3D reconstruction of archaeological artefacts from 2-D X-ray images

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This paper describes an experiment regarding the efficiency of the 3D reconstruction from multiple angles 2D X-ray radiographs of cultural heritage artifacts of different volumes and complexities. The goal of the study was to try of reconstruct 3D models of the said artefacts without any set-up adjustment or complex targeting system. Using a fixed X-ray generator, the objects were rotated at different angles following photogrammetry rules of area overlapping in the recorded images. Method limitations and recommendations are explained and discussed based on the resulted 3D models.

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1. Introduction

Although today the first thought that comes to mind while talking about 3D radiographs is about computer tomography (CT), there is a cheaper alternative: X-ray (radiography) photogrammetry [1]. There are many studies and terminologies regarding this method, including stereo-photogrammetric roentgen study, radio-stereometry study or radiogrammetry [2]. According to these studies, accurate 3D models of an object can be obtained using the same principles as in photogrammetry.

The first studies regarding the application of photogrammetry methods on X-ray radiographs emerged during the 70's mostly in medical research (i.e. [3] and [4]), along with the development of computational machines that allowed a faster implementation of mathematical algorithms of analytical photogrammetry. Analytical photogrammetry is based on mathematical modelling and the relations between image points and scene points are described through numerical calculations based on the collinearity equations. At the time, photogrammetry was realized by instrumental means (analogue photogrammetry) which were subjected to the operators' skills. Theoretical and practical contributions of Dr. Hellmut Schimdt (1953) and Duane Brown (1963 onward) by implementing a series of devices that no longer needed highly-trained technicians to perform client-oriented measurements [5]. This was an important step, and opportunity, for experts from different fields of research to access this type of approach on their visual data.

Photogrammetry has been developed mostly in regard with applications in aerial survey and terrestrial civil engineering. Today, photogrammetry is applied in the most advanced research areas in almost every scientific domain from microscopy [6] to space exploration [7]. In the last decade, due to the technological advances and the transition to digital cameras, the applications of photogrammetry greatly expanded to the so-called non-topographic applications such as: high-precision industrial metrology [8], architectural photogrammetry [9, 10], medical imaging or forensic [11] and others. Although in close competition with laser scanning technologies, with the development of automatic block orientation and the improvements in image matching, digital image correlation and stereo correspondence problem in digital image processing (coming from computer vision area) photogrammetry established itself as "the most complete and flexible technique for collecting and archiving 3D information" [12]. Photogrammetry is now intertwined with the younger field Computer Vision in a wide area of advanced applications [13]. Optoelectronic systems are relying on using machine vision in industry automation or medicine.

In the light of current developments in digital photogrammetry that benefits from automated image alignment and point cloud generation, the question of using X-ray radiographs for three-dimensional reconstruction emerged. In this paper we are discussing the possibility of using current user-friendly photogrammetry methods for the 3D reconstruction of different types of artefacts from X-ray digital radiographs, without any prior calibration or special targeting system.

2. Methodology

2.1. About photogrammetry

An exhaustive definition of photogrammetry was given by the ASRPRS as "the art, science, and technology of obtaining reliable information about physical objects and environment through processes of recording, measuring and interpreting photographic images and patterns of recorded radiant electromagnetic energy and other phenomena” [14]. We will come back later about the latter part of the definition regarding the sources of the imaging that can be employed in photogrammetry.

The defining principle of photogrammetry is stereoscopic parallax. Parallax (παράλλαξις - Greek word parallaxis meaning: alteration) can be simply defined as the apparent displacement of an object caused by a change in the point of observation. The use of two images of the same object or scene from different points of observation results in stereoscopic parallax. The same phenomenon in our brain is responsible for our 3D sight.

