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AUTOMATED GENERATION OF A DIGITAL MODEL OF AN OBJECT'S MICRO SURFACE FROM A SEM-STEREO PAIR BY AREA-BASED IMAGE MATCHING

Purpose. The goal of this work was the development and research of a method of automatically constructing a digital model of the micro surface of an object from SEM stereo pair of digital images taking into account the specifics of the survey SEM and evaluating the accuracy of digital modeling. **Methods.** The developed method consists, firstly, in generating a dense set of input points in the left SEM image of a stereo pair in regions with local features and using an iterative process in accordance with the levels of the image pyramid. Secondly, the search for the corresponding points in the right SEM image of the stereo pair is carried out on the basis of sequentially shifting the points (centers of the search windows) by a shift parameter from the possible parallax's range using the correlation method. For research, we have used two stereo pairs of digital SEM images. Digital images of the deformed surface chrome steel specimen were acquired with the JSM 7100F (JEOL) with magnification 750x. Images of loess soil were acquired with the SEM "Hitachi" S-800 with magnification 1000x. When calculating the spatial coordinates of the points of the surface micro relief, the values of geometric distortion inherent in the SEM image were taken into account. To eliminate some anomalous values of the heights of the 3D model, an adaptive median filtering procedure was applied. To evaluate the accuracy of micro surface simulation test models were created by manually measuring coordinate feature points of the digital stereo pairs for both specimens. **Results.** The proposed method for shifting parameters reduces the search area and the probability of mismatch and, in addition, speeds up the matching procedure in a pair of images. Formulas are obtained for calculating the coordinates of the center of the search window and the corresponding point in the right image at the k-th step of the shift process. To estimate the accuracy, the differences between the heights of the test model and the heights interpolated at the same points using the created models were computed. For the chrome steel specimen micro surface about 79 % of the points, and for the micro surface specimen of the loess soil about 70 % of the points were within tolerance $\Delta Z \leq \pm 2$ μm. **Scientific novelty.** For the first time in Ukraine, a method was developed for an automatic search of corresponding points based on a shift of parameters taking into account the features of SEM survey. The proposed technological reconstruction automation scheme of a digital model of an object's micro surface from SEM stereo pair, and the creation of this authoring software show its efficiency and expediency. **The practical significance.** The ability to reproduce the surface micro relief of an object automatically using a stereo pair of SEM digital images was established in accordance with the requirements of both the accuracy of determining the spatial coordinates of points and the structure of the micro surface of the object.

Key words: scanning electron microscope (SEM)**,** SEM stereo pair, image matching, accuracy, 3D model.

Introduction

Modern high-tech industry in machine and aircraft engineering, microelectronics, materials science, geology (in the study of the microstructure of geological rocks, soils), medicine, and in other fields requires to receiving high-precision quantitative information about micro surface metric parameters.

Methods of SEM photogrammetry allow creation of digital models of micro surfaces of experimental objects from their SEM stereo images and to obtain their quantitative parameters (surface profiles, the magnitude of its deformation, microcrack sizes, micro surface area, etc.) [Baghaie et al., 2017; Balamucki et al., 2006; Cornille et al., 2003; Ivanchuk, 2019; Kudryavtsev, 2017; Marturi et al., 2013, Melnik et al., 1999, 2009, 2010, 2017; Nicolls, 2004; Shostak, 2012; Tafti, 2016; Voloshin, 2004; Zhu et al., 2011]. The use of digital models made it possible to represent the structure of micro surfaces by changing angle, viewpoint, projection, scale visually.

As a rule, the processing of SEM stereopairs of research micro objects, that is, the measurement of their characteristic points on the digital photogrammetric workstation (DPW) "Delta" in stereo mode, takes considerable time. In this case, after 2–3 hours of operation, the operator's eyes get tired and the measurement accuracy decreases.

Therefore, the task of automating the measurement of SEM images and creation of a digital model of the micro surface of an object is an urgent challenge of modern research in the field of nanotechnology. This problem became the purpose of our study.

*A review of related stu***dies**

The basis of the automatic method of three-dimensional reconstruction of an object from a stereo pair of images is the algorithms for detecting and matching image points. For best matching, it is necessary to choose points whose neighborhoods have distinctive features. Such points are called interest points or key points. A review and analysis of existing points of interest detection algorithms is presented in [Lowe, 2004; Krig, 2014; Kudryavtsev, 2017; Popielski, et al, 2012, Tafti, 2016], their comparison is given in [Mikolajczyk, Schmid, 2005; Salahat, Qasaimeh, 2017; Suprun, 2016].

Scientists have been engaged in the issues of automation of image measurement in photogrammetry and other sciences for a long time, and they have been reflected in bibliography [Dorozhynskyy, Tukai, 2008; Gorbachev, 2014; Vizilter, Zheltov, 2010].

Processing of SEM stereo images has its own specificity. For the first time, questions of measurement automation in Ukraine were studied by prof. V. M. Melnik and the results of research were presented in his monograph [Melnik, Shostak, 2009]. In recent years, this issue has been developed by his disciples [Melnyk Yu., 2013; Ivanchuk, Tumska, 2016–2019]. The article proposed by the authors is a continuation of the development of this actual topic.

A method for generating a digital model of a micro surface

SEM stereo pairs are obtained from the zero basis and by tilting the studied object stage at fixed angles along the *x*-axis of the SEM image. In this case, a longitudinal parallax of points arises, due to which it is possible to obtain the elevations of the points of the micro surface of the object. As a result of the orthogonal scanning by the electron beam of the micro surface, there is practically no transverse parallax of the points of the SEM stereo pair.

The method for creating a digital model of the micro surface of an object, which is based on the generation of a dense set of input points in the SEM image and the search for corresponding points by the parameter shift method using the correlation identification method, has been developed. Since there is almost no transverse parallax, the search for the corresponding points in the right SEM image is performed by shifting the parameters along the *x* axis [Vizilter, 2010]. The procedure is (a) to generate the input points on the edges and on the boundaries of the regions in the image; (b) to search for corresponding points based on the shift of the parameter along the *x* axis by a value from the possible range of parallaxes; (c) to computed the spatial coordinates of the obtained points; (d) to evaluate an accuracy of the created model using the test model. The accuracy of the constructed model was evaluated by comparison to the test model with the standard deviation (STD) and by the maximum error of elevation.

