

Modeling of biological microreliefs using the method of photogrammetry (on the example of cycloidal scales)

M.L. Tyagun¹, T.A. Khodzher²

Limnological Institute of the Siberian Branch of the Russian Academy of Sciences

¹ ORCID: 0000-0002-9574-0647, mary@lin.irk.ru

² ORCID: 0000-0002-3470-9478, tatty-80@mail.ru

Abstract

To reconstruct a biological relief object, we used a modeling method using a digital photogrammetric system that analyzes data from stereo pair images obtained by scanning electron microscopy. The method allows to analyze the principle of organization of both complex and simple microobjects, the construction of which requires clarity or refinement.

Using this method, the authors can describe the principle of organization of the cover relief layer of cycloid scales, characteristic of most Teleostei (evolutionarily late fish). Obtaining such three-dimensional images is relevant for understanding the construction of evolutionarily different types of fish exoskeleton. Also, the method will greatly facilitate the interpretation of the features of microrelief formed cyclically, which is necessary to accurately determine the age of modern fish species.

Keywords: photogrammetric method, stereopair method, self-organizing biosystem, microrelief.

1. Introduction

At present, along with new imaging methods of "computer vision" long-known theoretical techniques are used. In classical photogrammetry aerial photographs of the terrain were previously used for making plans and maps (phototopography) [1, 2]. The current stage offers a solution to such mapping tasks using drones and unmanned aerial vehicle [3, 4, 5, 6]. Satellite systems obtain images of the Earth to study its natural resources and to control environmental protection (space photogrammetry) [7]. The wide application of photogrammetric method for a certain range of tasks in various fields of science and technology constitutes the subject of research in applied photogrammetry [8, 9, 10, 11]. Photogrammetry is often used by surveyors, architects, engineers, and contractors to create topographic maps, grids, point clouds, or drawings based on the real world [12, 13, 14]. Modern digital photogrammetric systems allow simulating almost all processes performed in classical photogrammetry.

The use of photogrammetric methods made it possible to obtain three-dimensional images of simple and complicated relief surfaces by stereo pair. Construction of three-dimensional objects on the basis of geometric properties of stereo pair images became the basis of many modern software products. Operation with digital images obtained with the help of digital video and photo cameras significantly reduces the technological chain from image processing to creation of a digital terrain model. The processing of such images requires the development of digital photogrammetry, which increases productivity and saves time. Modern digital photogrammetric station is a set of software and hardware, providing a set of technological processes and operations, necessary to obtain digital maps and orthophotomaps. The most famous foreign systems are products of Intergraph Corporation [15], LH-systems LLC [16], ISM [17], ERDAS [18]. Developments in digital photogrammetry are also carried out in Russia: Racurs company presents PHOTOMOD system [19], Siberian digital stereo plotter SDS created at the Department of Photogrammetry and Remote Sensing of the SGGA (Novosibirsk)

[20, 21], Agisoft software package [22], etc. All these programs in one way or another have developed functionality and high productivity, with their help it is possible to solve specific tasks of automatic or semi-automatic creation and editing of digital terrain matrix. Moreover, work with modern digital photogrammetric system in contrast to analog-analytical methods does not require special photogrammetric education, which significantly expands the areas of its application.

Currently, 3D modeling systems are improving methodologically due to the involvement of multiscale objects in this field. Thus, stereoscopy and subsequent 3D modeling are actively used in biomedical sciences, where research objects are relatively smaller and images are acquired using scanning electron microscopy (SEM) methods [23, 24, 25].

Before the invention of electron microscopes, the use of photogrammetric methods in microscopy was limited. This was due to the fact that light microscopes had low resolution and a low depth-of-field. In time of creation of raster electron microscopes with a significant depth of field of view (approximately 300 times greater than that of light microscopes) the use of stereo method becomes effective and is of practical interest when determining morphological features of biological microstructures [26]. At present time raster stereo pairs using SEM are widely used mainly in biomedical field and partly in industrial one [27].

We had the task of constructing a 3D model of a biological object - an element of the external skeleton of fish.

Cover tissues of representatives of the living world, as well as structured biominerals, have both simple and complex microrelief. This peculiarity attracts the attention of biologists, since the regularities of relief patterns formation of such tissues are of diverse interest: both in the applied aspect (for species diagnostics) and theoretical - as a self-organizing system [28, 29, 30, 31].

We selected an object with a regularly recurring relief - fish scales (Fig. 1). The main element of the relief is sclerite [32, 33]. The sclerites of the most common types of scales, cycloid and ctenoid, are concentric formations. From above, they look like circles or rings diverging radially from the geometrical center. On histological section, they are represented as ridge-like elevations (Fig. 1a). Due to this, the surface of scales is heterogeneous in height. The scleritic pattern can be conventionally called a map of scales, and if we take into account that the sclerites are different-sized elevations, and the scale plate itself is a slightly curved plane, then we can talk about the architectonics of the object, and the object itself can be considered a topographic map.

