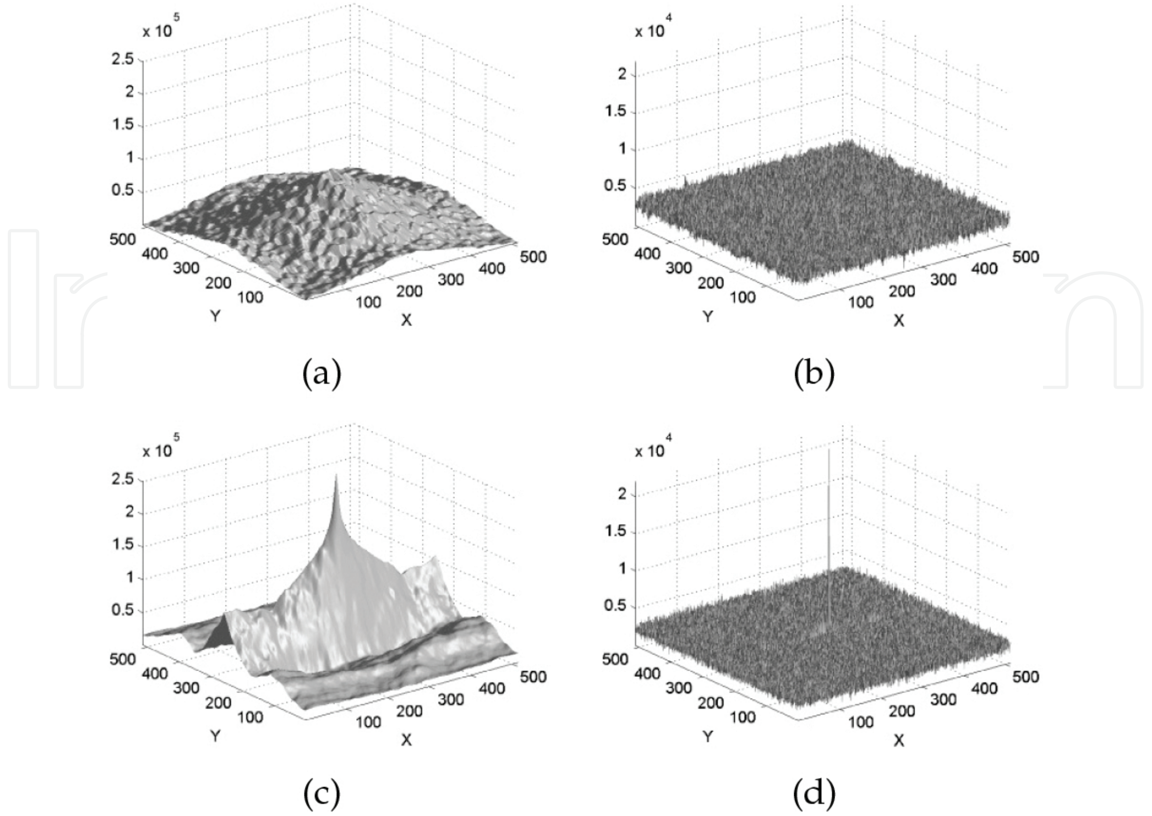


Figure 13. Cross-correlation signal: $|f_1 \otimes f_{1,\alpha}|$ (a), $|\phi_1 \otimes \phi_{1,\alpha}|$ (b) the conventional recognition; $|g_1 \otimes g_{1,\alpha}|$ (c), $|\chi_1 \otimes \chi_{1,\alpha}|$ (d) the recognition with the use of the Fourier-Mellin transformation; $\alpha = 20^0$.