The process creating a digital model of the micro surface of an object from the SEM stereo pair consist of ten steps described below:

1. Gaussian pyramid construction of the SEM images.
2. Generation of input points in the left image of the upper level of the pyramid.
3. The calculation of the coordinates of the initial centers of the search windows in the right image.
4. Formation of the shift sequence of the centers of the search windows in the right image.
5. Finding the matching points in the SEM stereo image pair of the upper level of the pyramid.
6. Refinement of the coordinates of the corresponding points by the levels of the image pyramid.
7. Computation of the spatial coordinates of the points X, Y, Z of the micro surface of the object.

8. Construction of a digital grid model of the micro surface of the object.

9. Elimination of anomalous elevations by adaptive median filtering.

10. Evaluation of the accuracy of creating a digital model of the micro surface using a test model.

Input points generation in the SEM image

The input points were generated in the left top-level image of the pyramid using Sobel operators and global Otsu threshold [Otsu, 1979] to obtain respectively, the points of the edges and on the borders of the regions. Points on the boundary of regions were thinning using a morphological gradient [Gonzalez, 2005, 2006]. The results of these operations after reducing the number of points in a given range were combined into one array. It can be expected that in the vicinity of points obtained by the above method, there are local features. Thus, the probability of finding the best matching region in the right image by using correlation techniques increases.

Formation of a sequence of shift centers of search windows in the right image

If the minimum and maximum parallax values are known, then the value of the displacement p_k center of the search window center along the x-axis is defined as:

$$p_k = p_0 + k \cdot \Delta p_x; \tag{1}$$

$$n = round((p_{\max} - p_{\min}) / \Delta p_x) \tag{2}$$

where k = 1, 2, ..., n; n – number of displacements; p_0 is the value of the initial displacement; Δp_x is the shift step along the x-axis (the value is chosen within the range of 3 to 7 pixels); $p_{\min}$, $p_{\max}$ – the minimum and maximum value of the parallax.

If the relief of the micro surface is characterized by a growing function $Z(h)$, then, as the initial value of the displacement, choose $p_0 = p_{\max}$ in the opposite case $p_0 = p_{\min}$. The value of the displacement p_k center of the search window satisfies the conditions

$$\begin{cases} Z(h) \ge 0 : \Delta p_x \le 0,\ p_{\max} = p_0 > p_1 > \cdots p_k \cdots > p_n; \\ Z(h) < 0 : \Delta p_x > 0,\ p_{\min} = p_0 < p_1 < \cdots p_k \cdots < p_n. \end{cases} \tag{3}$$

In the event that parallax limits are unknown, they can be found interactively, changing the values of $p_{\min}$ and $p_{\max}$ and observing on-screen intermediate results of the biasing process.

Computation of the initial coordinate values center of the search window in the right image

For the generated points, the corresponding points were computed taking into account the displacement due to the angle of tilt of the right image

$$\left.\begin{aligned} x_{C_{0,i}} &= round((x_{li} - x_{Ol}) \cdot \cos \alpha_r + x_{Or}) \\ y_{C_{0,i}} &= round((y_{li} - y_{Ol}) + y_{Or}) \end{aligned}\right\}, \quad (i=1,2, \ldots N), \tag{4}$$

where N is the number of generated points; the round (...) operation means rounding the expression in brackets to the nearest integer; O_l (O_r) – the origin of the coordinate system in the center of the left (right) image; and α_r – the tilt angle of the right image. The found points were taken as the initial center $C_{0,i}$ of the search window W_i in the right image. The size of the search window W is specified in pixels mxm, where the value of m is equal to the shift value for an odd value of $m = \Delta p_x$ and for an even $m = \Delta p_x + 1$. Thereby, the search area and the probability of false identification are reduced. To clarify the y-coordinate, the search window is set in the form of a rectangle or square for small window sizes.

Finding the corresponding point coordinates in the right image by correlation

The centers of the search windows in the right image were sequentially displaced along the x axis by shift parameters, which were selected from the range of possible x-parallax values caused by the surface relief. The correlation coefficient is computed at each step of the shift process between the template window centered at the generated point in the left image and a similar region, the center of which moved from pixel to pixel in the search window in the right image. The corresponding point in the search window is the one with the maximum value of the correlation coefficient r_{max}, if its value satisfies the correlation criterion R_c. The coordinates center of the search window $C_{k,i}$ at the k-th step the shift process are given by the relations:

$$x_{C_{k,i}} = x_{C_{0,i}} + p_k,$$
$$y_{C_{k,i}} = y_{C_{0,i}}, \quad (5)$$

where p_k is the shift value in the possible range of parallax values.

The coordinates of the corresponding right point $(x_r, y_r)_i^{(k)}$ at the k-th step of the shift process are as follows:

$$\begin{cases} x_{r_i}^{(k)} = x_{C_{k,i}} + \delta_{x_i} \\ y_{r_i}^{(k)} = y_{C_{k,i}} + \delta_{y_i} \end{cases}, \; i=1,2, ..., N_{k,1}, \; k=1,2, ..., n, \quad (6)$$

where $(\delta_{x_i}, \delta_{y_i})$, $\left|\delta_{x_i}, \delta_{y_i}\right| \le \frac{m}{2}$ – the coordinates of the point relative to the center of the search window $C_{k,i}$, and $N_{k,1}$ is the number of points in which the coefficient of correlation $r_{\max_i} \ge R_c$. $N_{k,2}$ is the number of points not satisfied by the above condition and that pass at the next step of shifting process. Process is completed if the number of shifts is equal n or $N_{k,2}$ =0. The set of pairs of points $(x_l, y_l, x_r, y_r)_i$ satisfying the correlation criterion are combined and recorded in an array of results. Note that some of the sets may be empty. After the displacement procedure, all points that satisfy the correlation criterion pass to the next level of the pyramid for clarification.

Fig. 1 shows a sequence of the displacement of the center of the search window along the x-axis for the case of positive values heights. (Parallax values decrease from positive to negative values).

