Abstract — In the paper we study energy methods for image restoration, when a restored image is obtained after minimization of an integral functional. Although such a functional is global, only few pixels in a small neighborhood of any pixel on the initial image can influence on the corresponding pixel on the restored image. We call this neighborhood an "influence area" and propose a technique for calculation of such areas and their visualization on computer screen. We apply the whole testing technique based upon this approach to a couple of known image restoration methods. The parameters of these methods, ensuring their better performance, are found.

Keywords — energy minimizing methods, image processing, image restoration, testing.

I. INTRODUCTION

Image restoration is widely considered as one of the important problems in image processing. In the present paper, we focus on the energy minimizing restoration methods, where the output image is the result of minimization of a certain functional in an integral form. Nowadays, many types of such functionals, which are used for the restoration of distorted images, are known [1]-[14]. Similar approaches to the restoration problem are intensively studied in recent publications [17]-[21]. The variety of methods creates the need to select the optimal one for a specific practical task.

One can say that image restoration is a state of art technique for enhancement of image quality, based on a few absolute criteria. Generally this process involves some methods for elimination of distortions, for example, such as noise. But in practice this cannot be done ideally. However, in some cases, significant improvements can be achieved.

In this paper we restrict ourselves to considering the following properties of energy minimizing methods:

a) to reduce significantly the noise level in the parts of the image where the intensity changes smoothly;

b) to protect from blurring the high contrast intensity changes (in other words, to preserve the boundaries of objects on the processed image).

These properties are essential for practical applications and, therefore, their thorough study is important.

The "influence areas" introduced in the paper is a tool which allows one to find out some important features of image restoration methods. We introduce the testing technique based on the use of influence areas and apply it for testing of two known energy minimizing restoration methods. In particular, we find the values of the methods' parameters ensuring their effective performance.

The paper is organized as follows.

In Section II we formulate the main problem considered in the paper.

In Section III we introduce the “influence areas” (further on, we use this term without quotations and propose a technique for their calculation.

In Section IV, the formulas of functionals for two energy minimizing restoration methods: PL [11] and GR [5], [8] are given. These methods are studied with the help of the influence areas.

The results of the study are presented in Section V.

Finally, we make the conclusions on the optimal methods’ parameters choice for both good noise reduction and good contrast boundaries preservation.
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Let \( I(x_0, y_0) \) be intensity of a pixel at the location \((x_0, y_0)\) on the initial image \( I \) (Fig.1.a). The corresponding pixel on the restored image \( u \) has the intensity \( u(x_0, y_0) \) (Fig.1.b). Starting points for our study were two following observations.

a) It appears reasonable that the value \( I(x_0, y_0) \) exerts the most influence on calculating of the value \( u(x_0, y_0) \) under restoration process. It is possible that the value \( I(x_1, y_1) \) of closely spaced pixel \((x_1, y_1)\) has some influence on calculating of the value \( u(x_0, y_0) \). At the same time, it seems highly improbable that a peripheral pixel \((x_2, y_2)\) can have measurable influence on the value \( u(x_0, y_0) \). Really, if this were not the case, the restored image \( u \) simply would not be similar to the original image \( I \).

b) On the other hand, image restoration with functional (1) is a solution of a global optimization task: all the pixels of the initial image are used to find \( u(x, y) \). Hence, the neighboring pixel \((x_1, y_1)\) and the distant pixel \((x_2, y_2)\) can formally affect the intensity values of \( u \) (Fig.1.a) can have noticeable influence on the value of \( u \) (Fig.1.b).

Points a) and b) look like a contradiction. So, despite the functional (1) is global, only some significant pixels located in close proximity to pixel \((x_0, y_0)\) on the image \( I \), really can have noticeable influence on the value of \( u \).

Result of this contradiction is the notion of influence area. This area is located on the image \( I \). It is a small neighborhood of the pixel \((x_0, y_0)\) consisting of significant pixels on \( I \).

The goal of our study is to assess shape and size of such areas. We develop a technique for calculating such areas (Section III) and demonstrate this technique on example of two known energy minimizing methods (Section IV). For this purpose we use synthetic image Fig.2. This image is taken from the test image database of our PICASSO framework [15].

This image has an inner boundary in the middle. Its contrast varies from bottom to top. On Fig.2, the contrast of the boundary pixels is determined by ordinate \( y \) and continuously decreases from the most value at the bottom of the image to the least value at the top. The performance of energy image restoration methods significantly depends on contrast values near the boundaries [16]. This image allows efficient studying specific characters of these methods. It appears that influence are significantly different a) if a tested pixel is afar from the boundary and b) if it is close to the boundary.

