The 3D Digitisation of Artefacts to be Displayed in a Virtual Museum

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Abstract: There is an increasing number of applications for 3D models in virtual environments and hence a growing demand. 3D content is generally created with laser scanning systems or designed manually in modelling softwares. Photogrammetry is able to generate digitised models of a real object by mapping its surface in the form of 3D coordinates by comparing overlapping images from a set of photographs. Any digital consumer level camera or smartphone has the required resolution, rendering this technique extremely portable and cheap. The correct image capture process must be followed to ensure accurate models are obtained, the object is subject to some restrictions such as it cannot be non-textured, flat or made from transparent or reflective materials. If these requirements are met, the quality of the 3D models produced are comparable to that achieved if it was manually designed in a 3D modelling software.

1 Introduction

As virtual reality grows in popularity and with the recent launch of augmented reality, the demand for realistic and authentic 3D models for visualisation purposes is increasing. All assets used in virtual environments must be designed in 3D modelling softwares or with costly laser equipment. The manual creation of 3D content is a time consuming task and requires a high level of expertise to design detailed and realistic models. Photogrammetry is a powerful tool which bypasses this obstacle and bridges the gap between 3D content producers and users at the consumer level.

Photogrammetry is capable of generating digitised textured models of real objects from a set of photographs. Photogrammetric softwares are able to calculate the camera's focal point from its focal length value stored in the images as well as the camera's position and orientation relative to the centre of the object. All photographs are compared using this information and data is extracted from overlapping images in the form of 3D coordinates mapping the surface of the object photographed [1]. This technique has been used in multiple applications, mainly cultural heritage for reconstruction, preservation and documentation but has the potential to be applied in numerous other fields. Photogrammetry has also been quoted 'to produce models with accuracies comparable to a lidar scanner' [2].

This project researched and tested multiple image-based 3D modelling softwares and analysed their performance to choose the most suitable one. The effect of camera resolution on the accuracy of generated models was investigated and various objects were tested in regards to their shape, size and material to discern any requirements and limitations of this technique. Once these requirements have been identified, a virtual museum was designed in Unreal Engine 4 (UE4) where scanned items could be displayed and interacted with by the user. The goal of this project is for the user to freely explore a virtual museum, interact with an object by observing it from multiple angle as it rotates on its central axis, and obtain a description of the item as per depicted in [3] in regards to 'a small archaeological piece'.

Aim: To scan a museum object and with as minimal delay as possible, incorporate it into a virtual reality environment to avoid the need to manually create the 3D object.

Objectives:
1. To identify and evaluate appropriate scanning systems using a camera or mobile device.
2. To 3D scan example museum objects (statue, fossil, etc.)
3. Incorporate the 3D object into a VR system using Unreal Engine and Blender applications.
4. Explore limitations of the level of detail that can be obtained using this method.
5. Document the 3D capture process with examples.
6. Development of a virtual museum environment.

2 Methodology

The methodological approach for the successful completion of the project was largely based on the project objectives. After researching background information about photogrammetry, the first step was to test and compare various photogrammetric softwares and select one for the project, essentially objective 1. Various cameras and objects can then be tested to identify any requirements to achieve accurate 3D models. The results gathered could then be used to create a user guide documenting the 3D image capture process and would set of the limitations of the level of detail which can be obtained (objectives 5 and 4). Once these requirements and restrictions are established, the virtual museum can be designed to start incorporating scanned models into the environment (objective 6 and 3). Lastly, the user movement and interaction with objects inside the museum can be coded before testing the completed system to receive some feedback. This approach is illustrated in figure 1 as a flow diagram.

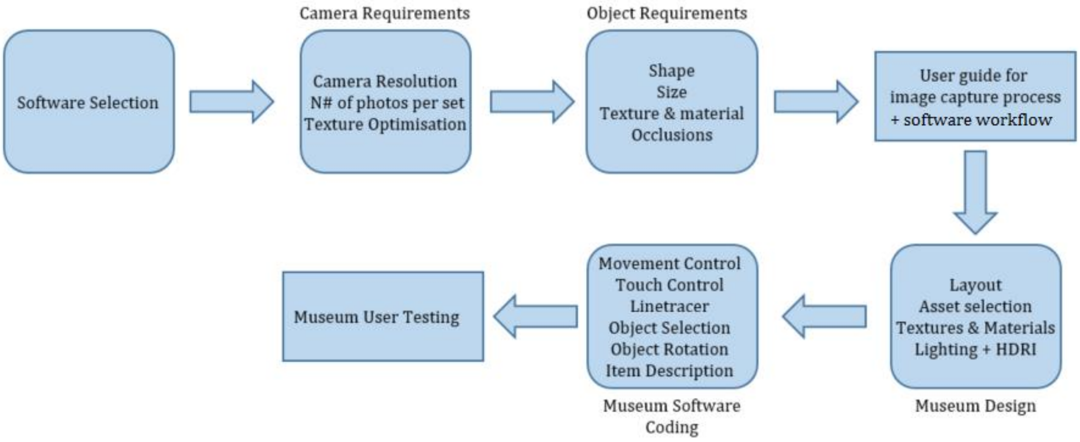

Figure 1: Flow diagram of the methodological approach

2.1 Software Selection

A wide range of photogrammetric softwares are available on the market as mobile applications, online services or professional stand-alone softwares. Some are only specialised for close range photogrammetry to obtain high levels of details with small scale objects or are specific to building and site reconstructions from aerial shots. Others require additional hardware usually retailed at high costs, such as the Structure Sensor worth $379 [4]. The price range of image based 3D modelling programs varies extensively from applications free of charge to professional softwares worth thousands. Most mobile applications are free and never exceed £10 while stand-alone programs are far beyond the project budget.

The selection process to determine which software will be chosen for the project was carried out in three stages. An initial list of potential programs was compiled from softwares which don't require additional hardware and are free of cost or within the project budget. Additionally, the software must be suited for close range photogrammetry and small scale objects as opposed to large scale projects.

The second selection stage consisted of testing each software for their user interface, workflow process and reliability of the servers if rendering is performed through cloud computing. Since the aim of this project is to obtain digitised models of objects in a short amount of time, the software must be efficient and therefore the modelling workflow must be automatic or streamlined and require minimal user attention. Any software with an overly complex or counter intuitive user interface is considered to be inefficient and therefore disregarded. To test the reliability of servers, models are generated at various times during the day with the rendering times recorded.

