Research of algorithms for generating point clouds with various software tools on the example of the monument to Bohdan Khmelnytsky

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Key words: monitoring, cultural heritage sites, cloud of points.

1.SUMMARY

Ukraine is a country with centuries - old traditions and a long history. The role of living witnesses of centuries-old traditions is played by objects of cultural heritage, research and preservation of which is the task of the state level in accordance with Art. 54 of the Constitution of Ukraine. It is important for the existence and preservation of our mentality to monitor the cultural heritage sites and preserve geospatial data about objects. The most common methods of collecting geospatial data today are photogrammetric methods - laser scanning, leader, UAV - the result of which is a cloud of points as a source type of data for further processing, analysis and modeling. Obviously, the quality of the source cloud determines the quality of the reproduced surface of the object and depends on factors such as sensor accuracy, object complexity, shooting conditions, operator level, etc. Methods of generating point clouds based on executive surveys are implemented in various software tools, in particular, the algorithms for processing survey data Agisoft Metashape, 3DF Zephyr, RealityCapture, Bentley Context Capture are considered. The analysis of the effectiveness of the implemented tools was performed on the basis of a comparative analysis of the obtained point clouds from one set of UAV images of the historical monument of Bohdan Khmelnytsky in Kyiv, Ukraine. A 3D model of the monument, based on ground-based laser scanning with an accuracy of 5 mm, was used as a reference. The results of the study will ensure the effectiveness of the choice of tools for generating point clouds in the high-precision reconstruction of objects with complex shapes, such as historical and cultural monuments.

2.INTRODUCTION

The role of living witnesses of centuries-old traditions is played by cultural heritage sites, the research and preservation of which is the task of the state level. Cultural heritage sites include significant buildings, complexes or objects that are of archaeological, aesthetic, ethnological, historical, architectural, artistic, scientific or artistic value and have retained their authenticity. [1] Monitoring the status of the cultural heritage sites includes, in particular, the collection, processing and analysis of information on the status of cultural heritage sites. Photo-fixation of the object: photos of the general view, photos of the object in context (environment), photos of the most valuable (characteristic) elements of the object, photos of moving objects (details), photos of threats (actions of negative factors) are obligatory component in the inclusion of cultural heritage sites in the State list of cultural heritage sites [2]. This causes the urgency of the use of photogrammetric methods for collecting data on cultural heritage sites.

An important result of using photogrammetric cultural heritage sites data collection methods is obtaining a cloud of points for the cultural heritage sites object. The technology of creating and processing point clouds is becoming cheaper and easier to use. Thanks to the capabilities of modern technology to process and use large amounts of data, point clouds are becoming more accessible. We can get a cloud of points for cultural heritage sites by processing modern photogrammetric types of images, such as: laser scanning, leader and UAV shooting.

On the other hand, the availability of high-quality digital data on cultural heritage sites opens a number of opportunities for its further implementation in the innovation space. Advanced computer technology offers a wide range of options for preserving, restoring and restoring historical and cultural heritage: 3D modeling, virtual tours, high-precision reproduction, and more. The main feature of cultural heritage sites modeling, in contrast to, for example, engineering buildings and structures, is their uniqueness and complexity of forms. Sculptural monuments are the embodiment of the artist's thought and work, historical buildings preserve the flow of time in the form of architectural elements and deformations, the fixation and reproduction of which is a prerequisite for modeling cultural heritage sites. The most effective way to digitize non-standard objects is to build a mesh model - a set of vertices, edges and faces that describe the shape of the object. High-precision imaging provides fixation of geometry to the smallest detail, and modern algorithms for data processing - their visualization and modeling.

3.SETTING ODJECTIVES

The process of preserving and monitoring cultural heritage sites begins with the collection of geospatial data about this site. High-precision methods of executive shooting include photogrammetric - based on the processing of digital images from cameras and sensors. The result of the primary processing of photogrammetric data is a cloud of points with certain coordinates X, Y and Z of the outer surface of the object. Given that the cloud of points is the source data for any modeling and analysis, the accuracy of its generation, crosslinking and processing determines the final accuracy of the model or the result of cultural heritage sites analysis. The subject of research of this work is the analysis of algorithms for generating point clouds with various tools with the assessment of their quality and efficiency.

4.ANALYSIS OF SOURCES

Many publications are devoted to the technology of processing clouds of laser scanning points, including the modeling of cultural heritage sites (Barkova,2019; 5, Kotsyubivska , 2020).

