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Image recognition in diffraction intensity correlators

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The ways of image recognition in optical systems using space-incoherent monochromatic illumination are considered. It is shown that convolution of the images with a sign-variable pulse response and also some types of nonlinear image processing can be performed in such derives by using space-time light modulators. These operations are applicable as far as the improvement of the image quality and the transformation of images into a form convenient for recognition are concerned. The methods are suggested for realization of efficient recognition algorithms, including nonparametric sign and rank ones, in a diffraction intensity correlator. All these facts widen substantially the possibilities of optical processing, because they permit not only to incorporate the advantages of coherent and incoherent computers, but also to get a new quality, i.e. to perform nonlinear operative image processing in optical systems without feedback.

In a general case recognition of the images $f(x, y)$ reduces to calculation of decision functions $S_m\{f(x, y)\}$, the values of which are extreme for all $f(x, y)$ belonging to the m class. In optics the calculation procedure of $S_m\{f(x, y)\}$ can be, as a rule, divided into two steps: the first one, being a transformation of the $f(x, y)$ image, independent of the m class (subsequently this operation will be referred to as image preprocessing), and the second one, being the image processing related directly to definition of the m class name. In view of a great number of papers on nonlinear image processing, it may be stated that the operations employed most frequently in contemporary optics are the convolution-type transformations, i.e.

$$S_m(x, y) = \{f(x, y)\otimes h(x, y)\}\otimes g_m(x, y), \tag{1}$$

or

$$\tilde{S}_m(u, v) = \tilde{f}(u, v)\cdot\tilde{h}(u, v)\tilde{g}_m(z, v). \tag{2}$$

Here, the functions $h(x, y)$ and $\tilde{h}(u, v)$ are common for all the classes, while the functions $g_m(x, y)$, $\tilde{g}_m(u, v)$ characterize the m class. From (2) it follows that in many cases it is advisible to combine the preprocessing and recognition proper in a number of cases, by assuming $\tilde{g}'_m(u, v) = \tilde{h}(u, v)\cdot\tilde{g}_m(u, v)$. In this paper only the case of parallel processing of the whole field of the input image $f(x, y)$ is considered.

The above operations are performed in linear (in amplitude an intensity) optical systems. In the first case (the amplitude correlators) the high resolution processing of the complex functions is possible, since the operation of such devices is based on the diffraction laws. The papers [1, 2] show that rather complex decision functions providing high quality of the image recognition can be realized in such correlators. But all the elements of the optical device require an accurate phase correction and adjustment, because the complexity of the functions in coherent systems is provided by modulation of both amplitude and phase of the light wave.

The majority of well-known intensity correlators are based on the principle of geometrical optics, and the functions $f(x, y)$, $h(x, y)$, $g_m(x, y)$ are real and nonnegative. Due to these circumstances the application of noncoherent devices is limited in spite of their considerable noise stability and easy construction.

At the same time, such efficient recognition algorithms, as dispersion, sign and rank ones [3], operate for real sign-variable functions. Hence, it is advisible to introduce an operation of substraction into the processing linear with respect to intensity. To improve the resolution the diffraction intensity correlator should be used for image processing [4, 7].

In this paper we consider methods of realization of sign-variable pulse responses in the diffraction intensity correlators using differential STLM (space-time light modulators) [8]. The paper is, moreover, the first one to suggest methods of realization in a parallel version of such non-parametric algorithms of image recognition, as sign and rank ones.

The differential STLM is a device consisting of two optically conjugated electrooptical light modulators, the functioning of which is appropriately coordinated. If, for example, image proportional in intensity to

$$T_1(x, y) = f(x, y) \otimes h_1(x, y)$$

is recorded on one STLM, and an image proportional to

$$T_2(x, y) = f(x, y) \otimes h_2(x, y)$$

is recorded on another STLM, in subtraction mode, then we obtain the output intensity proportional to

$$T(x, y) = \{f(x, y) \otimes h_1(x, y) - f(x, y) \otimes h_2(x, y)\}. \tag{3}$$

Such an operation is equivalent to processing of the image $f(x, y)$ with a sign-variable pulse response of the form

$$h(x, y) = h_+(x, y) - h_-(x, y) = h_1(x, y) - h_2(x, y).$$

Whenever two STLM are set in the multiplication mode and

$$T_1(x, y) = f(x, y) \otimes h_1(x, y)$$

is recorded in one of them, and

$$T_2(x, y) = [1-f(x, y)]\otimes h_2(x, y)$$

in the other, then in the output the nonlinear processing algorithm the operation

$$T(x, y) = \{f(x, y)\otimes h_1(x, y)\cdot[1-f(x, y)]\otimes h_2(x, y)\}^2 \tag{4}$$

will be realized.

