AUTOMATIC MATCHING OF SCULPTURE FRAGMENTS AS MODERN TOOL FOR ARCHAEOLOGICAL VERIFICATION OF HYPOTHESES ON THEIR ORIGIN

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Commission V

KEY WORDS: Archaeology, Model, Surface Matching, Visualization, Database

ABSTRACT:

The paper presents the final part of the research project carried out by authors, concerning use of photogrammetric approaches to support the archaeological hypotheses on the origin of various sculptures. Connection of the separate pieces to the complete sculptures would allow to identify more accurately their origin. The first part of this research, presented already by the authors in 2006 during the ISPRS Symposium of Comm. V, was related to photogrammetric reconstruction of thirty three 3D models of contact surfaces for pieces of the broken sculptures. Automatic matching of 3D models of contact surfaces of each two adjoining parts can be executed by extraction of various features describeing both surfaces. The proposed method is based on similarity function, which makes use of features directly resulted from geometric shapes. The objective function is described by two components; the first relates to average distance between two surfaces and the second to compensation of different size of the matched surfaces. Algorithm and computer programme elaborated by authors, were tested on base of matching of two contact surfaces of the test-granite stone and afterwards on surfaces of pieces of some museum sculptures. Within this research, a concept of special sculpture'database was also designed. The presented research, sponsored by the Polish State Committee for Research has been already completed and accepted.

1. INTRODUCTION

The archaeological small items, such as for example, statuettes, stone plates, pots and others are very often in the pieces, which are placed in various museums over the World. In many cases, there is no record or indication to which items the museum pieces belong to. To identify the origin of museum sculptures, it is important to analyze not only their separate pieces, but first of all their relative connections which would allow to make some indication on assignment of the adjoining pieces. Therefore, identification of sculpture parts on base of the archaeological characteristics of the items (such as type, dating, material, etc) and control of their relative correspondence is one of the important task within archaeological research activity.

Possibility of connection of separate pieces to the complete sculptures would allow to identify more accurately their origin, especially date and place, on the base of the comparison of iconographical and stylistic characteristics. Simple manual methods, applied by the archaeologists for checking whether two adjoining parts of sculptures fit to each other, use the plaster casts for covering the contact surfaces of those parts. However, such approach is arduous, slow, less accurate and reliable and can damage those contact surfaces and definitely is not suitable for checking of huge number of sculptures placed in various museums.

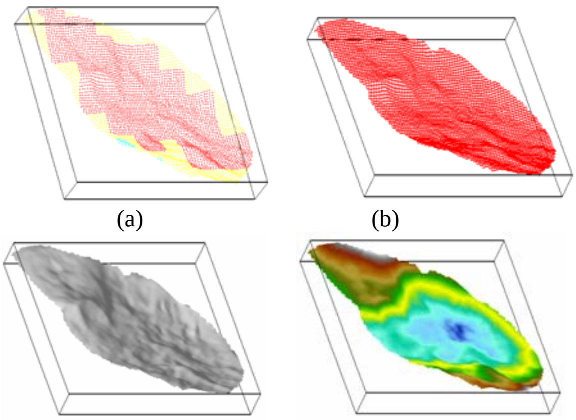
The aim of research undertaken by authors, was to propose a reliable, accurate non-contact method for checking whether the initially chosen adjoining parts of the sculpture fit to each other. The first part of this research, presented already by the authors in 2006 in Dresden during the ISPRS Symposium of Comm. V (Bujakiewicz et al, 2006a) was concerned with photogrammetric reconstruction of 3D models of contact surfaces for pieces of the broken sculptures. The method applied for reconstruction of 3D contact surfaces was based on very large scale digital stereo images (at scales 1: 20 to 1: 40) taken by the semi metric digital camera CANON EOS 20D equipped with three various lenses, calibrated in advance ((Bujakiewicz et al, 2006b). In advance to acquisition of images, the sculpture pieces had been placed within the spatial precise metal frame with control points. The numerical models of all contact surfaces (DSM's) were determined by automatic image matching with the ISAE module of Z/I Imaging workstation (the special programmes for close range automatic processing of stereo images were not available for this project). Altogether thirty three 3D models of contact surfaces of different types of sculpture parts (statuettes, stone plates, flat pots) from the Egyptian Museum in Cairo and the National Museum in Warsaw, were determined with the hight accuracy of 0.3÷0.5 mm. However, not all these measured pieces had their corresponding parts. To verify the proposed method for matching of two contact surfaces of two adjoining parts, two 3D contact surfaces of the granit stone, broken to two parts for purpose of this project, was also measured, in addition to the museum sculpture fragments. Those two stone' parts had not been affected by erosion, as in case of the real museum pieces, and therefore their contact surfaces (DSM's) should fit to each other. This allowed to analyze an efficiency and accuracy of the method for matching of two corresponding surfaces, proposed by authors. The entire project, sponsored by the Polish State Committee for Scientific Research, was carried out in the Digital Photogrammetric Laboratory of Faculty of Geodesy and Cartography at WUT.

