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Single Camera Photogrammetry for Reverse Engineering and Fabrication of Ancient and Modern Artifacts

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Abstract

Photogrammetry has been used for recording objects for well over one hundred and fifty years. Modern photogrammetry, or digital image capture, can be used with the aid of a single medium range digital single lens reflex (DSLR) camera, to transform two-dimensional images into three-dimensional CAD spatial representations, and together with the use of additive manufacturing or 3D Printing technology, geometric representations of original cultural, historic and geological artifacts can be fabricated in a process known as Reverse Engineering. Being able to replicate such objects is of great benefit in education; if the original object cannot be handled because it is too old or delicate, then replicas can give the handler a chance to experience the size, texture and weight of rare objects. Photogrammetry equipment is discussed, the objective being simplicity of execution for eventual realisation of physical products such as the artifacts discussed. As the processing power of computers has increased and become more widely available, and with the use of computer software programs it is now possible to digitally combine multi-view photographs, taken from 360° around the object, into 3D CAD representational virtual images. The resulting data is then reprocessed, with a secondary computer program, to produce the STL file that the additive manufacturing machines can read, so as to produce replicated models of the originals. Three case studies are documented: the reproduction of a small modern clay sculpture; a 3000-year-old Egyptian artifact; and an Ammonite fossil, all successfully recreated, using additive manufacturing technology.

Keywords: photogrammetry; reverse engineering; DSLR camera; non-invasive reproduction; 123D Catch; PhotoScan; Studio Pro5; cultural heritage; education; additive manufacture.

1. Introduction

Three-dimensional (3D) imaging has been in existence since the invention of Lenticular's Stereoscope in 1860. Thus, the idea of a two-dimensional (2D) image being converted to a 3D image is not new. Photogrammetry, as it is referred to, "is the practice of determining the geometric properties of objects from photographic images and is as old as modern photography" [1] and dates from the mid-nineteenth century. Since the late 1990's, Laser Scanning (LS) has moved to the predominant non-invasive method used to replicate both large and small objects, such as large historic buildings and small statues.

The first digital camera was invented in 1975 by Sasson, who was an engineer working for Eastman Kodak® [2].

These cameras have developed from the low resolution 0.01megapixel early camera to 60 or 80 megapixels at the top end of today's professional range. Photo-manipulating/enhancing computer programs have been able to stitch 2D digital photo images together for a number of years, creating panoramic views of city, sea or landscapes [3]. More recently, with the help of i5 and i7 CPUs and the large amount of RAM that modern computers can now accommodate, software is available which is capable of stitching 150 or more, high resolution digital images together to form a virtual 3D representational image [4].

2. Research Objectives

In this paper, it is shown that with the use of photogrammetry, virtual 3D models can be created, without a high level of computer expertise and without the use of relatively expensive or complicated 3D laser scanning equipment. Many software programs claim to be able to convert 2D digital photographs into 3D virtual images. On investigation, it has been found that many are still in development and are not necessarily available for use except experimentally. Several commercial computer programs are available with a proven and reliable record to "stitch" multi-view digital images together to produce a 3D image.

Two programs were used in this research for the primary software processing of the digital images [4, 5]. In addition, the high resolution point cloud images produced were filtered and converted to STL files by a third program [6], ready for additive manufacturing (AM) machines to replicate and produce geometric representational models. The use of this technique could contribute to the reproduction, restoration or repair of damaged or broken antiquities by non-invasive methods at modest cost and by laypersons, who are computer literate but not necessarily expert in the use of specialised software.

By using a relatively modest DSLR camera, expensive LS is not required to capture the data necessary to produce 3D virtual images, and experienced technicians are no longer required to operate such equipment. A comparison between photogrammetry and laser scanning, their techniques and characteristics has been shown in Barsantia et al [7]. The primary research task investigates how well these software programs convert the digital 2D image into AM models, and compares results obtained with the original object. The research investigates the tactile surfaces of the replicated models and compares them to the original objects; it considers whether those replicated models, when scaled up and down, lose surface detail and whether the AM models created could be substituted for the original.

3. Data Capture Methods

One of the main objectives of the research was concentrating on the ease of reproducing artifacts without complex hardware or software. A mid-range Nikon D3100® DSLR camera was used, the digital data obtained being in JPG, or common image format. A standard fixed focus prime 50mm lens, which has a wide f1.4 or f1.8 aperture and minimum lens distortion and very good depth of field, was considered, but a Nikon 18/55mm DX® auto focus lens was chosen, being directly compatible with the camera and able to automatically refocus around the subject from the many positions and angles encountered. Minimum lens distortion was achieved by keeping to the higher focal length end of 35/55mm on the lens. The disadvantage of this lens as opposed to a fixed lens is that the depth of field is not as good and slower shutter speeds are required as the aperture is not as wide. A resolution of 3456 x 2304 pixels per frame was used throughout, which equates to approximately 8 megapixels.