III. INFLUENCE AREA AND TECHNIQUE FOR ITS CALCULATION

We develop the following technique in order to evaluate the size and the shape of influence areas. To do it, the following steps are necessary (1-12):

1. Choose a noisy image having inner boundaries. In this paper we use Fig.2.b. Denote this image as \( I \).
2. Restore the image using functional (1). Denote the resulting image as \( u \).
3. Select a pixel \((x_0, y_0)\) both on \( I \) and \( u \).
4. Perform series of modifications of the image \( I \): Replace \( I \) with new ones \( I_{\Delta x, \Delta y} = I(x_0+\Delta x, y_0+\Delta y) \) where \( \delta \) is a small value, the same for each \( I_{\Delta x, \Delta y} \). That is, the image \( I \) is changed in a single pixel. In all other points the image \( I_{\Delta x, \Delta y} \) is equal to \( I \). Values \( \Delta x \) and \( \Delta y \) are sequential integers with step 1. In our experiments we took \(-5 \leq \Delta x, \Delta y \leq 5\).

The \( \delta \) value should be chosen for the following reasons.

a) Any change of the initial image shouldn’t influence the result of restoration essentially. This means that the reduction of \( \delta \) for several times should not considerably change neither the size, nor the shape of the influence area. Our experiments have shown that for \( \delta = 1.0 \) and \( \delta = 0.1 \) both size and the shape of the influence areas are practically stable. So, such values for \( \delta \) are appropriate. Further \( \delta = 0.1 \) is used.

b) For the correct search of distinctions between \( I \) and \( I_{\Delta x, \Delta y} \), both images should be processed under the same scheme. As restored image is found by an iteration method, then in both cases the number of iterations should be the same. For \( \delta \) choice equal to 0.1, it was so in all measurements.

5. Perform restorations of all the images \( I_{\Delta x, \Delta y} \). The restored images will be denoted as \( u_{\Delta x, \Delta y} \).
6. Find the function \( D(\Delta x, \Delta y) = u_{\Delta x, \Delta y}(x_0, y_0) - u(x_0, y_0) \).

Fig.1.a. Original image Fig.1.b. Restored image

Fig.2.a. Ideal image. Fig.2.b. Noisy image \( I(x,y) \).
D(Δx, Δy) is considered as an image, and Δx, Δy are its coordinates. The values Δx=0 and Δy=0 indicate the center. Intensity value D(Δx, Δy) shows the influence of change in initial image I(x₀,Δx,y₀,Δy) on the restoration result u(x₀, y₀).

Following points are for better computer screen displaying. Now we make several transformations of the function D but we keep the same evident notation for it.

7. Cover the function D(Δx, Δy) using two-dimensional spline interpolation. Due to this, the coordinates Δx, Δy can be treated as floating-point values.

8. Scale the arguments Δx, Δy of the function D so that their range becomes 0…127. In all subsequent Figs the influence areas are enclosed in squares 128×128 pixels of size.

9. Calculate negative image 255 – D. Then the points with the greatest influence on restoration look black, and the points with the least influence look white.

On Fig.3 we can see a typical example of influence areas in case when a restoration method “works well”. Some other Figs will be shown in Section V. Here σ is Gaussian noise deviation, and x₀ accepts values from 123 to 133; y₀ = 27.

The size of each image on Fig.3 is 11×11 pixels; however the images are stretched to the size 128×128 pixels by means of splines. The boundary is located between the pixels number 128 and 129 on abscissa axis. Most interesting is the dynamics of influence areas if tested pixels are approaching to the boundary. One can see that if the pixel (123, 27), (left image on Fig.3), is far enough from the boundary (x₀ = 128), influence area is large. While approaching to the boundary, influence area deforms and decreases.

Thanks to this fact the image is blurred in the image areas with no boundaries, so the noise is reduced. But in image areas with boundaries there is no blurring and contrast boundaries are preserved.

IV. ENERGY FUNCTIONALS FOR TESTING

Now we apply the technique from the Section III for testing two functionals of type (1). We will keep the notations PL and GR both for functionals and for corresponding image restoration methods.

1) PL: functional with Piecewise Linear energy minimizing function, [11];
2) GR: modified Geman-Reynolds functional, [5], [8].

10. Scale the intensity of D in such a way that its range for non-negative values of D becomes 0…255. Negative values of D (if any) are marked as gray.