Photogrammetry is a three-dimensional measurement technique, which uses central (or perspective) projection imaging as its fundamental mathematical model. The shape and the position of an object are determined by reconstructing bundles of rays in which, for each camera, each image points a-e, together with the corresponding perspective, center P defines the spatial direction of the ray to the corresponding points A-E. If the internal geometry of the camera and the location of the imaging system in the object space are known, then every image ray can be defined in 2D object space (A’-E’).

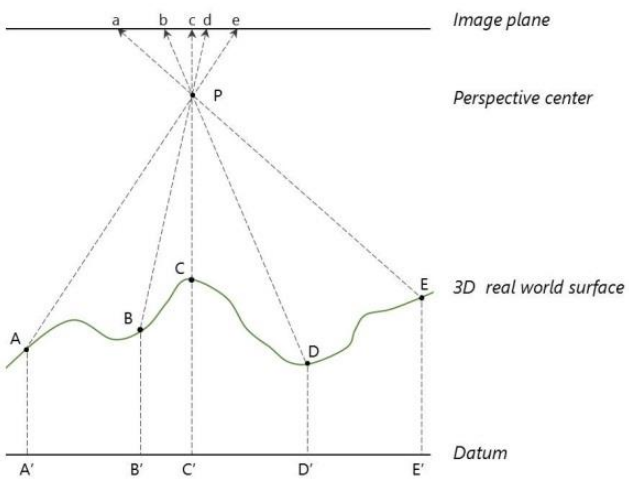


Fig. 1. Central projection model in photogrammetry

From the intersection of at least two corresponding image rays, an object point can be located in three dimensions. Stereo photogrammetry uses two images to achieve this, while multi image photogrammetry can use an unlimited number of images. Usually a single stereo pair will not provide the coverage necessary for a complete 3D reconstruction of the entire subject. Therefore, today larger sets of images are used and we are no longer constraint to parallel input images. Oblique and convergent images can be used as well, along with parallel ones with advantages in terms of a 100% overlap of images or minimizing the systematic errors caused by lens distortion [15].

2.2. About X-ray imaging

X-Rays are electromagnetic radiation much like the visible light or the radio waves, but with different properties: shorter wavelengths and higher energy. Due to their ability to penetrate differently diverse materials (or to be differently absorbed), X-rays are used in many non-destructive evaluation and testing applications (NDE/NDT). X-rays are generated in a direction toward a subject; it propagates through the target structure and it is captured by a detector (film or digital sensor). The internal features of the transited subject are displayed as shadows on the detector.

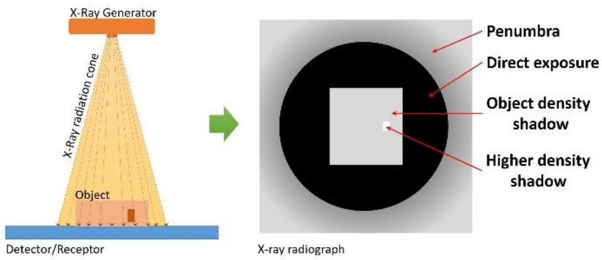


Fig. 2 X-ray image formation of complex objects

This non-destructive technique is extremely useful for cultural heritage sector. In art conservation, it can give important information to conservers, restorers or historians about the conservation issues of the object. Data that can be obtained with this technique include information about the composition and condition of painting canvases, panels [16] and wooden sculptures. It can also help the assessment of the location, extent and nature of damages such as internal cracks, tears, holes and even pest infestation traces.

X-rays also help archaeologists to view, without any physical intervention, forms and shapes of objects obscured beneath corrosion layers and burial accretions or determine thickness of materials with known chemical composition [17]. Also X-ray radiography may provide information necessary to identify, classify, date and illustrate an object that has been deteriorated beyond reconstruction [18].