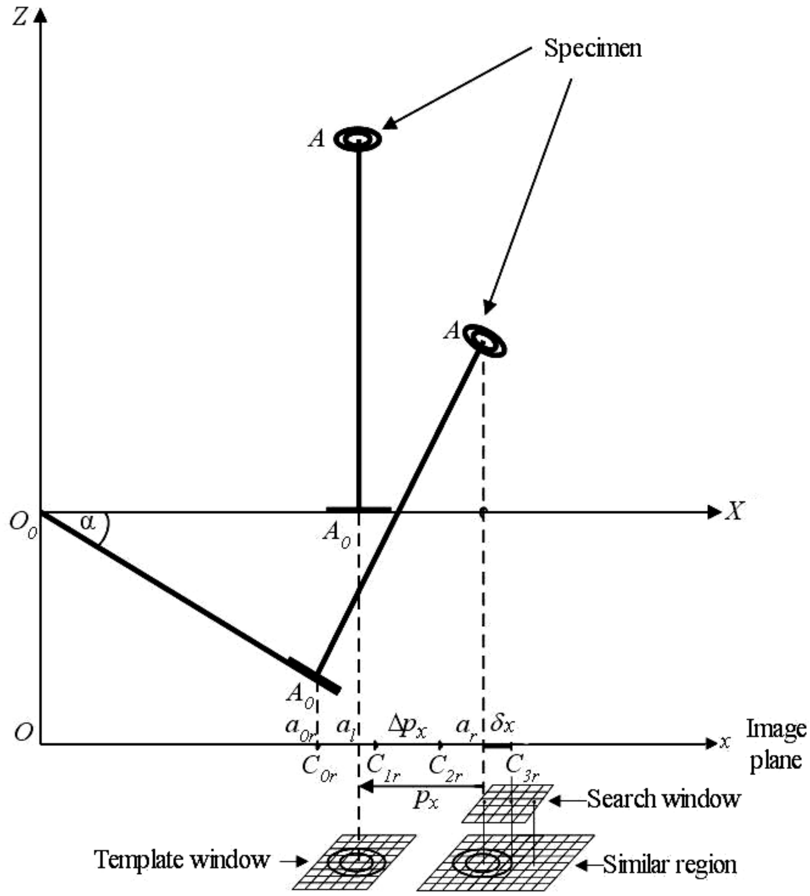


Fig. 1. Shifting the center of the search window along the x axis in the right image for the normally – convergent SEM survey ($\alpha_l = 0^\circ$, $\alpha_r \ne 0^\circ$). a_l is the center of the template window in the left image (a_l is the projection of the 3D point A); a_{0r} is the initial center C_{0r} of the search window in the right image (a_{0r} is the projection of the 3D point A_0); C_{ir} (i = 1, 2, 3) the location of the centers of the search windows in the right image; Δp_x is the shift parameter; δx is the coordinate of the corresponding point a_r relative to C_{3r}, p_x is the necessary parallax

The spatial conditional coordinates of the points of the micro surface *X*, *Y*, *Z* (*h*) are determined by the formulas of the normally convergent case of SEM survey [Ivanchuk, 2016]. When computing the spatial coordinates, the values of geometric distortion inherent in the SEM image were taken into account [Ivanchuk, 2015]. Based on the obtained spatial coordinates of the generated points, a grid model of the micro surface was constructed in the Surfer package. Taking into account the high density of the generated input points, a simple and fast Inverse Distance to a Power method was chosen to create the grid model. For the local interpolation, this method provides the required accuracy.

To eliminate anomalous of the grid model of the micro surface, an adaptive median filter was used [Baghaie et al., 2017]. Before filtering, the grid model was converted to an image, where the elevations were displayed in proportion to the brightness values at the range [0,1].

Evaluation of the accuracy of the digital model of the microrelief surface of an object using a test model

The test model is formed from the spatial coordinates of the micro surface points *X*, *Y*, *Z*(*h*), μm, computed from the coordinates of the points x_l, y_l, x_r, y_r, measured manually on the left and right SEM images of the stereo pair. The measurement of stereo images was carried out uniformly over the entire field of the micro surface at characteristic points [Ivanchuk, Khrupin, 2012].

To evaluate the accuracy of the simulation, the heights in the *X*, *Y* coordinates of the points of the test model were interpolated using the constructed grid model of the micro surface. The height of the point Z_{int} *(X, Y)* was determined by the heights of the four nearest vertices of the grid cell by the method of bilinear interpolation [Dorozhynskyy, Tukay, 2008]. The row and column numbers of the lower left corner of the grid cell are calculated as follows:

$$i = \left[\frac{X}{\Delta X}\right] + 1 \quad ; \quad j = \left[\frac{Y}{\Delta Y}\right] + 1, \qquad (7)$$

where the value in square brackets means the largest integer does not exceed the quotient of the division; ΔX, ΔY – respectively, the width and height of the cell. The vertices of the cell are numbered counterclockwise, starting from the lower left corner. Then the coordinates of point 1 are equal to:

$$X_1 = (i-1)\cdot\Delta X \ , \ Y_1 = (j-1)\cdot\Delta Y . \qquad (8)$$

The height value Z_{int} *(X, Y)* is interpolated from the values of its neighbors using the relation:

$$Z_{\text{int}} = Z_1 + \frac{Z'_4}{\Delta X}\cdot X' + \frac{Z'_2}{\Delta Y}\cdot Y' + \frac{Z'_3 - Z'_2 - Z'_4}{\Delta X\cdot\Delta Y}\cdot X'\cdot Y' , \qquad (9)$$

where

$$X' = X - X_1, \quad Y' = Y - Y_1, \quad Z'_i = Z_i - Z_1, \quad i = 2,3,4$$

The accuracy was estimated by the difference between the elevation values, which were computed using manually measured coordinates of the points of the Z_{test} test model, and the interpolated Z_{int} by the constructed grid model micro surface.

$$\Delta Z = Z_{test} - Z_{int}. \qquad (10)$$

For the normally convergent case of SEM survey, the theoretical accuracy of obtaining the spatial coordinates of *X*, *Y*, *Z* (in mm) of the micro surface of objects is determined by the expression [Ivanchuk, 2016]

$$m_{X(Y)} = m_{x(y)} \big/ M ,$$

$$m_{Z(h)} = m_{\Delta p(x)} \big/ (2M\cdot\sin(\alpha_r/2)) \qquad (11)$$

at M = const, M is the magnification (scale) of the SEM image α_r is the angle of tilt of the right image. The proposed method was implemented using the program for micro surface simulation written in MatLab system.

Experimental study and results

For research, we have used two stereo pairs of digital SEM images, namely, digital images of a specimen of chrome steel with a deformed surface and images of a specimen of loess soil. The characteristics of the stereo pairs are shown below.