11. After scaling of size and intensity, the values of D have to be rounded to integer. Zero intensity integers outline the borders of the received image D.

12. Maximum of D is marked as a center localization pixel.

The resulting image D we call influence area. This area contains all points around I(x₀, y₀), where the change of intensity affects the restored image intensity u(x₀, y₀).

To calculate influence area at another pixel (x₁₀, y₁₀), the steps 1-12 has to be repeated for this pixel. Next we consider series of points (x₀, y₀) from the left and from the right sides of the inner boundary on Fig.2.

Rewrite the formula (1) as

\[ E(u) = (1 - \lambda) \int_{\Omega} (u - I)^2 + \lambda \int_{\Omega} c^2 \phi \left( \frac{||\nabla u||}{c} \right)^2, \quad (2) \]

where

\[ c^2 = \mu^2 \max_{(x,y)\in\Omega} ||\nabla u(x,y)||^2, \quad 0 \leq \varphi(r) \leq 1. \]

Here 0 < \lambda < 1, and 0 < \mu ≤ 1 are two parameters of the functional (2). The parameter \lambda regulates relative contributions of two terms in the right hand side of (2). Small values of \lambda restrict a solution to be close to the initial image. Large \lambda force the solution u to be smooth. The parameter \mu controls the properties of the restoration term. The smaller is the value of \mu, the better is edge preserving qualities and the worse is noise reduction (see below, Fig.4).

The value c is chosen for proper calculations. Due to such a form of c, both integral terms in (2) have approximately the same order respective to change of the contrast of the image I.

PL functional. In [11], [16] were studied functionals of type (2) with piecewise linear function (3):

\[ \varphi(r) = r, \quad 0 \leq r \leq 1, \quad \text{and} \quad \varphi(r) = 1, \quad \text{if} \quad r > 1. \quad (3) \]

GR functional. Primarily, D.Geman and G.Reynolds worked out their functional [5] for image restoration and simultaneous boundary extraction. In [8] this functional was modified for the task of image restoration only. It obtained the form (2) with minimization function (4):
\( \varphi(r) = r/(1+r) \).

The value \( r \) depends on the gradient (2). Functions (3), (4) increase rapidly with \( r \) when the gradient and \( r \) are small on noisy areas with slowly varying intensity. Due to minimization, both gradient term in (2) and gradient are effectively restricted on such areas what results in smoothing of the image \( u \). Contrarily, the functions \( \varphi \) are constant or increase slowly if the gradient and \( r \) are large near boundaries. In this case, the gradient is less restricted what results in preserving of contrast boundaries.

\[
\text{Fig.4.a. } \mu = 0.5 \quad \text{Fig.4.b. } \mu = 0.9
\]

On Fig.4, we show two images restored using PL method. Here \( \lambda = 0.8 \). If \( \mu = 0.2 \ldots 0.7 \), the boundaries are well preserved (Fig.4.a), but the noise reduction is bad. If \( \mu = 0.8 \ldots 0.9 \), noise reduction is better. However, only most contrast boundaries are preserved on the restored image (Fig.4.b). Black arrows on Fig.4 indicate boundary points with critical contrast values. If the boundary’s contrast is greater than critical then such a boundary remains contrast after the restoration procedure. If not, the boundary is blurred. Further on, we show that the technique of influence areas allows precisely determine critical contrast values.

V. TESTING RESULTS

Minimization problem (2) can be solved by standard iteration method (for example, [8]). Our experiments have shown that the parameter \( \lambda \) mainly affects the speed of convergence of the iteration process. For both methods, we obtained good convergence with \( \lambda = 0.8 \) to \( \lambda = 0.9 \). So, further we use such values of \( \lambda \). As to the parameter \( \mu \), it varies within the range \( 0 < \mu \leq 1 \). The result of calculations \( u \) very significantly depends on the value of \( \mu \).

Next we give some examples of influence areas for PL and GR functionals. In all cases, we chose noisy image Fig.1.b with Gaussian noise deviation \( \sigma = 10 \). We tried other values of \( \sigma \). The results were not quite the same, but similar.

\textbf{PL method.} Fig.3 corresponds to PL method at \( \lambda = 0.9, \mu = 0.3, \sigma = 10, y_0 = 27 \). Such influence areas are typical for the values \( \lambda = 0.8 \ldots 0.9, \mu = 0.2 \ldots 0.8 \).