The authors Shults, Voloshin, Voronin consider in detail and thoroughly the method of three-dimensional modeling of cultural heritage sites using laser scanning and photogrammetry. All of the proposed approaches describe object point clouds as an intermediate result and do not consider their metric characteristics. That is, the task of generating a cloud of points from digital images is one of the stages of processing the results of photogrammetric surveys and is not considered separately. In (Shults et al 2017; Voloshin 2021; Voronin 2020) only the quality of the final modeling result is investigated without assessing the accuracy of each type of work.

It should also be noted the general trend of approximating the results of modeling without reference to professional software. Most authors in their conclusions justify the accuracy and quality of the simulation results of the parameters of technical means - sensor or camera, and to increase them, if necessary, suggest redundancy - merging data from different sources. But the algorithms implemented within the applied photogrammetric packages have significant differences. For example, the study of Honcheruk, 2017. indicates significant differences in the calculation of camera calibration parameters in different software tools. [4, Honcheruk, 2017]. So it is obvious that the packages of ready-made instrumental algorithms proposed by the developers have significant differences that affect the accuracy of the final result. However, quantification of such an impact or comparative analysis of modeling results based on a single data set has not been performed.

Thus, the study and determination of differences in the generation of point clouds in different tools is a practical task to justify the feasibility of using a software tool in the conditions of free choice to effectively solve the problem of modeling cultural heritage sites methodology.

To unify the approach to the analysis of point cloud generation algorithms based on the results of photogrammetric surveys in various software, a general method of digital image processing is proposed in the following stages: Downloading data, Recognition of control points in images, Image alignment -models, Data export (Fig. 1)

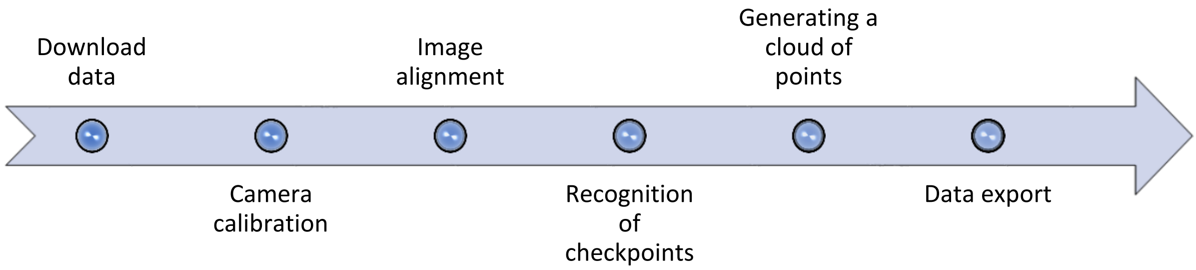


Fig. 1. General algorithm for generating point clouds

Tools for generating point clouds based on executive surveys are implemented in the most common software tools: Agisoft Metashape, 3DF Zephyr, RealityCapture, Bentley Context Capture.

To assess the quality of the generation, the resulting point cloud is compared to a standard, the point cloud, resulting from a ground-based laser scanning of the object.

It is worth noting that some software tools (such as RealityCapture) skip the stage of generating a cloud of points, and build a mesh model immediately after the alignment of images. This is due to the use of depth maps (depth maps) in 3D reconstruction. This method requires much less resources and works much faster and is increasingly being implemented in new versions of software. Therefore, the paper also compares the characteristics of the generated mesh models.

The following metric characteristics are defined as elements of comparison of point clouds: number of cloud points, density of cloud points, processing time, average deviation from the standard. In addition, the curvature and roughness of the generated surfaces were analyzed for the resulting point clouds. These indicators allow us to assess the level of detail of the obtained models.

5.Practical implementation.

Experimental implementation of comparative analysis of generalization algorithms was performed on the example of photogrammetric surveys of the monument to Bohdan Khmelnytsky in Kyiv - a monument of monumental art of national importance, located on Sofia Square in the capital of Ukraine. Architect - Vladimir Nikolaev, sculptor - Mikhail Mikeshin. The art monument is made of bronze, stones, bricks in the classical architectural style (Fig. 2).

Fig. 2 Monument to Bohdan Khmelnytsky in Kyiv, Ukraine.

