OPTICAL STRUCTUROSCOPY: DEVELOPMENT OF EFFICIENT DIGITAL ALGORITHMS IMPROVING MEASRUREMENT ACCURACY

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Abstract: Approaches to solve an important problem of complex image processing in the course of structural analysis – image restoration are considered. The approach described differs in that the point spread function (PSF) used in the linear model of image restoration is not known a priori. Methods are suggested to solve the identification problem for a digital electro-optical image-forming system, consisting in estimating the point spread function of the image system. The image restoration problem is solved proceeding from the methods of the Tikhonov theory of ill-posed problems.

Introduction: As is known, quantitative analysis of the images of microstructures by application of optical inspection method for non-destructive examination is one of the principal stages for taking an expert decision. However, the distortions introduced in the image of the controlled object in the course of study materially worsen the accuracy of estimation of various quantitative parameters of the images, which decreases the value of the information obtained. Therefore the task of elimination of distortions introduced by actual devices used for optical inspection is of considerable current interest.

One may single out two essentially different ways to eliminate distortions. The first one proceeds from the fact that various technical solutions allow to improve the structure of the actual device, achieving minimum distortions in the image-forming system. But technical perfection of the measuring equipment, first of all, inevitably increases its complexity and, secondly, increases its cost. Besides, the measuring processes themselves may be connected to various uncontrollable factors, the distorting impact of which cannot be removed by any constructive improvement of the equipment.

The second way to eliminate distortions consists in the restoration of the images themselves. Restoration of images usually means the process of estimation: an image received as a result of supervision or measurement is transformed to find an estimation of the ideal image, which would be observed at the output of a hypothetical image system introducing no distortions. The process of restoration provides posterior inversion of the image formation stages having caused its distortion. At that the actual phenomena causing distortions are replaced with their mathematical model.

Image restoration becomes an extremely acute problem in connection with an ever growing computer analysis of optical control data. The use of computer-based complexes in non-destructive optical inspection assumes the reception of digital images of the objects studied, which, in turn, requires effective algorithms for digital processing of the images. The task of image restoration is of particular importance for portable digital electro-optical systems, which include, as a rule, a microscope, video or photo camera, PC with the software for data processing and devices for the output of the control results. It should be noted that portability of the optical inspection system imposes certain technical restrictions thereon, affecting the quality of the images received. In this instance the computer digital image processing system can materially offset distortions introduced by such portable optical systems.

To build up effective algorithms for digital image restoration it is necessary to know quantitative estimates of the distortions introduced by the actual image system. The procedure of restoration consists in modeling followed by inversion of distorting transformations. Therefore for effective image restoration adequate modeling of the process generating distortions is required.

One may distinguish two principal approaches to modeling distortions: prior and posterior [2]. In the first instance responses of the actual image system to some test image are used. In case of posterior modeling the model of distortions is formed on the basis of measuring the parameters of a specific distorted image to be restored.

The work presented uses the posterior approach to modeling distortions introduced by the actual portable electro-optical image-forming system. This is explained by the difficulty to provide identical conditions of obtaining images required for prior modeling.

It is suggested to break the task of image restoration into several stages. At the initial stage homogeneous areas of the image are located, within the limits of which the point spread function (PSF) may be considered stationary. The second stage consists in estimating PSF [3-5] for each located area of the image. At the third stage, assuming PSF is approximately known, an inverse problem of restoring the initial image is formulated and solved [1]. The basic method of the image restoration technology is the application of the Tikhonov theory of ill-posed problems [1] allowing to solve Fredholm bivariate convolution integral equations of the 1st kind. The fourth stage performs "patching" of the restored fragments of the image.

The work presented gives effective algorithms for estimating the point spread function and microstructure image restoration for the employed linear model of the image-forming system.