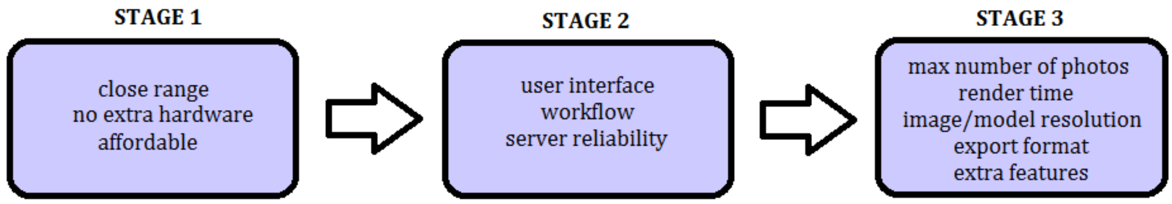

Figure 2: Parameters analysed during the software selection process

Finally, the remaining softwares are compared in more detail based on the features they offer, the efficiency and quality of the renders. This includes the maximal number of photos which can be uploaded per model, if the resolution of the photographs is downscaled, the rendering time, the level of detail obtained and any post processing editing feature. Furthermore, the models must be able to be exported in .fbx or .obj formats with the appropriate textures to be compatible with UE4 [5]

Multiple companies who own professional image-based 3D modelling softwares were contacted in the hope of utilising their software for this project. A project description and scope was included in the message requesting the possibility of obtaining free license keys for the following programs: SURE by nFrames, ReMake professional version by Autodesk and PhotoScan professional edition by Agisoft.

2.2 Image Capture Setup

Each software have some guidance on image capture and object requirements on the program's home page or as user manual document. A detailed guide on equipment, camera settings, object requirements, correct image capture process, lighting requirements and troubleshooting help was written as a separate document. It also covers the workflow process for the software used in this project. Any person interested in photogrammetry can follow this guide and obtain highly accurate models regardless of any knowledge in the field. The most significant information is in regards to object restrictions.

Some object characteristics can confuse the algorithm of photogrammetric softwares and therefore cannot be correctly analysed. This results in discoloured textures and geometrical distortions of the mesh model. The subject should not be transparent, reflective, shiny or non-textured. Furthermore, flat objects with little surface depth are more challenging to analyse due to the lack of reference points and differences between overlapping images.

Two sample objects (see figure 3) were chosen as subject to compare software renders and for further testing described in the next section. The reflective features, hidden areas and small details of the sample objects allow for a more complete analysis and comparison between the 3D capture programs.

Sample object 1: a plastic skull with small engraved patterns (~/5 mm)
Sample object 2: an analogue camera with reflective and semi-transparent parts.

Figure 3: Chosen sample objects

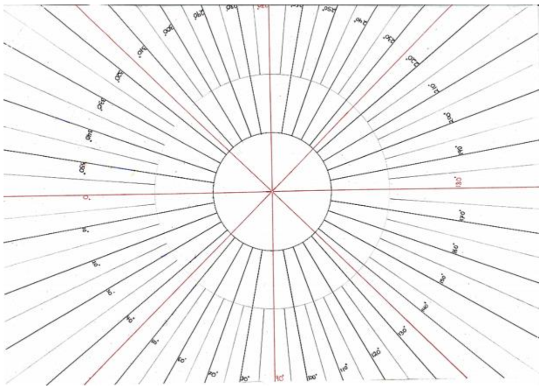

Figure 4: 360º drawn compass

All photo captures for all renders were shot with the exact same set up and configuration. If shooting inside, the aim is to obtain a dome lighting to replicate the luminosity of a cloudy summer day [6]. In order to achieve the necessary lighting, a table was placed in the middle of an empty room between four overhead lights to minimise self-shading effects. The blinds on windows were also shut to avoid exposure levels from varying when the camera is facing the windows. Figure 4 represents a 360º protractor drawn on an A3 size paper. This prevented light from reflecting off the glossy table and interfering with the software's algorithm. It also ensured that all photo sets were taken from the same angles and that each subsequent photographs have a consistent overlay.

2.3 Camera Requirements

The quality and shape of the digitised model are mostly dependent on the effectiveness of the photogrammetric software used. The resolution of the camera also affects the quality of the model as higher resolution images provide more accurate references for the software during the comparison of overlapping photos, resulting in more precise mapping of 3D coordinates of the model. Furthermore, the quality of the texture is entirely based on the set of images. For authenticity purposes and for a virtual environment application where the replicated model will be closely observed, it is crucial for it to be geometrically accurate and photorealistic.

Photo Set	Camera	Resolution (MP)
1	iPhone 4	5
2	iPhone 4 HDR mode	5
3	iPhone 6	12
4	iPhone 6 HDR mode	12
5	Nikon D7100	24

Table 1: Cameras used for each photo set

To observe the effects of camera resolution and identify the minimal resolution necessary, three cameras were compared, each corresponding to a photo set as shown in table 1. Additional photo sets were taken with the iPhone 4 and iPhone 6 cameras on HDR mode to average the exposure levels and obtain a smoother texture.

To ensure consistency between results, all parameters were kept constant. The skull was chosen as the subject and all models were generated with the same software on identical settings. The five photo sets consist of 36 photographs taken at eye level with the subject at 10^{o} intervals and 18 photos from a higher point of view at 20^{o} intervals for a total of 54 images per set. All five photo sets were taken a second time with this time 36 photos taken at eye level with the object at 10^{o} intervals, 36 photos from a higher point of view at 10^{o} intervals and an additional 36 photos from various other angles focusing on small details and occlusions for a total of 108 images per set.

2.4 Object Requirements

As mentioned previously, objects to be scanned must meet certain requirements to ensure the photogrammetric software is able to generate an accurate 3D models with no artefacts in the mesh.

To test the limitations of the software and identify which object characteristics and features cannot be correctly rendered, objects of various shapes, sizes and with different material properties were scanned. The two sample objects (skull and analogue camera) already have some occlusions, small details and semi-transparent features. The following six objects were chosen to further explore the limitations of the software:

Item Number	Object	Properties Description
1	White plate	Flat with a monochrome reflective texture
2	20p coin (20 mm)	Very small with flat surfaces
3	Glass	Transparent material
4	Microscope	Odd shaped with a single colour casing
5	Pinecone (95 mm)	Small occlusions from scales
6	Fish tank rocks	Multiple gaps and porous material

Table 2: Cameras used for each photo set

The testing was performed as per described in the previous section. All items were placed on the 360^{o} compass paper in between overhead lighting and all settings on the image-based 3D modelling software were kept identical. A total of 100 pictures were taken for each object: 36 at eye level, 36 from a higher elevation angle and the remaining consisting of close up shots of occlusions or photographs with 5^{o} increments.

2.5 Museum Design

The first step to creating the virtual museum was sketching a blueprint of the layout by deciding the number of rooms along with the dimensions for each. It was decided the museum required a minimum of four rooms to be deemed explorable and resemble an actual museum design plan. All assets placed inside the virtual environment have been downloaded from free online repositories [7-9]. All imported models have been edited in some way with Blender by modifying the mesh, rectifying the normal vectors for textures to render properly or adding materials to different sections. A pedestal was also designed with Blender and imported into UE4 to display the scanned objects (see figure 5). The texture files for all assets imported were not compatible with UE4 with exception to paintings. Ergo, material and texture packs were downloaded to customise each individual asset [10-11].