2. PRINCIPLES OF THE PROPOSED METHOD FOR SURFACES MATCHING

In advance to the process of matching of two adjoining surfaces of the pieces of archaeological sculpture, their 3D models have to be visualized in a way which would help to analyze their topography. Four forms of visualization of the perspective views of surfaces were analysed. For the surface of the broken statuette indicated in figure 1 (a) (reconstructed from stereo images fig. 1 (b)), these four visualization forms are presented in figure 2 (a ÷ d).

(a) (b)

Figure 1. (a) the broken statuette - code CG 181 (the Egyptian Museum in Cairo) (b) Stereo images applied for surface model reconstruction)



(a) (b) (c) (d)

Figure 2. Four forms of the perspective view of the surface for the broken statuette (a) spots of different colour (b) grid (c) shading (d) 'Z' colour coding lines

After searching the contact surfaces' topography of various types of pieces, the shading surface representation was selected from four examined forms of visualization for the subsequent process of surfaces matching.

Automatic matching of two corresponding surfaces can be executed if some selected features are extracted from surfaces. Such features can refer to the primitives, it means to the various types of real data describing those surfaces, or they can be mathematically defined by the high level features, which are invisible. A few theoretical proposals for the second approach are presented in (Luong Chinh Ke, 2005). For matching of two surfaces one of them has to move relatively to the other. This would be reached if such movement minimize the objective function, which describes the differences between these surfaces. Most existing methods for matching of surfaces are based on the similarity measures, means on the function which applies features directly resulted from the geometrical shapes of objects covering those surfaces [Habib et al., 2000; Schenk at al., 2000]. The applied objective functions for surfaces matching do not necessary require the extraction of the features but the coordinates of the surface points and their topology might be also utilized. However, in such cases the difference in the spatial orientation of surfaces can not be large and therefore the initial approximate transformation has to be executed before the final matching.

In the proposed method for matching of two surfaces, the objective function was described by the average distance between the points of first surface from the second surface approximated by triangles. The main assumptions of the proposed method are formulated as follows:

- Surfaces are determined by the coordinates of the regular grid points in differently oriented coordinate systems but with the constant scale.
- Surfaces are matched by six parameters transformation, it means by the shift and rotation of the first surface relatively to the other, without change of scale. The scale constancy was secured during the surface models reconstruction.
- For compensation of different size of the matched surfaces, in case of demage of museum sculptures by long time erosion, the second component to the objective function has to be added. This component is important when two surfaces can not be matched on their entire area and therefore some places have lack of the corresponding points.
- The parameters are determined by minimization of the objective function with use of one of the standard optimization method (Hooke'a – Jeevesa).

The proposed method would give the satisfied results if a proportion between two components of the objective function is properly selected. However it has been found, that determination of all single values for the objective function is very time consuming since each point of the first surface has to be checked with all triangles of the second surface. To speed the matching process, a function of the Bufor 'Z' in the Graphics Processor Unit (GPU), has been applied. The specialized units of GPU execute the transformations and interpolations much faster than the computer central unit and access to the GPU units is possible via OpenGL function. The objective function with help of GPU can be therefore executed as follows:

- detemination of the Bufor 'Z' differences for the corresponding sets of triangles of two surfaces, from which the average re-scaled distance between surfaces is estimated, and
- determination of number of pixels for the second component of the objective function.