Results and Discussion: Mathematical model of a digital optoelectronic system of metallographic microscopy. The purpose of restoration is to form a set of readings $\hat{F}_I(m_1, m_2)$, being the estimates of the readings of an ideal input image represented by function $\hat{F}_I(m_1, m_2)$, which are formed at the output of the ideal image system. The first step to develop the model of digital restoration requires to define the ratios between the readings of the image observed $F_R(m_1, m_2)$ and the values of the initial image in nodes (readings) $F_I(m_1, m_2)$. Thus, the task of digital restoration of the image consists in the inversion of the following transformation system of the ideal digital image:

Fig. 1

As has already been mentioned above, the first stage necessary to restore the image is identification, i.e. construction of the mathematical model of the digital system introducing distortions shown in fig. 1.

The basic prior assumption concerning the distorting system (fig. 1) will be the assumption of its linearity and spatial invariance of the relevant pulse response characteristic or point spread function (PSF). Let us consider that the ratio between the input and output of this system is defined by the bivariate convolution equation:

$$F_R(m_1, m_2) = \sum_{n_1}\sum_{n_2} h(m_1 - n_1, m_2 - n_2) F_I(n_1, n_2),$$

where $h(i, j)$ – pulse response characteristic of the system (PSF), and $\sum_{i,j} h(i, j) = 1$.

Posterior estimation of the pulse response characteristic of the distorting system

The complexity in estimating the pulse response characteristic of the system is that the estimates are to be obtained from a diffuse (blurred) image. Since the model of the distorting system is supposed to be linear, and the pulse response characteristic – to be spatially invariant, the actual blurred and, quite possibly, interfered image should satisfy certain conditions. First of all, the degree of the image blurring should be homogeneous across the image according to some criterion of invariance. If the image does not satisfy the criterion of invariance, it should be broken out into stationarity areas, within the limits of which the pulse response characteristic form remains unchanged. Secondly, the area under study should contain objects with contrast brightness jumps.

Analysis of the pulse function of the image formation system is usually performed by point or linear extended objects. Such objects may be, for example, borders of metal grains. If the degree or character of these diffused jumps is estimated, it will be possible to restore the form of the point spread function, too.

One of the approaches to estimate the diffuseness degree is to build the so-called gradient image, on which the extreme values of these "diffuse" gradients refer to the object borders which should be "clearly seen", with no blurring. The ways to restore the point spread function considered below are posterior, as the estimated pulse response characteristic, within errors, is adequate to specifically realized observation conditions, and not known in advance. All the algorithms given below are realized in the system of computer mathematics MatLab.

Spatial differentiation of the image. Let $F_R(m_1,m_2)$ be the matrix of the image observed. Using this matrix, we shall build a matrix of gradients $D(m_{1,}m_2)$, each element of it equaling the maximum from the modules of brightness differences between the given element and those next to it. Then from matrix $D(m_{1,}m_2)$ thus constructed there are chosen elements with the values within some neighborhood of the gradients maximum. Experiments have shown that the dimensions of this neighborhood or range of values of the gradients are strongly dependent on the quality and structure of the image. Thus, the range of values of the gradients further used to estimate the point spread function is one of the parameters of the algorithm described.

Estimation of the discrete PSF. The approach used to estimate the discrete PSF is that employed to estimate the continuous PSF, which is as follows. Let us consider a continuous linear model of an image formation system with a spatially invariant PSF having circular symmetry:

$$F_R^0(x,y)=\iint H(x-\xi,y-\eta)G(\xi,\eta)d\xi d\eta$$

where $H(x,y)$ is the point spread function of the system. PSF may be believed to be normed. Let us consider the PSF diagram in the system of coordinates $Oxyz$. Then in the zOx plane projection the point spread function will be

$$H_l(x)=\int_{-\infty}^{\infty}H(x,y)dy,$$

where $H_l(x)$ is the line spread function. For the semiplane edge the brightness distribution in the direction perpendicular to the edge is described by the function:

$$I(x)=\int_{-\infty}^{x}H_l(u)du$$

Thus, $H_l(x)=\dfrac{dI(x)}{dx}$**.** If the spatial PSF has circular symmetry, it can be restored by one section – PSF projection on plane zOx. In this case $H(x,y)$ is estimated by section $H_l(x)$ by means of setting radius-vector $r = \sqrt{x^2 + y^2}$, i.e. $H_l(r) = H(r)$. Thus, to restore PSF by the actually blurred image it is necessary to estimate the edge spread function. Then it should be differentiated to obtain the PSF section. After that the PSF estimate $\hat{H}(x, y)$ should be normed. To minimize errors in estimating brightness distribution $I(x)$ it is necessary to obtain an average section for several points with the maximum gradients.