Photogrammetric images were performed using a DJI Mavic 2 Pro UAV with 1 ”CMOS sensor Hasselblad L1D-20c, the results obtained 375 images with the following parameters:

- Resolution: 5472x3648
- Focal length: 10.26 mm
- Pixel size: 0.00241071 mm

Data processing was done with the following PC configuration: 6-core Intel Core i7-9750H CPU, 32 GB RAM, 6 GB NVIDIA GeForce RTX 2060 GPU. In all software data processing was done with full image resolution. For Agisoft Metashape, 3DF Zephyr and Bentley

ContextCapture camera model was selected automatically. For RealityCapture camera model "Brown 3 + Tangential" was selected. Results of image alignment are presented in the table 1.

Table 1. Comparison of image alignment results

Software	**Number of aligned images**	**GCP error**		**Alignment time, hours**
		pixels	**mm**	
Agisoft Metashape	374	1,1	2,5	00:12
3DF Zephyr	375	1,1	3,1	00:43
RealityCapture	375	0,8	3,1	00:05
Bentley ContextCapture	375	0,69	3,4	00:30

All software demonstrates very close alignments results. Almost all images are aligned automatically. Reprojection error for ground control points is at level of 3 mm. Only alignment time is significantly different, It can be explained by different algorithms of image preselection and feature points extraction. But in this circumstance with very similar alignment results Agisoft Metashape and RealityCapture demonstrate significantly higher processing speed.

Camera calibration results obtained simultaneously with image alignments during the bundle adjustment. All the software again demonstrates very close calibration results (table 2).

Table 2. Camera calibration results

Camera calibration parameters		**Agisoft Metashape**	**3DF Zephyr**	**RealityCapture**	**Bentley ContextCapture**
Focal length	**f**	10,41	10,3	10,4065	10,399
Principal point	**cx**	2726,79191	2713,48689	2726,8854	2724,71
	cy	1828,82331	1828,54676	1828,7859	1824,67
Radial distortion	**k1**	-0,00192354	-0,019491	-0,012304	-0,00613537
	k2	-0,00246928	0,039746	0,012999	0,01152740
	k3	0	-0,052335	-0,019610	-0,01574440
	k4	0	0	0	0
Tangential distortion	**p1**	-0,000948342	-0,001307	-0,000683	-0,001132630
	p2	-0,001001690	-0,001270	-0,000859	-0,000454689

Generated point cloud results were loaded into CloudCompare software for statistical analysis and comparison with the reference (table 3). No additional filtering of the point clouds were made. RealityCapture software allows to visualize results as a point cloud, but only meshes are available for export. For this comparison mesh model was exported from RealityCapture and vertex were extracted from it as a point cloud. These results are marked with "*" in the table below.

Table 3. Comparison of dense point cloud generation results

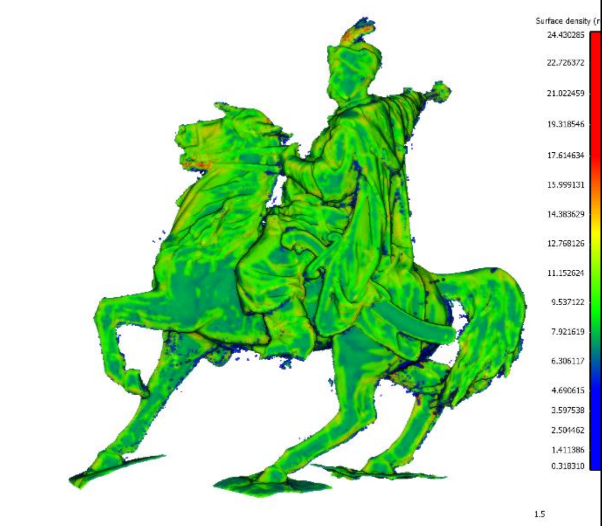
Software	Number of points	Average point density (pts/cm^2)	Average deviation from reference, mm	Dense cloud generation time, hours
Agisoft Metashape	4030336	10,39	6,0	2:20
3DF Zephyr	568856	1,61	4,2	5:40
RealityCapture*	1818214	5,85	4,3	0:24
Bentley ContextCapture	22401376	62,22	4,5	1:47

Despite of the very similar processing parameters and use of the full resolution of photos number of points in cloud differs a lot. There is 40x difference between 3DF Zephyr and Bentley ContextCapture.

