Application of Photogrammetry in 3D Scanning of Physical Objects

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***Abstract* – This paper explains the 3D scanning procedure of creating a virtual 3D model from photographs by using a process called photogrammetry. It starts by giving a technical explanation of different technologies for 3D scanning, explains why photogrammetry was chosen and gives general specifications of hardware and software used in the process. The whole procedure is then thoroughly shown step by step on a physical object, and in the end an analysis of the generated 3D model and its variations is given.**

***Keywords* – 3D scanning, photogrammetry, 3D modelling, virtual 3D models, information technology**

1. Introduction

3D scanning is rapidly rising in popularity all over the world because it is becoming more accessible and, maybe even more importantly, easier to use for people who are not specialists. Since the cost of the equipment is dropping while the quality is increasing, it is becoming a technology of choice for documenting in many different areas, such as cultural heritage, archaeology, civil engineering, medicine, multimedia etc.

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This research aims to explain the process of creating a 3D scan from photographs in a concise way along with some of the issues that might arise and how to solve them.

This paper derives from a project aiming to connect Croatian culture, heritage and tourism through a process of digitisation. The first step of this project includes choosing an adequate physical object and digitising it.

The authors of this paper chose to digitise the bust of Ivan Meštrović. The physical object is located in Zagreb, Croatia and the author is Stipe Sikirica. It was installed in 1984.

Ivan Meštrović was chosen as he is one of the greatest Croatian artists, author of many works in well-known locations, such as:

- "Zdenac života" (eng. *The Well of Life*) from 1905, located in front of the Croatian National Theatre in Zagreb, Croatia;
- relief "Seljaci" (eng. *Peasants*) from 1907, which is overlooking the Ban Josip Jelačić square, the central square in Zagreb, Croatia;
- statue "Grgur Ninski" from 1929, in Split, Croatia;
- sculpture "Job" from 1945, which is located in Syracuse, New York, United States of America.

It is appropriate for a sculpture in his image to be carried over to a new visual medium, this time virtual. This is done as part of an ongoing project which aims to create an integrated process by which Croatian culture, artwork and heritage locations can be promoted, all by using new technologies.

The intention of the initial phase of the project is to create a virtual 3D model by utilising easily accessible technology (personal computers, mobile phone cameras etc.), and assessing the effectiveness of such an approach.

2. Related work

One research presents different uses for photogrammetry for the purpose of conservation and study of heritage [1]. Three case studies with various purposes were used, their processes explained and results compared to each other.

Another research describes two approaches to creating a 3D model from photographs [2] for the purpose of cultural heritage documentation and analysis. The approaches are tested on two case studies and they are compared by using RMSE (*Root Mean Square Error*), which shows the difference of length between two points on photographs and the length of the same points on the 3D model.

An algorithm for reconstructing 3D structure from unordered photographs is presented in [3]. The theory of Structure-from-Motion (SfM) and its implementation is explained in detail along with a software implementation of the whole procedure named COLMAP.

One study highlights the potential of multi-image photogrammetry as a rapid survey tool and for community engagement [4]. It shows that the technology can be used with very limited budget both for the survey part and for the post-processing of the data while also maintaining a short time frame.

A qualitative and quantitative assessment has shown that low-cost photogrammetry can be used for documentation and preservation of historical and cultural heritage with a case study of a World War II fortification [5].

A qualitative and quantitative comparison between 3D scanning approaches has been made using a laser scanner and photogrammetry, in which a reference 3D model is created using a 3D scanner and then compared to a 3D model created from photographs of the object [6].

According to [7], a methodology to collect 3D data of objects with complex geometry through a case study of a church was presented. The proposed process clearly shows that using readily available equipment can match expensive specialised equipment, and, in some cases, even outperform it, e.g. when reaching inaccessible areas.

3. Different approaches to creating a 3D model

Different approaches to creating a 3D model out of physical objects are sorted by accuracy and presented hereafter.

