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3D VISUALIZATION OF THE FRACTURE SURFACE BY THE SERIES OF MULTILEVEL IMAGES

O. R. Berehulyak, R. A. Vorobel, I. B. Ivasenko, H. V. Krechkovska, O. Z. Student, H. M. Nykyforchyn

H. V. Karpenko Physico-Mechanical Institute of the NAS of Ukraine, Lviv

E-mail: olena.berehulyak@gmail.com, roman.vorobel@gmail.com, ivasenko.iryna@gmail.com, krechkovskahalyna@gmail.com, oleksandrastudent1@gmail.com, hnykyforchyn@gmail.com

The method for visualization of details on the image of the still fracture surface of impact testing specimen on the base of the series of optical microscope images with the small focus depth is proposed. A series of images of a still object was obtained by successive change of the distance to focal plane with a certain fixed step. The local contrast maximum principle was applied to images in the sequence for construction of aggregated all-in-focus image. A level map was formed from the indexes of the image in the series, which at certain pixel indicates the most probable distance to the corresponding point of the object. The Chebyshev best approximation was used for estimation of the height of the relief to provide better 3-D visualization of a three-dimensional image of the fracture surface. The area of fracture surface was estimated by triangulation of alpha shape.

Keywords: *shape from focus, local contrast, 3D fracture surface, best Chebyshev approximation.*

3D ВІЗУАЛІЗАЦІЯ ПОВЕРХНІ ЗЛАМУ ЗА СЕРІЄЮ РІЗНОРІВНЕВИХ ЗОБРАЖЕНЬ

О. Р. Берегуляк, Р. А. Воробель, І. Б. Івасенко, Г. В. Кречковська, О. З. Студент, Г. М. Никифорчин

Фізико-механічний інститут ім. Г. В. Карпенка НАН України, Львів

Запропоновано метод формування фрактографічного зображення зламу сталевого зразка, випробуваного на ударну в'язкість, та візуалізації елемента його поверхні за серією зображень малої глибини різкості, отриманих за допомогою оптичного мікроскопа. Серію зображень нерухомого об'єкта отримано послідовною зміною відстані до фокальної площини з певним фіксованим кроком. Мала глибина різкості унеможливлює отримання різкого зображення неплоского тривимірного об'єкта. Агреговане зображення побудоване на основі вибору оптичного зрізу (чіткої частини) кожного зображення серії з урахуванням критерію максимуму характеристик локальних околів, що описують чіткість, а саме степеневого контрасту. Вибір степеневого контрасту зумовлений його адаптивністю. Сформовано карту рівнів з номерів зображення зі серії, що для кожного піксела вказує найвірогіднішу відстань до відповідної точки об'єкта. Для побудови просторової моделі об'єкта координати на площині обчислено за роздільною здатністю зображень та за збільшення оптичного мікроскопа, а висоту оцінено відповідно до фокусної відстані зображення послідовності відповідного номера карти рівнів. Під час оцінки висоти для візуалізації тривимірного зображення поверхні застосовано чебишовські наближення, що дало змогу краще відтворити поверхню зламу. Площу поверхні зламу оцінено на основі триангуляції альфа-форми. Наведено приклад застосування запропонованого методу для побудови агрегованого зображення, формування карти рівнів та візуалізації поверхні зламу сталі лопатки парової турбіни за серією зображень, отриманих за допомогою оптичного мікроскопа NEOPHOT-21 зі збільшенням 500 та кроком 1 мкм. Проаналізовано проблеми зростання часу опрацювання даних та збільшення їх об'єму, які виникають під час відтворення 3D поверхонь зламів великих розмірів.

Ключові слова: *форма з фокусу, локальний контраст, 3D поверхня зламу, найкраща чебишовська апроксимація.*