- **Method 1 – open room set-up**

The methods of lighting and camera positioning for the artifacts were different in each case study, the common factor being that shadowless, flat lighting was required to illuminate all the artifacts, as any shadow distorted the image captured and processed by the software. The same was true for any highlights or reflections that the lighting might have caused. In Fig.1 the windows are covered so as to diffuse the natural daylight and help create a shadowless room. The main indoor lighting consisted of two bip® fluorescent floodlight control units on telescopic stands, each with three separate switched 50W 5000K bulbs and white defusing front covers and, if needed, two small lamps with 45W 5500K bulbs. Indirect daylight was utilised if available. Any small difference in colour temperature, known as White Balance, was automatically adjusted by the D3100 camera "as digital cameras have a far greater capacity to compensate for the varying colours of light" [8].

The first study, a small modern clay head sculpture, has been included to show a comparative method in both AM printing and data capture. This semi-glazed painted head, measuring 105mm x 95mm x 85mm, was placed in the centre of a room on a pedestal whilst the camera was moved in a full circle around the object and a digital image captured every 20°. The model clay head is seen, arrowed, in the centre of the room (Fig.1).

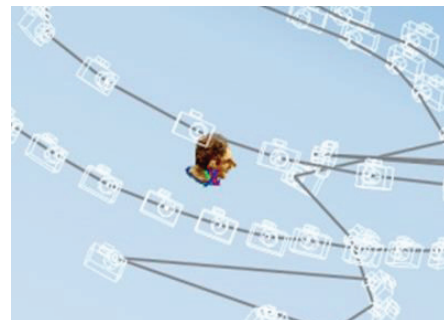Fig. 1   Indoor Open Room Setup

Fig. 2   Multi Camera positioning around Clay Head

All reflective surfaces are covered (television and glass coffee table), to stop any light flare or reflection. A second and third circle of data, at a higher and lower elevation of 20° to 30° to the horizontal, was obtained, ensuring that every part of the head was recorded and that a good overlap of images was obtained (Fig.2). The digital data capture of the clay head was processed using AutoDesk's 123D Catch®, and the high resolution point cloud image data obtained was processed via AutoDesk's internet cloud technology. The returned data image was then cleaned and the file was processed using Netfabb's Studio Pro4® to produce the STL file which the Stratasys' Dimension® Fused Deposition Modelling (FDM) machine could accept and use to fabricate the model.

- **Method 2 – Light Tent**

The second method of digital data capture used a collapsible Light Tent; (Fig. 3). This was constructed specifically for this purpose, from 20mm plastic tubing and suitable angle corners to make a metre square enclosure, covered in white poplin fabric with a front opening. So as to obtain strong contrast between the subject matter that was being photographed, interchangeable Chroma Key [8] backdrops were used, either white or green, depending on the colour of the subject. As seen in Fig.3, the lights were placed outside the tent allowing the fabric to soften the lighting and disperse any shadows. Natural light coming from the window behind (unshaded) helped to counteract any shadows.

The light tent was used to digitally capture images of the artifacts from antiquity, a 3000 year old Egyptian figurine and an Ammonite fossil, and processed using Agisoft's PhotoScan Pro®. Netfabb's Studio Pro4® was then used to produce the STL file which the AM machine requires in order to print the replications. The models that were made using this technique were processed on a 3D Systems DTM Sinterstation®, Selective Laser Sintering (SLS) machine, in a plain white Nylon 12 (polyamide).

Fig. 3   Light Tent in Kendal Museum

The light tent used to capture the Ammonite data was different in that the white linen cover was not used, as the natural light in the indoor environment was very soft and it was felt that only a small amount of "fill in" artificial light was needed. However a contrast green backdrop was used to enhance the contrast with the greyish colored Ammonite

(Fig. 4).   In both Fig. 3 and Fig. 4 a turntable can be seen which was used to revolve the artefact around 360°. The camera was stationary, only being moved once in the vertical plane for every complete revolution of the subject.