In respect to the main principles of the proposed method for matching of two congruent surfaces of the sculpture pieces, the computer programme executes the process in two steps:
(1) initial transformation, based on three corresponding points (colour spots) selected on two congruent visualized 3D surfaces. For this purpose, the graphic method for indication of those three common points on two surfaces, was compiled. This has required the analysis of topography of two surfaces, visualized a' priori in the shading representation.
(2) optimization process, where the transformation is based on a huge number of points placed on the common area of two surfaces.

3. PRESENTATION AND ANALYSIS OF RESULTS

The proposed method was verified by checking of matching for 3D contact surfaces of two adjoining parts of the granit stone, cut under control for this project (not destroyed by erosion), as well as for matching of the real museum sculpture fragments. For each case of surfaces matching the results were presented in the following forms :

(1) The perspective views of two adjoining surfaces in the shading representation with three corresponding spots, selected on base of surfaces topography analysis. Those points were used for the initial transformation.
(2) Spatial distribution of relative deviations after final matching of adjoining surfaces; the results of matching are shown in colours, black for the best matching, green and red for increasing positive and negative values of deviations.
(3) Relative deviations in matching of surfaces presented in form of crossections, selected in two perpendicular directions.

The left images of two stereopairs for the adjoing surfaces of two parts of the granit stone are shown in figure 3.

Figure 3. Left images of two stereopairs for the adjoing surfaces of two parts of the granit stone

Figures 4 (a÷c) show the above listed forms of results presentation for matching of two parts of the granit stone.

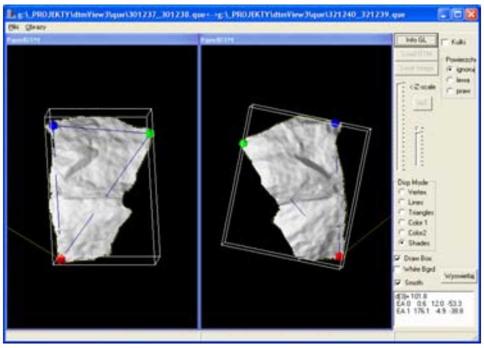


Figure 4a. Two shading surfaces of adjoining parts of test stone with three corresponding colour spots.

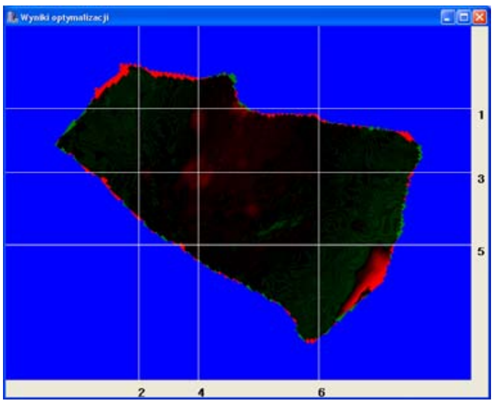


Figure 4 b. Spatial distribution of deviations after final matching of adjoining surfaces of two stone parts (black colour– the best matching). RMS = ± 1.1 mm, no of points: 116734