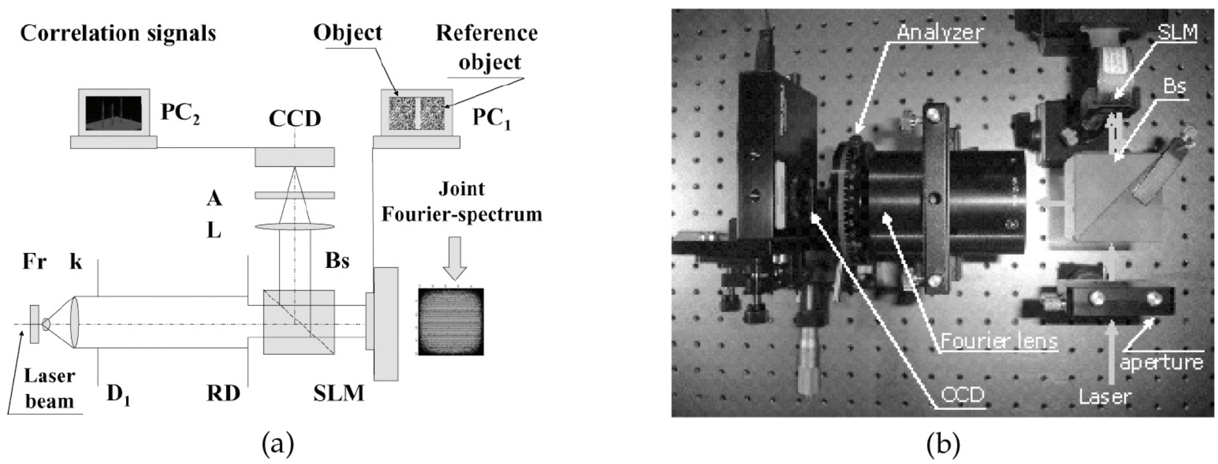


Figure 14. (a) Scheme and (b) photo of a digital-optical JT-correlator: Laser beam, P, D_1, RD, Bs, SLM, PC_1, L, A, CCD_1, CCD_2, PC_2—He-Ne (543 nm) laser beam, polarizer, circle and rectangle diaphragms, beam splitter, spatial light modulator HEO 1080 Pluto, Fourier lens, analyzer, a 12-bit SPU620 CCD with the BeamGage software and PC.

In view of the similar results obtained for the whole set of objects, we may say that the SPO-method is applicable for the rotation invariant recognition and conserves the same own advantages, as in the conventional recognition.

3.2. Optical experiment

For the corroboration of the results obtained in numerical experiments, we carried out experiments with an optical-digital system of recognition (see **Figure 14a** and **b**) on the basis of a JT-correlator. For this purpose, we got the autocorrelation signals for the objects $f_1(x, y)$, $g_{1,0}(exp(\rho), \theta)$, $\phi_1(x, y)$, and $\chi_{1,0}(x, y)$. The cross-correlation signals were obtained at the rotation of the indicated objects by $\alpha = 5°$.