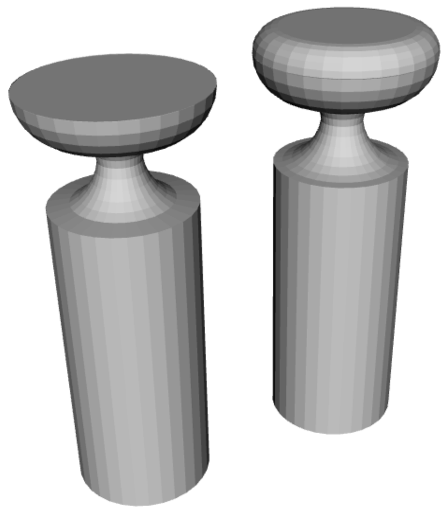

Figure 5: Pedestals created with Blender

The final museum layout is illustrated in figure 5 with all assets correctly placed. The user spawns into an entrance hall furnished with columns and a large sculpture to keep the room spacious, inviting and more museum-like. The main exposition room is the largest and contains all objects scanned displayed on pedestals as well as a large couch in the centre of the room (see appendix 1). A corridor decorated with a large statue and paintings separates the main exposition area from the entrance hall. Toilet doors can be found at one end of the corridor and a staircase leading to a 'staff only' door at the opposite end. Both sets of doors do not lead to a room but are entirely for aesthetics purposes (see appendix 2). Two secondary galleries are located on either side of the entrance hall to increase the explorable area of the museum but only contain paintings and couches. All rooms are decorated with cornices, skirting boards and separated by archways to create a more opulent and realistic environment. A melodic tune was added to the environment to contribute to the museum setting [12].

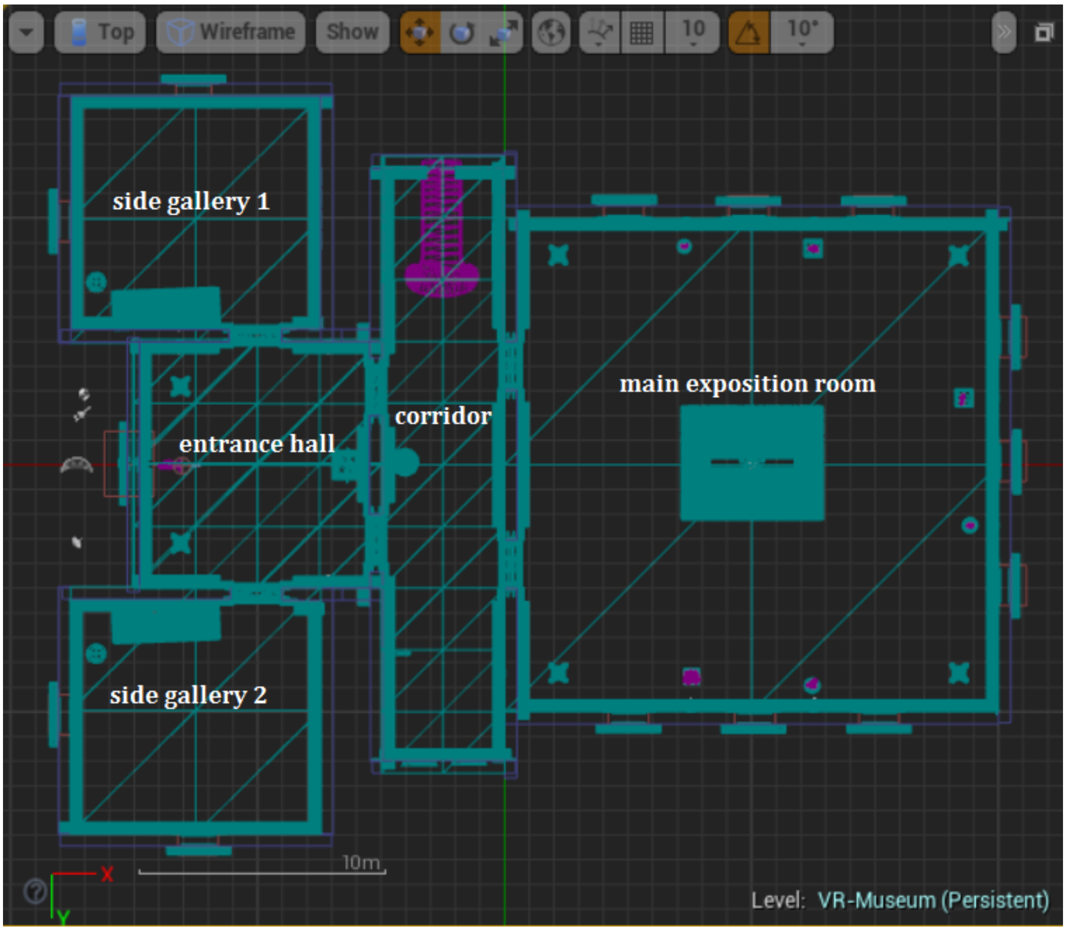

Figure 6: Snapshot of museum layout in UE4

Finally, the lighting was organised in such a way to attract the attention of the user towards the objects displayed. Wall lamps are arranged throughout the museum and above the pedestals in the main exposition room with a chandelier acting as the central lighting piece. Ornamented windows are positioned on walls where space is adequate to simulate natural light entering the rooms. High Dynamic Range Imaging (HDRI) is a photography technique employed to code a greater range of colours and brightness levels than standard images. Luminance values are stored in each pixel for applications replicating photorealistic scenes [13]. By applying an HDR image to a spherical mesh larger than the museum and with inverted normals (the texture is displayed on the inside of the mesh as opposed to the outside), the illusion of a realistic environment with a sunlight source is created. For example, if no lighting was setup in a room of the museum, light would be observed entering the room through the windows casting shadows. An HDR image of a park was acquired from [14] to represent the garden area of the museum.

2.6 Coding Museum Interactions

UE4 uses a Blueprint Visual Scripting (BVS) system to code the environment designed in the program. It is grounded on the concept of a node based interface to program gameplay elements. UE's homepage has multiple pages and tutorials teaching how the BVS works with examples [15]. Most of the coding was learnt through their database and from advices given on the UE4 forums.