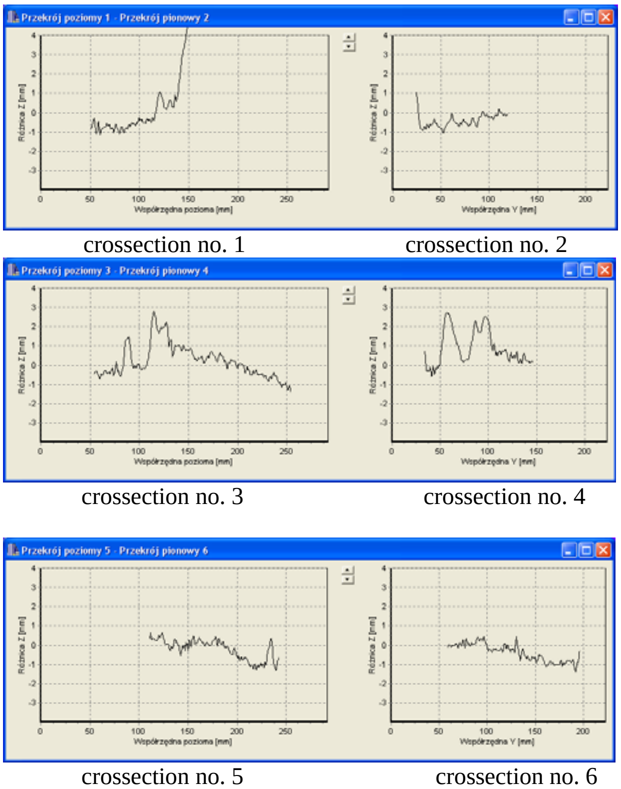


Figure 4c. Relative deviations in matching of surfaces of two stone parts presented in form of six crossections, selected in two perpendicular directions (horizontal – odd numbers, verical – even numbers)

As it can be seen from figure 4 (a), the shapes of two corresponding surfaces of stone parts are very similar, in respect to topography around the entire area as well as to their edges. This is obviously caused by the fact that they are not affected by the erosion. Therefore the results can justify the efficiency and accuracy of the proposed method of matching.

As it can be observed from figure 4 (b), the surfaces matching accuracy is homogeneous nearly around the entire area. The black colour, which corresponds to deviations of range ± 1mm cover most of the area. Only two small circles are in red colour, which refer to the small local hollows in one of the surface, where during its reconstruction the image matching was disturbed. Also the shapes of the surfaces egdes are very similar. As it can be seen from six crossections in figure 4 (c), the deviations mostly oscillate in range of less than ± 1mm. Only in places where the crossections pass through these two local hollows the deviations reach the values from –1mm to 2.5mm.

Assuming the results of matching of two parts of the test stone as the basis for verification of correctness of the main principles of the proposed matching method, the efficiency of matching was then checked for the real museum sculpture fragments. From 33 reconstructed surfaces for various types of sculpture pieces, half of them had no adjoining fragments. For some pieces, such as stone pots, the congruent surfaces were available but their matching has not been successful because of very narrow areas with to small number of interpolated points. This could be solved by taking the images in much larger scale.

Finally six fragments, belonging to two stone plates from the National Museum in Warsaw, were selected for verification of matching real museum sculpture fragments.

In figure 5, one of two stone plates (kod 149 046), which consits of four parts (A1, A2, A3 and A4) with three breaks, is shown. The red arrows show the breaks A1/A2 and A2/A3 for which the results of matching are presented.

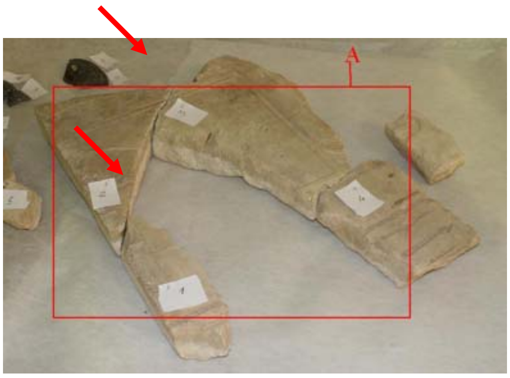


Figure 5. Four parts (A1, A2, A3 and A4) of stone plates (kod 149 046) with the red arrows showing the breaks A1/A2 and A2/A3.

The left images of two stereopairs for the adjoing surfaces A1/A2 and A2/A1 of the break A1/A2 are shown in figure 6.

Figure 6. Left images of two stereopairs for the adjoing surfaces A1/A2 and A2/A1

Analysis of figures 5 and 6 indicates that the adjoining contact surfaces have no the same edges shape and size.

The contact surface A2/A1 of the part A2 is much smaller than surface A1/A2 of the A1 part (because of demage).