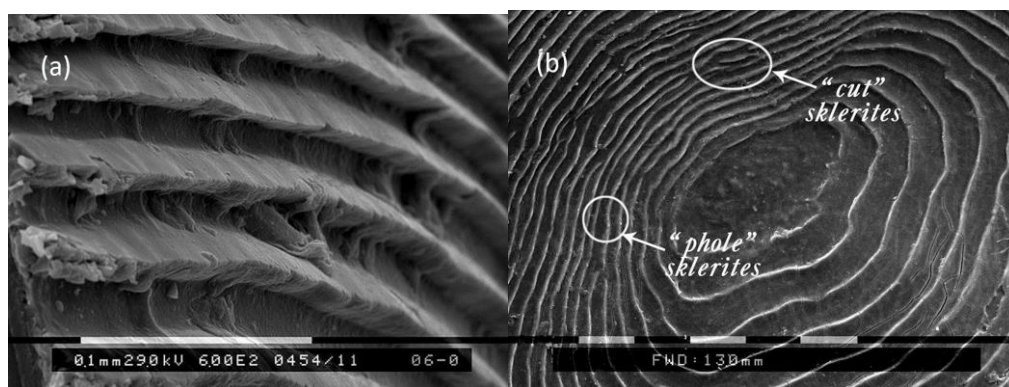


Fig. 1. Baikal omul scale (*Coregonus migratorius* Georgi):
a) fragment of the relief of the cycloid scale cover layer,
b) central part of the cycloid scale, top view (photo SEM Philips 525-M)

Scales are a peculiar biological "passport" reflecting the regularities of the fish life cycle. The characteristics of fish growth are reflected in the peculiarities of the "stacking" of relief structures of scales having an annual periodicity [34, 35]. Biochemically, the scales' relief formations are hypermineralized structures. Sclerites, the concentrically arranged ridge-

shaped elements, are composites of extracellular protein matrix and mineralized components, mainly calcium phosphates close to hydroxyapatite [36, 28]. If we look at the relief pattern of scales frontally, it becomes evident that it has periodic repetitions: widely placed whole sclerites and the so-called "wedging out" or "shearing" ones [37] (Fig. 1b). This recurrence has a seasonal aspect, due to which we can distinguish annual zones (the set of two seasons) in the scale pattern [38]. The isolation of the annual zones gives the key to solving a number of scientific and practical problems related to the growth of individuals and the determination of age. However, researchers working with the same specimen of scales may have different results in counting the number of annual zones. The discrepancy in most cases is 1-2 annual zones. Thus, we are convinced that the accuracy of determining the age of fish depends on the correct interpretation of the relief of the scale plate and that errors are possible in the visual method of reading. This forces us to turn for help to the methods of volumetric study of the relief of scales, which can provide additional information.

To test the photogrammetric method, a scale of Baikal omul, a species of commercial value for which an accurate age determination is in demand, were selected.

2. Creating a 3D microrelief model

Obtaining a model is based on principles similar to human vision converted into computer vision techniques. The first step of the work is to obtain sparse correspondences between the original images, with the help of which automatic camera calibration is performed. The second step is to reconstruct the volume from the points reconstructed for computer stereo vision. The third step is the reconstruction of the surface by merging these points.

2.1 Preparation of a biological object

Any biological micro-object is prepared for SEM imaging in accordance with the requirements for imaging under a scanning electron microscope [39]. The specimen must be cleaned, fixed, dehydrated and dried. In the case of delicate fragile objects, cleaning can be performed in a special ultrasonic bath. The object is immersed in a bath carrying an aqueous medium, which subsequently retains suspended insoluble nanoparticles [40]. Biological tissues containing fluids are dried at the next stage using cryo-drying methods.

In our case, the scales selected for imaging were cleaned with plain water and ammonia (1%) added. During surface treatment, the dermal epithelium was removed. Then the scales were glued with Cosmofen glue to a table designed for imaging on a scanning electron microscope with a relief layer upwards and dried in this form. Before vacuum SEM imaging, the object was sprayed with a thin layer of gold.

2.2 Technology of obtaining stereo pairs

The method used in this work involves the creation of a digital 3D model on the basis of two images obtained from different angles; software connection of locally-identical images by multiple superposition of photographs of the same object.

To obtain stereo pairs required for further modeling, the angular displacement of the Philips 525-M SEM detector was used (Fig. 2). In spite of the fact that the recommended angular stereobase for this SEM model is 16° , tests with different angles of detector displacement were performed. The tests were conducted in 1° increments and ranged from 17° to 21° . A test with an offset of 16° resulted in a further accurate model. The stereo pairs obtained at different offset angles were then saved at 300 dpi in bmp format. The choice of image format was determined by the allowable input data of the digital photogrammetric system with which the digital elevation model was obtained.

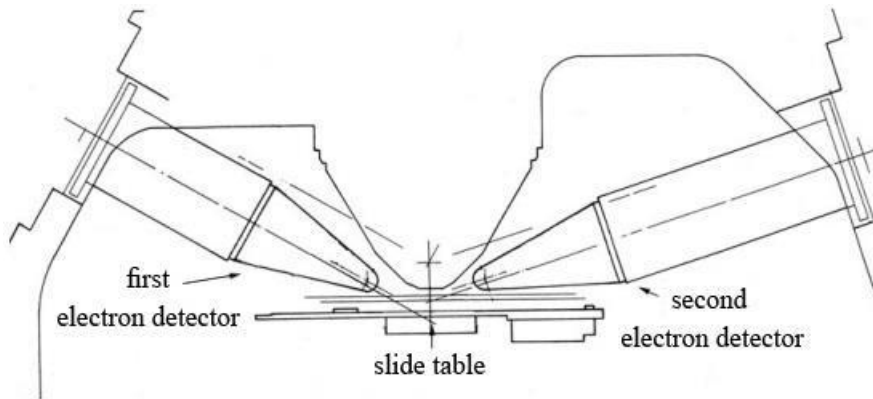


Fig. 2. Layout of secondary electron detectors in Scanning electron microscope Philips SEM 525-M.