The coding for the project was divided into five tasks: movement control, creating a linetracer to select objects, controlling the object to rotate it and observe it from multiple angles, and finally obtaining a description of the item. The first task was to allow the user to move around the environment using the mouse and keyboard and then with the Touch Controllers. The code for mouse and keyboard movement was already compiled in the '1st person shooter template'. Movement using the joystick of the Touch Controllers was also already available. The blueprints containing the mesh of the mannequin hands and code to track the position of the Touch Controllers was available in the 'VR template' and could be implemented in the 1st person shooter template with minor editing. Having mannequin hands tracking the movement of the touch controllers contributed to making the VR experience more immersive.

The linetrace or raycast is essentially a 'laser' propagating away from the player and returns the reference of the first object it collides with and is explained on the UE4 main site [16]. The handling of objects with the use of the linetracer is explained in a video tutorial by a channel dedicated to teaching UE4 [17]. See appendix 3 for the linetracer code.

A master actor (any object placed in the environment) is created with a blueprint containing an empty static mesh. Any object desired to be interacted with is created as a child of the master actor and will inherit its blueprint and properties. The linetracer is activated by a trigger button and if it collides with an object which holds the blueprint of the master item, its location and rotation relative to the environment is stored as a variable. A separate mesh object is placed in front of the player camera. The selected 'child of master item' comes into view where the mesh object was positioned (in front of the camera), the character movement is disabled and a function is called to handle the object. The function called enables the user to rotate the object in the x and y directions with the movement controls (joystick or keyboard inputs) (see appendix 4). When the trigger button is activated a second time, the object returns to its original location and rotation which was stored and the character's movements are re-enabled.

To obtain a description of the object selected, the master item is attributed a blueprint interface which contains a structure with a single string variable. Whenever the linetrace collides with an object which holds the properties of the master item, the data held by the string is displayed on the screen (see appendix 5).

This code is written in such a way that any scanned item can be spawn into the virtual environment as a child of the master item. The mesh of the scanned object is attributed to it and a description can be entered in the details panel of the object. Therefore, any scanned object can be added to the virtual environment in matter of minutes and will be fully interactive.

3 Results

3.1 Software Testing

A large number of photogrammetric applications was obtained after the first stage of the software selection process. This list was then reduced to only four options after the second selection stage: 123D Catch by Autodesk, Trnio, ARC3D and ReMake also by Autodesk. A comparative analysis was undertaken to establish which one offers the best features and generates models of the highest quality.

123D Catch by Autodesk: A free mobile application with an easy to use interface. All photos of the object to be scanned must be taken with the application and a 360^{o} progress indicator which specifies which angles lack information and require additional photographs (see appendix 6). A maximum of 50 images can be uploaded per model and are downsized to a low resolution of 3 MP. Models take a few hours to render depending on the server traffic. No post-render editing features are included but the models can be exported in an .obj format compatible with UE4.

As of early 2017, the development of the application has been discontinued and all servers have been shut down (see appendix 7). Since it is a cloud-based photogrammetry engine, all renders were stored online and are no longer accessible. Only one render of the analogue camera could be retrieved (see appendix 8). The 3D model was of higher quality than expected considering the resolution of the images and only has a few minor distortions. The skull sample object 1 however could not be rendered by the software for unknown reasons and hence 123D Catch was disregarded.

Trnio: A free mobile application with the simplest user interface to come across. Photos of the object to scan can be uploaded from the camera roll or taken with the application using a burst mode feature: the software automatically captures images of the object as the user moves his phone around the subject. A maximum of 70 images per model can be uploaded to the online servers at full resolution. Again, renders can take a few of hours to render depending on server traffic. No post-render editing feature is available but the model can be cropped.

Renders of both sample objects were obtained and can be observed in appendix 9. The engravings on the skull were not rendered accurately but appear as smooth, and the texture is discoloured towards grey. More so, the analogue camera model was also of poor quality. Multiple holes are present in the mesh, the texture is blurry and the flash extension was duplicated on both sides of the camera. Moreover, the download link of the models sent via email were broken and could not be accessed on a computer. For these reasons, Trnio was concluded to be an application to introduce beginners to photogrammetry but with renders of minimal quality.

ARC3D: A free webservice and desktop software with a simple two stage workflow. The program's homepage contains instructions on how to correctly capture images to maximise the chances of obtaining an accurate 3D model and displays the number of jobs currently being processed [18]. Depending on the amount of jobs being processed, models are generated between 30min to 4h. Images are loaded into the software and then uploaded at full resolution to online servers to take advantage of cloud computing.

Multiple renders of both sample objects were obtained with ARC3D webservices (see appendix 10). All renders have multiple holes and are extremely pixelated. The results produced are inconsistent with floating mesh points and the colours of the textures vary from point to point in the same model. Slightly better results could be obtained by including a higher number of images per model but overall the terrible quality of the models render the software unusable.

ReMake by Autodesk: A free version is available with limited capabilities but the professional version was acquired by contacting the company who offered a student license. A maximum of 250 photos can be loaded into the desktop application at full resolution and rendering can be performed locally on the machine or online. On average models are generated within an hour and be downloaded through the application which is also a mesh editing software. Multiple model editing features are available such as filling holes and reducing the mesh density. The final model can then be exported into a wide range of formats including .fbx which is recommended for UE4.

The quality of the generated models by ReMake were impressive with all meshes being accurate with no visible holes. The engravings on the skull and small details on the analogue camera were almost perfectly replicated. The only distortions observable are around the flash of the analogue camera made out of a semi-transparent material which is known to be prone to artefacts. The textures are non-blurry and of high resolution with no hue or exposure irregularities. Overall ReMake generates 3D models of high quality which surpasses all other applications.

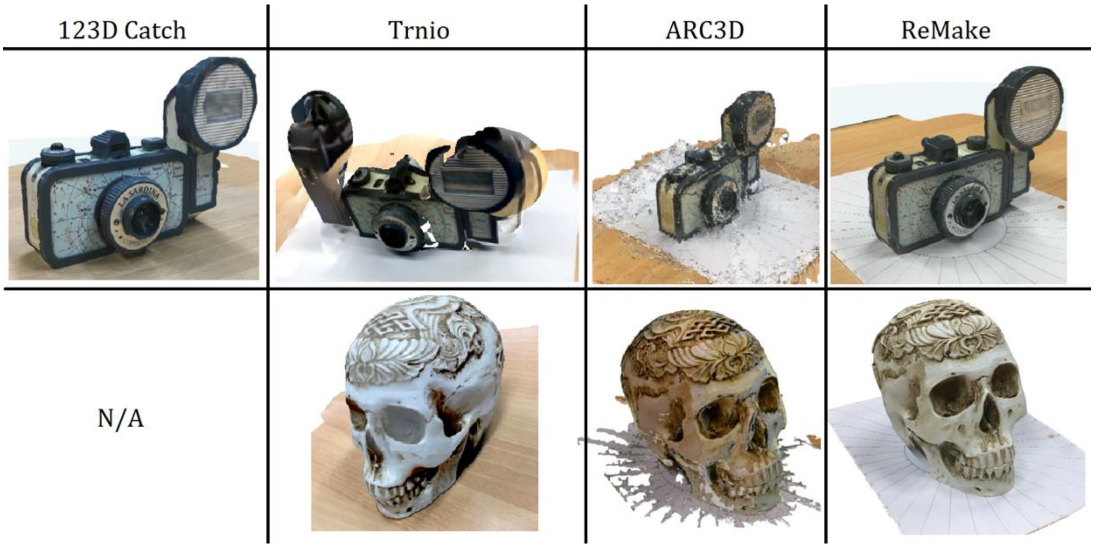

Figure 6: Comparison of renders of softwares

From the comparative analysis of the features of each program taken into account along with their render results, it is clear that ReMake is the obvious choice. Large photo sets of objects can be uploaded to Autodesk's servers and very accurate 3D models can be obtained within a short amount of time. Furthermore, the mesh model can then be edited and exported into the desired format within the same application.