2.3. X-ray photogrammetry

X-ray photogrammetry is not a new concept. Using the photogrammetry method to measure details or even reconstruct structures from radiography films has been tested decades ago, mostly in medicine field. Although today a Computer Tomography scan might seem the easiest and logical approach to obtain a full 3D representation of both interior and exterior of an object, this method is quite expensive. More than that there are several limitations, especially regarding artworks: it has a limited space for the artworks and is fixed – which means the artwork must be brought to the CT scan. X-ray generators are also expensive, but much cheaper in comparison to CT scan machines. Also performing the scans are cheaper. There are X-ray generators that are mobile, so they can be transported on site where fragile artefacts are stored/conserved. Therefore, the question whether X-ray radiographs can be used and processed in a user-friendly way is reasonable.

The main problem in applying photogrammetry principles to X-ray radiographs is the way the image is obtained. Modern digital photo-cameras makes it easy for photogrammetry algorithms to estimate interior and exterior parameters of the camera in order to generate a correct three-dimensional coordinate space. Older cameras or film cameras required camera calibration algorithms [19]. The digital scans of the X-ray radiographs are not calibrated to any coordinate system therefore most of the researches that have attempted to apply photogrammetry principles used the uncalibrated stereo image rectification method and the fundamental matrix. D. Talmage et. al. [20] built a special calibration frame that was placed around the subject during x-ray acquisition. The grid lines of the frame defined the coordinated system X, Y, Z to which the measurements were referenced.

Another characteristic of radiography images that poses problems to photogrammetric processing is the lack of texture and features. The image features are created by the more or less dense "shadows" cast by the material density of different compounds in the object structure in shades of white or black. Therefore, objects with large volumes of uniform density will appear with a uniform shade in the radiography image thus making it unusable for photogrammetry processing. In a recent study [21] is mentioned a different method to calibrate the measurements without using markers or other targets that are attached to the subject. This method uses for the first image acquisition a special calibration frame in the background of the subject. The X-ray generator has an RGB-D depth camera attached so that each acquired radiograph image is paired with a depth image. The subject is rotated allowing the acquisition of several images from different angles. 3D reconstruction was achieved with millimetric precision. Other studies are using premade 3D templates of the irradiated subject with a known structure (like femoral bone) and determine a new 3D model for the investigated object [22].

2.4. Data acquisition

Our experiment's goal was to use a simple workflow that could be easily repeated without extensive knowledge of advanced perspective geometry and stereo calibration. Simply put, we tried to apply a similar procedure to X-ray radiographs as we would with normal photography-based photogrammetry. For the purpose of the study we selected different types of art objects:

- Subject 1: disk shaped archaeological artefact
- Subject 2: rectangular archaeological artefact
- Subject 3: metal goblet
- Subject 4: decorated oriental ibrik/pitcher

The X-ray set-up consists of a fixed generator tube that is oriented vertically downwards at 90cm distance from the detector film. The irradiated objects are placed onto the film cassette with zero distance between them and the film. The generator is able to emit radiation between 20 and 160 kV for different exposure times, so it is versatile regarding the type of materials that can be studied. Because the generator tube position and direction is fixed the objects had to be rotated at different angles respecting photogrammetry rules regarding the overlapping areas in each of the acquired images.

The irradiation is realized on digital reusable films. The film is scanned with a resolution of 35μm per pixel. The images are saved as JPEG files at 5753×7222 pixels (about 41.5 megapixels). 3D reconstruction of the objects required the masking of the background areas and manual positioning of several alignment markers.

2.4.1. Subject 1

This is a bronze disk shaped object with four axis that meet in the middle. Its main characteristic is that it has a repaired part, a filling made from a resin. This characteristic was easily highlighted with x-ray imaging.

The acquisition strategy was based on the positioning of the object at three different angles (67˚, 46˚, 27˚) to the incident X-ray plane on the film while rotating it for exposures from different directions.