Creation of three-dimensional model of scales. The program Z-Space 1.2 developed in the computer vision laboratory of the Institute of Information Technologies (Moscow) [41, 42], which includes functions of internal, external and mutual orientation of images and allows reconstructing relief elements, was used for creating the three-dimensional model. The main functional blocks of Z-Space 1.2 represent all basic stages of the technological process of obtaining a digital elevation model (DEM - for short) process based on a stereo pair of digital images (Table 1). The system is intended for fast generation of digital elevation models in the form of regular height matrix, creation of orthophotomaps, as well as vector contours survey using stereo pairs and orthophotomaps.

Table 1. The main functional blocks of the Z-Space system 1.2.

Module	Functions
Project	Creating, loading and monitoring the status of the project
Interior Orientation	Internal Image Orientation
Relative Orientation	Mutual orientation of images
Exterior Orientation	External orientation of the stereo model
MakeDTM	Creating a DEM
Rectification	Rectification of images*
EditDTM	Viewing and editing DEM

* Image rectification is the transfer of two image planes into one plane so that all epipolar lines are parallel to the abscissa axis and the corresponding epipolar lines on both images have the same ordinates [43].

The processed stereo pair (with interior orientation markup) is loaded into digital photogrammetric system Z-Space 1.2. Digital data input is performed by "RA-3DM" module developed for creation of digital elevation matrix (Fig. 3) [41, 42].

The purpose of Interior Orientation is to establish a relationship between the pixel coordinate system and the image coordinate system. The correlation of pixel coordinate data is determined during the calibration procedure. Then the parameters of formulas for pixel conversion to the interior coordinate system are specified. Thus, the program builds a regular digital grid projected for the analyzed image. The results of internal orientation are used for mutual and external orientation and provide precise definition of terrain coordinates. The process of internal orientation in Z-Space 1.2 includes four steps:

1. Setting the digitizing parameters, shooting scale, focal length,
2. Setting the parameters and how to use the markup,
3. Initial setting of markers for markup crosses,
4. The process of calculating the orientation parameters.

Relative Orientation step defines parameters of relative position of right and left images coordinate systems and allows to build free stereomodel. Relative orientation parameters in-

clude two rotation angles of the left image coordinate system α, γ and three rotation angles of the right image coordinate system α, ω, γ .

In order to determine the parameters of mutual orientation, it is necessary to mark the connecting points on both images. This operation can be done in manual, semi-automatic and automatic modes.

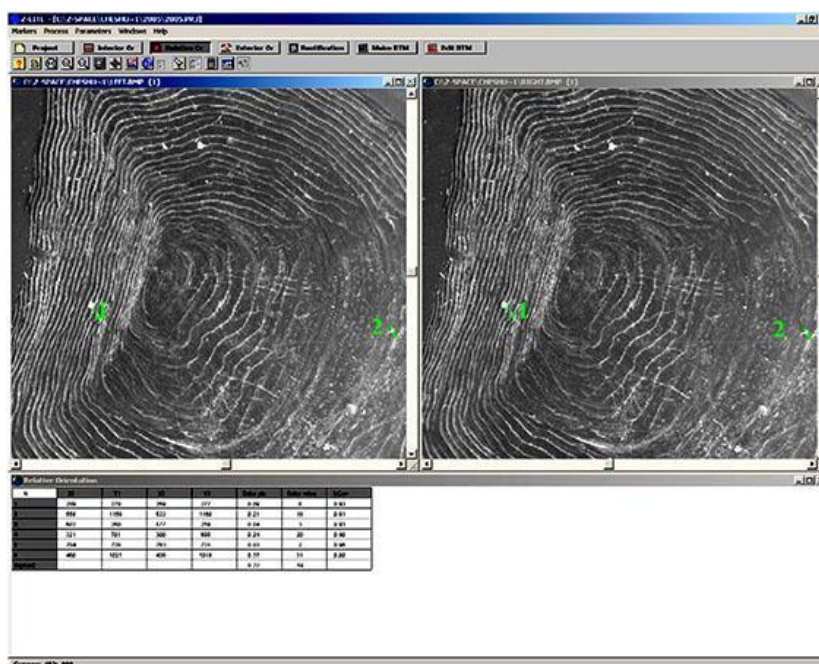


Fig. 3. Z-Space 1.2 interface with loaded with a stereo pair of Baikal omul scales (stage of mutual orientation)

As a result of using the created information system, the researcher can build an orthophotomap of the scale area of interest to him, obtain and analyze the section of the reconstructed 3D scale model of interest to him (Fig. 4), and also build a graph of heights along any given direction.