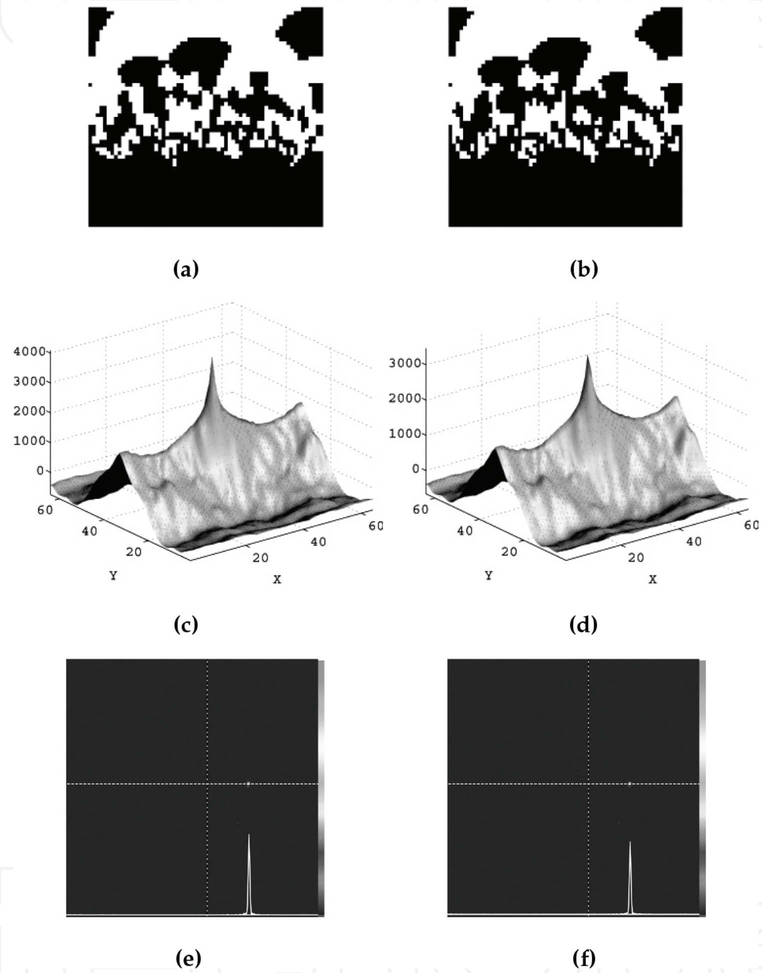


Figure 15. Pattern recognition results with Fourier-Mellin transformation: object's plane—reference g_1 (a) and recognition $g_{1,\,5°}$ (b) objects; calculation—autocorrelation (c) and cross-correlation (d) signals; experimental peaks—autocorrelation (e) and cross-correlation (f) in the correlation plane of the JT-correlator. The size of objects and JF-spectra is 64 × 64 and 512 × 512 elements, respectively.

The recognition in the JT-correlator includes two steps:

Formation of the joint Fourier spectrum (*JF*) *of compared objects*. With the help of a camera (is not shown in the scheme), the object of recognition is introduced in computer PC_1. We calculate the JT-spectrum moduli of a given object and the reference object. Then, JF-spectrum moduli is supplied to an SLM.

http://dx.doi.org/10.5772/65370

Production of a correlation signal. The collimated light beam of a He-Ne laser (543 nm) after masking by a working aperture is reflected from the SLM. In the correlation plane, a *CCD* camera registers the correlation signal obtained as a result of the inverse Fourier transform, which is performed by the lens *L*, of an optical signal reflected with the help of a splitting cube *Bs* from the SLM. The result is supplied to and is processed by computer PC_2.