The Agisoft Team offered free licensing keys for the use of PhotoScan, their state-of-the-art image-based 3D modelling software for the duration of this project. The results generated by PhotoScan are discussed in section 4 when exploring the limitations of the level of detail which can obtained with extremely high mesh densities.

3.2 Camera testing

As mentioned in section 2.3, a total of ten renders were generated with cameras of different resolution and exposure settings. All results are displayed in table 3 below. The renders for each test can be found in appendix 11. It was already established in the software testing that ReMake is able to produce accurate 3D models and therefore only one object was chosen to compare the effects of the different cameras. The term 'blending' in the 'Mesh Detail' column of the table refers to any merging of meshes between the object and the table on which it was placed. The jaw section on both sides of the skull have a gap where jaw ligaments and muscles would normally be found. The 'x/2 jaws' description denotes how many of those gaps were properly rendered and not filled.

Render Number	Camera	Number of Photos	Number of polygons ($x10^3$)	Number of Holes	Mesh Detail	Texture
1	iPhone 4	54	96.3	0	Minor blending, 0/2 jaws	Slightly blurry
2	iPhone 4 HDR	54	131.0	0	Some blending, 0/2 jaws	Lighter and more even
3	iPhone 6	54	190.4	0	Minor blending, 1/2 jaws	Realistic
4	iPhone 6 HDR	54	197.6	1	Minor blending, 2/2 jaws	Realistic and lighter
5	Nikon D7100	54	182.3	1	No blending, 0/2 jaws	Exposure settings are off
6	iPhone 4	108	117.2	0	Some blending, 0/2 jaws	Slightly blurry
7	iPhone 4 HDR	108	195.5	0	Minor blending, 0/2 jaws	Occlusions darker
8	iPhone 6	108	205.5	0	Minor blending, 1/2 jaws	Realistic
9	iPhone 6 HDR	108	281.4	1	Minor blending, 0/2 jaws	Shadows more pronounced
10	Nikon D7100	108	173.0	0	No blending, 0/2 jaws	Exposure settings are off

Table 3: Render analysis of skull object for camera requirements

The number of photos used per set increases the density of the mesh in terms of polygon count but does not certify that the digitised model will be more accurate to the original object. The software was only able to generate both gaps of the jaws with one set of photograph, render number 4. In all other cases, the gaps were filled with the texture of the table and compass drawing. In other words, the software noticed that a different material was present in that area but was unable to identify it as a hole in the mesh. A higher number of photos focusing on those small occlusions seemed to only confuse the software's algorithm instead of helping it. The renders from the camera with the lowest resolution had a more blurry texture while those generated from higher resolution images had no visible blending of meshes. The exposure settings of the Nikon D7100 weren't optimised for the scene which resulted in the colour hue being darker and the surface of the skull appearing as matte.

It can be concluded that a higher resolution camera produces more accurate digitised models with a better texture quality if the exposure settings are appropriate. HDR settings obtains an average of the exposure levels for smoother textures. Finally, a larger photo set will increase the density of the mesh but can also mislead the software.

3.3 Object testing

Once the camera requirements have been identified, the object requirements and restrictions can be investigated with full knowledge that the camera settings will produce the best results. The renders of objects defined in section 2.4 can be found in appendix 12 and the result analysis is displayed in table 4 below.

Object	Number of Photos	Number of polygons (x10^3)	Number of Holes	Mesh Detail	Texture
Plate	95	N/A	4 large	Heavy distortions and blending	Reflective characteristic rendered as a texture
20p Coin	86	N/A	1 large	Shape is disproportionate and blended	Completely missing
Glass	102	N/A	N/A	Only the base is rendered	N/A
Microscope	100	78.0	2 small	Some distortions	Accurate
Pinecone	155	86.5	0	Most scaled are blended	Slightly blurry and blended
Fish tank rocks	162	280.9	0	Porous material well rendered but gaps are not rendered	High resolution

Table 4: Render analysis of various objects

The mesh of the plate is completely distorted with spikes appearing in the centre of the plate. The border of the plate is roughly 15 mm above the table but both are completely merged. Multiple large holes are present in the mesh, further evidencing that the software cannot properly render non-textured flat objects due to the lack of reference points. The 20p coin was the smallest of all objects scanned and could not be rendered. Although the general cylindrical shape of the mesh was formed, it was extrapolated and no texture was obtained. The transparent glass could also not be rendered as expected. The base and top ring were generated but the software completely ignored the main body of the glass since no reference points could be identified between overlapping images. Generally the 3D model of the microscope was accurate and correctly represented the original. Small distortions appear around the mesh due to the single-coloured casing while smaller details such as knobs and eye lenses had a better resolution. Words and logos were perfectly identified. The pinecone was the second smallest object with occlusions difficult to identify due to the numerous scales creating a repetitive pattern. Some of the scales at the top of the pinecone were singularly generated but all others were merged and blended together. The texture was slightly blurry with some sections underneath the scales non-textured due to the lack of visibility from the image set. Finally, the fish tank set of rocks presented interesting results. The porous material was surprisingly well replicated but none of the gaps were identified as such by the software. A large number of close up shots of those gaps were taken from various angles in an attempt to highlight the hole in the mesh. Similarly to the jaw section of the skull, those gaps were filled and the texture of table or background image covered those areas.

From these test, a set of requirements can be identified. Scannable objects must be of a certain size to obtain accurate renders, any feature smaller than 50 mm is likely to be distorted. Items with flat sections or which were non-textured are also likely to be distorted due to the difficulty in distinguishing common reference points between overlapping sets of images. The mesh model of glossy and reflective materials can be successfully rendered but the texture is prone to artefacts from light reflections. Transparent materials however are not recognised by the software and will spawn holes in the mesh. Finally, odd shaped object with occlusions are unlikely to produce accurate renders due to the limitations of the software resulting in the gap areas being filled with the texture of the background in the images.