3.1. Manual modelling

Refers to 3D modelling by hand in one of 3D modelling software packages [8]. If a physical object is being modelled, usually photographic references of the object are being used in the process. This approach is frequently used for objects that have been physically damaged and when there are not enough photographs for the automatic 3D reconstruction, such as in the case of Bamiyan Buddhas in Afghanistan, which were destroyed by dynamite in 2001 [9].

3.2. 3D scanning

There are a lot of technologies but the ones most used are contact 3D scanning, non-contact active and non-contact passive 3D imaging solutions [10]:

Contact: for scanning of small and simple objects (e.g. coins). The scan is created by using a thin probe which touches the physical object in many predefined positions. The resulting 3D model is a set of virtual points in the same positions where the probe touched the object.

Non-contact active: devices emit light and measure the time needed to get back to the device, and in that way, they reconstruct the distance from the scanner for all the points on the object. This group consists of laser scanners, LiDAR (*Light Detection And Ranging*) and structured light scanners. Such devices are quite expensive but precise. Their downside is that, when scanning larger objects that cannot be rotated on a turntable (like e.g. monuments), the devices have to be carried to different locations around the object which is time-consuming and physically exerting. In cramped spaces sometimes even that is not possible.

Non-contact passive: devices that receive light (such as photo and video cameras) reconstruct a 3D object by using the photographs made from different angles around that object. This approach is the simplest to use, but it depends on multiple factors: quality of their sensor, lighting conditions, a large number of photographs is required, operator experience, software tools that can convert photographs to 3D models etc. Such devices are very mobile so they can be used in different conditions like scanning from the air or for underwater scanning. This approach also includes photogrammetry [11]. Photogrammetry is the science of obtaining reliable information about the properties of surfaces and objects without physical contact with the objects, and of measuring and interpreting this information [12].

Oftentimes it is possible to find specific 3D models on the internet. Such models have been modelled either by hand or through 3D scanning. Available models on the internet, that are similar to a new 3D modelling task, can sometimes be adjusted to fit the requirements of a particular project in order to save time.

4. Research

This research will be discussed in detail in the following subsections.

4.1. Technology employed

For the purposes of this research the photogrammetry method of 3D scanning was used. Such a procedure is simple, does not require specialised technical equipment and the fieldwork, i.e. photographing the object, can be done in a reasonable amount of time by an experienced operator.

4.2. Technical data

In this experiment a mobile phone camera with the following technical specifications was used for photographing the bust of Ivan Meštrović in Zagreb, Croatia: 16 MP resolution, 2.2 aperture, focal length 31 mm, sensor size 1/2.6", pixel size 1,12 µm.

The total number of photographs taken was 199. As for the lighting conditions, the object was in shadow during sunset.

The statue is composed of a bronze bust on a stone pedestal. The whole size of the statue is approximately 108 cm W x 203 cm H x 80 cm L. The bust itself is 82 cm W x 61 cm H x 52 cm L.

For the reconstruction process of creating a 3D model from photographs, a specialised proprietary software was used called Agisoft PhotoScan (now Agisoft Metashape): "Agisoft PhotoScan 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." [13].

The computer used for the reconstruction has the following specifications: 4,2 GHz quad core processor, 16 GB of DDR4 RAM, graphics card with 4 GB of VRAM.

When it comes to location, the bust of Ivan Meštrović is in a place which has no physical obstructions in the vicinity, which means a 3D model viewable from all sides could be created. Also, it was close to the operator so any kind of potential changes and reworks were not a problem.

As for the physical characteristics, the total height of the statue is such that the operator could access the whole surface without using any kind of technical tools (e.g. tripod, monopod, ladder and such), which significantly decreased the time required for this phase of the project.

In terms of appearance, the surface of the selected bust is of low visual frequency, i.e. smooth, so there was a lesser probability of visual artefacts (error in the calculation and display of the surface). Although the monotony of a surface makes the reconstruction harder, as the 3D modelling software has problems differentiating points on the surface [14], in this particular case, there was enough diversity to successfully perform the reconstruction.