The results of matching are presented in figures 7 (a÷c)

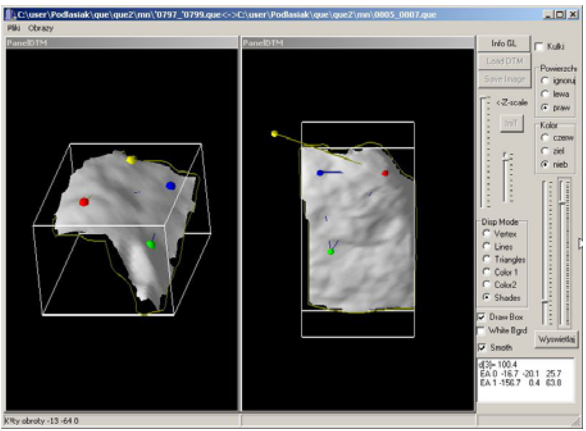


Figure 7a. Two shading surfaces of two adjoining parts of the break A1/A2 of plate stone 'A' with three corresponding colour spots.

Analyzing of two adjoining surfaces in figure 7 (a) it can be observed, that in spite of considerable differences in shape of the edges, the similarity in topography of the corresponding areas of surfaces is visible. Therefore, these three colour points for the initial transformation can be identified and the final matching process for this area can be executed.

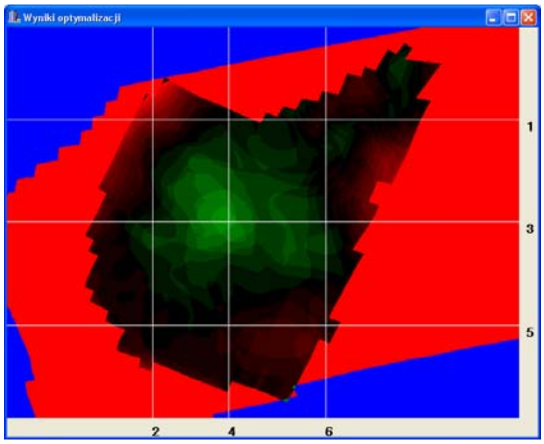
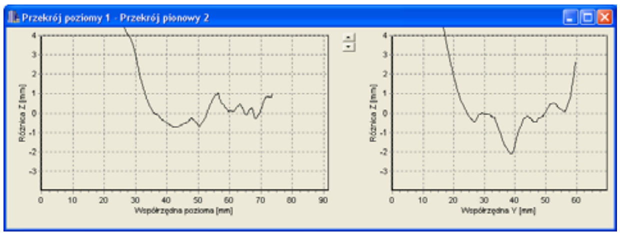
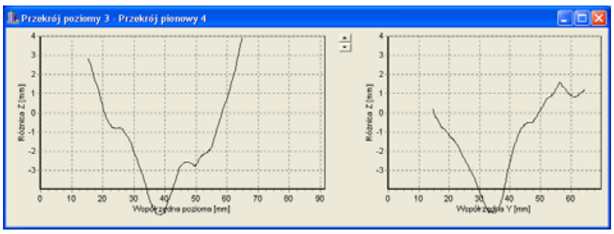


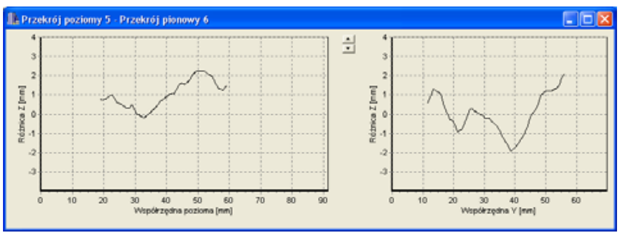
Figure 7 b. Spatial distribution of relative deviations after final matching of adjoining surfaces of the break A1/A2 of the stone plate 'A' (black colour– good matching, green – decreased accuracy of matching, red colour no matching). White lines - crossections. RMS = ± 1.9 mm, no. of interpolated points in the matched area: 132 130..



crossection no. 1 crossection no. 2



crossection no. 3 crossection no. 4



crossection no. 5 crossection no. 6

Figure 7c. Relative deviations in matching of surfaces of two plate parts presented in form of six crossections, selected in two perpendicular directions (horizontal – odd numbers, verical – even numbers)

The results in figures 7 (b) show that the spatial accuracy of matching of these surfaces is not so homogenous as in case of test granit stone (fig. 4 b). Though some parts of area are covered with black colour (good matching) but there is green colour area in the central part (incresed negative deviations) and red colour, specially in the outside parts, which indicate the places where the matching process failed because of demage of these areas of surfaces. For the common part of the surfaces (where matching could be executed) the RMS was estimated as ± 1.9 mm. The maximum deviations along six crossection within this common area were in range of - 6mm to 5 mm.