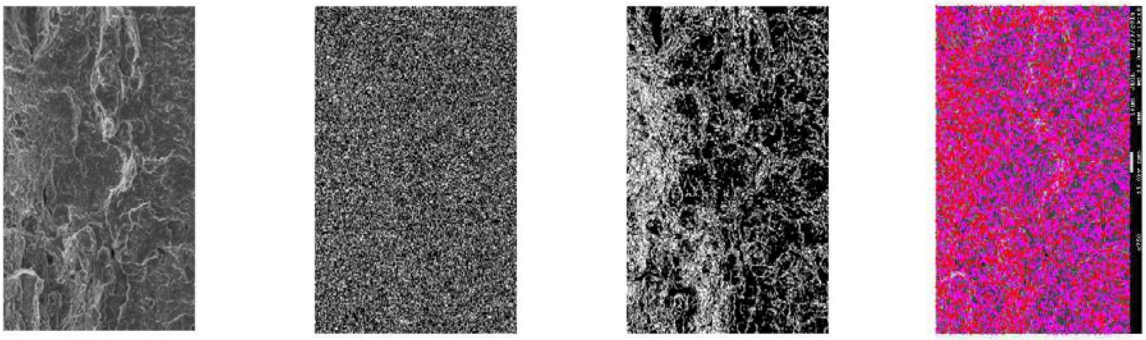
3D surface reconstruction from stereo a pair of SEM images of a chrome steel specimen

Attributes of a stereo pair of digital SEM images of a chrome steel specimen

Digital images of the deformed surface chrome steel specimen were obtained from the JSM 7100F (JEOL) with magnification 750x. The left SEM image was obtained in the horizontal position of the specimen (α_r = 0º), and the right image was obtained by tilting goniometric table by an angle α_r = 8º along the *x* axis. The size of the left (right) image is 1024×1280 pixels, (96×120 mm). The pixel size is 0.099375 mm, approximately 0.1 mm. Resolution is 270.94 dpi.

Input point generation in the SEM image of a chrome steel specimen

Fig. 2 illustrated for the process of generating input points in the left top-level image of the pyramid using the Sobel operators and global Otsu threshold.



a *b* *c* *d*

Fig. 2. Illustration of the generation of points in the left image: a – original left image (1024x1280 pixels); b – points on the edges obtained with threshold T=3 (415776 points); c – points on the boundary of regions (924112 points) after thinning regions using a morphological gradient (376004 points); d – the result of combining; b and c – after reducing to a given range the number of points (10057: 3009 red boundaries; 7048 magenta edges)

For the generated points, the corresponding points were determined taking into account the displacement due to the tilt of the right image (4).

Parameters shift in the right image of the chrome steel specimen of the SEM stereo pair

Figure 3 shows the process of sequentially shifting the centers of the search windows in the right image along the *x* axis with shift parameters that were selected from the range of possible *x*-parallax values. For each generated point, a normalized correlation coefficient was computed between the template window and a similar region, the center of which moved from point to point in the search window of the right image. Points for which the maximum correlation coefficient did not satisfy the acceptance criterion were displaced on the next shift parameter from a given set. After the displacement procedure, all points that satisfy the correlation criterion, passed to the next level of the pyramid for clarifications.

After combining all the points that satisfy the correlation criterion, the number of generated points (10057) decreased by 1.3 times (Template window size 17x17 pixels, search window size 5×5 pixels; correlation criterion R_c = 0.7). The computational speed in the Matlab system in the interpretation mode for the input image was about 18 points / sec. To clarify the coordinates of the corresponding points in the right image of the chrome steel specimen, a transition to a more detailed zero level of the image pyramid was performed [Gorbachev, 2014]. At the 0th level of the Gaussian pyramid, the left and right input images were expanded twice, respectively, the coordinate values of the points doubled [Gonzalez, Woods, Eddins, 2006]. For the centers of the search windows, the corresponding points found at the 1st level of the pyramid were taken. As a result of filtering with the correlation criterion R_c=0.7, the number of points at the 0th level of the pyramid decreased by 0.4 %. The processing parameters at the 0th level of the pyramid are as follows: window sizes in pixels: template 25×25, search 21×21; correlation criterion R_c=0.7. With these parameters, the computational speed in the Matlab system in the interpretation mode was approximately 5 points / sec.

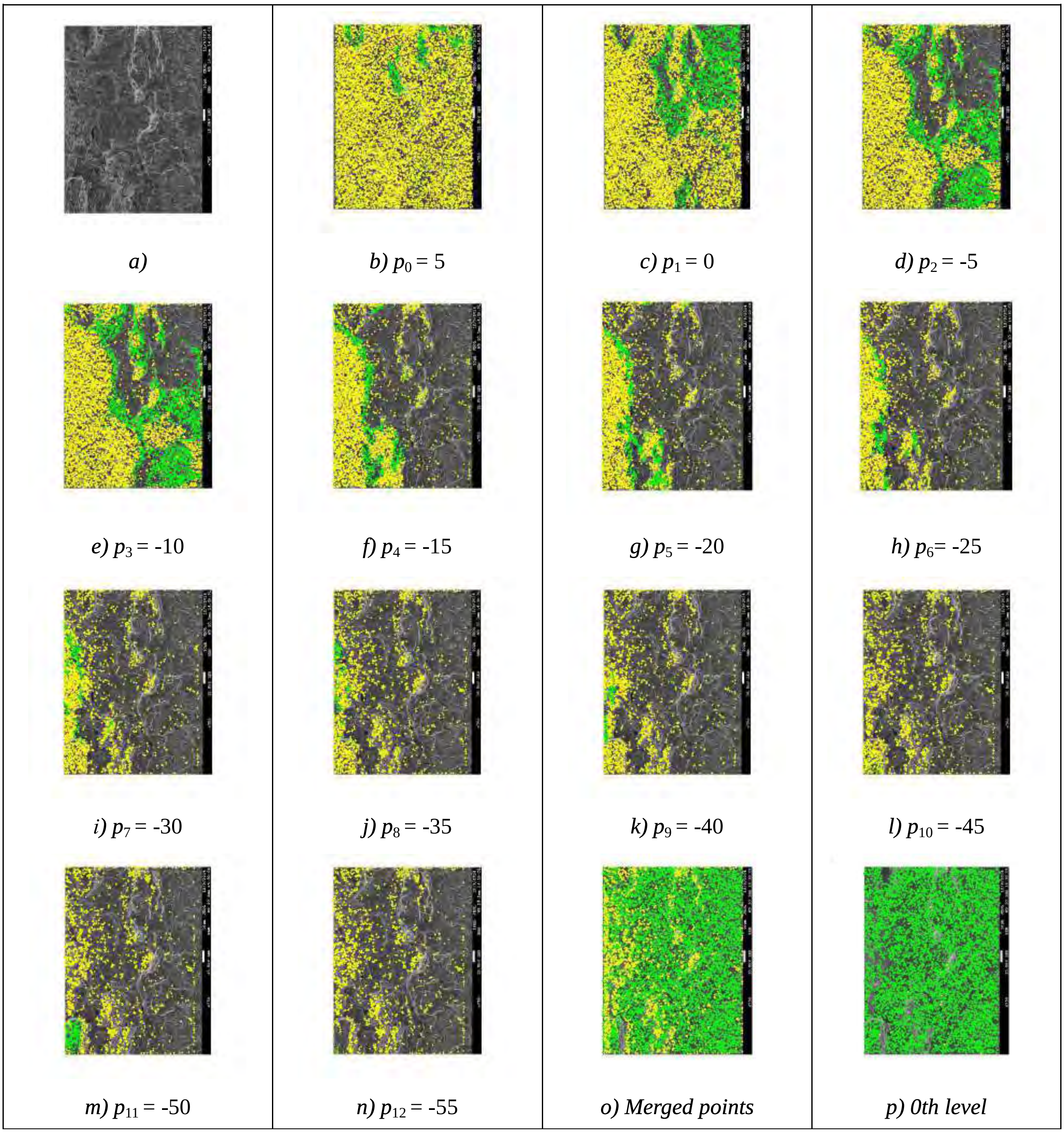
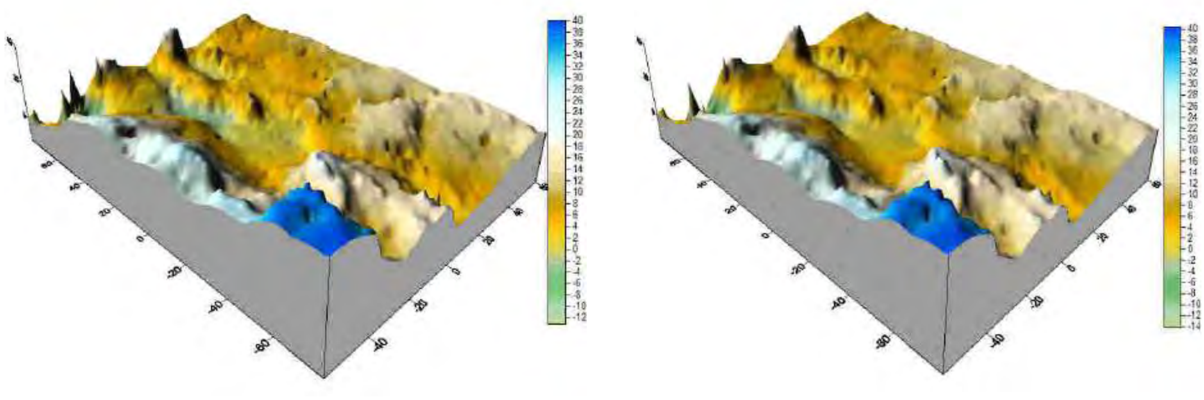