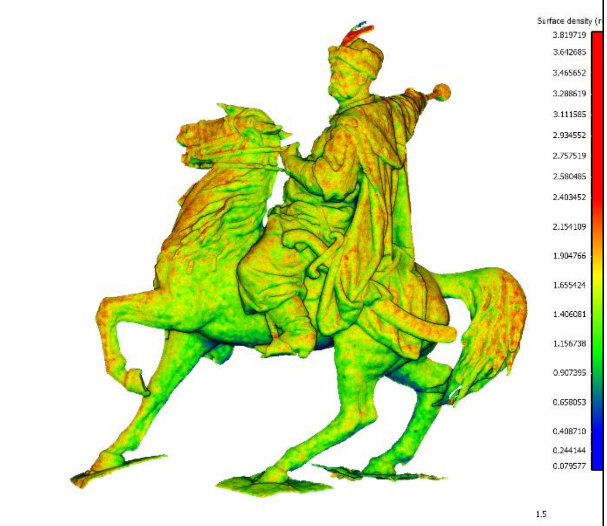
By visualizing the average point density in the generated point clouds, we can conclude following:

- 3DF Zephyr algorythms try to keep the same point cloud density for the whole model (table 4.b);
- Agisoft Metashape reduce the point density in the smooth areas of the object with preserving the details in other areas(table 4.a);
- Reality Capture significantly reduce the amount of points in smooth areas but saves a lot of details in other areas (table 4.c);
- Bentley ContextCapture probably use almost all point from stereo-matching process and tries to keep maximum in the areas with small details (table 4.d).

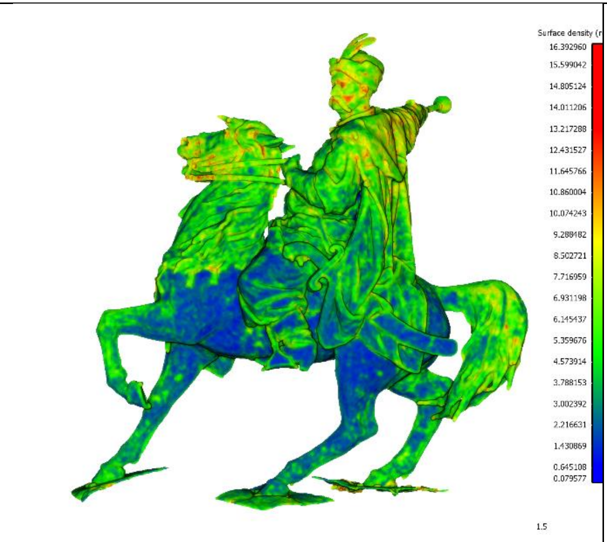
Table 4. Visualizing the average point density of the generated point clouds



a. Agisoft Metashape



b. 3DF Zephyr

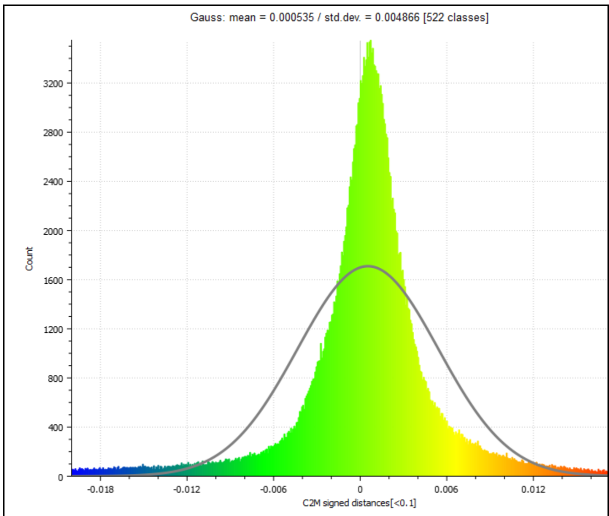


c. Reality Capture

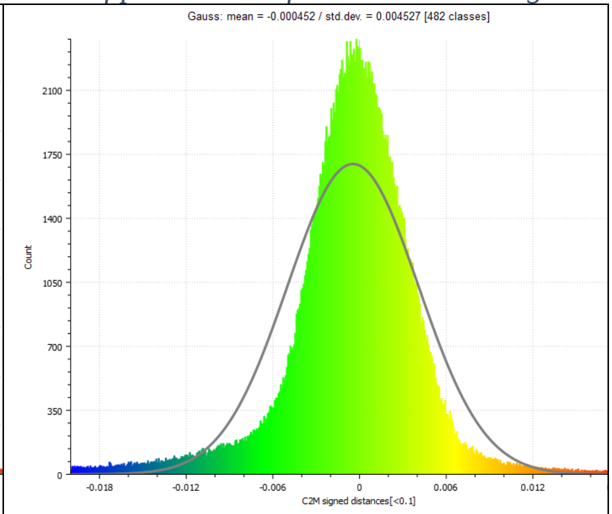
d. Bentley ContextCapture

Comparison of deviation of photogrammetric point cloud from laser scanning data (table 5) shows approximately the same results for all of the software – around 4 mm, except Agisfot Metashape, which shows 6 mm of average deviation.