The left images of two stereopairs for the adjoing surfaces of the second break A2/A3 of stone plate are shown in figure 8.

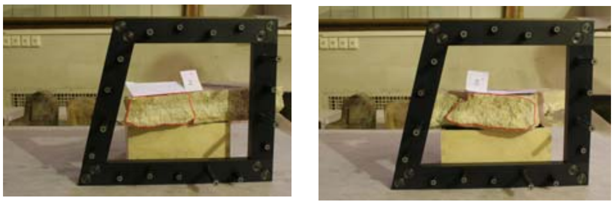


Fig 8. Left images of two stereopairs for the adjoing surfaces of the second break A2/A3 of stone plate (fig. 4)

The results of matching of adjoining surfaces A2/A3 and A3/A2 of the second break A2/A3 are presented in figures 9 (a÷b)

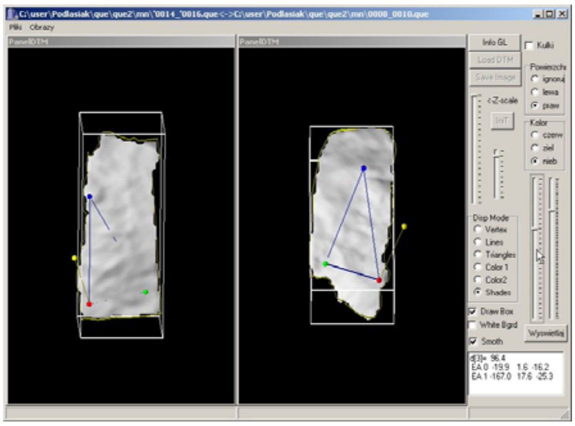


Figure 9a. Two shading surfaces of two adjoining parts of the break A2/A3 of plate stone 'A' with three corresponding colour spots.

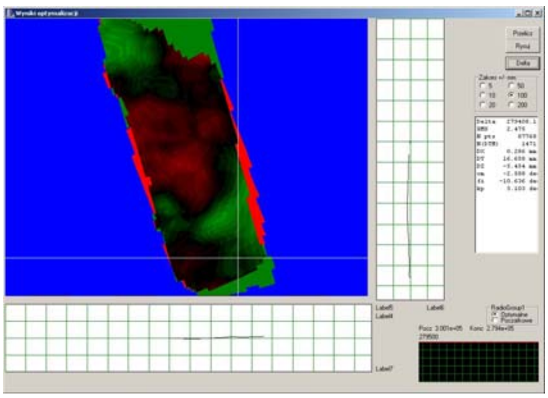


Figure 9 b. Spatial distribution of relative deviations after final plate stone'A' (black colour–good matching, green and red colours decreased accuracy of matching).
RMS = ± 2.5 mm, no. of interpolated points in the matched area: 87 768.

As it can be seen from figures 9 (a) and (b) the adjoining surfaces of nearly entire area of the break A2/A3 have been matched. The edges have not exactly the same shape but the surfaces topography is similar. The black, green and red colours, representing deviations of various magnitudes, are distributed around the entire area. RMS is equal to ± 2.5 mm and the maximum positive and negative deviations reach 6mm.

The accuracy of matching the adjoining surfaces of the third break A3/A4 of the same stone plate is similar, the RMS is equal to 2.4 mm and the maximum positive and negative deviations are also 6 mm.

4. INITIAL PROPOSAL FOR SCULPTURE DATABASE

The aim of such type of database is to: (1) systematize the archaeological and geometrical data related to various types of sculptures and their parts, located in many museum collections around the world, and (2) connection of the affiliated fragments of sculptures. Identification of the fragments of sculptures is based on knowledge of certain grups of features, describing these items. Among the most important are: the material of sculpture, type of fragment, origin (date). Additional information can relate to some inlays describing the sculpture, name and place of museum or collection where the item is archived. The diagram of the archaeological sculptures database structure is presented in figure 10.