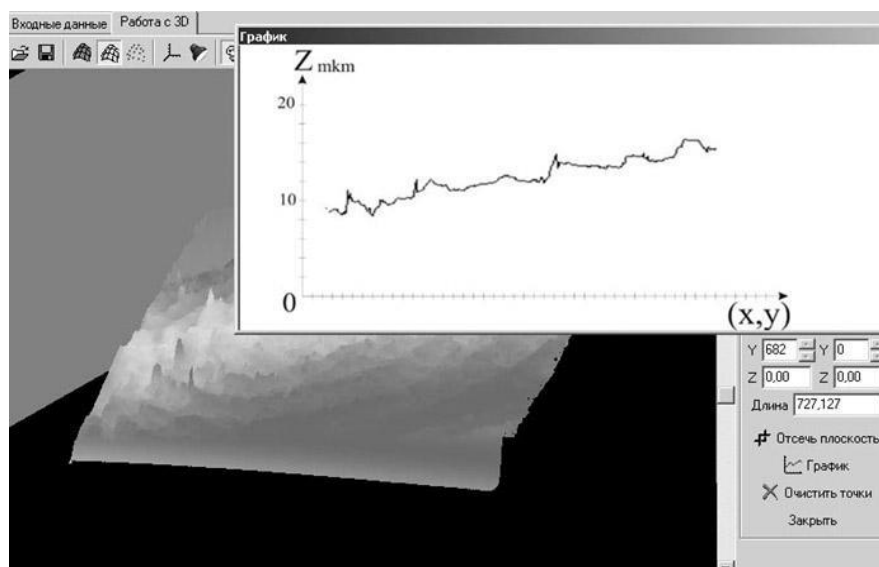


Fig. 4. Using the SLICE tool: 3D DEM slice and plot of DEM heights along a given clipping line

3. Analysis of the principle of relief organization

Based on the image reconstructed using the approved methodology, we can conclude that the relief surface of modern cycloid scales is structured (Fig. 5a). The main components of the relief are thin plates, which are located in relation to the scale plane at an angle and are immersed in the main substance of the upper layer of the scale. An analogue of similar structures is known for the ancestors of modern herrings - these are the so-called stries [38, 44]. In the case of modern cycloid scales, the detected plates are arranged parallel to each other and represent a densely packed structure. Each plate is armed with a number of teeth. Teeth are located relative to each other at an average distance of 0.24 mm. The principle of distribution of teeth on a separate plate provides the possibility of combining the teeth of neighboring plates into a circular sclerite. In this connection, it can be stated that the sclerite body is not monolithic; the sclerite is a set of teeth of neighboring plates (Fig. 5b). The width of the tooth base is ~0.15 mm, the height of the tooth ~ 0.80 mm. The distance between the teeth composing the sclerite is ~0.015 mm.

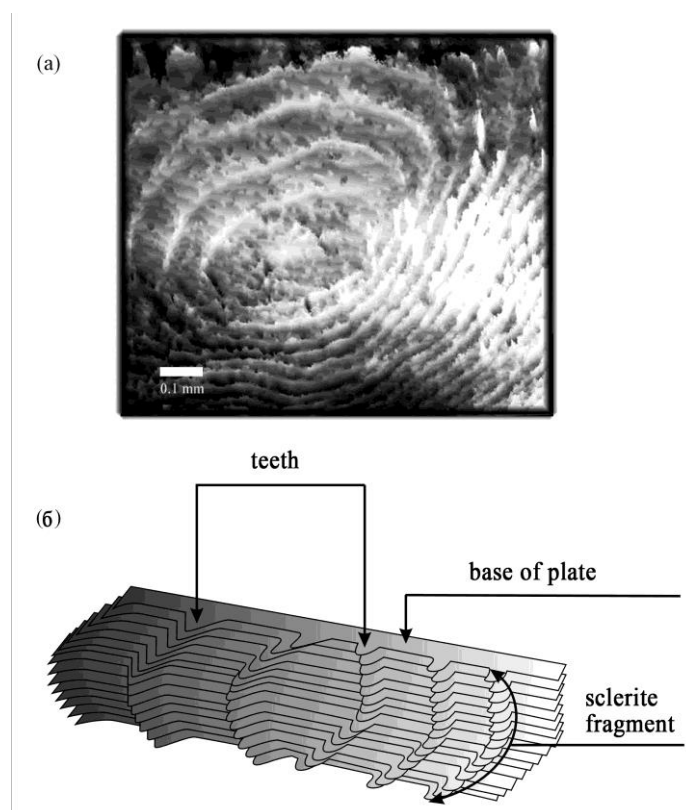


Fig. 5. Three-dimensional image of the relief layer of modern cycloid fish scales, reconstructed from stereo-images obtained with the Philips-525-M SEM:
(a) - original; (b) - scheme of the scales area with relief structures

4. Confirmation of the principle of organization of the scales relief

On the 2D Philips-525-m SEM image, which shows a fragment of the relief of another section of the scale (Fig. 6), we can also see the plates protruding between the sclerites. Their edges protrude to the surface by 0.5 μm at the base of the sclerite. With the total thickness of the upper layer of scales being 0.06 mm, we can assume that the body of the plate is almost entirely immersed in the substance of the upper layer, and we see them only partially. Therefore, it is better to identify the plate in the place of formation of a denticle on it, where its projecting area to the surface gradually increases.