The restored image is obtained as a solution of a nonlinear differential equation, so influence areas are not always as good as on Fig.3. The situations when a restoration method fails maybe are most informative. On Fig.5 we show influence areas for \( \mu = 0.1 \). One can see gray homogenous domains. Within such domains, the function \( D \) is less than zero. It means that small gain of the intensity near the pixel \((x_0, y_0)\) on the initial image \( I \) does not results in the gain of intensity at \((x_0, y_0)\) on the restored image \( u \). Conversely, the intensity at \((x_0, y_0)\) on \( u \) decreases. Thus, PL method makes certain distortion of the boundary on \( u \), and for this value of \( \mu \) proves to be “bad”.

\[
\text{Fig.5. PL method. } \lambda = 0.8, \mu = 0.1, y_0 = 26
\]

Next let us consider Fig.6. If \( y_0 = 27 \), such a value of \( y_0 \) defines too low contrast of the boundary for the given value \( \mu = 0.8 \) (see Fig.4). Thus the initial image is blurred around all points \((x_0, y_0)\) we test, and the boundary is not preserved at all. On Fig.6 we can see large influence areas what means blurring.

\[
\text{Fig.6. PL method. } \lambda = 0.8, \mu = 0.8, y_0 = 27
\]

Now let us consider Fig.7. The ordinate \( y_0 = 27 \) defines critical level of the boundary contrast for \( \mu = 0.7 \). If \( y_0 < 27 \), then more contrast boundary is preserved; if \( y_0 > 27 \), it is not (Fig.4). As is seen on Fig.7, the shape of influence areas is almost arbitrary and the PL method fails. This
means that some boundaries of critical contrast can be corrupted.

**GR method.** As show our tests, good convergence is obtained for $\lambda = 0.8...0.95$. Thus in the following examples we use the value $\lambda = 0.85$. Choosing another $\lambda$ somewhat changes shape and size of influence areas. However, these changes are not considerable. On the contrary, the choice of the second parameter $\mu$ is very essential for GR method. Next we show pictures for $\mu = 0.2, \mu = 0.7,$ and $\mu = 1.0$.

Within the images on Fig.8-10, there are big homogenous gray domains where the function $D$ is less than zero. It means presence of distortions on the restored image. The distortions are most considerable when $\mu$ is small ($\mu = 0.2$) on Fig.8). Note that if the tested pixel is close to the boundary ($x_0 = 128, 129$), influence areas are very small. It means that the preserving of contrast boundary is good. So, in the case of small $\mu$, GR method has a special feature. It rather distorts the areas with slowly varying intensity than boundaries.

Typical influence areas for $\lambda = 0.85, \mu = 0.3..1.0$ are shown on Fig.9,10. If a pixel is relatively far from the boundary ($x_0 = 123$ and $x_0 = 133$), influence areas are large. Hence, initial image is blurred in the neighborhoods of such points. Due to this we have noise reduction effect. Most characteristic are images with $x_0 = 128$ and $x_0 = 129$. However, for greater values of $\mu$, the size of influence areas increases near the boundary (see below, Fig.9,10). It means that GR method blurs even the most contrast boundaries.
VI. CONCLUSION

As seen from the above, the influence areas play the key role in the novel technique for testing of energy minimizing restoration methods. We used this technique for calculation of these areas and applied the whole testing procedure to a couple of restoration methods: PL and GR. We studied their ability to simultaneously reduce the noise and to preserve contrast boundaries on the restored image. In our testing procedure, the evaluated method is considered as a black box with input parameters which control its performance.

Our tests showed that for both of the methods there are critical contrast values, which may lead to distorted boundaries of objects on the restored image.

For the PL method, the optimal values of its input parameter $\lambda$ are in the range from 0.8 to 0.9 and $\mu$ are from 0.2 to 0.8. For the smaller $\mu$, the distortions on the restored images may be observed; bigger values of $\mu$ often lead to the loss of high contrast boundaries.

The GR method almost always creates distortions on the restored image. Increasing the intensity value at a certain pixel of input image, one may get the decrease of intensity on the restored image. However, this is not a disadvantage of the method, because this effect can increase the contrast of blurred object’s boundaries, or in other words, it can increase the image’s sharpness. According to our test results, the optimal values of $\lambda$ for the GR method lay in the range from 0.8 to 0.95. For the high contrast preservation of the object boundaries, the optimal values of $\mu$ are from 0.1 to 0.2. If noise suppression is the main priority, one should take $\mu$ from 0.3 to 1.0.

In the paper only one type of influence areas has been considered. One can consider another type of influence areas on the restored image, which consists of the points, affected by intensity changes at a single pixel on the initial image. We leave a thorough study of influence areas for the future.

REFERENCES


