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Method for replacing objects in 4F-correlator: testing

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Abstract. The method of pattern recognition based on replacement of object images incoming to the correlator by object-dependent synthesized phase objects calculated using the iterative Fourier-transform algorithm was developed by us earlier. In this work, we performed experimental testing the above method by using an optical-digital 4F-correlator. Synthesized phase objects were inputed into the correlator through the spatial light modulator LC2002. Holographic matched filters were recorded using self-developing photopolymers PPC-488. For two test objects, we obtained unified (δ-like) correlation signals with the signal-to-noise ratio reaching 24 dB, while the diffraction efficiency of these filters was up to 30%.

Keywords: pattern recognition, hybrid optical-digital 4F-correlator, synthesized phase object, iterative Fourier-transform algorithm.

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1. Introduction

As shown in [1], when solving the recognition problem for binary or half-tone objects by using 4F-correlators, the replacement of these objects with unambiguously related to them synthesized-phase objects (SP-objects) results in increasing values of signal-to-noise (SNR) correlation signals as well as in unification of their form: the signal possesses a δ-like shape independently of the object type. The latter allows to formalize the pattern recognition problem at the stage of choosing some characteristic (distinctive) features of the object.

It is well known [2–5] that the procedure for choosing the characteristic, often multiple signs of the object in most of the cases takes a subjective (heuristic) character and is rather laborious. In the offered method, this procedure is excluded and changed by a single mathematical criterion for all the recognized objects. It is this criterion that is used in iteration calculations for respective SP-objects. In the case, the recognized object is considered as a whole – all its distinctive features are reflected in the structure of respective SP-objects by some integrated way.

In this work, we represent experimental results after testing the offered method by using an optical-digital 4F-correlator. As the test-objects, we chose a random amplitude and a phase masks.

In the section 2, represented is the schematic view of a hybrid optical-digital correlator using the spatial light modulator (SLM) LC2002 as a dynamic transparency. Also considered are regimes of the correlator operation capable to realize the recognition procedure with SP-objects.

In the section 3, we represent results of testing and calibrating SLM at $\lambda = 441.6$ nm when operating in the phase regime. Summarized there are calculation results for SP-objects, recording the holographic filters and matched filtering, as well as the analysis of results obtained. In the section 4 we summarized our results.

2. Correlator layout

The principle scheme of the hybrid optical-digital correlator is represented in Fig. 1. The correlator is nominally divided by two parts: digital, Fig. 1(1), and optical, Fig. 1(2), ones. The recognition procedure [1] implies the following operations.

1) Record of the holographic matched filter for the standard object:
   i) input amplitude image of the standard object $a_{st}(x, y)$ into the correlator digital module (Fig. 1(1));
   ii) obtain the SP-object $\phi_{st}(x,y)$ from $a_{st}(x,y)$ and input it into the entrance plane P_2 of the correlator optical part by using SLM (Fig. 1(2));
   iii) record the holographic matched filter of the $\phi_{st}(x,y)$ using PPC-488 in the Fourier plane P_3 of the correlator optical part (the reference beam is not shown).
2) Matched filtering:
   i) input the SP-object $\phi_{in}(x, y)$ obtained from $a_{in}(x, y)$ into the entrance plane P_2 of the correlator optical part by using SLM;

ii) realize the matched filtering procedure for the ϕ_{in}; obtain of the correlation signal $r(x,y) = \iint \phi_{in}(x_1,y_1)\, \phi^*_{st}(x + x_1, y + y_1) dx_1 dy_1$ at the exit plane P_4 of the correlator optical part;

iii) record $r(x, y)$ by using the CCD_2 camera and estimate the recognition result in according with the threshold criterion.

Matched filter recording regime. Fig. 2 illustrates the recording scheme suitable to obtain holographic filters by using self-developing photopolymers. The He-Cd laser beam passing through the attenuator **Att** and dividing cube **Bs** is divided by the referent and object beams. The half-wave plate $\lambda/2$ sets the necessary polarization for the object beam, which provides the mostly phase regime for SLM operation.