In the case of lighting conditions, the photographs were created in November 2018, in the afternoon, when there was no direct light which creates shadows, but there was still enough ambient light to acquire photographs of sufficient quality. The whole procedure of photographing was done during the weekend, because it is less probable that a random passer-by might appear on some of the photographs.

Any kind of change between photographs interferes with the matching algorithm which looks for similarities between photographs, so the appearance of a person, even in one of the photographs, negatively affects the algorithm. If that person appears on more than one photograph while moving around the object (i.e. appears to be in multiple locations on different photographs), it is possible that the process of 3D model reconstruction fails completely. In that case, photographs can be retouched in one of the specialised software applications to remove the person, but that is a time-consuming process and it still does not guarantee success. In this research, since the time of photographing was carefully chosen and the operator was paying attention to the surrounding area, there were no people appearing in the photographs.

Regarding the photograph selection and data set compilation, after the process of taking photographs, it is necessary to go through all of the photographs by hand, and to remove all the problematic ones which might negatively impact the reconstruction process.

Such procedure requires an experienced operator in order to minimise issues that might arise in the later part of the process. Not only should the operator know how to take good photographs and inspect them visually, but the same person should have a good knowledge of the whole reconstruction process in order to recognise visual cues that could impact the quality of the final 3D model.

4.3. Process and methods of photographing

The most important element of the photogrammetric process is to get as much coverage of the object as possible. It is not enough to get the whole object on a minimum number of photographs – a lot of attention must be put into getting a lot of overlap between photographs [15].

The algorithm that reconstructs the form of the physical object compares photographs of the object and puts them into pairs, so a bigger overlap allows the algorithm to compute a larger number of shared points from which it creates a model later on [15].

A larger overlap also means that every point on the object is visible from multiple photographs, so if one point is visible on at least three photographs, that point can be precisely triangulated in three-dimensional space [15]. Such photographs were taken for this research as well.

Another important element is the camera's resolution as the number of pixels has a direct impact on the number of points the algorithm can analyse, and, by that, it affects the final resolution of the 3D model [15]. The camera used in this research has 16 MP and, as such, has more than sufficient resolution for a texture that satisfies the needs of this experiment.

Alongside having the resolution impact the model's point density, the quality of the texture is also a result of the same photographs [16].

Certainly, the number of pixels on a photograph is not necessarily a measure of a photograph's quality. It is better to have pixels with good focus, i.e. a quality lens and sensor of the camera that create the least amount of noise [17]. It is better to have less pixels of high quality than a large number of low-quality pixels. A large number of low-quality pixels implicates longer processing time to recreate a 3D model that will, eventually, have worse surface quality and a bad texture [17].

Besides the coverage from photographs and their resolution, lighting of the object is also of great importance [18]. As the complexity of colours makes it easier to find shared points, so do the shadows on the object help with reconstructing the form of the object. Having too many shadows is bad, because they have a negative influence on the reconstruction of both form and texture [19].

In controlled conditions there are ways to completely remove shadows while also having a good reconstruction of the 3D model and texture. That is achieved by a combination of well-placed lights, a ring flash and using a polarisation filter which filters reflections from the object [20]. In outdoor conditions it is optimal to take photographs in the middle of a cloudy summer day, because there is a lot of ambient light colours and details are showing up on the object without having shadows.

For a simple reconstruction process, it is preferable to have the whole object on all of the photographs, although this is not necessary. In this way the algorithm easily recognises all the locations of points on the object, and can use the silhouette of the object to further simplify the process.

The best overlap of photographs is when they have a radial offset of 10 to 30 degrees, while the maximum offset is 5 to 45 degrees [15]. When the offset is larger than 30 degrees, there is not enough overlap and the 3D model will be reconstructed with holes (missing parts) or it might not be reconstructed at all [15]. With offset of less than 10 degrees, there is a lot of redundancy between photographs which greatly increases the required time for reconstruction without actually increasing the quality of the 3D model [15].