By a proper selection of the functions $h_1(x, y)$ and $h_2(x, y)$, some rather complex algorithms of image preprocessing as well as different kinds of contouring operation of the image $f(x, y)$ can be realized in a relatively simple way. Such operations are used most frequently to realize a recognition procedure, because the better part of information on the object under recognition is contained in its configuration, i.e. the entropy is maximum on the image boundary.

Let us present some examples of image preprocessing with the differential STLM, which are equivalent to the processing in the coherent optical system with a sign-variable pulse response. The most frequently employed is operation $\Delta = \partial^2/\partial x^2+\partial^2/\partial y^2$. It is realized in the finite differencies, according to (3) for

$$\begin{aligned} h_1(x, y) &= \delta(\sqrt{x^2+y^2}), \\ h_2(x, y) &= \frac{1}{c_1}\,\delta\{\sqrt{(x-d_x)^2+(y-d_y)^2}\}, \end{aligned} \tag{5}$$

where

$$c_1 = \iint\limits_{-\Delta}^{\Delta} \delta\{\sqrt{(x-d_x)^2+(y-d_y)^2}\}\,dx\,dy,$$

$$d = \sqrt{d_x^2+d_y^2}$$

is a discretization step, and the normalization means that whenever the input is uniform, the output must be equal to zero.

The method of a blurred mask well-known in photography is another example of contouring. This operation is realized according to (4) for

$$h_1(x, y) = \delta(\sqrt{x^2+y^2}), \qquad h_2(x, y) = \frac{1}{c_2}\,\mathrm{rect}\left(\frac{\sqrt{x^2+y^2}}{d}\right)$$

and by varying the values c_2, d, i.e. the contrast and the blurring area size, a particular region of spatial frequencies can be isolated, while the other — supressed [9].

The ways of realization of seperations such as logic ones, separation of equidensities, etc. in the differential STLM are given in [8].

Thus, using differential STLM, practically all operations which were performed earlier by spatial frequency filtering in coherent systems only, and also some new operations not typical of the optical processors, can be performed on the images. Note, that for this purpose any illumination: coherent, incoherent or partially coherent can be used. Such a processing is of interest by itsels (e.g., to improve the image quality), but for us it is of interest only as the preprocessing operation, after which correlation to the reference should be made, i.e. the calculation of the proper decision function. In this sense the diffraction intensity correlators are of particular interest [4–7], they combine such advantages of incoherent correlators, as intensitivity to phase distortions, accuracy of adjustment of optical elements and filters, etc., and those of coherent computers using holographic filters, i.e. operation of the principles of diffraction optics, multichannelness, etc.

Let us consider now some examples of realization of the most efficient recognition algorithms in such diffractional correlators (with preprocessing of the images recognized on the differential STLM), which have been realized before in coherent systems only, and sometimes only in series.

In the paper [2] the dispersion recognition algorithm is considered which is based on computation of normal and tangential (to the boundary of the object recognized) dispersion. According to [3] it is efficient for recognition of the images given in photographs. Its realization by using the coherent optics is rather complicated. However, if a pulse response $h(x, y) = h_1(x, y) - h_2(x, y)$ with $h_1(x, y)$ and $h_2(x, y)$ defined in (5) is applied to a differential STLM, and to a diffraction intensity correlator, the obtained pulse response (reference contours) $g_m(x, y)$ has the form

$$g_m(x, y) = g(s, n) = \delta\left\{n(s) - \frac{d}{2}\right\} + \delta\left\{n(s) + \frac{d}{2}\right\} \tag{6}$$

where information on the m class is contained in (s, n), as it is a rectangular coordinate system (the origin of which lying on the boundary of the object under consideration), and the axes directed along the tangent and normal directions, respectively [1]. Hence, it follows that with the input intensity $I_0(x, y) = f(x, y)$, the intensity obtained on the differential STLM output is equal to

$$I_1(x_1, y_1) = \{f(x_1, y_1) - m(x_1, y_1; d)\}^2 = k(x_1, y_1; d) \tag{7}$$

which represents a quadratic value of the contrast at an arbitrary point $f(x, y)$ relative to the mean intensity on the circle of the radius d. Since $I_1(x_1, y_1)$ is an input of the dffraction intensity correlator, taking account of (6) and (7) we get at its output

