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Photogrammetric 3D Scanning of Physical Objects: Tools and Workflow

Ivan Reljić, Ivan Dunđer, Sanja Seljan

Department of Information and Communication Sciences, Faculty of Humanities and Social Sciences, University of Zagreb, Ivana Lučića 3, 10000 Zagreb, Croatia

***Abstract* – Ease of access to and low cost of hardware and software for 3D scanning have made 3D technologies increasingly popular in recent research. One of the possible 3D scanning approaches is photogrammetry which relies on using a data set consisting of photographs of the same physical object. In this paper are evaluated different 3D models generated from the same input data set by specialised software packages for photogrammetry. The main attributes of the 3D models are examined in comparative analyses and their differences highlighted. Furthermore, visual qualitative inspections are performed on the models and the results are compared.**

***Keywords* – photogrammetry, 3D scanning, virtual 3D models, comparative analysis, information technology.**

1. Introduction

Factors like increasing availability and quality of digital cameras, progressively more computing power and a steady decrease in price of photogrammetry software, have led to a sudden expansion in popularity of photogrammetry as an approach for 3D scanning in many areas, especially in science. The purpose of this research paper is to provide comparative analyses of multiple photogrammetry reconstructions which were examined through selected software packages. All of them use photographs of the same physical object as the input data set and, as a result, generate a 3D model from that data. The idea was to propose a workflow which would be adequate for creating 3D models that could be used for different purposes. These 3D models could be utilised in virtual form for e.g. research, industry, ICT, cultural heritage preservation, tourism and marketing.

2. Related work

One evaluation [1] of multiple software packages for photogrammetry has been made using different objects in differing lighting conditions. The evaluation was both qualitative and quantitative. All of the resulting 3D models have been compared to a high-resolution 3D model created using a white light scanner.

A paper [2] assesses software packages in order to create a benchmark for precision of the software used. Reconstruction has been performed on different objects and under two lighting conditions (indoor and outdoor). Previously released data sets have been used in order to establish a ground truth. One of the sets has been used for reconstruction with 3D printing in mind.

Application of photogrammetry is shown in a paper [3] about 3D scanning of ceramic fragments. These scanned fragments were matched and reconstructed in virtual space to create the final 3D model. The acquired 3D data is expected to be applied in cultural heritage preservation. Negative space between the fragments was used to create a 3D model of a fragment holder for the ceramic pieces. The holder was 3D printed and physical fragments were assembled on it. Both the holder and the fragments were used for an exhibition in a museum.

An introduction to the photogrammetric process is given in a paper [4] by using examples of geomorphological structures in order to show that the basic principles of photogrammetry are the same even when presented with extremely vast difference in scale of the object. Different areas were scanned using a mobile phone camera and a digital camera,

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Corresponding author: Ivan Reljić,
Department of Information and Communication Sciences, Faculty of Humanities and Social Sciences, University of Zagreb, Zagreb, Croatia
Email: ireljic@gmail.com

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and then compared to results from a laser scanner. The results show that there was a comparable result even when using suboptimal equipment: mobile phone camera and online 3D scanning service (Autodesk 123D Catch, which is now discontinued) that automatically reduced the size of photographs to 3 MP.

One study [5] shows how small unmanned aerial systems (sUAS) in conjunction with photogrammetry can be used to create topographic 3D models, but also how the technology can be employed in hard-to-reach areas. The results demonstrate that high-quality data can be produced without using expensive equipment even in an area such as topographic mapping.

Another research [6] compares the quality of photogrammetrically acquired 3D data versus traditionally acquired 3D data when quantifying fluvial topography (river beds). While dry river beds and submerged ones are measured using different technologies, using rotary-winged unmanned aerial systems (drones) along with photogrammetry can produce high-quality results while simplifying the whole process.

For the purpose of forensic facial reconstruction (FFR) the authors used completely open-source software to 3D scan a skull using photogrammetry and compared the results to a laser scan of the same skull [7]. Results show that even when using open-source software, which may be considered sub-par by some, compared to a specialised scanner the difference in 3D scans is close to 0 mm in an overwhelmingly large area of the skull.

3. Research

This section will discuss the utilised equipment in this experiment and the research methodology in each subsection. The first subsection details the technical characteristics of the applied technology, whereas the second subsection covers the use of photogrammetry as the chosen 3D scanning method which is followed by comparative analyses of the selected 3D scanning software packages.