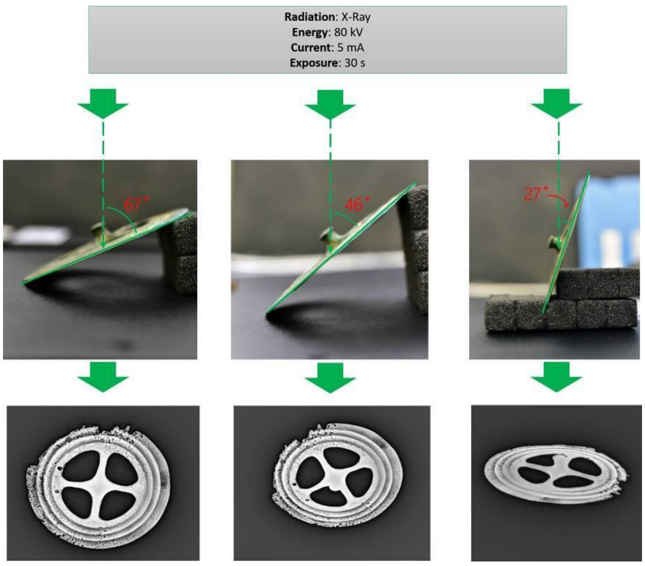
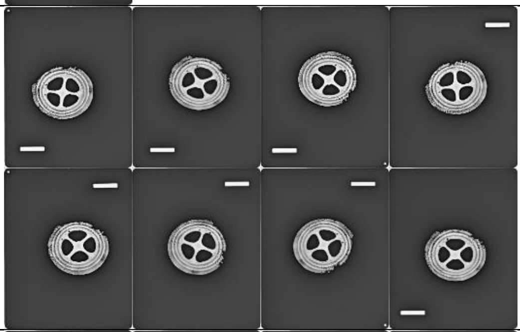
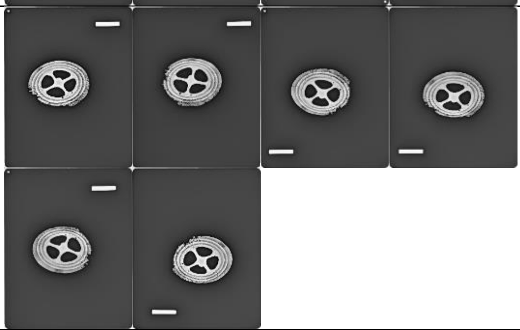
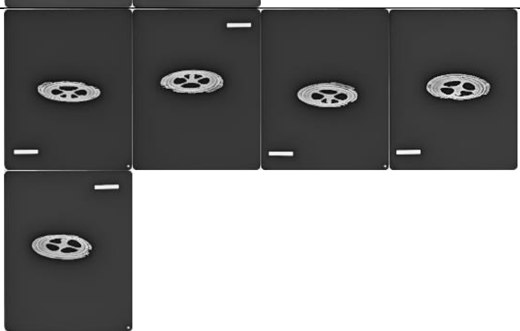


Fig. 3. Irradiation method from different angles of Subject 1

Table 1. Object 1 radiography set

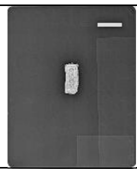
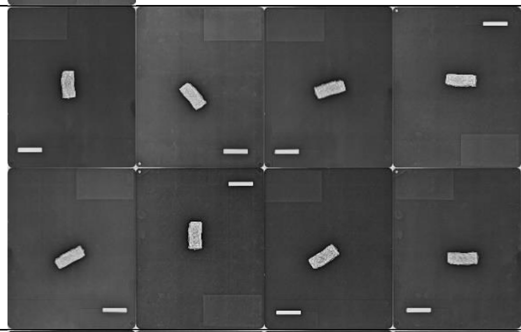
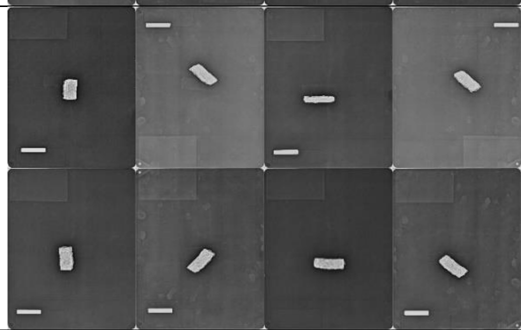
90°	
67°	
46°	
27°	
0°	

2.4.2. Subject 2

This small object is also flat but rectangular. What is special about this object is that it is partially embedded in a soil layer so it is not visible to the eye.