The analyzer **A** sets the vertical plane for the polarization of the phase-modulated wavefront. Using the controlling computer $\mathbf{PC_1}$, SLM is given with a graphic file containing the necessary amplitude distribution of gray halftones which is obtain by taking the characteristic curve into account. The object beam and the collimated referent beam created the holographic matched filter on PPC-488 at the correlator Fourier plane **Pt**. The He-Ne laser, photodiodes $\mathbf{Ph_{1,2}}$, analog-digital converter unit and computer $\mathbf{PC_2}$ form the registration system, which enabled us to control recording the holographic filters on self-developing polymers in the real time scale.

The use of photopolymer compositions developed in the Institute of Physics, NAS of Ukraine [6-7] as holographic registration media is caused by the fact that matched filters recorded in these media are formed during exposing them by an interferential field and do not require any additional operations to develop and fix the respective interferential structure. Diffraction efficiency of the plane gratings reached to an 99.8 % and matched filters about 70% [8].

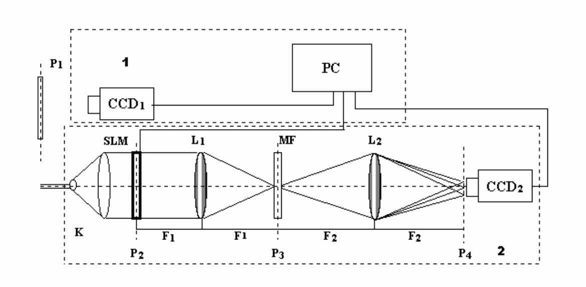

Fig. 1. Scheme of an optical-digital correlator.
a) 1, 2 – digital and optical parts of the correlator;
b) P_1, P_2, P_3 and P_4 – the input, object, Fourier, and correlation planes of the correlator;
c) CCD_1 and CCD_2 – the input camera for images and the registration camera for correlation signals;
d) K, L_1 and L_2 – collimator and Fourier-objectives;
e) PC, SLM and MF – computer, phase spatial light modulator LC2002 and the matched filter.

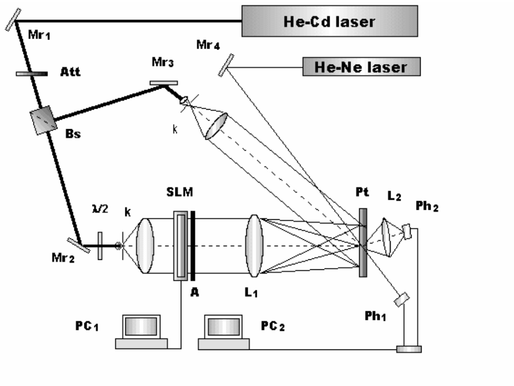

Fig. 2. Scheme of a Vander Lugt optical-digital correlator in the recording mode.
1) $Mr_{1,2,3,4}$ and Bs – mirrors and a beamsplitter; 2) Att – attenuator; 3) $\lambda/2$ – half-wave plate; 4) k – collimators; 5) SLM, A, PC_1 – spatial light modulator, the analyzer and a computer to control SLM; 6) L_1 – Fourier-objective; 7) L_2, Ph_{12}, PC_2, He-Ne laser – lens, photodiodes, computer with an analog-to-digital converter and a laser (λ = 633 nm) of the registration system; 8) Pt – photopolymer; 9) He-Cd Laser – a laser with λ = 441.6 nm.

Matched filtering regime. The scheme of the correlator operating in the matched filtering regime is depicted in Fig. 3. The collimated laser beam with the necessary polarization direction passes SLM addressed with the respective SP-object and the lens $\mathbf{L_1}$, falls onto the plane **Pt** where the filter **MF** is located. Then, in the correlation plane the **CCD** camera register the correlation signal obtained as a result of the inverse Fourier-transform performed by the lens $\mathbf{L_2}$ with the product of the Fourier-images inherent to SP-objects of the incoming and standard objects. To register the correlation signal in the output correlator plane, we used the special software and analog-digital converter made by "Spiricon", camera Sony4800 with the pixel dimensions 30x30 μm and the size 580×470 pixels.

3. Experiment

As recognized objects, we chose the following ones:
a) f_1 – the binary amplitude mask (AM) with the optical density [0,1] containing randomly distributed elements, where the number of transparent elements is equal to that of the opaque ones;
b) f_2 – the binary phase mask (PM) with the random distribution of the $\pm\pi$ pixel elements where the number of $+\pi$-elements is equal to that of $-\pi$-elements.