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Introduction. Reconstruction of high-quality images of three-dimensional objects is very important for assessing the real shape of destroyed elements (in particular, the operating surfaces of fractures of elements of important structures such as blades and disks of rotors of thermal power plant steam turbines, elements of the drill strings, damaged sections of gas and oil pipelines, etc.). This is necessary for comparing them with original shape and analyzing the loading circuits of these elements, which led to their failure. However, even more important is the reconstruction of the surfaces relief of the fractured elements, which is necessary to establish the fracture mechanism of failure and the causes of its occurrence as a basis for choosing an action program to prevent such damage in the future. The scanning electron microscope provides a detailed and clear image of fracture surfaces and the experience of reconstruction of fractographic images provides good opportunities for quantitative assessments of the defining elements of such images [1]. In particular, its use made it possible to build the correlation dependence between the fractographic features of the failure of steels operated on gas pipelines and current value of their impact toughness [2–4]. But such a microscope is expensive and often inaccessible to the staff operating such facilities. At the same time, the optical microscope is used by almost all metallographic laboratories at energy, gas and oil production and pumping enterprises. Unfortunately, this microscope has a drawback – a shallow depth of field, due to which it is impossible to obtain a clear image of a non-planar three-dimensional object. In this regard, it is advisable to use image processing methods to form two-dimensional image aggregated from all images of series and restore the three-dimensional surface of the object of observation [5].

In addition, a three-dimensional reconstruction of the fracture surfaces will make it possible to estimate their area, which is important for electrochemical studies. The cycle of electrochemical studies [6–7] is carried out using not ordinary polished specimens with a known area, but also using fracture surfaces, the areas of which are unknown. It was shown that the sensitivity of electrochemical parameters to degradation of steels during their long-term operation on gas pipelines determined on the surfaces of fractured specimens is much higher than on the conventional polished samples. However, this did not take into account the actual areas of the fracture surfaces, which also depended on the degradation degree of the steels. After all, the current density determined in such studies depends on the surface area of the metal in contact with the corrosive-active environment. Consequently, the estimation of the actual fracture area of the specimens by their reconstructed surface using 3D modeling, opens up prospects for the creation of a highly sensitive method for monitoring the real technical state of steels during long-term operation using electrochemical studies.

One of the approaches is to use a series of multi-focus images of shallow depth of the field of a stationary object, obtained on optical microscope by changing the focal length [8]. The idea of the method is to establish a criterion for selecting a clear part (the so-called optical slice) of each image and to form the original image from the optical sections of the image sequence. The relief height is estimated according to the focal length of an individual image from sequence in order to build a spatial model of an object.

Gaganov and Ignatenko [9] formulated a shape from focus problem in a Bayesian framework using Markov random fields (MRF). Their method can produce stable depth estimates in non-textured regions. The 3D model of the scene is found as a minimum of the MRF energy function. This energy function combines sharpness cues taken from images and smoothness priors on reconstructed surface shape. Enforcing smoothness priors allows their algorithm to produce stable results in poorly exposed, non-textured and highlighted regions.

Aydin and Y. Akgul [10] proposed a new focus measure operator for Shape From Focus to recover a dense depth map of a scene. Their method can handle depth discontinuities and edge bleeding by using adaptively shaped and weighted support windows.

The weights of the support windows are selected according to similarity and proximity criteria. This method has high computational complexity due to the need to calculate the weights for the support windows.

A new focus measure that more reliably measures the degree of focus was proposed in [11]. By setting a gap and viewing pixels that are farther from the pixel of interest, the filter can detect more informative pixel values. The disadvantage of this method is the quantization effect.

A sum-modified-Laplacian operator developed to provide local measures of the quality of image focus was proposed in [12]. The author developed a model to describe the variation of focus measure values due to defocusing. The Gaussian interpolation is used for focus measure values and depth estimates.

A combination of depth from focus and depth from defocus approaches was proposed in [13]. Authors calculated defocus distance by depth from the defocus method. Then this result is used as a search step in searching the stage of the depth from the focus method. Experimental results show that the method efficiency is at least 3–5 times higher than that of the traditional DFF method. However, an inaccurate estimation can directly affect the searching efficiency or lead to focusing failure.

Pertuz and Puig [14] analyzed focus measure operators for shape-from-focus. They experimented with gradient-based, Laplacian-based, wavelet-based, statistics-based, discrete cosine transform-based and miscellaneous operators that do not belong to any of the previous five groups. The root mean square error (RMSE) has been used as a quality measure for the comparison of the performance of different focus measure operators. Experiments showed that Laplacian-based operators had the best overall performance in normal imaging conditions.

Pertuz et al. [15] experimented with image fusion for combining images captured with different camera settings to yield a higher quality all-in-focus image. The proposed algorithm includes focus measure, selectivity measure and image fusion. It was performed on gray-scale images and can be extended to color images by applying the fusion rule independently to each color plane.