Fig. 4   Green Chroma Key backdrop and open-sided light tents

- **Data Processing**

In 2011, Verhoeven, [9] using stereoscopic photography, and after processing the digital images using PhotoScan Pro®, produced a series of virtual 3D images. It was noted that although the software claimed to be able to process, in theory, a very large number of photographs, in practical terms this is a maximum of approximately 1024 images. Verhoeven records that the relationships between the processing time, speed, quantity and high resolution data, are all interlinked. The more detailed the photogrammetric data, the greater the speed of processor required with a computation time penalty.

For the clay head, three attempts were made, gradually increasing the number of images from 40 to 70, which were taken from different angles, encircling and arcing around the object from above and below. This ensured that there was an image overlap of about 15-20%. Using one of the primary software programs, the images were processed to generate point cloud data sets [5]. This program used internet web-based cloud services provided by Autodesk to turn the JPG processed data, taken from the camera, into image formats for importing into third party software programs. Using this software, a video could be created by selection or rejection of the 60 photographic images in the path the images had taken. The software seamlessly converted the images selected into a moving 3D virtual representation. The time taken for this process was dependent on the quantity and quality of the images (as well as internet speed), but a reduction in either could result, as Nguyen et al show [10], in processed image data which is badly degraded. The data image having been cleaned, it was then exported as an OBJ file and a 3D textured mesh was created.

The other two items were photographed using the light tent: Sobekhotep, the Egyptian figurine and the Ammonite fossil were processed in the same way to each other. As seen from Fig.1, in the "open room" system of data capture, the main subject, in this case the clay head, was in a static position and the camera was rotated at a distance of approximately 1.2 to 1.5 metres away. With the light tent

system of data capture, depending on the artifact's size, the camera was placed much nearer the subject. The artifact was then rotated on a turntable between 10° and 15°, as each frame was shot (Fig. 5b). This method allowed for small objects to be photographed with the use of close-up ring lenses which screwed onto the front of the camera's prime or zoom lens. In Fig. 3, Sobekhotep can be seen on the turntable ready to be photographed using the standard Nikon 18/55mm DX® lens. For each object, 130 images were taken. But being much nearer the subject increased the criticality of the focusing and the depth of field became far more important; the closer the lens to the subject, the shallower the depth of field became. Shooting at f/5.6 to f/9 in an open room became f/18 to f/22+ in a light tent. These smaller apertures required increased illumination on the subject or required longer timed exposures.
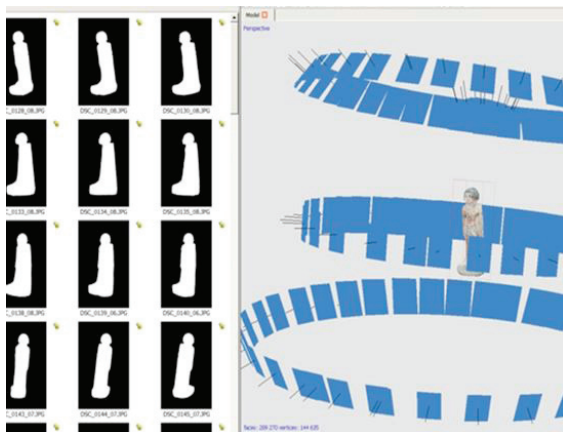
Fig. 5a.   Masked Images   Fig. 5b.   Multi Image positions

In this method, the software, PhotoScan Pro®, also allowed for more control, by the operator, over how the data was processed. Instead of processing data via the internet, as with the first example, and as long as the host computer had an i5 or preferably i7 CPU, with a minimum 12GB memory, the data could be processed on the host machine. Before processing the data, each image was masked from the surrounding background with a built in tool in the software, as can be seen in Fig. 5a. The actual original model (Fig. 6a) shows no discernable loss of detail compared to the screen shot of the high point cloud data image (Fig. 6b).

Experimentation with inter-changeable Chroma Key backdrops was undertaken; this type of backdrop provided a very good contrast between the main subject matter and its surroundings. It was found that the time taken to mask each digital image was considerably quicker with the use of a Chroma Key background. The more RAM that was available, the faster the digital data could be processed, and the more detail that was forthcoming. Unfortunately the software did not have the facility to convert the captured images into a video. If required, this could be done using a proprietary video processing program.