For identification of the discrete PSF it is first of all necessary to define the direction of the maximum brightness difference for each gradient chosen. This task is solved with the use of the Haralick-Watson facet model [3].

Algorithms for the discrete PSF restoration. The discrete pulse response characteristic of the linear image formation system having a circular symmetry property looks like a matrix symmetric with respect to the central element.

To ensure the symmetry of the brightness distribution function derivative, the points equidistant from the centre of the segment (on which the "section" is defined) may be assigned identical values equal to their arithmetic mean.

When modeling the PSF restoration process in the MatLab system the following algorithms were employed.

PSF restoration by the "inscribed circle". Applying the algorithms described above we shall obtain the distribution of brightness values along the direction of the maximum difference and its derivative. Since in accordance with the assumption PSF has circular symmetry, it is possible to consider that we know the values of the derivative of brightness distribution along the median line of the chosen window. Now, to restore any unknown element of the window it is necessary to calculate the distance to it (in the chosen metrics) and assign the value of the median line element located at the same distance from the central one. The window elements further away from the central element than the median line element most distant from the centre are taken to equal zero. After all matrix elements are restored, it is normed.

PSF restoration with the window truncation. The application of this algorithm results in that PSF is restored in a smaller window than that in which brightness distribution was defined. The algorithm performance may be reduced to two steps. The first step coincides with the algorithm of restoration by "the inscribed circle", and the second step consists in that as the PSF carrier there is chosen a square with the centre coinciding with the centre of the initial window and with the side equaling the distance to the nearest element of the initial window, to which the zero value was assigned in performing the first step. After that the matrix is normed.

Difficulties arising in restoring PSF. Experimental results have shown the following principal difficulties in restoring PSF.

1. In case the window by which PSF is defined is chosen too large (or if there is noise in the central point of the window, but there is no edge of the object), the distribution function for the brightness values by the maximum jump may be non-monotonic (theoretically it should be a strictly increasing function with the flex point at the centre of the segment), and, as a result, the derivative of this function will take negative values, and, consequently, PSF will also be negative in some points, which will introduce significant errors in the process of restoration.

2. As the maximum gradients by which the average brightness distribution is defined may happen to belong to one segment (when the windows of these elements overlap and the directions of the maximum brightness difference coincide), this will also introduce errors in the PSF restoration process.

Algorithms reducing errors in the course of PSF restoring. To overcome the influence of the negative factors specified in paragraph (1) of the previous section two approaches are suggested. The first of them is based on the rejection of the gradients the brightness distribution in the

neighborhood of which is non-monotonic. If all maximum gradients are rejected, it is necessary to reduce the window used to restore PSF. The second approach is based on replacing the negative values of the brightness distribution derivative by the zero ones, and then PSF is restored.
To avoid the presence of the negative factors specified in paragraph (2), there is suggested an algorithm to check that the two gradients used to restore PSF should not appear on parallel and intersecting segments by which PSF is restored.
Algorithm of the digital method of image restoration. The work presented employs the algorithms of image processing in the frequency area using Fourier processing based on the Tikhonov method of ascent [1]. These algorithms contemplate sequential performance of the following procedures: synthesis of the transfer function of the restoring filter according to the calculation formulas of the Tikhonov method of ascent, calculation of Fourier processing of the image observed, multiplication of the spectrum of the image observed by the transfer function of the restoring filter, calculation of the inverse Fourier transformation of the restored image spectrum.

Assuming the digital image formation system is linear and spatially invariant, the digital image restoration can be presented as follows.

1. The transfer function of the restoring filter is chosen as

$$h_{в}^{\alpha}(u,v)=\frac{h^{*}(u,v)}{|\,h(u,v)\,|^{2}+\alpha Q(u,v)},$$

where $h(u,v)$ and $Q(u,v)$ are obtained as a result of applying the discrete Fourier transformation to the pulse response characteristic of the system and stabilizer, α – regularization parameter.