An analysis of the state-of-the-art of research shows that the creation of new methods for three-dimensional surface visualization using microscope image processing, based on the "shape from focus" approach, is an important task at present.

The proposed method. Let $\{I_n\}_{n=1}^{N}$ be the series of images with the small focus depth, where $n=\overline{1, N}$ is index of image in series, N is number of images in series, $I_n(i, j)$ is intensity of pixel with coordinates (i, j) on the n^{th} image ($i \in \overline{1, N1}$, $j \in \overline{1, N2}$ $N1 \times N2$ is the size of image), I is resulting aggregated image.

For every coordinate (i, j) the index of image in series is chosen to best fit the distance to the corresponding point of the object. The maximum principle of local window characteristic is the criterion for image index choice. This characteristic should describe sharpness. Dispersion of gradient module, contrast etc. can be selected for such characteristic [5, 16]. We propose to use the power description of image contrast [17], because it has a certain degree of flexibility due to the value of power:

$$C_n(i, j) = \left(\frac{I_n(i, j) - \bar{I}_n(i, j)}{LMAX} \right)^p , \tag{1}$$

where $C_n(i, j)$ is local contrast at pixel with coordinates (i, j) in n^{th} image, $\bar{I}_n(i, j)$ is the mean value of intensities in local window centered at (i, j) on the n^{th} image, $LMAX$ is the maximum possible value of intensities, p is power parameter.

The mathematical description of criterion for image index choice is the following

$$R(i,j) = \arg\max_n (C_n(i,j)), \qquad n = \overline{1,N} \tag{2}$$

The map of levels R is constructed by assignment to $R(i,j)$ the index of image in series that has maximum local contrast value at pixel with coordinates (i,j).

The aggregated image is formed by assignment to pixel with coordinates (i,j) the intensity of pixel with the same coordinates (i,j) at image of series in which the maximum of local power contrast (1) is achieved

$$I(i,j) = I_{R(i,j)}(i,j). \tag{3}$$

The height $h(i,j)$ estimation for 3D visualization of fracture surface should be accomplished taking into account the index of image with maximum local contrast $R(i,j)$ and height coefficient k_h:

$$h(i,j) \sim R(i,j) \cdot k_h ,$$

the height coefficient k_h is set by the step of focal length change for the series of images. While the image in series is taken with this certain step of focal length, it is possible that real height is between two consecutive steps of focal length. Therefore, for the estimation of the height we propose to use the best Chebyshev approximation [18] as it minimizes approximation error. The height is calculated as the value of abscissa at the vertex of the parabola $P(x) = Ax^2 + Bx + C$ that approximates seven values

$$Y = \{y\} = \{C_m(i,j),\ m = \overline{R(i,j)-3 : R(i,j)+3}\}$$

the maximum value of contrast and three closest values from the series on the right and on the left:

$$\max_{x \in X} |y(x) - P(x)| = \min_{U \in V} \max_{x \in X} |y(x) - U(x)| \tag{4}$$

where

$$V = \{U \mid U(x) = ax^2 + bx + c\}, \quad X = \overline{R(i,j)-3 : R(i,j)+3}.$$

Then the height is estimated with the parameters of parabola calculated by the best Chebyshev approximation

$$h(i,j) = -\frac{B}{2A} \cdot k_h \tag{5}$$

The 3D visualization of steel fracture surface is performed with estimated height values (5).

The area of the fracture surface is estimated by alpha-shape triangulation [19]. The alpha-shape creates a bounding volume that envelops a set of 3-D points with the usage of alpha radius – the smallest radius of the alpha sphere that sweeps over the points enclosing all of them to create the alpha-shape. The area of such alpha-shape created on the set of points $\{(u(i,j), v(i,j), h(i,j)) \mid i \in \overline{1,N1},\ j \in \overline{1,N2}\}$ is taken for estimation of the area of steel fracture surface. Here *u* and *v* coordinates on the plane are estimated based on the image of the length standard taking into account resolution of images and microscope magnification and height *h* is approximated by the proposed method described above (4)–(5).

Experimental results A fracture surface of the specimen fractured during impact tests from the 15Х11МФА steel of steam turbine blades was used for research. Using an optical microscope NEOPHOT-21 at a magnification of 500, a series of 18 images with a shallow depth of focus with a resolution of 300 dpi and size 531×551 pixels was obtained. The step of changing the focal length was chosen equal to 1μm. The obtained series of images is shown in Fig. 1.