3.4 Museum testing

The final testing stage was user testing. It was essential to invite a number of people to test the finished virtual museum to gather feedback on the intuitivity of the user controls, the quality of the virtual environment but most importantly any difference which can be noticed between imported models and scanned objects. For the project to be truly successful, the quality of scanned objects must match that of designed models. If the scanned objects are of lower resolution than manually designed 3D models, then there is still a need for the manual creation of models and the aim of this project has not been reached.

A small questionnaire of nine questions was written for users to complete after exploring the virtual museum (see appendix 13). A total of six people tested the system with all results tallied in table 5 below.

Question	User 1	User 2	User 3	User 4	User 5	User 6
1 – VR experience	3	2	1	1	1	1
2 – intuitivity of controls	5	5	3	5	5	5
3 – level of detail	5	4	3	5	4	2.5
4 – effect of details	5	5	5	5	4	3.5
5 – difference between scanned and designed models	2	5	4	5	3	5
5. a – reason	No obvious difference but scanned objects are more realistic besides fish tank rocks	N/A	N/A	N/A	Couldn't always tell the difference	N/A
6 – motion sickness	1	2	3	3	2	3
7 – VR or mouse & keyboard	VR	VR	VR	VR	VR	VR
8 – overall experience	5	5	4	5	4	4
9 – other comments	N/A	N/A	Bronze mask thought to be scanned	Skull has better details than other objects	N/A	N/A

Table 5: Results of questionnaire

Most users were experiencing VR for the first time and all except user 3 found the controls to be intuitive so it can be assumed the movement and interaction controls were well coded. The average score for the level of detail was of 3.9 proving that the museum was designed at a reasonably high quality. Half the users stated they could not differ at all scanned objects from imported models which were designed in a 3D modelling software. User 1 scored a 2 for this question but commented that some scanned objects were more realistic than others. Elaborating on this point, user 3 confused an imported model for a scanned one and user 4 sated that the skull had the highest level of detail. Based on these results and comments, it can be concluded that digitised models of real objects obtained through photogrammetry can obtain the same quality or even better than manually designed models in 3D modelling softwares.

4 Limitations of Level of Detail

As outlined in sections 2.3 and 2.4, the level of details of models generated by photogrammetric softwares is dependent on the camera resolution, the materials and features of the object and the accuracy of the algorithms. A high resolution camera aids the matching algorithm in accurately mapping the 3D coordinates of the surface of the object and produces a higher resolution texture. Transparent materials or objects with shiny aspects will reduce the level of detail obtainable so mat colours are favourable. Occlusions are difficult to capture correctly so renders of simple-shaped objects are guaranteed to be exact replicas.

PhotoScan by Agisoft is one of the most advanced softwares available for close range photogrammetry. It offers a wide of features with advanced settings. Figure 7 shows a model of the skull generated on the highest accuracy settings with a set of 54 images at various angles. The level of detail obtained is unrivalled to every other model generated with other softwares. The model has an extremely high mesh density of over 5 million polygons (other models average around 200 thousand polygons) and every occlusion has been rendered correctly. The downside is that the software takes 12 to 24 hours to complete the generation of the model. Additionally, it is not practical for such high density meshes to be incorporated in virtual environments due to the computing power required to render such model without affecting the framerate and performance of the system. This might not be the case if the model is used as a static mesh but if it is intended for it to be moveable and interactive, the mesh must be decimate to a much lower density.

Figure 7: Highest level of detail obtainable with Photoscan

Conclusion

With the technological improvements made in photogrammetry, any individual with an interest in the field can obtain 3D mesh models of real objects of high quality. After comparing numerous image-based 3D modelling softwares, ReMake by Autodesk was identified as one of the best suited softwares. If the chosen object to be digitised meets a set of requirements and its image capture process is done correctly, 3D models of quality equal to that of manually design models in design softwares can be generated. Although there are a number of constraints with this technique, softwares such PhotoScan by Agisoft are able to generate almost perfect replicas of the original object in terms of shape and texture. These models can then be incorporated into virtual environments for a multitude of applications such as game assets, in the field of cultural heritage, to display merchandise in virtual shops or to replicate entire scenes.

Acknowledgements

I would like to express my great appreciation to the Agisoft Team for providing me with free license keys to their professional photogrammetric software PhotoScan. I would have not been able to reach the conclusions and explore some of the limitations of this technique without their support.

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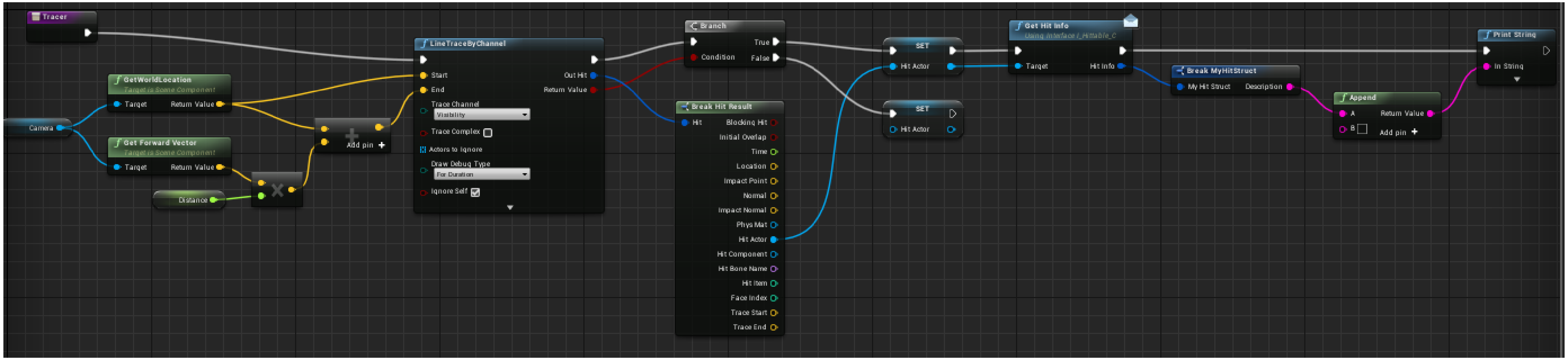
Appendix