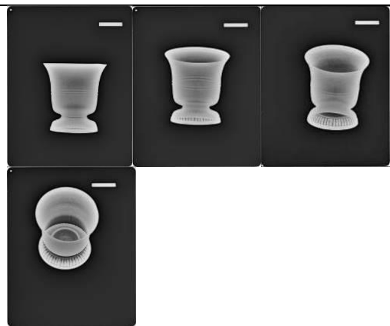
The radiographs were made at 90, 67, 41 and 10 degrees to the incident X-ray plane on the film.

Table 2. Object 2 radiography set

90°	
67°	
41°	
10°	

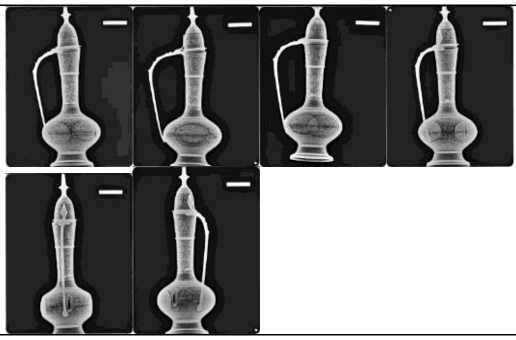
2.4.3. Subject 3

This object is a metal goblet with no decorations but some outlining near the top. Because of its shape and symmetry, the object was only rotated about a single axis within a 90˚ angle span.

Side	
Top	

2.4.4. Subject 4

This object is a decorative oriental metal ibrik (or pitcher). It was rotated about a single axis (perpendicular to the X-ray beam) over an 110˚ angle span. The detailed decoration and the distinct handle were thought to improve the image alignment process.

Side	

3. Data processing and results

The reconstruction stage was realized using a specialized photogrammetry software (Agisoft Photoscan). Like other similar software, this program is based on automatic point matching between images and has several steps of processing in order to generate a 3D reconstruction based on images: photo alignment, dense point cloud generation and 3D mesh generation. In the case of radiographs (a lot of background area and a scaling object) the images should be masked. This means that everything except the visible parts of the subject in the image are hidden under a special layer, called mask, that tells the software to ignore those parts of the image. This step improves processing speed and also helps the generation of an accurate model. Another helpful and optional step is to manually place alignment markers. These markers are actually manually set tie points (points that match in pair images).

3.1. Subject 1

Material characteristics (corroded and porous areas, cracks) helped the reconstruction algorithms to calculate the angles and cameras positions. The program matched 18 of the 21 images and the camera positions were correctly calculated. In the figure below "camera rotation" is marked with the red orbit lines to emphasize the plane for the recordings in each angle of irradiation.