Fig. 3. Illustration of the process of shifting the centers of the search windows in the right image of the SEM stereo pair of the chrome steel specimen and matching points (green in tolerance R_c = 0.7, yellow – no); a – original right image; b – through n – the results of sequential displacement along the x axis by 5 pixels within the parallax range from p_0=5 to p_{12}=-55; o – merged points; p – refinement of the position of the corresponding points at the 0th level of the pyramid

3D model of the micro surface of the chrome steel specimen

3D models of the micro surface of a chrome steel specimen, built on the basis of spatial coordinates defined at the 1st and 0th levels of the image pyramid, are presented in Fig. 4. The density of the obtained points at the 1st and 0th levels of the pyramid is 0.41 points/µm. The spatial coordinates of the points of the surface microrelief were computed taking into account the values of geometric distortion inherent in the SEM image [Ivanchuk, Tumska, 2017].



a *b*

Fig. 4. 3D models of the micro surface of a chrome steel specimen (grid size 100x76) computed from data obtained at the 1st (a), at the 0th (b) levels of the image pyramid.

It can be seen that the 3D model at the 0th level of the pyramid is smoother than at the 1st level of the pyramid. To eliminate abnormal heights, adaptive median filtering was applied to grid models obtained at the 1st and 0th levels of the pyramid. Before that, grid models were converted to images.

Accuracy assessment of a 3D model of the micro surface of chrome steel specimen

To estimate the accuracy, the differences between the heights of the test model and the heights interpolated at the same points using the created models were computed (10). The test model of a specimen of chrome steel was created based on manually measured 250 points. The distribution of ΔZ differences over 5 classes before and after adaptive median filtering is shown in Fig. 5.

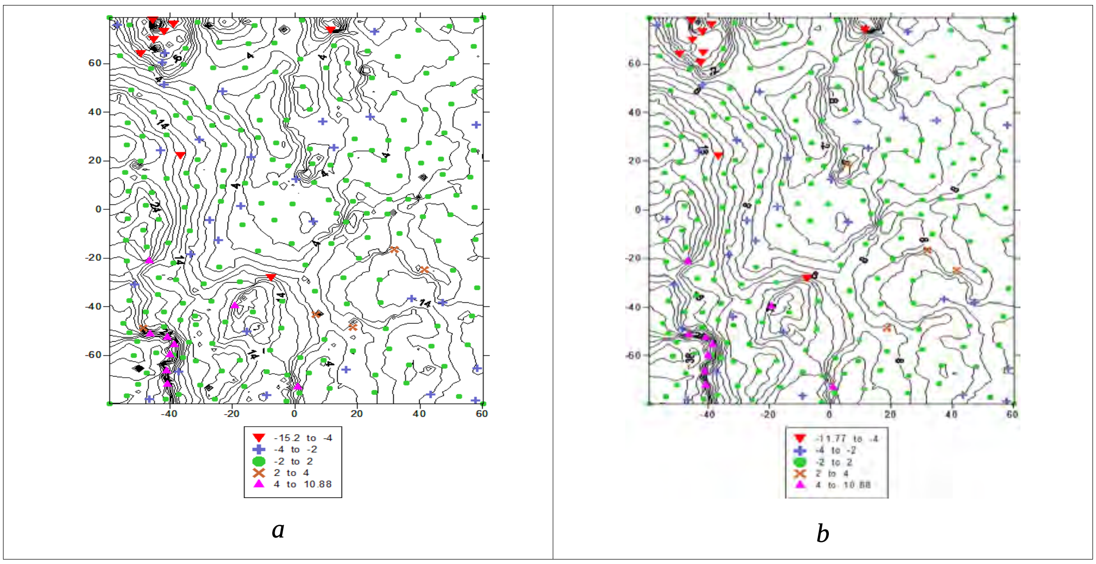


Fig. 5. Micro surface specimen of chrome steel in the contour lines, scale 750x. Symbols shows the differences between the heights of the test model and interpolated using to the constructed grid models before (a) and after (b) adaptive median filtering. Contours lines drawn at interval 2 μm

Analysis of the distribution Δ*Z* over 5 classes shows that the number of points before and after applying adaptive median filtering in the range of Δ*Z* = ± *2* μm is about 79 % both at the 1st and

0th levels (Fig. 5). About 13 % have an error within ±2 ÷ ±4 μm. Thus, about 92 % of the points are within $2m_{Z(h)}$. The value of the a priori accuracy of determining the height of the micro surface points of the chrome steel specimen is $m_{Z(h)}$ = 0.96 μm, for m_x = 0.1 mm, M = 750x [Ivanchuk, 2019].