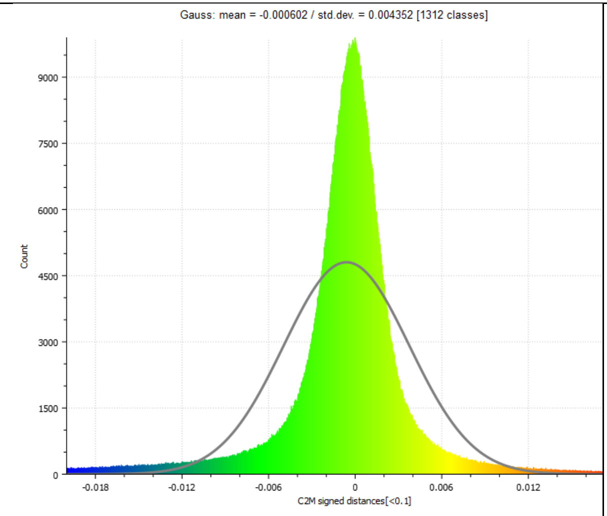
Table 5. Deviations of point clouds from laser scanning data



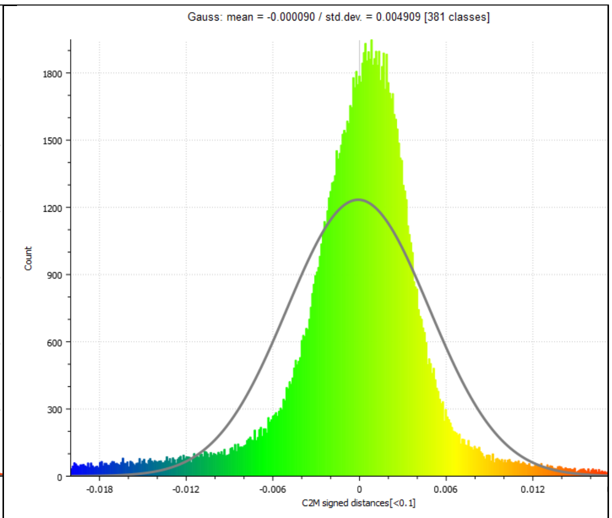
a. Agisoft Metashape



b. 3DF Zephyr



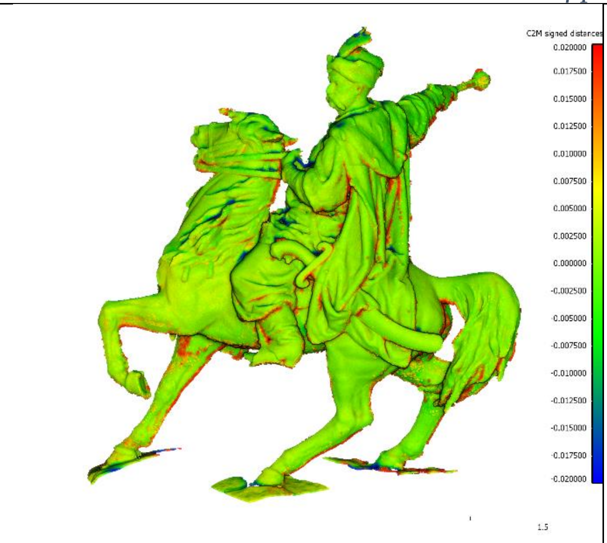
c. Reality Capture



d. Bentley ContextCapture

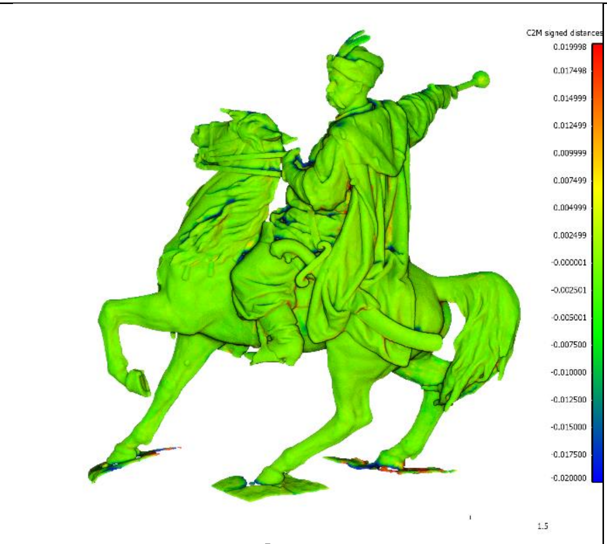
Colorizing the point cloud by deviation values (table 6) shows the presence of many uncertain points on the edges in Metashape point cloud (table 6.a), whereas in other software (6.b, 6.c, 6.d) those points are filtered and deviations are more smooth.