3.1. Equipment in the experiment

In this experiment the authors chose to use a mobile phone camera for taking the photographs of the physical object with the following technical specifications: camera with 16 MP resolution, 2.2 aperture, focal length 31 mm, sensor size 1/2.6", pixel size 1.12 µm.

The hardware used for running the reconstruction algorithms is as follows: 4.2 GHz quad core processor, 16 GB of DDR4 RAM, graphics card with 4 GB of VRAM.

Photogrammetry software packages that were used for the reconstruction of the 3D object are: Agisoft Photoscan (now available as Agisoft Metashape), CapturingReality RealityCapture, 3DFLOW 3DF Zephyr, AliceVision Meshroom:

- "Agisoft Metashape is a stand-alone software product that performs photogrammetric processing of digital images and generates 3D spatial data to be used in GIS applications, cultural heritage documentation, and visual effects production as well as for indirect measurements of objects of various scales" [8],
- "RealityCapture is a state-of-the-art all-in-one photogrammetry software solution which automatically extracts […] accurate 3D models from a set of ordinary images and/or laser-scans" [9],
- 3DF Zephyr allows automatic and easy reconstruction of 3D models from photos [10],
- Meshroom integrates the whole photogrammetric pipeline. Based on images, it will generate a textured mesh automatically [11].

All of the chosen software packages except Meshroom are proprietary while Meshroom is open-source. The aforementioned photogrammetry software packages were chosen arbitrarily by the authors.

3.2. Research methodology

Non-contact passive method of acquiring 3D data, also known as photogrammetry, is used in this research. It relies on multiple photographs taken from different positions around the physical object and processes them in specialised software to create a virtual 3D model of that object [12]. The data set of photographs is taken from an earlier research, i.e. 199 photographs taken during sunset on a clear day which influenced the quality of the reconstruction. All of the photographs met the required criteria for photogrammetry, such as good focus, low noise, good overlap etc.

Four software packages have been used for the 3D model reconstruction in this research. All of the software packages that use photogrammetry as the method for obtaining 3D models from photographs use a similar approach to create the final model: loading photographs into the software, matching photographs for similarities and angular offset, reconstructing camera positions in space, reconstructing positions of points matched from different camera angles (point cloud), reconstructing a dense point cloud, creating a 3D mesh from the dense point cloud, creating a coloured texture for the mesh, exporting the final 3D model (mesh and texture together) [13]. The term "mesh" refers to a 3D model without texture.

There are some differences between the selected software packages in regards to the amount of control over certain steps in the process, and most obviously in the user interfaces. Three of the used packages require multiple steps before creating the final model, whereas only Meshroom has a single-step solution for the whole process. The most notable difference when it comes to the 3D reconstruction is that one of the algorithms used prefers high-quality input and gives high-quality output in return, in this case RealityCapture, but it has issues with images of lesser quality. On the other hand, Photoscan works with input of lesser quality but manages to fully recreate a 3D model even though it cannot produce the same final resolution [1].

All of the used software packages can create 3D models in different quality levels of both the mesh and texture (e.g. low, medium and high). Even though mesh and texture combined provide the final quality of the 3D model, quality of the texture has a much larger impact on the perceived quality of the 3D model. It is better to have a 3D model with a high-quality texture regardless of the mesh quality than the other way around. Also, the processing time for the reconstruction of the mesh is much greater than the processing time for the texture. That difference is even more obvious when reconstructing in higher quality levels. The same logic is applied to file sizes as well. For the resolution in this research, in regards to the processing time and file size, medium mesh resolution and medium texture resolution were chosen.

Once the 3D models were reconstructed in all of the software packages, comparative analyses were carried out in regard to the main attributes of the 3D models which were followed by a thorough visual inspection performed by an expert in the field.

4. Results and discussion

A comparative analysis is made of the following: medium resolution of the model (i.e. mesh), model file size, processing time for the model, processing time for the medium resolution of the applied texture and texture file size.