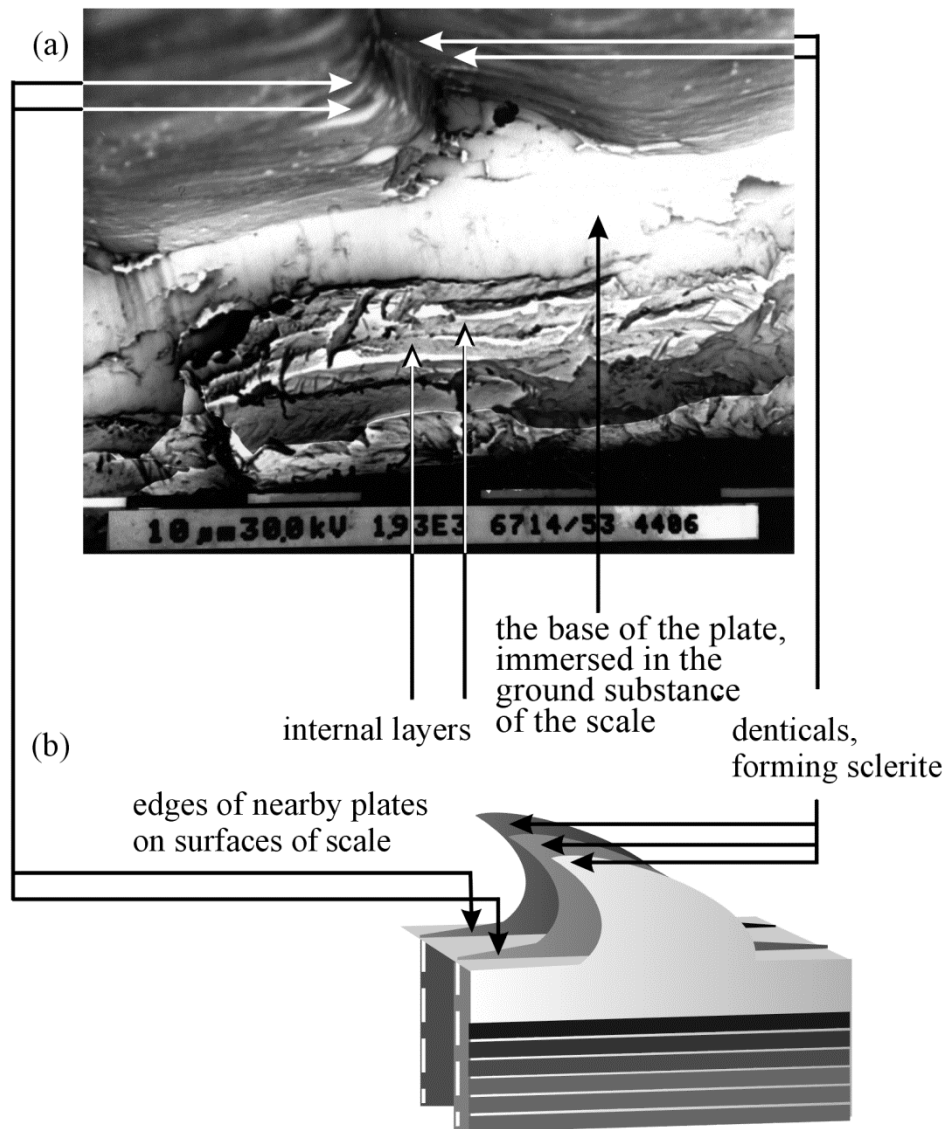


Fig. 2. External and internal scale structure:
 a) cross cut of the scale (image acquired from SEM-Philips 525-M)
 b) scheme of the scale cross cut

Fig. 6. A cut of a cycloid scale and a conditional scheme for organizing a section of a relief layer

Due to the method of digital photogrammetry, it was possible to reconstruct the relief layer of cycloid scales and determine the main elements that form the surface of the selected object. The method allowed us to obtain not only an image, but also information on the principle of the relief structure of cycloidal scales. The obtained three-dimensional model allowed us to make a number of assumptions. First, the plates with denticles are a kind of "armature" immersed in the substance of the upper layer of scales. A similar "framework", namely the collagen matrix, has been described for the cycloid type of scales of *Pagrus major* (genus *Tilapia*, family *Cichlidae*) (Feng et al, 2020). The main material forming the plates of cycloid scales is probably a substance similar to the collagen matrix. This assumption can be made based on the information on the principles of biomineralization of skeletal structures, which, in particular, states that the main component of the object is an organic matrix, which is mineralized at further stages of formation of the skeletal element.

5. Discussing

Due to the accuracy of the stereo pair method and the correct estimation of the spatial position of the elements of complex relief produced with its help, we can reconstruct an object with "informative" microrelief - cycloid scales. At present, there are known investigations using this approach for micro-objects. These investigations prove high efficiency of this technique [45, 46, 47, 48]. When analyzing the methodology, it is necessary to state that for each individual microobject at the stages of preliminary preparation there are purely specific nuances. In literature sources devoted to microrelief reconstruction, methodological preparation can be divided into single-projection (2D), multiview (3D) and hybrid strategies [47]. In single-projection approaches using different light directions (electron beam) in one perspective, a group of 2D SEM microphotographs is captured and used to model the 3D SEM surface. In multiview strategies, a set of 2D SEM images captured from different perspectives is necessary for the process of high-precision reconstruction of 3D SEM reliefs. In some cases, this step also includes not only the standard SEM detector technique, but also changing the angle of the stage on which the object is mounted or rotating it around its axis. With some assumptions, this type of imaging can be called "pseudo-convergent imaging. Hybrid mechanisms try to combine single and multiple representation algorithms to reconstruct a 3D relief model from 2D SEM images [47].