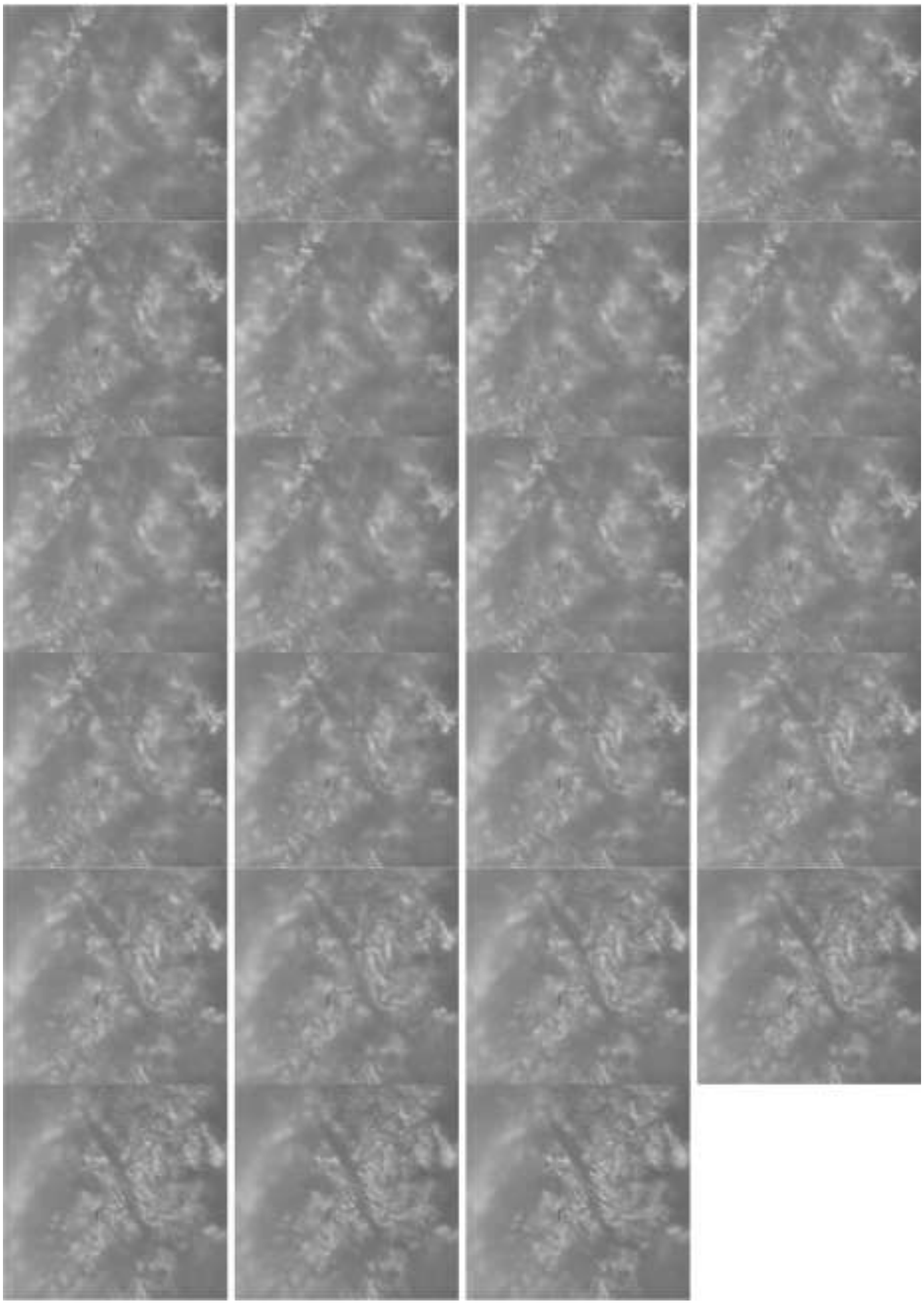

Fig. 1. Series of images of the steel fracture surface with the small focus depth obtained by optical microscope NEOPHOT-21 with 500 magnification through focal length change with a step of 1 μm.

The map of levels *R* and aggregated image *I* for series of images in Fig. 1 calculated by the proposed method (2)–(3) based on local power contrast (1) with $p = 0.8$ are shown in Fig. 2 (*a*) and (*b*) respectively.