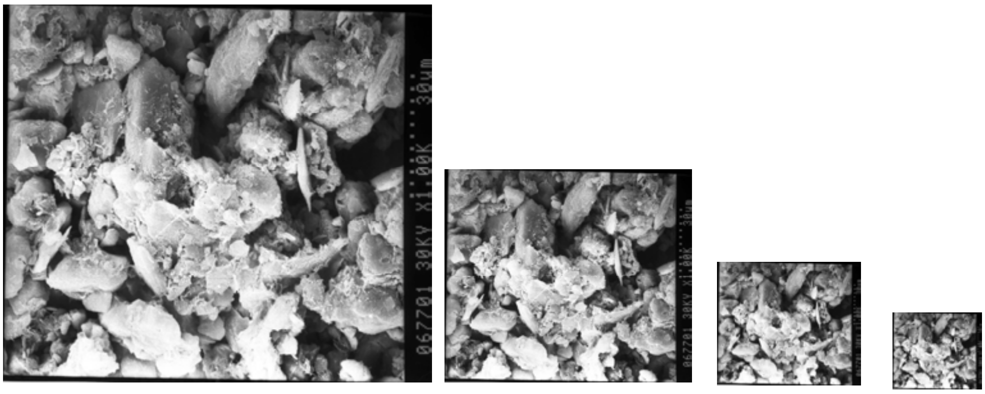
3D surface reconstruction from a stereo pair of SEM images of a specimen of loess soil

Attributes of a stereo pair of digital SEM images of a specimen of loess soil

Images of a specimen of loess soil were obtained from the SEM "Hitachi" S-800 with magnification 1000x, recorded on photographic film with a geometric resolution of 0.03–0.05 mm and scanned at a resolution of 1200 dpi by a photogrammetric scanner [Gruber, Leber, 2000]. The angle of the left image is 0º, the right - 8º.

Gaussian pyramid of the SEM images of a specimen of loess soil

For the images of the loess soil specimen, four levels of the Gaussian pyramid from low to high resolution were created (Fig. 6).



a b c d

Fig. 6. Gaussian pyramid of loess soil specimen image: a – original left image; a – through (d) Levels 1–4 respectively at resolutions: 1200, 600, 300, 150 dpi; respectively image sizes: 3243×2785, 1622×1393, 811×697, 406×349 in pixels

Generation of input points in the SEM image of the loess soil specimen and finding matching points on the pyramid levels

Before creating the Gaussian pyramid, the low-contrast SEM images of the soil specimen were improved using the histogram equalization method. As a result, the generated points appeared in areas unfilled before equalization, and the number of corresponding points increased by 2.6 % at the 2nd level of the pyramid. As in the previous case, the points were generated in two ways on the left image of the 4th level of the pyramid, where the contours are generalized and there are no additional details. Fig 7, *a* shows the generated points in the left image of the soil specimen. The sequence of shift parameters of the initial centers of the search windows (Fig. 7, *b*) is as follows: {0, 2, 5, 8, 11, 14} pixels. Fig. 7, *c* shows the results of the process of shifting parameters at the 4th level of the pyramid of the right image and clarification of the positions of the corresponding points by the levels of the pyramid (Fig. 7, *d*, *e*, *f*).

Window sizes on the right image of the 4th level of the pyramid, in pixels, are: search 5×5; template 25×25. The coordinates of the corresponding points were refined at 3, 2, 1 levels of the pyramid of the right image with the following window sizes, in pixels: search 11×11, 21×21, 41×41; template 25×25. The correlation criterion for all levels is R_c = 0.7. The number of successfully identified points is presented in Table 1.

3D model of the micro surface of the soil specimen

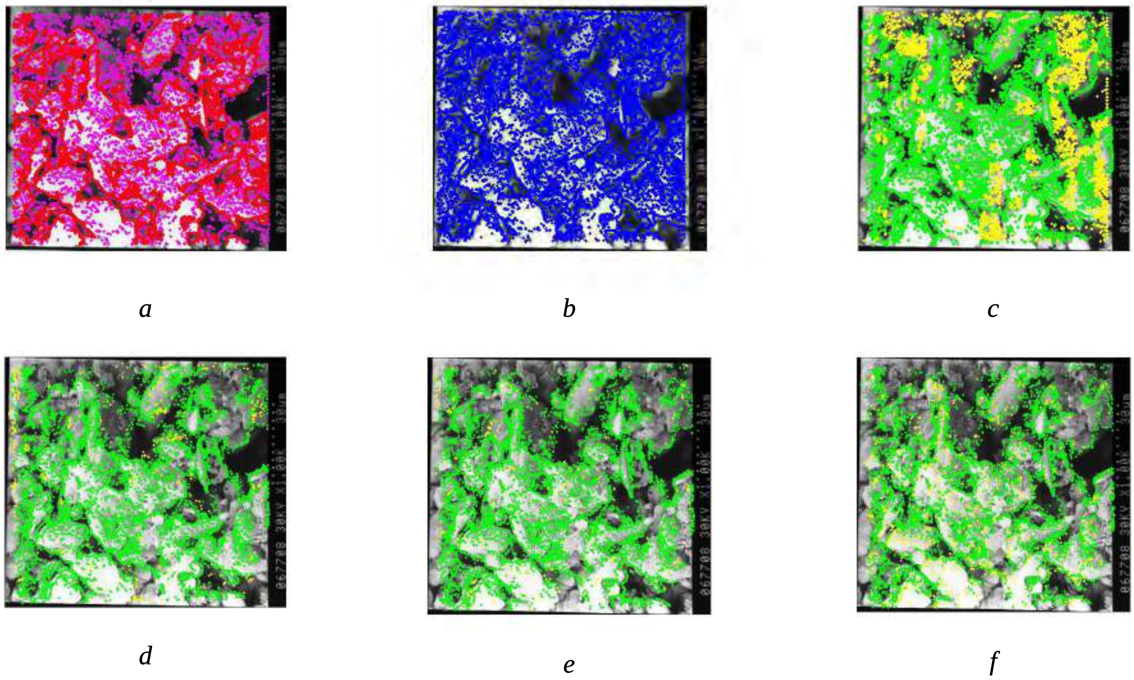


Fig. 7. Illustration of the process of correlation identification of points by pyramid levels. Upper row: 4th level of the pyramid: a – the generated points (11,687) in the left image of the soil specimen; b – initial centers of the search windows in the right image; c – matching points (green in tolerance R_c = 0.7, yellow – no). Bottom row: (d) – (f) Refinement of the position of the corresponding points at the 1st, 2nd, 3rd levels of the pyramid.