Table 1. Main attributes of the 3D model reconstruction phase

	Photoscan	**RealityCapture**	**3DF Zephyr**	**Meshroom**
Model resolution in medium quality (point number)	803,647	**10,453,031**	**420,856**	1,316,766
Model file size (MB)	**36.9**	**2277.11**	81.2	N/A*
Camera matching time (seconds)	245	147	569	28826***
Dense point cloud generation time (seconds)	12028	2897**	780	
Mesh reconstruction time (seconds)	440		859	
Texture creation time in 8K medium quality resolution (seconds)	181	517	199	
Total 3D model reconstruction time (seconds)	12894	3561	**2407**	**28826**
Texture file size (MB)	**8.47**	8.95	**9.68**	N/A*

Note:
* N/A: Meshroom was unable to reconstruct a working 3D model.
** both steps were processed at the same time
*** all the steps were processed at the same time

The largest number of points was achieved in RealityCapture (almost 10.5 million), whereas 3DF Zephyr had the lowest count (surprisingly cca. 25 times less). This huge difference in number of points was unexpected as they both used the same data set. The authors suspect that the reason for this might arise from the inner-workings of the proprietary algorithms. RealityCapture with default settings extracts far more points regardless of the input data set, but a larger point number does not necessarily guarantee higher quality of the 3D model. It has been shown that RealityCapture tends to produce highest quality 3D models only when an optimal input data set is used [1]. Since this condition was not met in this experiment, RealityCapture generated a 3D model of a far lesser quality.

Large number of points results in a large model file size. This is evident from the fact that the model created in RealityCapture is almost 62 times larger than the one created in Photoscan even though the number of points in RealityCapture is only 13 times larger.

Total 3D model reconstruction time sums camera matching time, dense point cloud generation time, mesh reconstruction time and texture creation time in 8K medium quality resolution. Dense point cloud generation takes up most of the 3D model reconstruction time, and once this crucial step is finished both mesh and texture can be generated without redoing the dense point cloud generation step. Each of the subsequent steps adds to the total time. This leads to a more time-efficient reconstruction of 3D models with regard to the different quality levels of their mesh and texture.

Since all of the textures were exported in .JPG format with the same resolution (8K) there was only a slight difference in file size – all the files were around 9 MB.

Although Meshroom managed to reconstruct more than 1.3 million points in 8 hours of reconstruction time – which is much more than any of the total reconstruction times of the other software packages used in the experiment – it was excluded from any of the comparative analyses as it failed to reconstruct a working 3D model.

Hereafter, the reconstructed 3D models generated by each of the selected software packages (shown each time on the left side) is presented next to the matching photograph which was taken from the same viewing angle as the 3D model. The matching photograph was extracted from the original photograph data set which consisted of 199 photographs. It should also be noted that the lack of clear contrast in colour and form of the physical object affected the reconstruction of the surface of the 3D model which is the key qualitative characteristic of the visual inspection.

Figure 1. presents the result of the Photoscan 3D model reconstruction. In general, visual inspection shows that the form of the virtual 3D model reflects the original physical object to a large extent. Although slight surface noise can be observed, the model is of decent quality and the defects can be manually post-processed in a short amount of time.

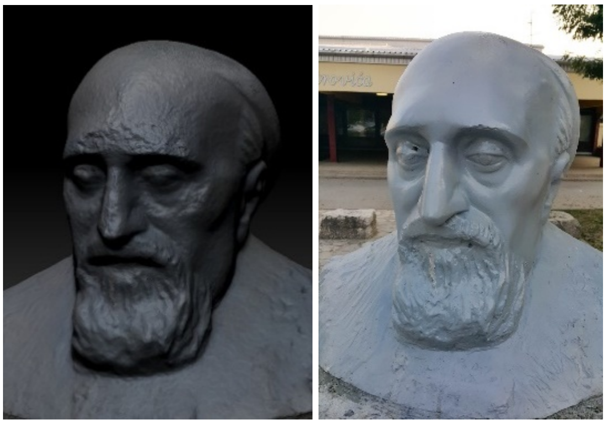

Figure 1. Photoscan results

Even though RealityCapture reconstructed the 3D model with millions of points using more than 2.2 gigabytes of data, the surface of the model is extremely noisy and does not reflect the smoothness of the physical object precisely (Figure 2.). Here it is once more confirmed that optimal data set is essential to RealityCapture. Also, it would take up a lot of post-processing time to correct the 3D model. All of this points to the conclusion that huge amounts of data do not imply a high quality of the 3D model.