Fig. 6a   Original artifact   Fig. 6b   high resolution point cloud image

4. Repair of Noisy, Distorted and Incomplete Data

The returned processed point cloud image, as seen in Fig. 7 (head identified), had to be filtered, or cleaned, to eliminate background noise that had been captured along with the original subject, such as other objects or furniture that were in the line of focus when the image was recorded by the DSLR. The resulting processed textured 3D mesh showed minor flaws or distortion which had to be corrected (Fig. 8). The processed photo-textured 3D mesh image head could have been repaired using software, but by adding and increasing the number of images, with more angled shots and greater image overlap, complex repairs to the point cloud and textured mesh were eliminated. The additional photographic digital images, once added to the original data set of images, were reprocessed and sent by the internet to be cloud processed and returned ready to be recleaned. By selecting the appropriate control in the editing section, a wire frame, wire frame and texture, or texture only model could be obtained. This would facilitate the model repair if required. Whichever software was used, the reconstruction of 3D models was semi-automatic due to the reconstruction problems and some user intervention was required.
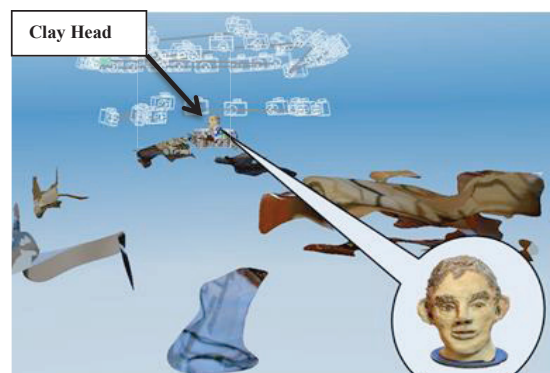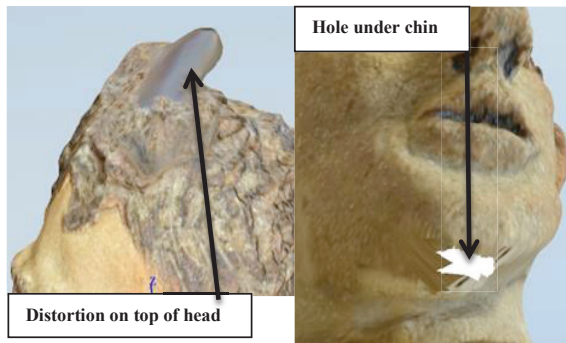

Fig. 7   Processed digital image ready to be cleaned

Fig. 8   Typical data flaws requiring correction

5. The Final Model

The OBJ file was created as a solid, but by hollowing the model, using this secondary software, the amount of material, and therefore its weight, was reduced; this could be in the region of 80% of the mass, making a great difference to the final material cost of manufacturing using AM.

Fig. 9   Original Clay model

Fig. 10   Virtual Point Cloud image   Fig. 11   Hand painted FDM model

The model that was then made was instantly recognisable as a copy of the original and although the FDM reproduction was a little smaller than the original (approximately 80%), the tactile surface finish was much smoother than the rough, prickly feel of the original clay surface. This could be attributed to similar geometric errors caused by the size of the extrusion nozzle and tool path of the Dimension® FDM machine on which it was made, as described by Brooks et al. [11]. The quality of build is well known [11, 12], as can be appreciated by the differences between the use of an entry level FDM machine costing a few hundred £/€ to that of a SLS machine costing several hundred thousand £/€, thus resulting in how much detail of the original model was lost or captured.

6. Scale and Physical Detail of AM Models.

It was found that the resulting dimensions of the 3D image obtained from the primary software very rarely matched the original dimensions of the object photographed, being created in a virtual arbitrary scale. For large objects such as buildings or monumental structures, this is a problem, but it is not within the scope of this paper, which only concerns itself with smaller sized artifacts, that can be easily measured.

The scaling feature which exists in the Studio Pro 4® software program is of great importance, as the final dimensional accuracy of the finished AM replicated artefact can be fine-tuned. By simply comparing the size of the 3D virtual model with the original, and by adjusting the percentage increase needed to scale up the model within the software, an exact dimensional copy was obtained in all x, y, z planes. The operator has a certain amount of control when using PhotoScan Pro®, for example, to process the final 3D point cloud image; but even this control was limited to the processing capacity of the computer. Guidi, et al, [13] discussed the control that the operator has over this software, a semi-automatic commercial software program.

However, in processing a range of artifacts in this research, the following factors played a key role in determining the time taken and quality achieved: the difference in the "Build Dense Cloud" function between Ultra High to Ultra Low (Fig. 12); the fact that a specification of an i7 CPU was being used; and whether the computer had 16MB or 32MB RAM. Only the smallest of objects with a relatively simple profile, could be processed with 16MB RAM using Ultra High setting. The processing times in the Ammonite fossil seen in Fig. 12, increased from around 30-45 minutes for the Ultra-Low build (using 16MB RAM) to up to 6 or 8 hours for Ultra High (using 32MB RAM), as well as increasing the size of the final STL file: which then was reflected in the quality of the AM build.