The 3D visualization of steel fracture surface by the proposed method (1)–(5) for series of images from Fig. 1 is shown in Fig. 3. For more realistic visualization the post processing by average smoothing in sliding window of 3×3 was applied. Based on the image of the length standard taken at the same resolution (300 dpi) and optical microscope magnification (500) the coordinates on the plane are estimated to have the distance between two adjacent pixels equal to 0.2 μm. The height is estimated by the proposed method (4)–(5), taking into account that focal length change of image series was set to 1 μm. The area of such fracture surface is estimated by alpha-shape triangulation. Direct estimation gives the surface area value equal to S = 0.029 mm^2. However, the problem of reliability of quantitative estimation of surface parameters remains the subject of further investigations. The resolution of the used optical system is the basic component of estimation. It determines the spatial distinction of the surface relief.

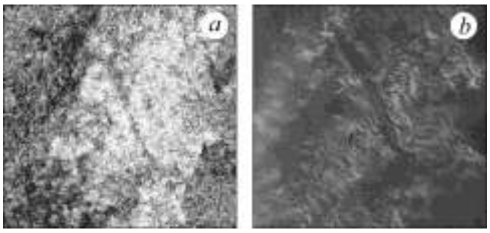

Fig. 2. The map of levels *R* (*a*) and aggregated image *I* (*b*) calculated by the proposed algorithm for series of images in Fig. 1.

The carried out experiment on 3D visualization of the steel fracture surface revealed a number of problems to be discussed. The first one is that in case of small difference in local contrasts of some pixel in all images of series, it is impossible to estimate credibly the surface height at this point. Such point on fracture surface with high probability doesn't belong to focal plane of any image in series. The second problem is connected with possibility of reconstruction of the overall fracture surface of investigated sample at once. Fig. 3 demonstrates the relief of the surface with height range of 0.02 mm. The construction of the surface relief with a wider range of height causes registration of images with significantly bigger size on the one hand, and bigger amount of data on the other. The time of acquisition of experimental data is growing. It makes difficult to satisfy the requirements of minimization of motion influence of the image registration system on the base of microscope. The time of data processing is also growing.

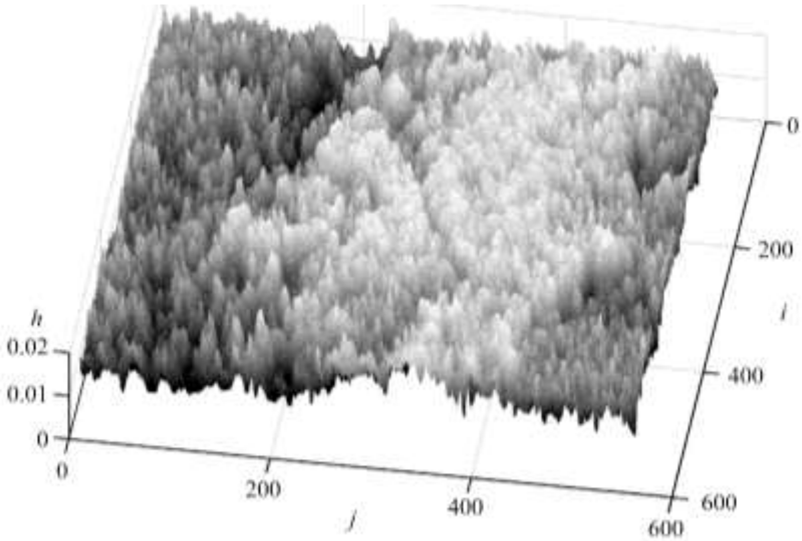

Fig. 3. The 3D visualization of the fracture surface by the proposed method, based on the series of multi-focus images from Fig. 1. (*i*, *j* are pixel coordinates, *h* is estimated height).

CONCLUSIONS

The method of 3D visualization of the steel fracture surface based on the series of multi-focus images is proposed. The Chebyshev best approximation is used to estimate the relief height of the surface and provide good 3-D visualization of the fracture surface. The local power contrast is used as sharpness feature estimator at pixel by images in series. For more realistic visualization the average smoothing is applied. The surface area is estimated by standard procedure for alpha-shape. The example of the method application to a series of microscope images is presented. The results of investigation approve the perspective of further development of the proposed approach.

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