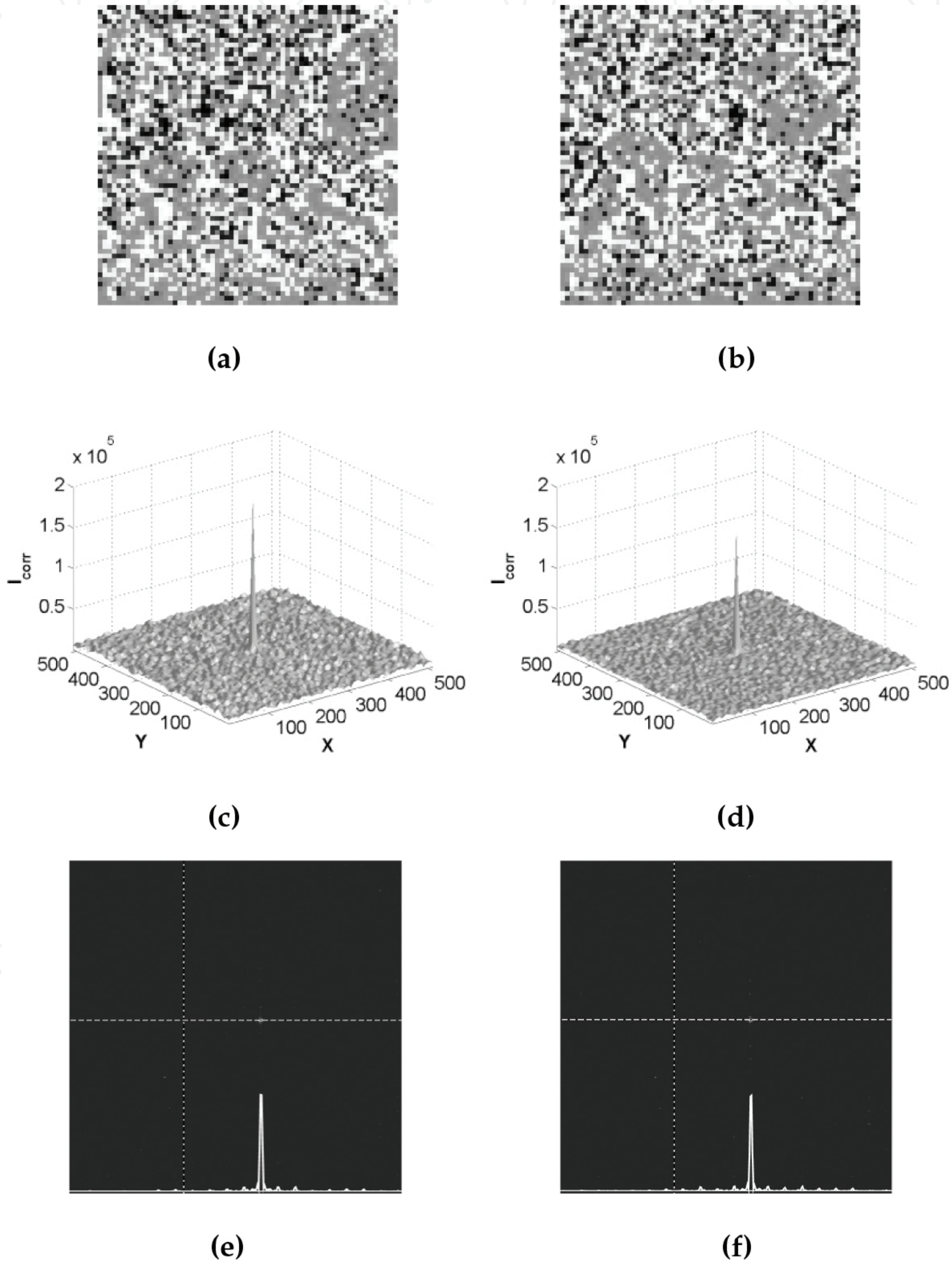


Figure 16. Pattern recognition results with the SPO-method and the Fourier-Mellin transformation: object's plane—reference χ_1 (a) and recognition $\chi_{1,5°}$ (b) SP-objects; calculation results—autocorrelation (c) and cross-correlation (d) signals; experimental peaks—autocorrelation (e) and cross-correlation (f) in the correlation plane of the JT-correlator. The size of objects and JF-spectra is 64 × 64 and 512 × 512 elements, respectively.

3.3. Results and discussion

The results of optical experiments and their comparison with the results of numerical experiments (at least the qualitative one) allow us to evaluate a degree of applicability of the SPO-method for the rotation invariant recognition. **Figure 15** demonstrates objects **Figure 15a** and **b**, calculated autocorrelation **Figure 15c** and cross-correlation signals **Figure 15d**, and the autocorrelation **Figure 15e** and cross-correlation signals **Figure 15f** registered by a camera (**Figure 14a**).

The similar experimental result was obtained also within the SPO-method. The presence of cross-correlation signals is clearly seen for the conventional and studied methods (**Figures 15** (**e**, **f**) and **16** (**e**, **f**)) in the case of the rotation invariant recognition by Fourier-Mellin.

The SNR for recognition signals is in the limit 23–25 dB. Thus, the results (the presence of a recognition signal at a rotation of the recognition object) confirm qualitatively the applicability of the SPO-method to the rotation invariant correlation.

Thus, the numerical and optical experiments show the applicability of the SPO-method to the rotation Fourier-Mellin invariant recognition for amplitude and half-tone objects of the binary type. The estimate of correlation signals and the obtained dependences of $SNR(\alpha)$ indicate that the SPO-method gives signals of the δ-like shape irrespective of the type of objects that gives a constant value of *SNR* exceeding *SNR* for the conventional method in the whole interval of the angles of rotation of comparison objects by 6 dB higher on the average for the rotation invariant recognition. These results are typical of the whole set of reference objects.

4. Conclusion

The hypothesis about the possibility to solve the problem of optical recognition by means of the change of the recognized objects by the corresponding object-dependent SP-objects in model and optical experiments is verified. The advantages and the drawbacks of such approach are determined. The conditions of recording of matched filters on original photopolymeric compositions, which ensure the optimum parameters of correlation signals at the recognition of amplitude objects, are determined. Auto- and cross-correlation signals for amplitude objects of various classes and for the corresponding SP-objects are obtained by computer simulation experimentally and compared at the recognition with a hybrid optical-digital VL-correlator. The influence of controlled changes in the structure of objects on correlation signals in the conventional and proposed approaches is experimentally studied in the optical-digital systems of recognition on the basis of the VL and JT correlators. The development of the SPO-method for the rotation invariant pattern recognition with an optical-digital JT-correlator is presented.

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