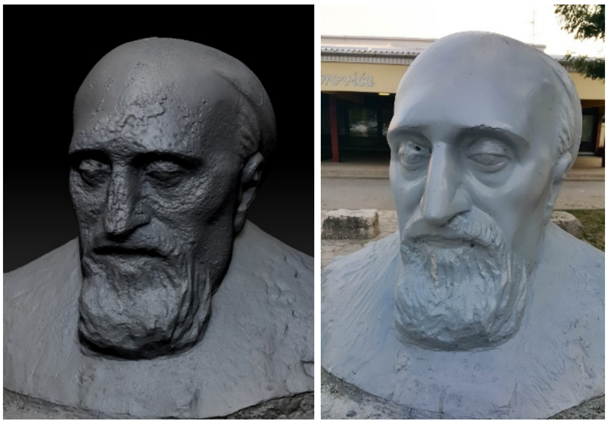

Figure 2. RealityCapture results

3DF Zephyr reconstructed the 3D model with the smallest number of points and took the lowest amount of time (around 40 minutes), but unfortunately this also led to a noticeable lack of surface details (see Figure 3.). The lack of details hinders post-processing significantly.

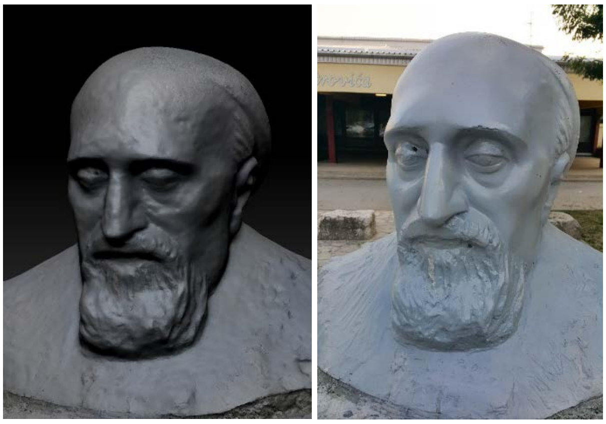

Figure 3. 3DF Zephyr results

The 3D model that was reconstructed with Meshroom was unusable, and the result was the same after multiple tries, as shown in Figure 4. Such a result was completely surprising and the reasons should be investigated in a separate deeper analysis.

Figure 4. Meshroom results

The only open-source solution used in this experiment failed to produce a working 3D model, hence only the proprietary software packages were taken into consideration for the visual inspection phase. Results of the visual inspection of the reconstructed models carried out by an expert in the field show that there is a clear difference in quality of the resulting scans. Lower quality directly impacts the usability of the 3D models which might also increase the amount of manual post-processing.

5. Plans for further research

Planned research will use the reconstructed 3D models for different purposes in multiple subject areas such as further scientific research, 3D printing, graphic design, cultural heritage preservation and tourism. Namely, when a 3D model is created it can be adapted for use in numerous real-world applications.

When it comes to scientific research, topics possibly include surface and volume analysis, stress simulations, prediction of deterioration over time, virtual 3D reconstruction by recreating missing parts or by putting broken fragments together (puzzle matching), simulating different materials etc.

3D printing uses the virtual 3D object to 3D print a physical copy. Since the size of the virtual 3D object can be changed at will, so can the 3D printing be done in different sizes which opens up many options for using such technology like printing keychains or copies in reduced size as souvenirs.

If the original object is in immediate danger whether from atmospheric impact or human interaction, it can be safely stored and a 3D-printed copy can be put into its place.

The final 3D model can be used for promotional purposes, such as being a subject in graphic design, which utilises the object for e.g. creating logotypes and posters.

Cultural institutions and tourism can adapt all of the aforementioned for different needs. Since the flexibility of using virtual 3D objects allows for easy manipulation of size and design, all the use cases do not have to be predicted beforehand. The data can be easily adapted at any point for a specific use. This lowers the amount of work needed at the time of creation of the 3D model.

6. Conclusion

3D technologies have a huge potential in science and other areas due to their flexibility, low cost, easily accessible hardware and availability of specialised software. Photogrammetry as one of the existing 3D scanning methods, also used in this research, is proving to be useful for many different purposes. Shown and described here are different 3D models generated by using four specialised software packages for photogrammetric 3D scanning. Afterwards, comparative analyses and visual inspections of the resulting 3D models were carried out. Out of the selected software packages, Photoscan and 3DF Zephyr have produced the best results with regard to the model resolution (point number), model file size (MB), total 3D model reconstruction time (seconds), texture file size (MB) and visual qualitative analysis performed by an expert in the field. Although the difference in results between Photoscan and 3DF Zephyr is small, Photoscan's 3D model had better surface detail. This is important since larger areas of the surface can be post-processed, but fine details are almost impossible to manually add in a precise manner, and hence Photoscan has shown to be overall the most versatile software package in this research.

Further research will move from the virtual realm into the physical one by using such 3D models for 3D printing.

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