2. The regularized solution of the convolution equation is defined by the formula:

$$G_{\alpha}(u,v)=\frac{1}{N^{2}}\sum\sum\frac{h^{*}(u,v)}{|\,h(u,v)\,|^{2}+\alpha Q(u,v)}F(u,v)\exp(\frac{2\pi j}{N}(ui+vk)),$$

where $F(u,v)$ – discrete Fourier transformation of the observed image.
As the image obtained with the help of the optical system has various blurring degrees in the centre and at the edges, it is expedient to split the image by the areas of uniform blurring, within the limits of which PSF is spatially independent, and to apply restoration algorithms separately for each of such areas.
As the function specifying the digital image in each obtained fragment is determined within a limited area (square, rectangle), there are considerable ineradicable errors appearing at its borders in the course of restoration. Therefore in numerically realizing the Tikhonov method it is essential to properly pass to the final area, in which the solution is to be found [3-5]. To reduce restoration errors at the image borders it is suggested to expand the restoration area by the size of the local carrier of the convolution nucleus (point spread function). This is always possible, because estimation of an unknown PSF is the preliminary stage for the image restoration [3-5]. After the area of restoration is increased, the solution is looked for in the whole increased area, and the boundary effects are shown only in the expansion zone. The difficulty arising when using this approach to image restoration consists in subsequent "patching" of these areas. To "patch" the

restored fragments, it is necessary to apply algorithms for the removal of the frame (expansion zone) for each area.
The algorithm described below takes into account the above problems and allows to effectively eliminate edge smearing arising on digital images obtained with the help of an electro-optical image-forming system.

Basic steps of the algorithm.

1. Fragmentation of the image into parts with an identical degree of "blurring". As a rule, significant smearing is seen at the edges of the image. It is assumed that all fragments have the form of squares.
2. The PSF restoration algorithm is performed for each fragment [1].
3. For each fragment the image restoration algorithm is performed, including the following stages:
   - expansion of the restoration area by the double value of the local carrier of the pulse response characteristic of distortions (PSF); at that the first step consists in outlining the fragment with a white frame of the size of the local carrier of PSF, the second step being the obtained image outlining with a black frame of the same size;
   - calculation of the restoring filter [1];
   - restoration of the image [1];
   - removal of the frames.
4. Patching of the restored fragments.
5. Visualization of the image.

Expansion of the image restoration area. As the image in being restored loses symmetry with respect to the black frame used to eliminate the restoration errors at the edges, it is suggested to use one more auxiliary internal white frame.
The basic advantage of the use of a double frame is that at the image restoration its placement against the white frame does not change. Therefore, to properly cut out the restored image, it is possible to use the algorithm of threshold search of the white frame border and frame removal.

Principal steps of the frame removal algorithm.
1. Two rectilinear sections of the outlined image – horizontal and vertical – are formed. As there is a black frame remaining at the image edges, the brightness profile along the sections will have pronounced areas (fig. 2) of increase (transition from the black frame to the white one) and decrease (transition from the white frame to the black one).