DEM reconstruction from stereophotos is a specific process, because in case of each specific relief it is necessary to estimate its spatial features in advance and, therefore, methodological development for each individual object will be unique. For example, in the work of Sohaib et al [46], the topography of the skin was measured before constructing the skin relief model. Since the authors studied with different skin types that had different color shades, the relief height reconstruction was performed for each individual color, red, green and blue (RGB - according to the PC standard), and the direct reconstruction process was performed using the BRDF - (software that operates with the Bidirectional reflectance distribution function). The methodology was proposed by the authors to develop a system of 3D imaging and subsequent static analysis of the skin microrelief, which finds application in the evaluation of the effectiveness of cosmetic procedures and surgical interventions.

In modern period, SEM stereo-photography followed by a DEM was used to analyze the surface of industrial polyethylene film. Measuring and visualizing the surface microrelief of the packaging material using this method was necessary for industrial quality control. In these investigations, the authors state the priority of the SEM stereophotogrammetry method with the reference method of profilometry (chromatic confocal microscopy) for a similar object. The quality of SEM stereophotogrammetry measurements is more accurate [48]. Two-dimensional SEM photos were obtained using a TESCAN MIRA3 GMU (TESCAN Brno, s. r. o., Brno, Czech Republic <https://www.tescan.com/>). Several SEM detectors were used and a secondary electron detector was chosen for pure topographic imaging. An eucentric tilt of the slide with an error of $\pm 5^\circ$ from the central tilt position of 20° was applied to create the stereo pair. Exactly such conditions allowed the authors to obtain higher topographic quality and contrast of the images.

In our investigation, just as in Martelo et al [48], a large displacement angle was initially used. The tests were performed in 1° steps ranged from 17° to 21° . A test with a displacement angle of 16° resulted in an accurate model. In our work, two secondary electron detectors were used, in contrast to the work of Sohaib et al. [46], where several detectors were used. Thus, our object does not have a high requirement for methodology and, due to this, it is easier to implement it on streaming work. The software processing is also not demanding on the PC resource in comparison with modern software complexes. The Z-Space complex is designed specifically for fast automatic construction of digital models. The program is capable of constructing digital terrain models based on stereo pairs of space or aerial photographs for interactive selection of 2D and stereo features, as well as for creating perspective scenes, including DTM and vector features [49]. In our case, luck is the use of this program for micro-

relief. With this investigation, we demonstrate not only the plasticity of the stereopair method and software, but also the adaptability of the software product to multi-scale objects. We also benefit within the framework of a biological task, describing the principle of its relief arrangement with the help of the tested object.

6. Conclusion

In this investigation we have proposed an approach which allows to reconstruct microreliefs using stereo pair method and digital photogrammetry. The approach includes three steps: preparation of the preparation for imaging with SEM, acquisition of a digital stereo pair with SEM and software construction by the Z-Space photogrammetric system on the basis of the obtained stereo pair images.

The 3D image of the object obtained by this approach is more informative than its photo. Relief microelements, which do not always allow one to judge the structure as a whole during normal shooting, are crucial in stereopair shooting. In the case of the cover relief of cycloid scales, the edges of the plates protruding to the surface in the places where the scleritic ridges exit, allowed us to see and come to an understanding of the principle of organization of the cycloid scales.

The results of the present approach allow: to visualize the structure, to set the necessary slice on the object and to analyze the slice of interest of the reconstructed 3D model, to extract from the slice the elevation changes of the relief.

For such an object as scales, the adaptation of photogrammetric methods allows to transfer the study of microstructures to a completely new qualitative level: to identify relief elements in more detail, to interpret their variability and to link features of this variability with ontogenetic processes.

Acknowledgements

Present investigation was prepared as part of the basic project FWSR-2021-0005 (121032300224-8) study of transformations of the state of water bodies and streams in Eastern Siberia in seasonal and long-term aspects in the context of climate change, geological environment and anthropogenic pressures (supervised by A.P. Fedotov), and with using equipment of the collective instrument center "Ultramicroanalysis" (<http://www.lin.irk.ru/copp/eng/>).

References

1. Orobinsky V. S. Fundamentals of aerial photography. Vladimir: Publishing house Vladimir state university, 2005, 71 p., <https://www.geokniga.org/bookfiles/geokniga-osnovy-aerofotogeodezii.pdf>, (in Russian)
2. Xiuxiao Y. On Stereo Model Reconstitution in Aerial Photogrammetry // Geo-spatial Information Science, Vol. 11, №4, 2008, pp. 235-242, doi:10.1007/s11806-008-0099-3
3. Steffen R., Forstner W. On visual real time mapping for unmanned aerial vehicles. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. Vol. XXXVII, Part B3a, 2008, pp. 57-62, <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.183.9519&rep=rep1&type=pdf>
4. Atutova Zh.V., Makarov S. A. The experience of use of unmanned aerial vehicles in geographical research // Proceedings of the All-Russian Scientific and Practical Conference (Irkutsk, May 22–23, 2018). Irkutsk: Publishing house of the Institute of Geography. V.B. Sochavy SB RAS, 2018, pp. 7-10, http://www.irigs.irk.ru/download/BPLA_sbornik.pdf, (in Russian)
5. Pix4d, photogrammetry software developer, <https://www.pix4d.com> (date of visit: 16.05.2022)
6. An unmanned aerial vehicle developer UAV LiDAR, <https://www.yellowscanlidar.com> (date of visit: 16.05.2022)