The position of the camera is easy to control if there is always an equal distance from the object and the camera is always at the same height level. After one circle around the object, the height at which the camera is held changes and another circle of photographs is made around the object.

It is important to tilt the camera towards the previous circle of photographs so they would all be radially offset vertically as well. If the circular sets of photographs are always facing the horizon (cylindrical camera positions), it is possible to have bad overlap. With photographs that have both horizontal and vertical offset, the overlap will be the best, and so the 3D model will be of a lot higher quality.

In summary, this research satisfied all of the conditions:

- the photographs had good focus;
- noise present in the photographs was in low amounts due to favourable lighting;
- there was no discrepancy of the surface colour of the physical object due to absence of cast shadow;
- the object had low amounts of cast shadows which improved the texture quality;
- more than sufficient overlap between photographs was present;
- camera positioning was hemispherical in regards to the centre of the object.

5. Selection of photographs and preparation of the 3D modelling data set

When using a camera with autofocus, it is common that some of the photographs come out blurred. Such photographs do not contribute to the process of reconstructing the 3D model, because the exact location of points on the model cannot be extracted from these photographs.

Furthermore, at the same time such photographs affect the quality of the texture as well. Although blurred photographs do not help with reconstruction of the model, if put into the same reconstruction data set with other photographs, they will also be included in the reconstruction process.

Therefore, it is important that even before the reconstruction process starts, the operator goes through all the photographs and leaves out the ones that are blurred.

With partially blurred photographs, the problem gets bigger the closer the blur is to the centre of the photograph. In underwater photogrammetry, all the photographs have blurring on the outer sides due to the properties of light passing underwater, but it is possible to create a 3D model if the central area of all the photographs is of adequate quality [21].

When the operator identifies a bad photograph, there are several steps he can take:

- remove the photograph from the reconstruction data set;
- make a new photograph of the object from the same angle as the original photograph;
- leave the photograph in the data set and try to reconstruct a 3D model despite the possibility that a part of the model does not get reconstructed.

All of these approaches have some negative consequences for the whole project. Since this research had favourable conditions in regards to the location of the object, complexity of the objects form, ambient lighting, obstructions, operator experience etc., there were no such photographs that would require any of the aforementioned procedures.

Removing the photograph from the reconstruction data set usually means that this particular part of the surface is not covered on at least three photographs.

That can be avoided by creating enough redundancy during the process of taking photographs of the object. When creating redundancy for only one photograph, if the maximum radial offset between two photographs is 30 degrees, that means that every photo should have a maximum of 15 degrees offset from the previous photograph. If there is a need for redundancy of two photographs in a row, the maximum offset would be 10 degrees. In this research, due to a relatively low number of photographs required, it was simple to add more photographs so the radial offset was around 8 degrees.

Whenever possible, it is best to create a new photograph instead of leaving the blurred one in the data set, but for different reasons that is not possible in many situations:

- the object is physically far away from the operator so retaking the photographs creates unforeseen costs in time and finances;
- a lot of heritage objects, especially ones being scanned due to danger of deterioration, require complicated procedures to obtain a permit for accessing the artefacts, and even then there is a limited timeframe in which access is granted, so if time runs out, the whole procedure has to be repeated anew;
- quality equipment is often being rented for a specific project in order to cut expenses, and it would have to be rented again just for a few photographs;
- weather conditions may change in the meantime: object might be covered in snow, there is a long rain period, weather changes from cloudy to sunny and vice versa, so new photographs do not match the old ones etc.;
- the object gets damaged or even completely destroyed, whether by natural occurrences or intentionally;
- politics and law might change making the physical object inaccessible.