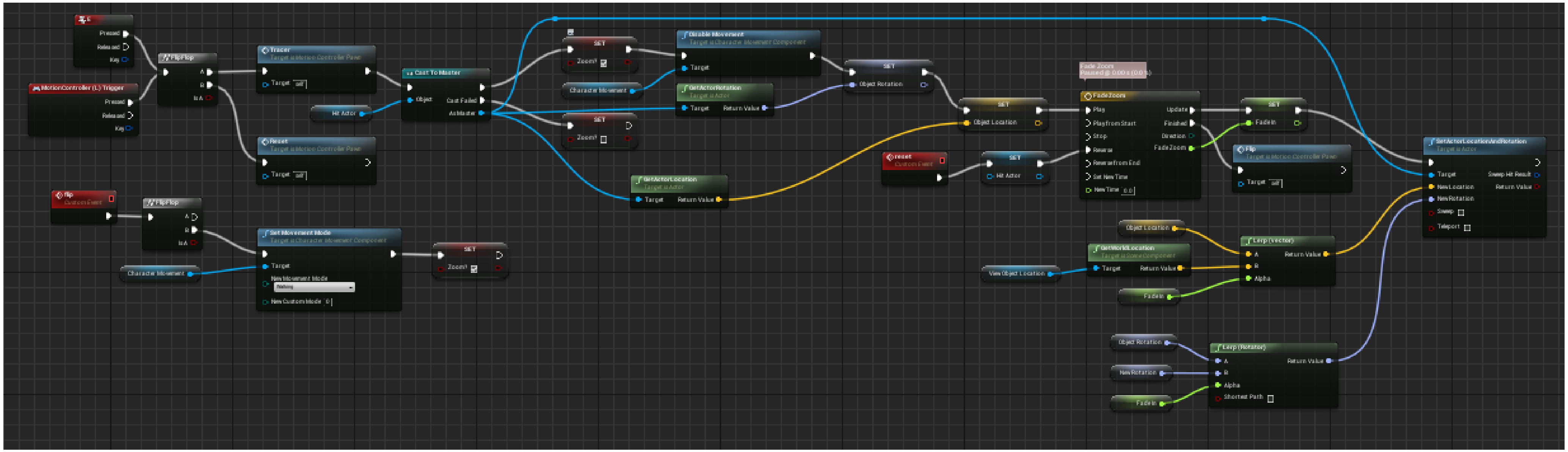
Appendix 1: Screenshot of the museum's main exposition room in UE4

Appendix 2: Screenshot of the museum's corridor in UE4

Appendix 3: Code for linetracer returning object description

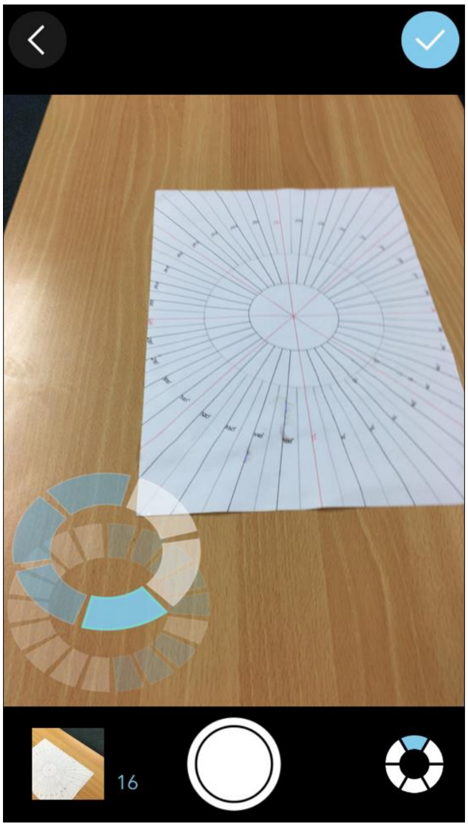


Appendix 4: Code for handling scanned objects

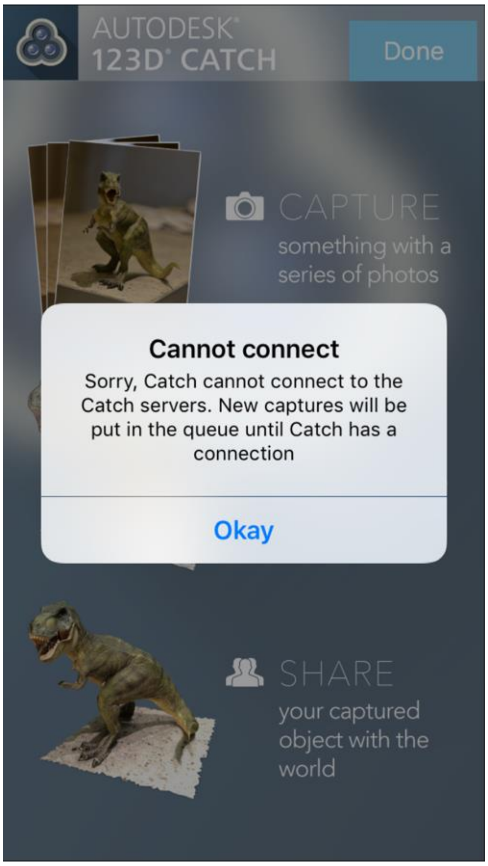


Appendix 5: Screenshot of object description being displayed on screen

Appendix 6: Mobile screenshot of 123D Catch's 360º progress indicator



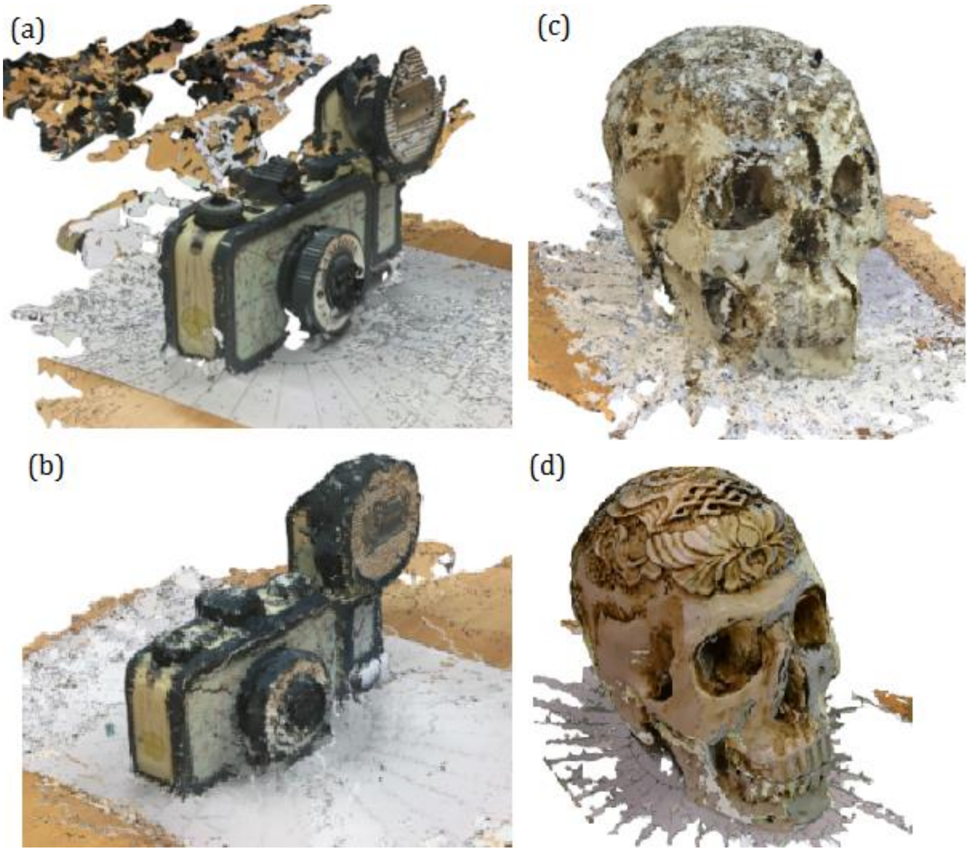
Appendix 7: Mobile screenshot of 123D Catch's message regarding server shut down.