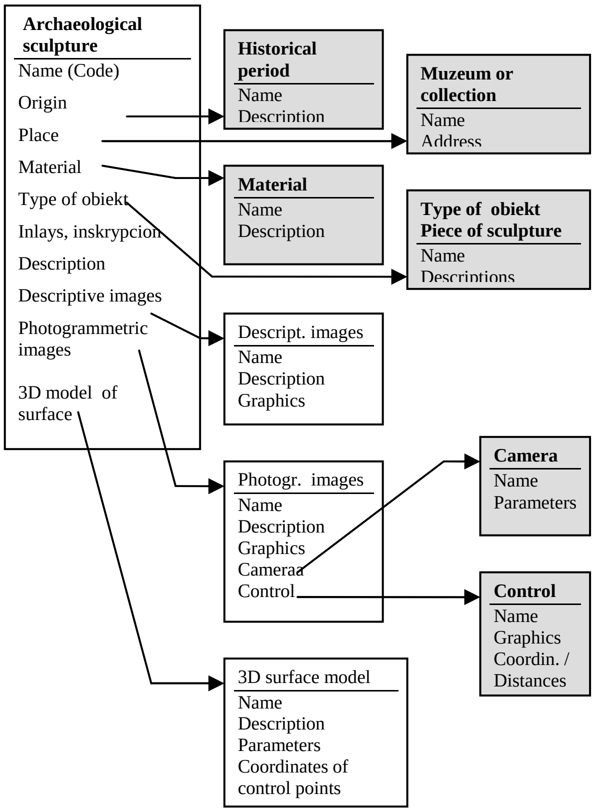


Figure 10. Diagram of the sculptures database structure

Descriptive part is supplemented by the set of images, which show the object from different views. The initial selection is carried out on base of some object features, presented in diagram. After initial selection of fragments of the sculpture, the reconstructed 3D models of adjoining surfaces are then compared for the final verification. The 3D models of these adjoining surfaces belong to the separate objects (sculpture fragments) in the database. Each sculpture fragment is related to the separate set of 3D models of surfaces for its breaks. The proposed sculpture database has been already provided with data concerning all 33 sculpture fragments from the Egiptian Museum in Cairo and the National Museum in Warsaw. The functions of database permit to find the fragments of the sculpture or the whole sculpture on base of assumed initial criterions, and also to archive all reconstructed 3D models of breaks surfaces, which are located in database separately for each object (scalpture fragment). The initial proposal for the database requires further modification.

5. FINAL REMARKS.

The comprehensive research, which was carried out, have shown the possibility for the use of the photogrammetric close range approach, based on the non metric digital images, for the very precise measurement of shapes of the 3D small surfaces of the archaeological pieces. However, very strict precautions have to be taken to ensure the required accuracy of sub millimetre for the DSM generation.

During the automatic matching process of contact surfaces of adjoining pieces of museum sculptures, it has been noted that their edges' shapes and also their sizes are usually not exactly the same. This is caused either by erosion which affects these surfaces differently or by identification of edges during the photogrammetric 3D reconstruction. However, it has also been noted that the vectorized edges do not increase considerably the accuracy of matching, the most important is similarity of the surfaces' topography within the common areas of two surfaces. Various local destructions of these surfaces decrease the matching accuracy. Very important is to secure adequately large number of the measured points on 3D surfaces during automatic image matching, otherwise the process of automatic surfaces matching would fail. It has happened in case of matching of very narrow surfaces of pots pieces. The problem could be overcome when the images are taken in much larger scale. The reached accuracy for automatic surfaces matching was ranged from 1mm (for test granit stone) to 2.5mm (for the real museum pieces). This shows that the principles of the proposed method for automatic surface matching are appropriate. However before recommandation and implementation of the method to archaeology practicing more types of sculptures with various sizes and shapes should be considered within the subsequent research programme.

The proposed initial version of the sculpture' database requires also further development and modification to satisfy the needs of archaeologists involved in research on identification of the origin of sculptures. This can be obviously the separate topic for research.

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ACKNOWLEDGEMENTS

The research was supported by the Polish State Committee for Scientific Research as part of the project - KBN T12 E 033 26 on 'Numerical modelling of the fragments of the archaeological pieces for reconstruction of the original context of the relic'.