In cases when blurring of photographs is of lesser intensity or on certain parts of object, one could try to leave the photograph in the data set and run the reconstruction with such inferior data, because even a lesser surface quality of the 3D model and texture looks better to the end user than completely missing parts of the 3D model.

This research had no blurred photographs so the issues mentioned were avoided.

Holes in the model should always be avoided if possible, as they break the illusion of realism of the 3D model.

A completely described 3D model looks like it is solid on the inside, but a model with holes shows the user that it is actually empty, and therefore a person will find it hard to enjoy the view. Moreover, the person might start to think about the technology instead of the content.

If the operator wishes to cap the holes, he would have to recreate the surface by hand and then project that part of the texture from surrounding photographs. This is quite labour-intensive and at the same time imprecise, so for some purposes that model becomes unusable. Holes in the 3D model are sometimes impossible to avoid due to the nature of the physical objects, in which case the models are not shown from those sides, but just the visible ones. Those types of objects include: statues and busts on a fixed base, buildings, carved rock, geographical locations etc. The 3D model created during this research had no holes in it except for the one on the bottom (the ground on which the statue stands) and, as such, it could not have been avoided.

Besides autofocus, cameras oftentimes have automatic exposition which can lead to colour discrepancy. In regards to the light source, one part of the model is more exposed to light than the other. When changing the light source is not an option, like it is with sunlight, the camera’s white balance should be set up. If the camera does not have that option, some of the photographs will be light and the others dark. The camera used in this research does not have auto white balance (AWB), therefore there were some discrepancies between photographs. When photographs of the same object have different exposure values, exposition should be manually changed afterwards. All the photographs were loaded into a software for editing photographs where all the expositions were normalised using a semi-automatic procedure: a middle value of exposition was extracted and the photographs with noticeable expositions were then adjusted to that middle value.

Differing lighting creates problems for the reconstruction algorithm, because it uses shadows as a reference for generating surface detail of the object, which means that differently coloured shadows on the object can lead to imprecise reconstruction of form. Because there was enough ambient light and the exposure was manually normalised, the shadows were even and, as such, did not create any issues during the reconstruction phase.

A 3D model reconstructed from differently lit photographs, apart from surface irregularities, will also have differently coloured texture. Such 3D model will then look like it has a part of its surface in shadow. This was avoided in this research by carefully choosing the time of day when to take photographs and manually correcting some of them in the software for editing photographs before starting the reconstruction.

If the virtual lighting of the 3D model, i.e. light source vector, does not match real lighting on the photographs, the 3D model will look like it has shadows in different directions, and that is something a user, unfamiliar with how this technology works, cannot understand, and the 3D model will look completely unnatural (even if he is not able to explain why) [15]. Since the object in this research was photographed with no direct sunlight on it and the photographs were manually edited in a software for editing photographs, the 3D model did not have visible shadows in the texture so it can be used with any kind of virtual lighting.

5.1. Analysis of the object selection process

When using photogrammetry, all the photographs which meet the following criteria should be discarded:

- photographs which are out of focus: photographs should have the same depth of field;
- photographs with too much exposition: this “burns” the photograph and there is a loss of colour information;
- photographs which do not receive enough light: it is hard to differentiate what is shadow and what is the object;
- photographs that are redundant: photographs made from almost the exact angle, as that increases processing time without improving the quality of the 3D model.

Since this research used a relatively simple subject and had an experienced operator, there were no discarded photographs.

6. Adjustment of photographs

As far as the photograph adjustment process, photographs can sometimes have smaller imperfections that can be removed in any of the photo processing applications – lesser blur, noise that appears in low-light conditions, unbalanced exposition, rotation of the camera etc. But, in this research, the only thing that needed to be adjusted was the exposition difference between photographs, which was expected due to equipment used and the lighting in which the object was photographed.

The exposition was normalised across photographs in such a manner that overexposed photographs were slightly darkened, and underexposed photographs were slightly brightened, which, in the end, turned out to be beneficial to the quality of the texture of the 3D model.