Table 6. Visualization of point clouds deviations from laser scanning data

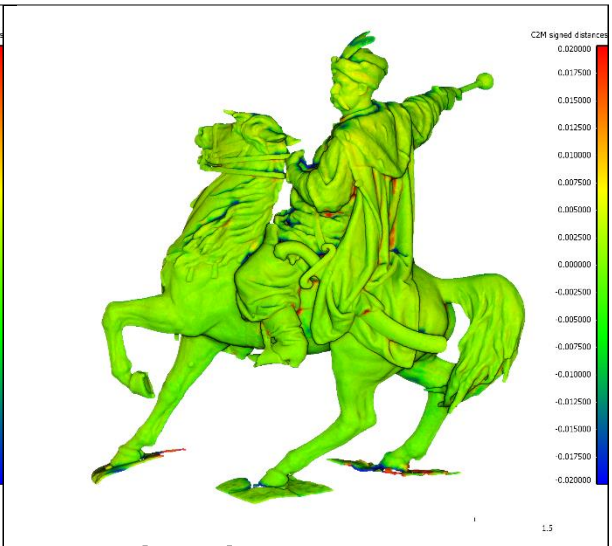


a. Agisoft Metashape

b. 3DF Zephyr



c. Reality Capture



d. Bentley ContextCapture

As a further step generated mesh models were compared (table 7).

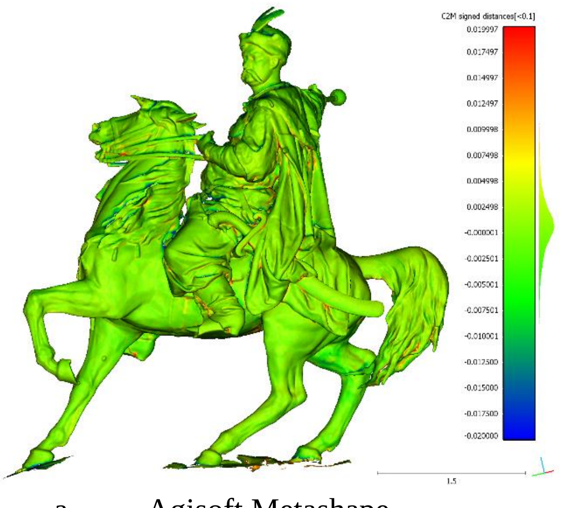
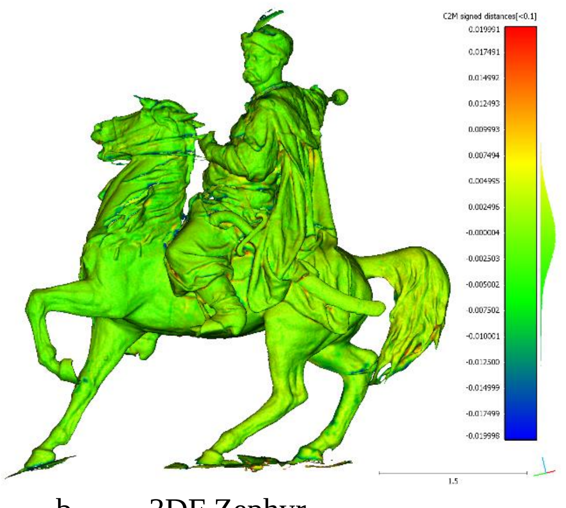
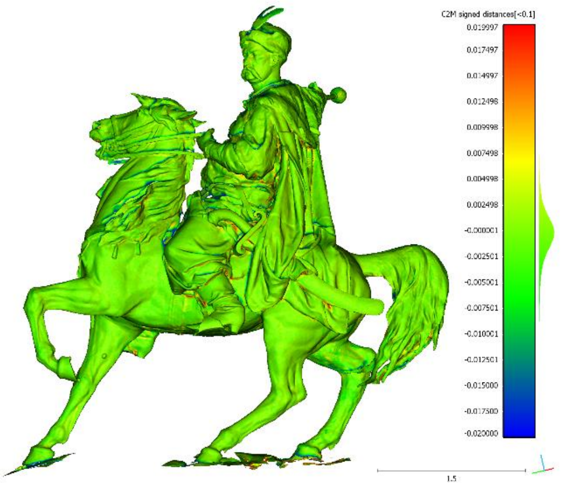
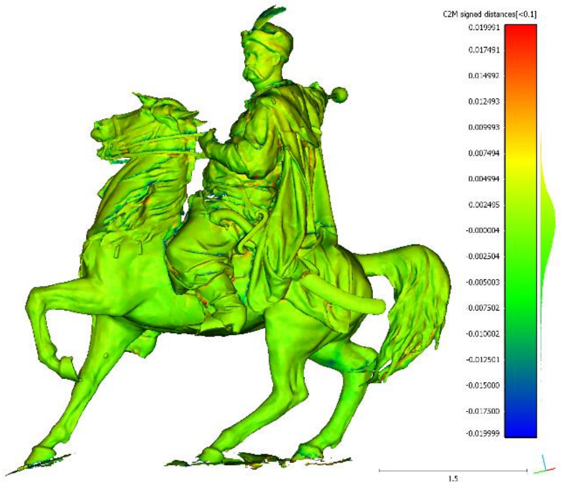
Table 7. Comparison of mesh gereration results