The image size is equal to 600×800 pixels. The recognition procedure for f_1 object was defined as follows:
a) calculation of the SP-objects ϕ_1 for f_1;

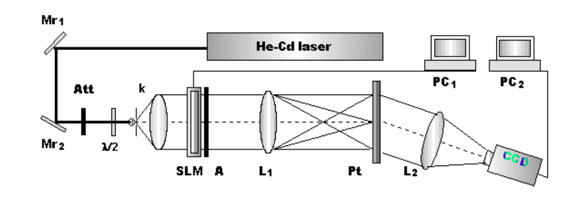

Fig. 3. Scheme of a Vander Lugth optical-digital correlator in the matched filtering mode.
1) $Mr_{1,2}$ – mirrors; 2) Att – attenuator; 3) $\lambda/2$ – half-wave plate; 4) k – collimator; 5) SLM, A, PC_1 – spatial light modulator, the analyzer, and a computer to control SLM; 6) $L_{1,2}$ – Fourier-objectives; 7) CCD, PC_2 – output camera, and a computer of the registration system; 8) He-Cd Laser – a laser with λ = 441.6 nm.

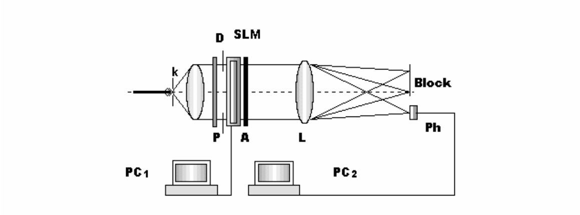

Fig. 4. Calibration scheme of SLM LC2002 in the phase mode for λ = 441.6 nm.
1) k – collimator; 2) P, D, SLM, PC_1 – polarizer, an aperture, spatial light modulator, an analyzer and a computer to control spatial light modulator; 3) L – Fourier-objective, 4) Ph, PC_2 – photodiode, a computer of the registration system.

b) inputing ϕ_1 into correlator by using SLM and recording the holographic **MF-filters** using the scheme of Fig. 2;
c) obtaining the correlation signals for ϕ_1 in accord with the scheme in Fig. 3 in the course of matched filtering.

The object f_2 – PM with the random distribution of elements – served as the test sample to check the correlator operation by comparing results as to their SNR and shape of correlation signals obtained for f_2 with the known results [9-10]. In this case, the recognition procedure was performed using the usual recognition scheme (without calculations of the respective SP-object).

3.1. Obtaining the characteristic curve for an SLM

SLM of the transmission type LC2002 (“HoloEye”) holds the SVGA standard 600×800 pixels with the frequency 60 Hz, the rated value of power density for incident radiation $P_{\max} = 1$ W/cm^2, dimensions of the elementary LC-cell is 32×32 μm, matrix dimensions 832×624 cells. We performed testing and choice of the operation regime for this SLM at the wavelength λ = 441.6 nm.

When SLM transfers the phase linearly, the phase of the set distribution $\phi(x, y)$ should be re-calculated into gray scale gradation $N(x, y) = \phi(x, y)(256/2\pi)$ and introduced by controlling voltages into SLM as a standard graphic file. The passing laser beam acquires the phase shift corresponding to $\phi(x,y)$. But in practice, SLM transfers the phase is non-linearly. Therefore, when working with it, it is necessary to make an account of the characteristic curve relating the phase shift with the gray scale gradation. This curve was obtained by us experimentally. Its shape depends on such parameters of SLM as the brightness (N_1), contrast (N_2), horizontal distortion (N_3), vertical distortion (N_4) – all of them are available for tuning in the program controlling SLM.

To obtain the characteristic curve for LC2002 at λ = 441.6 nm, was realized in the following way: in the first diffraction order we compared the intensity of the laser beam diffracted from the phase grating intputed into SLM (Fig. 4) and the calculated intensity for this grating under sequential increasing the grating effective height measured fractions of π.