7. Khan A., Singh S., K. Singh. Generation and analysis of Digital Elevation Model (DEM) using Worldview-2 stereo-pair images of Gurgaon district: A geospatial approach // *Journal of Geomatics*. Vol.11, N^o 2, 2017, pp. 186-190, https://isgindia.org/wp-content/uploads/2017/10/JoG_1102_05.pdf
8. Aguilar M.A., Aguilar F.J., Agüera F., Carvajal F. The Evaluation of Close-range Photogrammetry for the Modelling of Mouldboard Plough Surfaces // *Biosystems Engineering*, Vol. 90, N^o4, 2005, pp. 397–407, doi:10.1016/j.biosystemseng.2004.11.006
9. Arias P., Herraes J., Lorenzo H., Ordóñez C. Control of structural problems in cultural heritage monuments using closerange photogrammetry and computer methods // *Computer and Structures*, Vol. 83, Is. 21-22, 2005, pp. 1754-1766, doi:10.1016/j.compstruc.2005.02.018
10. Ye D., Liao M., Nana A., Wang E., Zhou G. Research on reef bathymetric survey of uav stereopair based on two-medium photogrammetry // *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. XLI-B1, 2016, pp. 407-4012, <https://pdfs.semanticscholar.org/f443/2da400cc3c6775d8e65db9a537e38a0doec4.pdf>
11. Santise M., Thoeni K., Roncella R., Sloan S. W. Giacomini A. Preliminary tests of a new low-cost photogrammetric system // *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. XLII-2/W8, 2017, pp. 229-236, doi:10.5194/isprs-archives-XLII-2-W8-229-2017, https://www.researchgate.net/publication/321219578_PRELIMINARY_TESTS_OF_A_NEW_LOW-COST_PHOTOGAMMETRIC_SYSTEM
12. Patias P., Karras G. E. Contemporary Photogrammetric Applications in Architecture and Archaeology. In book: *Digital Photogrammetry*, Eds: Y. Egels, Publisher: Hermes Science Publishing, Thessaloniki, Greece, 1995, pp. 300-335
13. Kraus K., Jansa J., Kager H. *Photogrammetry - Advanced Methods and Applications*. Vol. 2, 4th edition, Bonn: Dümmler, 1997, p. 466
14. Bryan P. G., Corner I., Stevens D. Digital rectification techniques for architectural and archeological presentation // *Photogrammetric Record*, Vol. 16, N^o93, 2003, pp. 399-415, doi: 10.1111/0031-868X.00131
15. Company-developer of an interactive environment for technical design, <https://hexagonppm.com/ru-ru/offerings/products/intergraph-smart-3d> (data of visit 20.05.2022)
16. Company-developer of modern digital cartography, <https://www.lhsystems.com> (data of visit 20.05.2022)
17. Company-developer of digital photogrammetric system ISPRS, hardware and software, <https://www.gim-international.com/content/article/digital-photogrammetric-workstations-2> (data of visit 20.05.2022)
18. Company-developer of ERDAS Imagine LPS, a photogrammetric processing package for aerial and orbital images, <https://gmvcast.uark.edu/photogrammetry/photogrammetry-software/lps-leica-photogrammetric-suite> (data of visit 20.05.2022)
19. System User Manual 3.10. PHOTOMOD. Program PHOTOMOD ScanCorrect. - M.: CSJ Company "Racurs", 2016. 22 p., <https://racurs.ru> (data of visit 20.05.2022), (in Russian)
20. Guk A. P. Siberian Digital Stereoplotter // *ISPRS Congress 19th*, Vienna, 1996.
21. SDS Digital Stereo Plotter. User's Guide. Intramural Edition, 1997, 23 p., (in Russian)
22. User's Guide. Agisoft PhotoScan: Professional Edition, version 1.2. – St. Petersburg: "Live Soft" LLC, 2016. 110 p., (in Russian)
23. Sakeev D. A., Ershenko E. M., S. V. Baryshev, Bobyl' A. V., Agafonov D. V. Deep microrelief measurement and stereo photography in scanning electron microscopy // *Technical Physics*. V. 56, 2011, pp.127–131