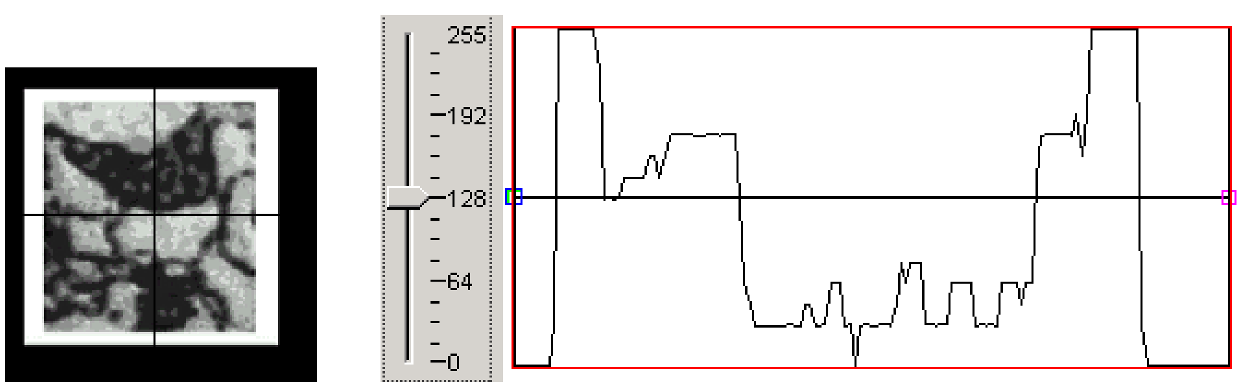


Fig. 2

2. Choosing the brightness threshold (for example, 128), the borders of the white frame are defined.

3. Using the borders established, a rectangular area of the image is cut out and in this way the black frame is removed.

4. A square inscribed in the resulting rectangle is formed, coinciding in size with the initial image being restored; at that the centre of the square should coincide with the centre of the rectangle; formation of the said square shall mean removal of the white (internal) frame.

Building of the initial image by the restored fragments. The building of the initial image by the restored parts means "patching" of these parts. However, it is necessary to note that on applying the restoration algorithm the image is slightly reduced in size. Therefore the edges (of an insignificant thickness) of the square image of the restored fragment obtained with the help of the frame removal algorithm will have significant brightness errors in comparison with the relevant true values. If such fragments are "patched" without additional processing, the resulting image will have pronounced streaks along the initial cut lines.

To minimize the said restoration errors, it is suggested to employ the following algorithm for each fragment:

- To define the mean brightness values for the restored and initial fragments;
- To add to (or subtract from) the brightness value of each pixel of the restored image the absolute difference of the mean brightness values for the restored and initial fragments; as a result the mean brightness values of these images will become equal;
- To "patch" the obtained fragments;
- To place bands along the patch lines with a width equaling the double size of the local carrier of PSF;
- To build rectilinear sections of the image for each band (for all lines or columns in each band);
- To compare the mean brightness of each section with the mean brightness of the relevant section of the initial image; if the difference of the mean values exceeds a certain threshold (for example, 10), the column or line of the restored image corresponding to the section is replaced by the column or line of the initial image.

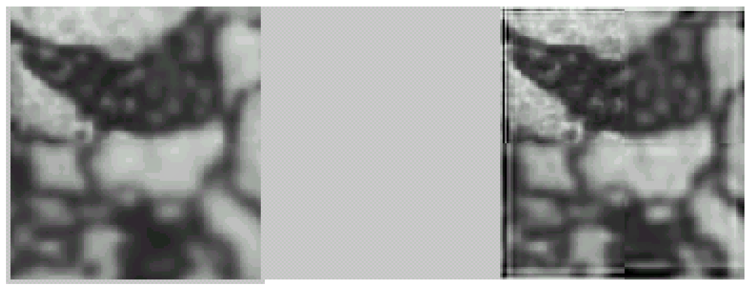
Example. In the given example the image of a metallographic polished specimen is cut into four parts, each fragment is defocused with the help of PSF (carrier value 15x15) as Gaussian functions

$$g(x,y) = A\exp\left(\frac{x^2+y^2}{\delta^2}\right)$$

with the parameters $\delta = 1$, $\delta = 3$, $\delta = 6$, $\delta = 9$ correspondingly (in fig. 3a – from left to right, from top to bottom), which were restored for the same defocused images with the help of the "inscribed circle" algorithm. At that, in the given example there were used the algorithms of elimination of negative values of the brightness distribution derivative and cutting off of gradients on parallel and crossing segments. The restored image (fig. 3b) was obtained with the help of the algorithm of restoration with the use of the stabilizer

$$Q(u,v) = u^4 + v^4$$

Restoration was performed using the following parameters $\alpha = 10^{-11}$, $\alpha = 10^{-10}$, $\alpha = 0{,}09 \cdot 10^{-10}$, $\alpha = 0{,}09 \cdot 10^{-10}$ (for fragments of the image from left to right and from top to bottom).



a **b**

Fig. 3

Conclusions: The algorithms considered in the given work, show good image restoration effectiveness for subsequent quantitative analysis of the structure with its image. Such results could be obtained by the condition of the optimal image fragmentation providing spatial invariance of PSF on each fragment.

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