Appendix 8: render of the analogue camera with 123D Catch.

Appendix 9: Renders of both sample objects obtained with Trnio application

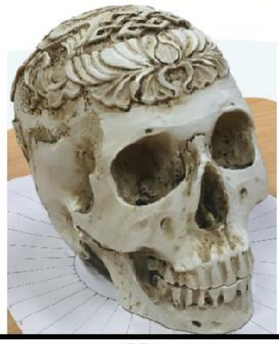
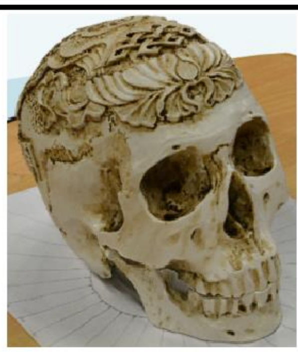
Appendix 10: Two renders of both sample objects obtained with ARC3D



(a) and (c) were obtained using a set of 54 images with an iPhone 6 camera.

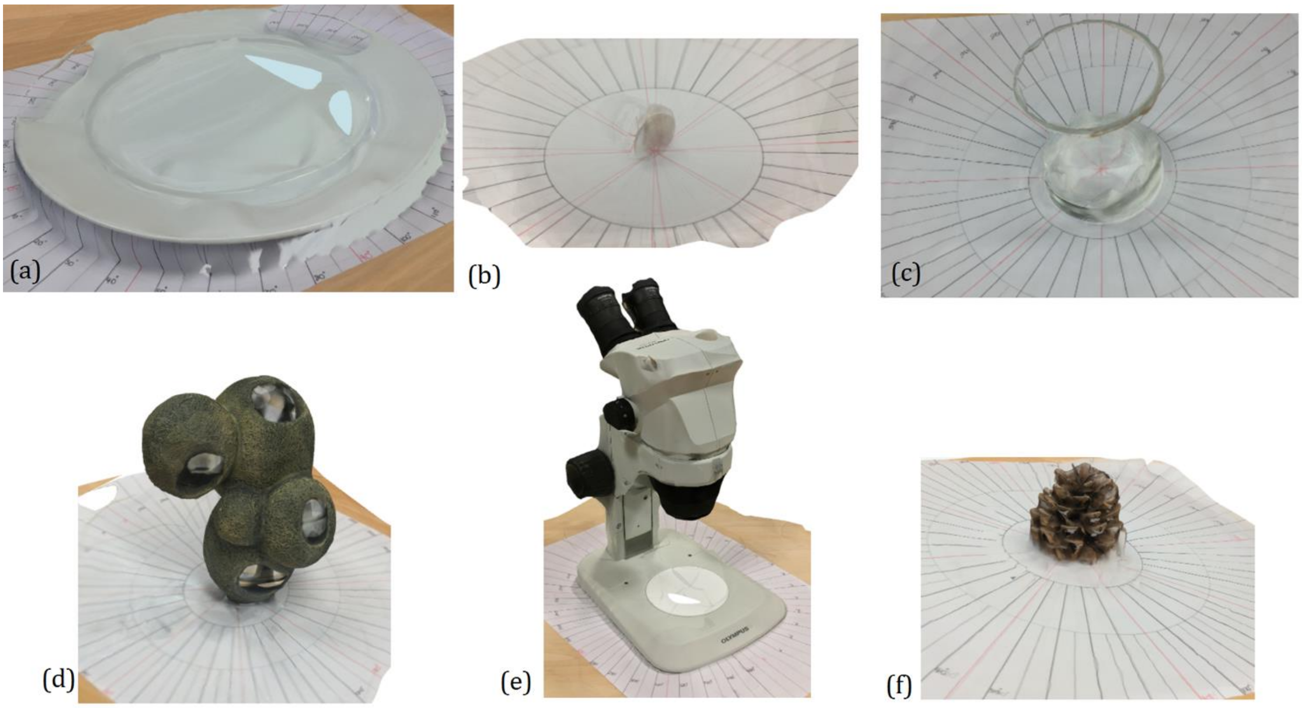
(b) and (d) were obtained using a set of 108 images with an iPhone 6 camera.

Appendix 11: Renders obtained with ReMake from different camera resolutions and exposure settings

	54 Photos	108 Photos
iPhone 4		
iPhone 4 HDR		
iPhone 6		
iPhone 6 HDR		
Nikon D7100		

Appendix 12: Renders of various objects obtained with ReMake to identify object requirements

Image sections (a), (b), (c), (d), (e) and (f) represent the renders of a plate, 20p coin, glass, fish tank rocks, microscope and pinecone respectively.



Appendix 13: Questionnaire handed to users who tested the completed virtual museum

Loughborough University

Testing of Project:
The 3D Digitisation of Museum Artefacts to be Displayed in a Virtual Museum

Participation Question Sheet

Please rate the following set of questions on a scale of 1 to 5, 3 being neutral.

1. How experienced are you with Virtual Reality? ☐
   never experienced 1 – 5 everyday
   a. If you have tried VR previously, which device have you used?

   ____

2. How intuitive did you find the controls to explore the museum? ☐
   illogical 1 – 5 intuitive
3. How realistic are the details in the virtual environment? ☐
   basic 1 – 5 realistic
4. Did the details make the experience less or more immersive? ☐
   less 1 – 5 more
5. Could you differentiate between objects (models) created with a software and scanned objects? ☐
   obvious difference 1 – 5 unnoticeable
   a. If you scored the previous question less than 5, please state a reason why.

   ____

   ____

6. Did you feel any motion sickness or headaches at any point? ☐
   none 1 – 5 constant sickness
7. Would you prefer exploring a virtual museum using a head mounted display (eg: Oculus Rift) or with a mouse and keyboard? Please circle one.

   VR: Oculus Rift **mouse & keyboard**

8. Overall, how would you rate your experience? ☐
   terrible 1 – 5 fantastic

9. Any other comments?

   ____