Software	**Number of triangles**	**Average deviation from reference, mm**	**Mesh generation time, hours**
Agisoft Metashape	580104	4,6	0:38
3DF Zephyr	477260	4,7	0:58
RealityCapture	3574791	4,2	0:24
Bentley ContextCapture	300629	4,4	1:33

Again, similar settings were selected for mesh processing. But in case of mesh generation Agisoft Metashape, 3DF Zephyr and Bentley ContextCapture have generated mesh model with similar number of triangles, whereas RealityCapture have created 7x bigger mesh.

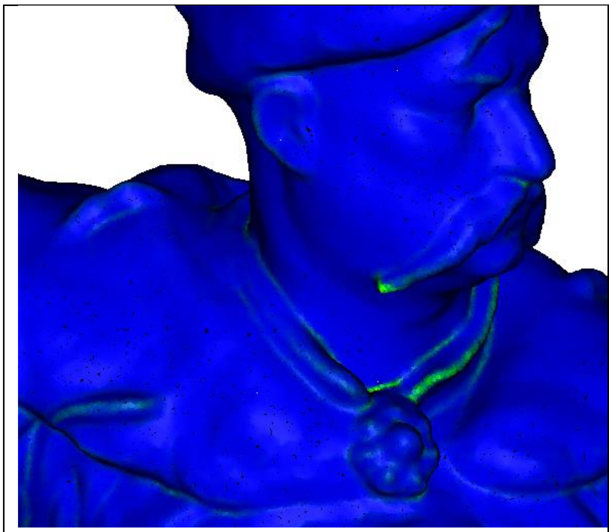
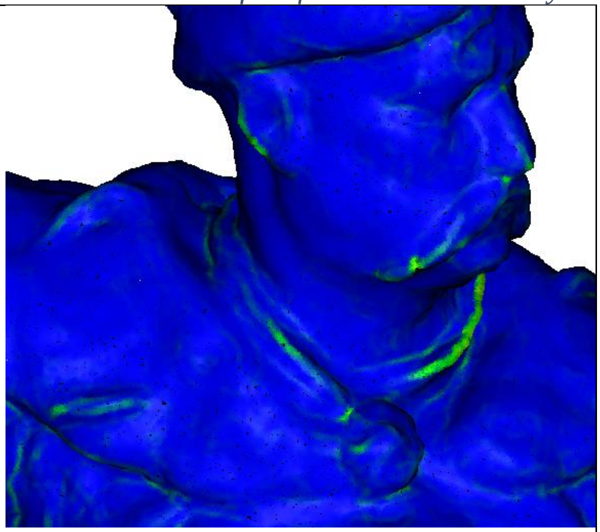
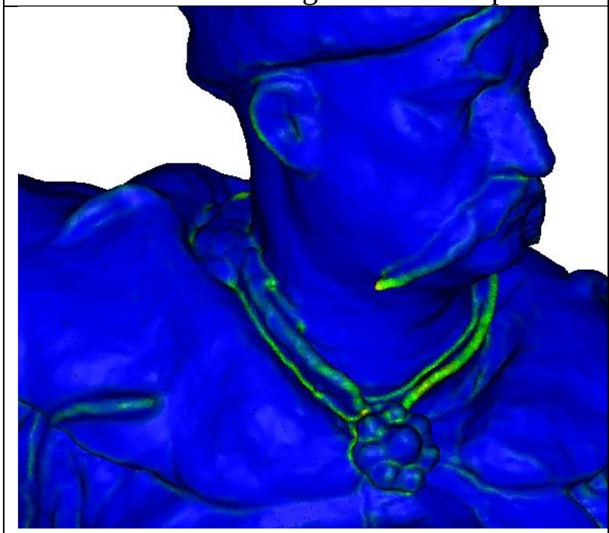
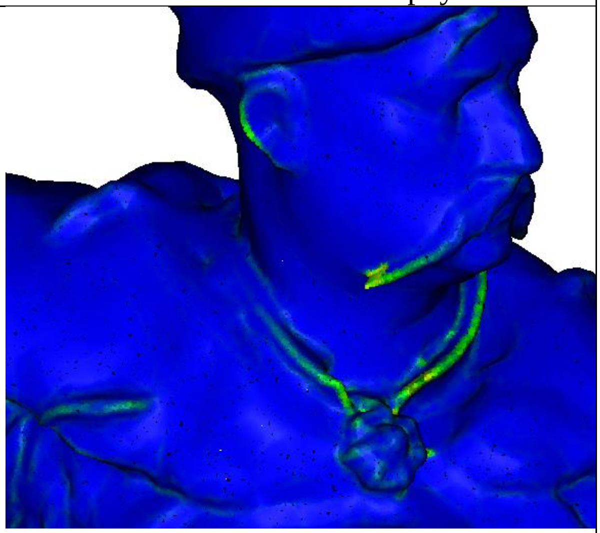
Comparison of the mesh models with the reference model (table 8) demonstrates very close results – around 4.5 mm for all software. Also, uncertainty points in Metashape were filtered in the mehs model.