$$I_2(x_2, y_2) = \langle k(x_1, y_1; d_1)\rangle|_{(x_2, y_2)} = D_d(x_2, y_2), \tag{8}$$

i.e. the dispersion $f(x, y)$ obtained by averaging the contrast over the reference contours (which is true for ergodic processes) for each of their positions with respect to the image under recognition, and output intensity (8) containing both tangential and normal dispersions. However, by choosing properly the parameter d in $h(x, y)$ and leaving it unchanged in $g_m(x, y)$ a tangential dispersion can be separated and, thus, the decision function formed.

The recognition algorithm considered is, perhaps, the only parametric recognition algorithm which provides rather high efficiency of recognition and is competitive to nonparametric algorithms. The thing is that the image recognition is related to the class of problems with high a priori uncertainty, and in this case the nonparametric algorithms give much better results. However, they contain such nonlinear transformations whose realization in optics is difficult, being in a parallel version quite impossible. For example, in [10], for their realization the following operation were performed: mechanical displacement of the image under recognition relative to the reference contours, scanning along the contour, introducing of a set of characters to the computer with subsequent calculation of the decision function. This, naturally, took a lot of time and did not permit, to a great extent, the advantages of parallel optical processing. Therefore, the process recognition was suggested to be conducted in two steps: to use a high-spead, though not reliable correlation algorithm during the first step, and to use a slow but efficient nonparametric algorithm after the information, is processed during the second one.

Hereafter, we will show that the two steps may be combined, and that such efficient algorithms as sign-variable and rank ones can be realized in a parallel version. The idea of the sign algorithm is in the following: On each realization defined by configuration of the reference contours there appears the length with the contrast exceending by $k(x, y; d)$ the intensity threshold fluctuations. Thus, the decision function in this case is equal to

$$S_m(x_2, y_2) = \langle \chi\{k(x_1, y_1; d) - k_0\}\rangle|_{(x_2, y_2)}, \tag{9}$$

where

$$\chi(Z) = \begin{cases} 1, & Z \geqslant 0, \\ 0, & Z < 0. \end{cases}$$

It is realized in the system consisting of a differential STLM, equidensity separation block (a line of equal intensity), zero indicator, and diffraction intensity correlator joined in series. The pulse responses $h(x, y)$ and $g_m(x, y)$ are determined according to (3), (5), and (6). A nonlinear operation

$$\varphi(Z) \begin{cases} = 0, & Z \neq 0, \\ \neq 0, & Z \neq 0 \end{cases}$$

is performed in the equidensity separation block, while

$$\psi(Z) = \begin{cases} 0, & Z \neq 0, \\ 1, & Z = 0 \end{cases}$$

is performed in the zero indicator, i.e. the two blocks serve for separations of equidensities, contrast inversion and threshold operation. The authors see no possibilities to perform the above operations in the same unit, even though $\psi\{\varphi(Z)\} = \psi(Z)$.

Whenever the voltage $U(t) = at' + k$ is applied to the equidensity separation block, the relation

$$I_2(x_2, y_2; t) = \langle \psi\{k(x_1, y_1; d) - at - k_0\}\rangle|_{(x_2, y_2)} \tag{10}$$

holds at the output of the whole system at arbitrary time moment and after the time averaging we obtain on the photoreceiver

$$I_2(x_2, y_2) = \frac{1}{T}\int_0^T I_2(x_2, y_2; t)\,dt = \langle \chi\{k(x_1, y_1; d) - k_0\}\rangle\Big|_{(x_2, y_2)}$$

which is the required decision function, becomes

$$\chi(Z) = \frac{1}{T}\int_0^T \psi(Z - at)\,dt, \text{ and } T = Z_{\max}/a.$$

Thus, to realize decision function (9) all the equidensities on the contoured image under recognition should be separated successively with the maximum intensity, beginning with a particular threshold, and, then the obtained light distribution be integrated with respect to both space (in parallel for all positions of the reference contours), and time (during the time of separation of all equidensities). Without going into details it may be noted that FOTOTITUS with sharp nonlinear characteristics can be used as a zero indicator, and PROM without dielectric layers as a equidensity separation block [11].