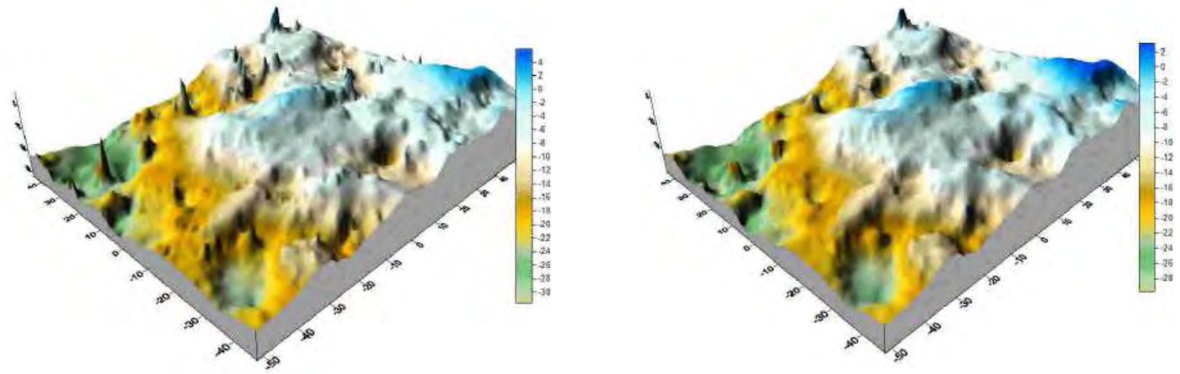
A digital model of the micro surface of the soil specimen (Fig. 8) was created using the spatial coordinates of the points. The density of the obtained points is 0.96; 0.91; 0.87; 0.74 points / µm respectively at 4 – 1 levels of the pyramid. As above, the spatial coordinates of the micro relief points of the surface of the soil specimen were computed taking into account the values of the geometric distortion inherent in the SEM image. Table 1 shows the characteristics of the input data and the parameters of digital micro surface models before and after applying adaptive median filtering.

Table 1

Comparison of 3D models of the micro surface of a soil specimen by pyramid levels before and after adaptive median filtration

Pyramid levels	Grid size 100x87; correlation criterion R_c = 0.7									
	Reso-lution, dpi	Number of input points	Before adaptive median filtering				After adaptive median filtering			
			Z_{min}, µm	Z_{max}, µm	$\sum \Delta Z/n$, µm	Std $m_{\Delta Z}$, µm	Z_{min}, µm	Z_{max}, µm	$\sum \Delta Z/n$, µm	Std $m_{\Delta Z}$, µm
4	150	8723	-33.45	10.43	–	–	–	–	–	–
3	300	8176	-32.86	10.38	-2.47	4.03	-29.53	4.97	-2.44	3.92
2	600	7851	-31.51	5.93	-1.77	3.67	-29.76	3.14	-1.73	3.55
1	1200	6706	-31.73	4.23	-1.50	3.69	-30.24	3.38	-1.49	3.58
Test model: number of control points: 626, Z_{min} = -34.64 µm, Z_{max} = 2.98 µm										

The standard deviations at the 2nd and 1st levels of the pyramid and the differences between the maximum heights of the test model and the created models after filtering confirm that it is unreasonable to scan a film with a geometric resolution of 0.03–0.05 mm with a resolution of more than 600 dpi (see Table 1). In the MatLab system, in the interpretation mode according to the pyramid levels, the speed of computing points per second are as follows: 4th level – 25.3; 3rd level – 11; 2nd level – 4; 1st level – 1.3.



a *b*

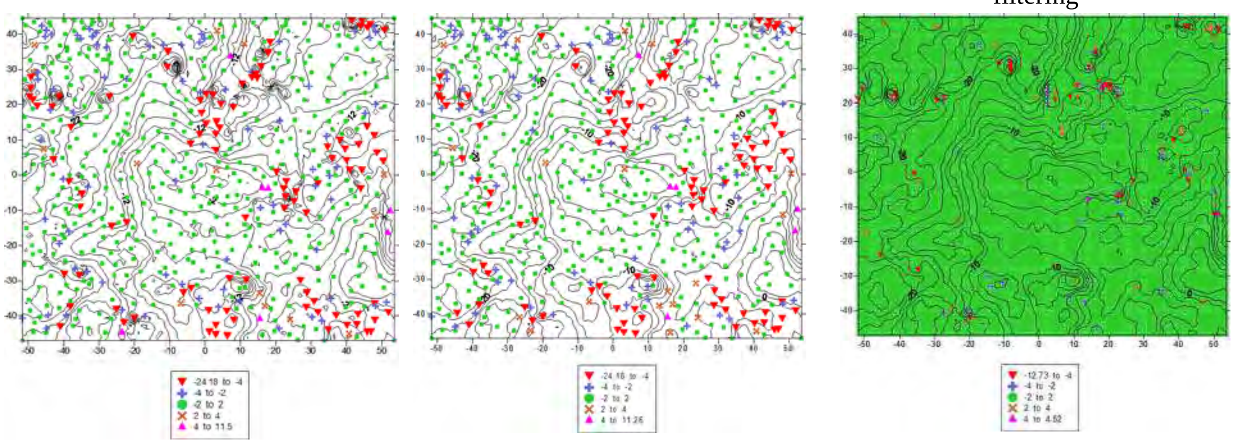
Fig. 8. 3D models of the micro surface of the soil specimen created using data from the 2nd level of the image pyramid. (a) Before and (b) after adaptive median filtering

The accuracy estimation was performed for a model created by the data of the 2nd level of the image pyramid, which has a minimum standard deviation and, in addition, the computation speed is greater than at subsequent levels.