24. Kim K. W., Biomedical Applications of Stereoscopy for Three-Dimensional Surface Reconstruction in Scanning Electron Microscopes // Applied microscopy 2016, pp. 71-75, <http://dx.doi.org/10.9729/AM.2016.46.2.71>
25. Feng H., Li X., Deng X., X. Li, Guo J., Mab K., Jiang B. The lamellar structure and biomimetic properties of a fish scale matrix // RSC Advances, Is. 2, 2020. pp. 875-885, doi: 10.1039/c9ra08189e
26. Finkovskiy V. N., Melnik V. N. Photogrammetric processing of images obtained on a scanning electron microscope // Geodesy and Cartography, No. 9, 1978, pp. 46-52, (in Russian)
27. Baghaie A., Tafti A. P., Owen H.A., D'Souza R. M., Yu Z. Three-dimensional reconstruction of highly complex microscopic samples using scanning electron microscopy and optical flow estimation // YuPLoS One. 2017, Vol.12, Is. 4, pp. 1-23, doi: 10.1371/journal.pone.0175078
28. Meunier F. J. Spatial organization and mineralization of the vasal plate of elasmoid scales in Osteichthyans // Am. Zool. Sci. 24, 1984, pp. 953-964
29. Birk D. E., Trelstad R. L. Extracellular compartments in tendon morphogenesis: collagen fibril, bundle, and macroaggregate formation // J. Cell Biol., Vol. 103, №1, 1986, pp. 231-240, doi: 10.1083/jcb.103.1.231, <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2113791/pdf/jc1031231.pdf>
30. Poulet N., Reyjol Y., Collier H., Lek S. Does fish scale morphology allow the identification of populations at a local scale? A case study for rostrum dace *Leuciscus leuciscus burdigalensis* in River Viaur (SWFrance) // Aquat. Sci., Vol. 67, №1, 2005, pp.122-127, doi:10.1007/s00027-004-0772-z
31. Ibañez A. L., Cowx I. G., O'Higgins P. Variation in elasmoid fish scale patterns is informative with regard to taxon and swimming mode // Zoological Journal of the Linnean Society, Vol.155, №4, 2009, pp. 834-844, doi:10.1111/j.1096-3642.2008.00465.x, https://www.researchgate.net/publication/230009825_Variation_in_elasmoid_fish_scale_patterns_is_informative_with_regard_to_taxon_and_swimming_mode#read
32. Chugunova N. I. Handbook on the study of the age and growth of fish. Moscow: Academy of Sciences of the USSR, 1957, 167 p., <http://kpabg.ru/sites/default/files/chugunova1957.pdf>, (in Russian)
33. Werder U. Zur Altersbestimmung an *Brycon cephalus* Gunther 1869 (Teleostei: Characidae). Dissertation. Hamburg: Reihe Biologie, 1996, 239 p.
34. Mina, M. V., Klevezal, G. A. Autobiography of animals. M: Znanie, 1970. 32 p., (in Russian)
35. Mina M.V., Klevezal G.A. Growth of animals. M.: Nauka., 1976, 291 p., <http://hdl.handle.net/123456789/2938>, (in Russian)
36. Schonborner A. A., Boivin G., Baud C.A. The mineralization processes in teleost fish scales // Cell Tissue Res., Vol. 202, 1979, pp. 203-212, <https://link.springer.com/content/pdf/10.1007/BF00232235.pdf>
37. Smirnov V.V., Smirnova-Zalumi N.S. Formation of annual growth zones on scales of Baikal omul *Coregonus autumnalis migratorius* (Georgi) // Vopros ikhtyologii, Vol. 33, No. 1, 1993, pp.121-129, (in Russian)
38. Chugunova N. I. Methodology of studying the age and growth of fish. Moscow: Soviet Science, 1952, (in Russian)
39. Nemova S. V. Sample preparation for transmission and scanning electron microscopy: new installations from leica microsystems for coating // Science and Innovations, Vol.10, №2, 2014, pp. 55-60, <https://scinn.org.ua/sites/default/files/pdf/2014/N2/Niemova.pdf>, (in Russian)
40. Rotter Sh. An ultrasound cleaning method with suspended nanoparticles // International application published under the patent cooperation treaty (pct). International Publica-

tion Number 43, International Publication Date WO 2015/159285 Al., 2015, pp. 1-27, <https://patentimages.storage.googleapis.com/f8/61/37/bd2619582d1700/WO2015159285A1.pdf>

41. User's Manual. Digital photogrammetric system Z-Space. Version 1.2, 1999, 104 p.

42. Nekrassov V. V., Chekalin V. F., Moltchachkine N. M. Ortho/z-space software: highly accurate orthorectification of very high resolution satellite image // ISPRS Technical commission VII Symposium on Resource and Environmental Monitoring and ISRS annual Convention. Hyderabad, India, Vol.34, Part 7, 2006, pp. 22-25, http://vinek.narod.ru/files/FO393_p.pdf (in Russian)

43. Pyankov V.D. Spatial processing of unsynchronized video sequences based on frame rectification // Software Products and Systems, №1, 2013, pp. 61-66, (in Russian)

44. Pechkurenkov V. L. Features of scale cover structure of West African sardinella *Sardinella aurita* Val. // Problems of ichthyology, Vol. 3, №. 1, 1963, pp. 131-143, (in Russian)

45. Sakseev D. A., Ershenko E.M., Baryshev S.V., Bobyl` A.V., Agafonov D.V. Deep microrelief measurement and stereo photography in scanning electron microscopy // Technical Physics, Vol. 56, 2011, pp. 127-131, <https://doi.org/10.1134/S1063784211010221>

46. Sohaib A., Farooq A., Atkinson G., Smith L., Smith M., Warr R. In vivo measurement of skin microrelief using photometric stereo in the presence of interreflections // Journal of the Optical Society of America A. Vol.30, Is.3, 2013, pp. 278-86, doi:10.1364/JOSAA.30.000278, <https://www.researchgate.net/publication/235777120>

47. Tafti A. P., Kirkpatrick A. B., Alavi Z., Owen H. A., Yu Z. Recent advances in 3D SEM surface reconstruction. Micron Vol.78, 2015, pp. 54-66

48. Martelo J. B., Andersson M., C. Liguori, Lundgren J. Three-dimensional scanning electron microscopy used as a profilometer for the surface characterization of polyethylene-coated paperboard // Nordic Pulp & Paper Research Journal, 2021, Vol. 36, Is.2, pp.1-8, doi:10.1515/npprj-2021-0003, <https://doi.org/10.1515/npprj-2021-0003>

49. Blokhinov Y. B., Sibiryakov A. V., Skryabin S. V. Z_Space - digital photogrammetric system for russian tk-350 images // IAPRS, Vol. XXXIII, 2002, 7 p.