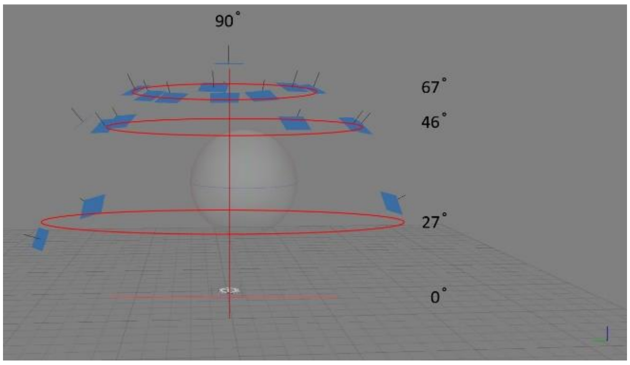


Fig. 4. Calculated camera positions for Subject 1, and rotation angles

Reconstruction processing took less than 25 minutes (only 18 images were usable for image association) and the final textured 3D model has 4 million polygons. The reconstructed model respects the shape of the object surface as it can be seen in the digital elevation model (DEM) image. The resin filling was not reconstructed because it was not recorded. The bump at the intersection of the four axes was also not reconstructed. One of the reasons might be that in all the radiographies the bump projection was overlapped with the rest of the object. Unlike photography where we can benefit from the parallax effect, in radiographies the projected images on the film are consisted by the amount of radiation that passes through the material. In this case the bump could not be differentiated from the rest of the object. The few images where it can be observed are those at 23˚. The processing algorithm only managed to generate a few points based on that data but that was not enough to reconstruct the shape of the bump.

Fig. 5. Renders of the resulted 3D model of Subject 1

In Fig. 5, one can see the final stage of the reconstructed model. The details of the surface can be better observed in the DEM image (Fig. 6 - warmer color corresponds to higher elevation). Areas where the metal is corroded, porous or of weaker quality, appears thinner in the model or is even absent.

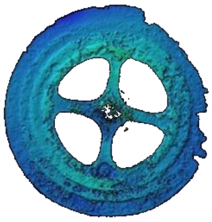


Fig. 6. Digital elevation model for 3D reconstruction of Subject 1

3.2. Subject 2

This object is considerably smaller but thanks to the great film resolution, the radiographs could be processed. The processing software matched for alignment 16 of the total 18 images. The total time of processing was less than 15 minutes. The reconstructed model counted less than 700.000 polygons.

Although the radiographs presented a textured and asymmetric surface, the processing software calculations detected the camera positions more or less in the same direction. In the figure below there are highlighted the calculated camera positions (with red) for the irradiating angles of 41 and 67 degrees. Their positions are mixed and not on two different planes on circular orbits as it was recorded. It seems that the texture of the object alone was insufficient for the software to correctly calculate the camera positions.

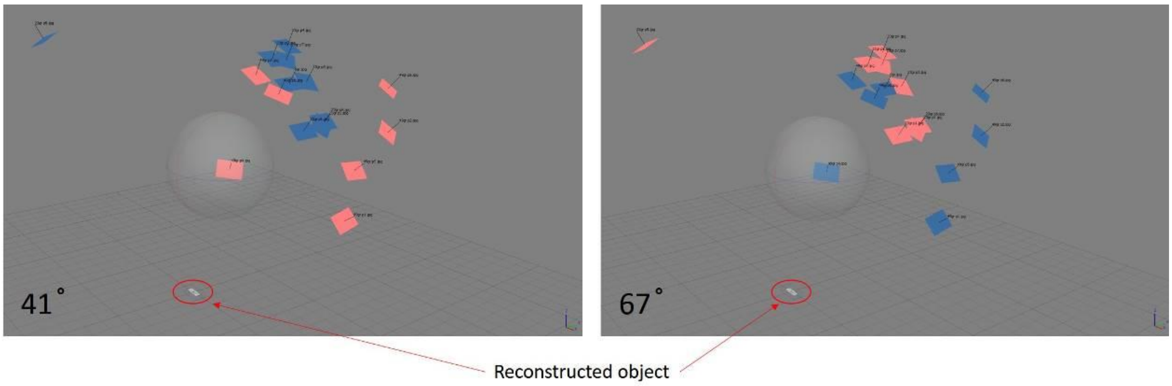


Fig. 7. Calculated camera positions of Subject 2

However, the object was still reconstructed as a planar object with the distinctive features visible only with the texture. The reconstructed mesh is a shell with no volume. The thickness of the object was partially reconstructed on one of the long sides as it can be observed in the digital elevation model in the figure below, but it cannot be used for any measurements.