Evaluation of the accuracy of digital modeling of the micro surface of the soil specimen

Fig. 9 shows maps of the distribution of differences ΔZ between heights by class. Differences ΔZ were calculated between the heights of the test model of the soil specimen and the interpolated heights using grid models before and after the adaptive median filtering. The test model for a more complex micro relief of the surface of a specimen of loess soil was created based on manually measuring 626 points. Grid models were created by the data of the 2nd level of the pyramid.

Before adaptive median filtering | After adaptive median filtering | Map differences between 3D models before and after adaptive median filtering



a *b* *c*

Fig. 9. Micro surface specimen of soil in the contour lines, scale 1000x. Symbols shows the differences between the heights of the test model and interpolated heights using to the constructed grid models (a) before and (b) after adaptive median filtering. On the right is a map of the differences between 3D models before and after adaptive median filtering (c). Contours lines drawn at interval 2 μm

The distribution of the differences between the 3D models constructed before and after the use of adaptive median filtering is also presented.

Class distribution of the difference between the heights of the test model and interpolated by the grid model of the soil specimen

The differences ΔZ between the heights of the control points interpolated by the grid model of the soil specimen and the corresponding heights of the test model before and after applying adaptive median filtering in the range of ±2 μm are 66–68 %. Approximately 16 % have errors within (±2 ÷ ±4 μm). Almost identical results were obtained before and after applying adaptive median filtering: about 85 % of the points are within $2m_{Z(h)}$. The value of the a priori accuracy of determining the height of the points of the micro surface of the soil specimen is $m_{Z(h)} = 0.30$ μm, for $m_x = 0.04233$ mm, M = 1000x.

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Conclusions

1. The authors developed a technology for automatically iteratively matching SEM stereopair points by the levels of the image pyramid. The proposed method for shifting parameters reduces the search area and the probability of mismatch and, in addition, speeds up the matching procedure in a pair of images.
2. The proposed combination of two methods to generate input points (Sobel operators and selecting the Otsu threshold method) yielded larger number of points whose vicinities contained distinctive features.
3. As a result of the improvement of low-contrast images of the loess soil specimen by the method of histogram equalization, the number of successfully matched points increased by 2.6 % (correlation criterion $R_c = 0.7$).
4. The transition to a more detailed zero level of the pyramid of the image of a chrome steel specimen made it possible to clarify the coordinates of the corresponding points. As a result, a smoother 3D model was obtained, which is clearly confirmed by the map of the height differences between the 3D models constructed from the data of the 1st and 0th levels of the pyramid.
5. Analysis of the distribution over 5 classes differences ΔZ between the heights of the test model and ones interpolated using the constructed grid models shows that for the micro surface of the chrome steel specimen about 79 % of points, and for the micro surface of the specimen of loess soil about 70 % of points are within the tolerance $\Delta Z \leq \pm 2$ μm.
6. Constructed from a large number of points 3D models are characterized by smoothness and replicate small elements of the structure of the micro surface. The largest deviations (8 %) of the heights interpolated using the micro surface created model from test values are observed at the boundaries of the model and in areas with a complicated shape micro surface. Such areas should be supplemented by manually measured point coordinates using the “Dimicros” program.
7. It is proposed that an automated method of matching points in SEM stereopair micro surface experimental specimens can significantly reduce the time for processing and DSM construction with the required accuracy.

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АВТОМАТИЗОВАНА ПОБУДОВА ЦИФРОВОЇ МОДЕЛІ МІКРОПОВЕРХНІ ОБ'ЄКТА ЗА РЕМ-СТЕРЕОПАРОЮ МЕТОДОМ КОРЕЛЯЦІЙНОГО ОТОТОЖНЕННЯ ІДЕНТИЧНИХ ДІЛЯНОК

Мета роботи – розробити і дослідити метод автоматизованої побудови цифрової моделі мікроповерхні об’єкта з використанням стереопари цифрових РЕМ-зображень з урахуванням специфіки РЕМ-знімання і оцінки точності цифрового моделювання. Розроблений метод полягає, по-перше, у генеруванні щільного набору вхідних точок на лівому РЕМ-зображенні стереопари в областях з локальними особливостями і використанні ітераційного процесу по рівнях піраміди зображень. По-друге, пошук відповідних точок на правому РЕМ-зображенні стереопари виконується на основі послідовного зміщення точок (центрів вікон пошуку) на параметр зсуву з можливого діапазону паралаксів із використанням методу кореляційного ототожнення. Для дослідження використано дві стереопари цифрових РЕМ-зображень. Цифрові зображення деформованої поверхні хромованої сталі отримано за допомогою JSM 7100F (JEOL) зі збільшенням 750^x. Зображення лесового ґрунту отримано за допомогою РЕМ “Hitachi” S-800 зі збільшенням 1000^x. Під час розрахунку просторових координат точок мікрорельєфу поверхні враховано значення геометричних спотворень, властивих РЕМ-знімку. Щоб усунути деякі аномальні значення висот тривимірної моделі, застосовано процедуру адаптивної медіанної фільтрації. Для оцінювання точності моделювання мікроповерхонь були створені тестові моделі шляхом ручного вимірювання координат характерних точок цифрових стереопар обох зразків. Заропоновано спосіб зсуву параметрів, який зменшує пошук і ймовірність помилкової ідентифікації і, крім того, прискорює процедуру ототожнення в парі зображень. Отримано формули для розрахунку координат центру вікна пошуку та відповідної точки на правому зображенні на *k*-му кроці процесу зсуву. Для оцінювання точності обчислені різниці між висотами тестової моделі і висотами, інтерпольованими в тих самих точках з використанням створених моделей. Для мікроповерхні зразка хромованої сталі близько 79 % точок, а для мікроповерхні зразка лесового ґрунту близько 70 % точок містяться в межах допуску ΔZ ≤ ± 2 мкм. Вперше в Україні розроблено метод автоматизованого пошуку відповідних точок стереопари на основі зсуву параметрів з урахуванням особливостей РЕМ-знімання. На основі вищевказаного методу розроблено технологію автоматизованого створення цифрової моделі мікроповерхні об’єкта за стереопарою РЕМ-зображень і створено авторське програмне забезпечення, яке показує її ефективність і доцільність. Можливість відтворювати мікрорельєф поверхні об’єкта автоматизовано з використанням стереопари цифрових РЕМ-зображень відповідно до вимог точності визначення просторових координат точок та структури мікроповерхні об’єкта.

Ключові слова: РЕМ-стереопара, кореляційне ототожнення, точність, 3D-модель.

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