The grating effective height implies the relief height (for calculations) or values of the LC-cell refraction index (when realizing the diffraction grating in SLM) corresponding to the definite phase shift measured fractions of π. The characteristic curve shown in Fig. 5 (1) corresponds to the SLM tuning parameters N_i summarized in Table 1. It is known that the error in transferring the phase by using SLM consists of the systematic (Fig. 5(2)) and random ones. The former arises due to inaccuracy of the characteristics and influences on the range width for transferred phases, and the latter is mainly determined by inaccuracy in rounding when quantizing the gray levels and can reach $\pi/128$. The choice of optimal N_i-values provides phase modulation in the range [0-2π] for the signal level in 256 gray gradations.

Depicted in Fig. 6 is the dependency of the normalized intensity $\boldsymbol{P_0}$ for the zeroth order of the grating with the effective relief height π inputed into SLM on the density of power incident $\boldsymbol{P_{in}}$ onto the grating: 1 – experiment; 2 – the straight line corresponds to the grating diffraction efficiency η_2; 3 – the straight line corresponds to the grating diffraction efficiency η_3, when $\eta_3 > \eta_2$. As seen from the figure, the power density taken from the range from 1 to 17 mW/cm^2 is suitable to obtain the most efficient modulation of the phase of the transmitting wavefront.

Table 1. Tuning parameters for a SLM.

Brightness, N_1	Contrast, N_2	Horizontal distortion, N_3	Vertical distortion, N_4
176	118	1054	200

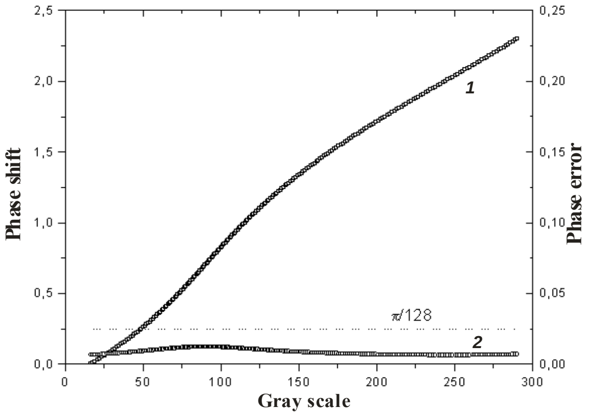

Fig. 5. Phase shift (1) and the phase error (2) in radians relatively to the gray levels.

3.2. Calculation of SP-objects

In [1], SP-object is defined as an object-dependent diffuser [11], the form of the function for which is determined by the form of the object function f(x,y) and calculated using the classical scheme of the iterative Fourier-transform (IFT) algorithm [12].

SP-object ϕ_1 for the objects f_1 was calculated using the starting phase distribution $\phi_0(x, y) \equiv \text{const}$. Beginning even from the first iterations, the structure of SP-object is PM with a random distribution of the phase values within the interval [0-2π]. While at first iterations ϕ_1 is binary, they become 256-level by their phase values with increasing the iteration number. Its Fourier-spectrum amplitude is homogeneous, the shape of the correlation functions is δ-like, the autocorrelation function $\phi_1(n)\otimes\phi_1(n)$ being maximal by its value and does not depend on the iteration number n. This form of SP-objects, their Fourier-spectra and correlation signals is typical for recognized objects of any type.

As each recognized object f_i is potentially corresponded by a set of SP-objects $\{\phi_i(n)\}$ calculated for various iteration numbers n, it is necessary to introduce the criterion to choose the only one of them the most suitable to replacement f_i-object in the correlator when recognizing the objects. By another words, it is necessary to define the criterion for determining the iteration number when calculating SP-object by using the IFT-algorithm. In the experiments, we used two criteria, namely: the calculation of SP-objects is finished at the iteration step providing a minimum to the parameter

$$A(n) = \max \left| \Im^{+1}(\phi(n)) \right| \qquad (1)$$

or to the dispersion

$$\sigma(n) = \frac{\sum_x \sum_y \left(|f_{st}(x,y)| - |\Im^1 \arg(\Im^{+1}(\phi_{in}^{(n)}(x,y) f_{in}(x,y)))| \right)^2}{\sum_x \sum_y |f_{st}(x,y)|^2} \qquad (2)$$

where $\Im^{\pm 1}$ is the direct (inverse) Fourier transformations, $\sum_x \sum_y |f_{st}(x,y)|^2$ is the full energy of the standard object, n is the iteration number.