Table 8. Visualization of mesh deviations from laser scanning data

 a. Agisoft Metashape	 b. 3DF Zephyr
 c. Reality Capture	 d. Bentley ContextCapture

Further analysis of surface curvature was made to check how the software deals with small details. Table 9 represents results of surface curvature analysis, which highlights the areas with rapid changes of normal directions. While Agisoft Metashape and Bentley ContextCapture demonstrate similar average results, 3DF Zephyr has significant loss in details and the edges are smoothed. However, RealityCapture shows very high level of detail and very sharp and thin edges of the model.

Table 9. Results of surface curvature analysis

	
a. Agisoft Metashape	b. 3DF Zephyr
	
c. Reality Capture	d. Bentley ContextCapture

6.CONCLUSIONS.

Analysis of the comparison of points and mesh models generated in different software tools with the standard shows that using the same approach, all tested software tools show almost identical results. It is worth to mention, that algorithms of image alignment and model reconstruction in RealityCapture works much faster than in competitors. But besides the raw processing time at the alignment stage, marking of control points is done manually and it is the most time-consuming process made by operator. 3DF Zephyr software provides the most comfortable interface for operating with the control points, which allows to reduce the time for placing of CPs by 2-3 times, comparing to the competitors.

Development of the software shows continuous improvements in mesh-modelling algorithms, providing results with same or higher quality than point clouds, and with faster processing speed. Therefore it is recommended to switch to mesh-modelling instead of point cloud generation for 3D-modelling purposes.

Also, the evaluation of the effectiveness of any software should consider the required capacity of the hardware. Most of the photogrammetric software is able to consume all available resources during the model reconstruction. But optimization of the resources is very important for quick processing. While RealityCapture provides nearly twice faster processing speed than Agisoft Metashape, 3DF Zephyr is almost 3 times slower than Agisoft while consuming same resources. And ContextCapture was not able to process the complete model due to RAM shortage, so it was divided into parts.

Considering the necessity of obtaining maximum level of detail in modelling of sculptural objects of cultural heritage, such as a monument to Bohdan Khmelnytsky, the ability of precise reconstruction with preservation of small details is very important. For these purposes RealityCapture demonstrates the best results.

Thus, the application of software for processing the results of photogrammetric surveys depends on the object of modeling, the available source data and the required end results.

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