7. Analysis of the 3D model creation process and discussion of the results

When it comes to the 3D model reconstruction, the whole data set consisting of 199 photographs was loaded into the selected specialised photogrammetry software application for 3D modelling.

Surface of the 3D model had a quality that can be used for different purposes, especially for online display which was one of the main purposes of the project. The quality of the texture was higher than needed but, since the images the texture was made from do not take up a lot of space for storage, they will be kept for future reference.

Qualitative analysis has shown that the described approach can provide data of higher quality than needed even when using non-specialised equipment for data acquisition and processing.

A model was reconstructed in different resolutions of the 3D model, and in different resolutions of the texture. All the variations of the same model are shown in Table 1.

The best result was achieved when all the photographs from this experiment were used and the 3D model was reconstructed in the highest quality with highest quality texture (size increase of ca. 242%), but in regards to the needs of the research versus processing time for the highest quality, that was not necessary.

Table 1. Variations of the reconstructed 3D model.

Model quality	**Model file size**	**Texture size**	**Total**	**Increase**
Medium + 4k texture	36,9 MB	2,92 MB	39,82 MB	Base model
Medium + 8k texture	36,9 MB	8,47 MB	45,37 MB	**13,94%**
Medium + 16k texture	36,9 MB	24,1 MB	61,00 MB	53,19%
High + 4k texture	112 MB	2,92 MB	114,92 MB	188,60%
High + 8k texture	112 MB	8,47 MB	120,47 MB	202,54%
High + 16k texture	112 MB	24,1 MB	136,1 MB	**241,79%**

The best ratio of reconstruction time and quality is when the whole set of photographs is used and the 3D model is reconstructed in medium quality with a texture in medium quality (size increase of ca. 14%). Such model requires less processing time and loads faster so it is easier to browse and edit collections of multiple models. They can also be uploaded faster to online services for displaying 3D models. For the same reason, they load faster on slower devices, such as mobile phones and tablets.

In this research, as the most suitable 3D model, the one with the best ratio of reconstruction time and quality was chosen (Medium + 8k texture). It has the following specifications:

- 3D model composed of 274.911 points (548.114 polygons);
- chosen file format: .OBJ;
- 3D model file size: 45,37 MB;
- texture with a resolution of 8K (8.000 x 8.000 pixels);
- single texture file in .JPG format;
- texture file size: 8,47 MB.

For the model and texture file, the formats that were chosen are .OBJ and .JPG because they are:

- industry standards;
- most widespread in the 3D scanning community and for general use;
- formats for storage, editing, viewing and displaying 3D models;
- cross-platform;
- for the stated reasons most suited for this project.

8. Conclusion

This research has shown a complete process of creating a virtual 3D model, from approaching the physical object to the final virtual 3D model. The assumption was successfully confirmed that even when using limited equipment (e.g. a mobile phone camera) a quality model can be created that is valuable for further use.

The obtained 3D model is split into information about the three-dimensional form of the object (virtual record of all the points in space) and information about the colour of the object (its texture).

Due to development of software tools and computer hardware, photogrammetry as a 3D scanning approach is becoming an increasingly useful tool in many areas in which it was not present until not long ago.

Through this research it was shown that many technologies that were restrictive until recently can be used now, with a greater focus on bringing cultural heritage to a larger audience.

This may, therefore, warrant future research on numerous aspects of 3D model generation and application. It should be investigated to what extent a 3D model without texture could be used in further analysis of the physical form of the object: e.g. for virtual simulations of other materials, for the reconstruction of damaged parts, for the simulation of deterioration and outside influence, for adding a different texture etc.

Moreover, more extensive comparative analyses of various 3D modelling software should be carried out in the future, in order to identify the necessary software prerequisites to create a 3D model with included texture that could be used for online display as a singular object or as a part of a larger virtual space alongside similar object (e.g. a virtual museum).

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