The rank algorithm is more complicated, but more efficient. When realizing the rank algorithm, unlike the sign one, the values of the contrast difference $k(x, y; d)$ and those of intensity fluctuations are previously ranked (in module) and then, the sum of the ranks of positive values of the difference $k(x, y; d) - k_0$ is determined. In other words, the length of contrast ranked with the account of the negative values and exceeding the intensity fluctuations is calculated. To determine this magnitude the optical system, similar to that described above, is used. The voltage

$$U(t) = (1-)^{m+1} a(t - nT_0)\,\mathrm{rect}\left(\frac{t - mT_0 + \dfrac{T}{2}}{T_0}\right)$$

is applied to the equidensity separation block, where

$$m = \left[\frac{t}{T_0}\right]+1, \quad n = \left[\frac{t-T_0}{2T_0}\right],$$

$$0 \leqslant tT, \quad M = \frac{T}{T_0},$$

$[Z]$ — is an integer part of Z.

Thus, the values of the contrast both above and below the threshold are scanned in succession. At the output of the whole system we have at an arbitrary time t, that

$$I_2(x_2, y_2; t) = \left\langle \psi \left\{ k(x_1, y_1; d) - (-1)^{m+1} a(t-nT_0) \right.\right.$$
$$\left.\left. \operatorname{rect}\left(\frac{t-mT_0+\frac{T}{2}}{T_0}\right) - k_0 \right\}\right\rangle\Bigg|_{(x_2,y_2)}$$

and after integration during the period T_0, we have on the photoreceiver at the times $t = mT_0$

$$I_2(x_2, y_2; m) = \frac{1}{T_0}\int\limits_{(m-1)T_0}^{mT_0} I_2(x_2, y_2; t)\,dt = \left\langle \left| \chi\left\{k(x_1, y_1; d) - k_0 \right.\right.\right.$$
$$\left. -(-1)^{m+1}\left[\frac{m-1}{2}\right]aT_0\right\} - \chi\left\{k(x_1, y_1; d) - k_0(-1)^{m+1}\right.$$
$$\left.\left.\left. \left(\left[\frac{m-1}{2}\right]+1\right)aT_0 \right|\right\}\right\rangle\Bigg|_{(x_2,y_2)}, \tag{11}$$

i.e. length of the sections where the contrast values are within the range determined from the equality of 0 arguments of the function $\chi(Z)$ in expression (11). The values obtained are then discretized

$$N_m(x_2, y_2) = I_2(x_2, y_2; m)/l,$$

where $\Delta < l \leqslant d/2$, and Δ is an element of resolution in the image under recognition, and the required sum of the ranks R is determined according to

$$R = \sum_{m=1}^{\left[\frac{M+1}{2}\right]} \left(\sum_{i=1}^{2m-2} N_i + \frac{N_{2m-1}+1}{2}\right) N_{2m-1}.$$

At the first sight the recognition algorithms considered seem to be more complex, than, e.g. the correlation method used traditionally in optics. It should be taken into account, however, that they provide much higher recognition efficiency [3]. The calculation time increases, but only slightly (time of equidensity separation), because the processing is made in parallel all over the area in which the object under recognition can be found.

In conclusion, the paper shows that using the differential STLM, the sign-variable processing can be done in the diffraction intensity correlators with the aim of both imaging quality improvement and image preprocessing. Various kinds of linear and nonlinear image preprocessing are considered. Methods of realization of efficient recognition algorithms in these systems, including nonparametric sign and rank algorithms, are suggested, which have not been carried out so far in the optical systems working in a parallel version. All these facts widen substantially the possibilities of optical image processing, as they incorporate simultaneously the advantages of coherent and incoherent computers and provide a new quality, i.e. the possibility of nonlinear operative parallel processing performed in optical systems without feedback.

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Распознавание изображений в дифракционных корреляторах интенсивности

В работе рассматриваются способы распознавания изображений в оптических системах, использующих пространственно-некогерентное монохроматическое освещение. Показано, как, используя пространственно-временные модуляторы света, в таких устройствах осуществляется свертка изображений со знакопеременным импульсным откликом, а также некоторые виды нелинейной обработки изображений. Причем, эти операции можно применять как с целью улучшения качества, так и с целью преобразования изображений к удобному для распознавания виду. Предложены методы реализации в дифракционном корреляторе интенсивности эффективных алгоритмов распознавания, включая непараметрические знаковый и ранговый. Все это существенно расширяет возможности оптической обработки, поскольку позволяет не только объеденить преимущества когерентных и некогерентных вычислительных устройств, но и получить новое качество — осуществить нелинейную поеративную обработку изображений в оптических системах без обратной связи.