As was established for $n = 2$, the spectrum is the most homogeneous by its amplitude, which give the optimal conditions to record holographic filters, SP-object structure being binary. It provides the optimal conditions to display them in SLM.

In the case of a weak dependency for the criterion (1) on the iteration number, one can use the criterion (2) that is identical to the criterion used in [11] for choosing an optimal phase diffuser, which is imposed on the object when calculating the kinoform. As it was noted in Introduction, this formalized procedure to choose the number of the optimal iteration in calculations of SP-objects $\phi_i(n)$ substitutes a heuristic procedure aimed at the choice of characteristic signs in recognized objects f_i.

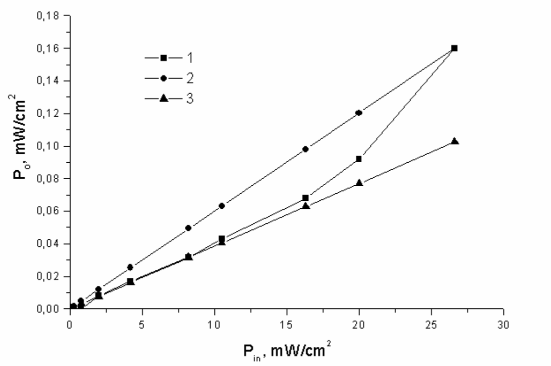

Fig. 6. Power of the zeroth order versus the power density incident on to SLM.

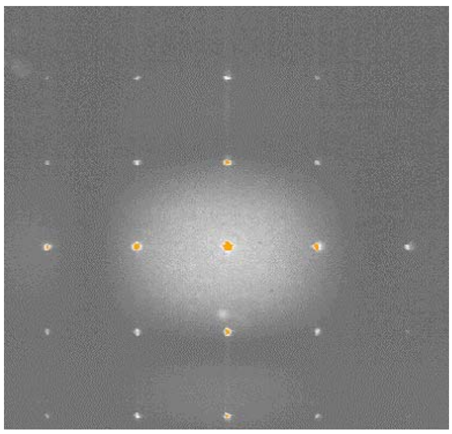

Fig. 7. Fourier-spectrum for SP-object.

3.3. Recording the holographic filters

The standard holographic filters for $\phi_1(2)$ and f_2 were recorded using PPC-488 and the scheme shown in Fig. 2. The angle between beams provided the spatial frequency 1000 mm^{-1}, the ratio of intensities inherent to the referent and object beams I_{ref}/I_{obj} being 2:1. All the filters are of the Bragg type. Therefore, when using the scheme shown in Fig. 3 for matched filtering, one can observe the only correlation signal from all the signal components. As it was shown in [8], the diffraction efficiency of holograms and matched filters for PM recorded using PPC-488 lies within the range (15-70)% under the condition that I_{ref}/I_{obj} changes from 26:1 down to 1:1. In our experiments, the diffraction efficiency was 25-30%, which can be explained by the fact that the image inputed into SLM is quasi-stationary, as this SLM operates at the frequency 60 Hz.

Shown in Figs 7 the Fourier-spectrum is registered using the CCD camera in the plane of recording the holographic filters for SP-objects – $\phi_1(2)$. Since the SLM cell is a square with the dimensions 32×32μm, the spectrum structure for SP-objects is very similar (identical) to that of the phase mask spectrum.

The spatial frequency spectrum in the main order is limited with the maximal frequencies 32.3 mm^{-1} for SP-object and phase mask. Both of the Fourier-spectra have the zeroth order, which is indicative of the presence of intrinsic noise in the optical-digital correlator itself caused at least by the following reasons:

- quasi-stationary regime of SLM operation;
- errors when transferring the SLM phase;
- presence of the optical noise in the correlator.

3.4. Obtaining the correlation signals

Concerning the matched filtering, our experiments were performed to estimate SNR for correlation signals when realizing the recognition procedure with SP-objects and comparison of the results obtained with those known for phase masks.