Mesh type	Ultra High
Polygons	4,846,416
STL file size	236,642 kb

Mesh type	Medium
Polygons	527,150
STL file size	25,740 kb

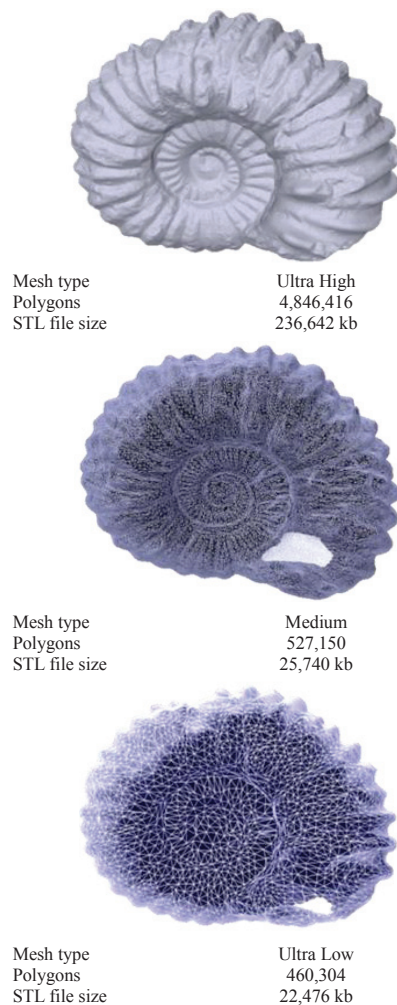| Mesh type	Ultra Low
Polygons	460,304
STL file size	22,476 kb

Fig. 12   Ammonite Fossil - wire mesh screen shots & Data

This ultra-high detail of the build was in itself controlled by the capabilities of the AM machine used, whether the machine could print in layers of say (typically) 100microns or (with recent advances) 16microns.

7. Conclusions & Future Work

The digital date for these artifacts, were all captured, using a single mid-range DLSR camera. The models were manufactured using different types of AM machines, but these models were processed with the minimum of computation. There was no CAD reconstruction or alteration to the point cloud image or the photo-textured mesh, only minor cleaning; this eliminated the need for software experts, one of the main objectives of the research. If the point cloud image was too badly distorted or holes in the mesh were present, either a new set of images were taken or manual photo stitching of additional photographic images was undertaken. There are obvious exceptions in which the DSLR camera cannot function, since it can only capture surface images, unlike volumetric scanning, or as in the examples of the MRI scanning of an Egyptian mummy by Steele and Williams [14] or the use of CT scanning and computer assisted surgical planning, combined with patient-specific surgical guides for patients with deformed bone structures, as in the work of Leong et el [15]. But for this research using the DSLR, it was only the surface data which was required to produce the geometric representation artifacts.

Further research is required to investigate how and whether adverse effects can be minimised or eliminated at the data capture stage. One of the main problems encountered was reflection of highly glazed surfaces. In some cases the silhouettes of the objects themselves were so complex that a greater number of images needed to be taken, thus slowing down the processing time. A series of tests using lower lighting levels, camera settings, lens filters, data pixel image size, is required to find a solution. A suggested starting point might be: graduated neutral grey filters, perhaps the use of a Polaroid filter, or aperture setting even smaller than f/18 or f/21, compensated by slower shutter speeds, but this means a longer processing time penalty. Ultimately, as stated, monetary budget is a very important factor, as to the final detail and standard of finished product. Ultimately, data acquisition, processing and build time will be reflected in the quality of the final version of the model.

Coloration of the replicated artifacts needs further work, as can be seen in differences between Figures 9 and 11. The original clay head (Fig. 9) was painted using pottery glazes, then 'fired', producing quite a different look to the brighter pigmentation of the Acrylic paints used on the FDM model (Fig. 11). Water colour paints, which are less intense than oil or acrylic paint, were tried, but would not dry properly on the nylon material from which the FDM model was made. Printing or painting on a sandstone material, in this instance, may have produced a better result. Producing models using a series of different materials, types of paint or inks, including a colour printer, might yield results nearer to the original coloration.

However, it has clearly been shown that simply with the use of a single DSLR camera, user friendly software and AM technology, both modern and ancient artifacts have been reversed engineered and replication models fabricated.

Acknowledgements

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