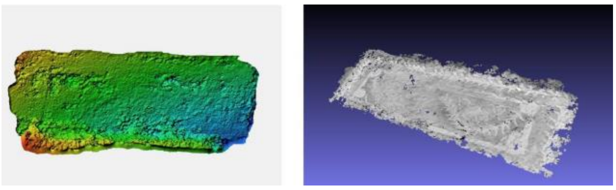


Fig. 8. Subject 2 reconstruction results; left: DEM, right: surface render

3.3. Subjects 3 and 4

Because of the shape and symmetry of these objects the number of working angles for X-ray radiography was severely limited. Rotating these objects over a wider angle span than 90˚ would have resulted in identical images. As a result, having only a few images to work with, the processing algorithms failed to align the images and no point cloud was generated.

4. Discussion and method limitations

Photogrammetry can be used for object 3D reconstruction using X-ray radiographs as its source. However, there are limitations in applying this method. The main limitation would be the fact that X-ray radiographs are similar with semi-transparent objects photogrammetry. X-ray imaging is relying on the X-ray propagation through the materials. A hollow object with thick walls will have its radiography image as a projection of all the irradiated volume components superimposed. This becomes an issue when the walls of the object do not have enough details or if the object shape does not allow for separate projections of its walls. This was the case with subjects 3 and 4: two hollow objects, with volumes that can be inscribed in a cylindrical shape.

In photogrammetry the transparency problem is solved with chalk spray, or paint, which makes the transparent materials opaque to the photo camera. In X-ray imaging this trick was approached differently. Using small, special targets – opaque to the X-ray – placed on the surface or even inside (where possible) of the object, it was possible to generate a reconstructed model with photogrammetry [23]. This method might have improved the results on subjects 3 and 4.

Subjects 1 and 2 provided much better results. The objects were reconstructed but with several issues. Subject 2 reconstruction largely resembles the original shape but the resulted surface is flat without any relief structure particularities of the original surface. The processing software did not estimate the correct positions of the cameras therefore the reconstruction was flawed from the start.

Subject 1 had the best results. Camera positions were estimated correctly and the reconstructed model resembles the original piece. However, X-ray irradiation parameters (energy, exposure time and intensity) can be used to highlight specific parts of the object. The X-ray image is a result of a uniform incident x-ray beam that is modified by the X-ray attenuation properties of an object that is positioned between source and detector [24]. For example, in the case of Subject 1 the goal of the study was to evaluate the quality of the metal component, therefore the parameters were set to highlight as much details of the metal quality as possible. In this regard the reconstruction process was successful. All the visible details from the radiographs were reconstructed with several exceptions: the central bump and a square shaped piece of metal that was attached to the bottom of the piece. This last detail is shown in the 3D model as a square shaped gap in the mesh.

A future development might 3D reconstruction involving material discrimination based on the X-ray attenuation in materials with different chemical [25] and structural composition.

5. Conclusion

The aim of these experiments was to test the capabilities of today's leading photogrammetry automated software for the 3D reconstruction of cultural heritage artefacts from X-ray digital radiographs. Although there is no "the best" software, we used Agisoft Photoscan, which is among the few most used programs by photogrammetrists. With a fixed source of irradiation, the objects were rotated about two axes in order to make X-ray radiographs from different angles. Four objects were recorded with different volume characteristics. The method was partially successful on the shell shaped flat objects (subjects 1 and 2) due to the lack of superimposing areas in the projected radiographs and the greater number of useful radiographs. On the other hand, the objects with complex volume and a hollow surrounded by decorated walls confused the algorithm.

Three-dimensional reconstruction of artefacts based on X-Ray radiographs is possible with current automated algorithms. The process of data acquisition is tedious and time consuming and requires a careful set-up design. Because of the nature of this imaging method, any solution for a successful targeting system will considerably help in the image alignment process and further the whole 3D reconstruction.

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