Before carrying out the experiments with SP-objects, the optical-digital correlator was tested using the standard procedure of matched filtering for the usual (non-synthesized) object f_2. In doing so, we registered the δ-like correlation signal with SNR reaching up to 43 dB.

The correlator intrinsic optical noise measured in the absence of the object was no more than 19 dB. Taking this fact into account, the correlation signal SNR was determined as the ratio of the correlation signal peak value to the correlator intrinsic noise one in all the following measurements. For our object f_2 and $\phi_1(2)$, SNR was equal to 24 dB.

Comparing the correlation signals obtained for PM [10] with our, one can draw the conclusion that the correlator noise was increased, but the signal peak values can be icreased by optimisation by the correlator operation. The growth of the correlator intrinsic noise is the consequence of reasons listed in the paragraph 3.2 as well as the development of the structure inherent to SLM LC2002 providing the constant part into the correlation signal.

Using the method offered in [1], we realized the matched filtering procedure and obtained δ-like recognition signals. Fig. 8 show the fragment of SP-object $\phi_1(2)$. Shown in Fig. 9 is the correlation peak describing $\phi_1(2)$.

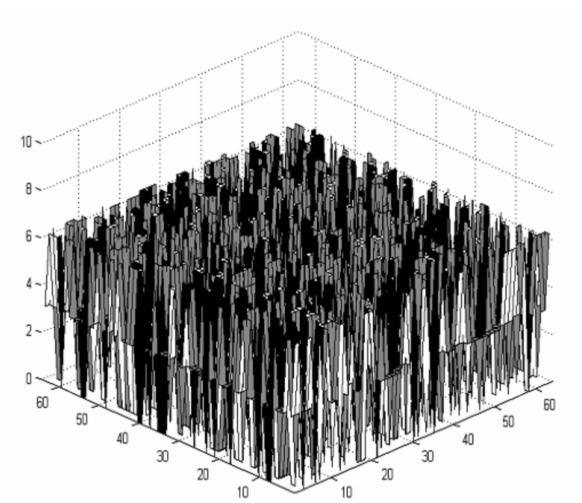

Fig. 8. Phase distribution of the ϕ_1 in the gray scale format (a fragment).

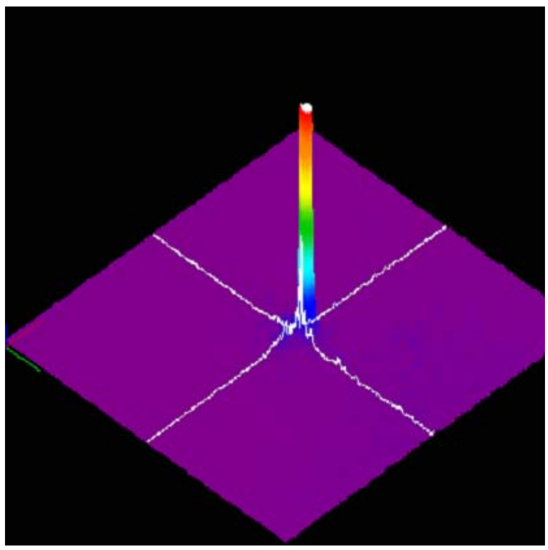

Fig. 9. Correlation signal of an SP-object.

Thus, our experiments show that application of SLM and PPC-488 in the recognition procedure with the 4F-correlator by using the method gives results comparable with that known for random phase masks [10, 13] and provides a high fidelity of recognition.

4. Conclusions

The results obtained allows to draw the following conclusions:

- phase distributions of SP-objects have a random character, in the first iteration steps the structure of these distributions being close to the binary one [0, π], with increasing the number of iterations the binary structure is smoothed, and eventually the phases almost homogeneously fill in the interval [0–2π];
- as a consequence of their random nature, SP-objects and their Fourier-spectra are practically homogeneous by their amplitude;
- correlation functions of SP-objects have the δ-like shape and provide the maximum possible signal-to-noise ratio inherent to phase masks with a random distribution. Obtained is the qualitative coincidence between calculated and experimental correlation dependencies;
- defined is the only criterion to choose SP-objects for replacing the recognized real objects. Application of it changes by itself the heuristic procedure of choosing the characteristic signs of the object in the common recognition method.

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