3D SCANNING AND MODELING FOR MUSEUMS

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Abstract:

This White Paper was created to introduce users to 3D scanning technology. It covers the major 3D scanners available on the market and introduces users to 3D scanning methods, software, file formats, and museum use cases.

TABLE OF CONTENTS

I. 3D Scanning for museums 3

How are Museums using 3D scanning? 3

Cultural Preservation Projects 4

Table 1. Technology and Software used by museums 1

II. 3D Scanning Methods and 3D Scanners 2

Overview of 3D Scanning Methods 2

3D Scanner Comparison Table 11

Overview of Significant Brands of 3D Scanners 13

III. Processing 3D Scans 19

Why 3D Scanning Post-Processing Software is Needed 19

Post-Processing Software Comparison Table 20

Overview of Significant Software Programs for 3D Scanning Post-Processing 21

IV. 3D Modelling Software 23

3D Modelling Software 23

3D Modelling Software Comparison Table 24

Overview of 3D Modelling Software Programs Commonly used with 3D Scanning 25

V. Description of 3D Model Files Formats 27

Overview of Significant 3D Model File Format Types 28

3D Model File Format Comparison Table 30

VI. Suitability of the Above Hardware and Software Components for use in Museums Projects 31

Recommendations for 3D Scanners 31

Recommendations for 3D Scan Post-Processing Software 31

Recommendations for 3D Modelling Software 32

Recommendations for 3D Model File Formats 32

I. 3D SCANNING FOR MUSEUMS

HOW ARE MUSEUMS USING 3D SCANNING?

Museums use 3D scanning for multiple goals, mainly for archival and culture preservation, but also to share information with the scientific community, and increase outreach with the general public by creating virtual exhibits.

Most museums can only display 5% of their collections at a time, which leaves museum assets idle, and buries a wealth of historic information in museum storages. Museums are solving this problem with 3D scanning technology. By scanning objects and producing realistic digital models, museums are increasingly creating virtual exhibits online for their collections. These exhibits are viewed in schools and universities, in research labs, and at homes.

CULTURAL PRESERVATION PROJECTS

Smithsonian Institute

One the most notable museums currently involved with 3D scanning is the Smithsonian Institute. The Smithsonian has used a $100,000 Kinolta Minolta laser scanner for their 3D scanning projects (Terdiman, 2012). The Smithsonian has also used a combination of photogrammetry, lasr scanning and structures light scanning for some objects, such as: the "Greek Slave" statue by Hiram Powers. 3D models created through the 3D scanning process are displayed online using a customized software program created in collaboration with AutoDesk. On the Smithsonian's website they provide 3D models in both the OBJ and the 3D printable STL formats. The Smithsonian Institute has previously made use of 3D Studio Max for presenting 3D models (Smithsonian Science, 2014).

The Smithsonian Institute has scanned a wide range of objects, ranging from fossils to antiques. They have prioritized 10% of their collection to be scanned which amounts to thousands of objects. They have relied on external help for a few of their projects, but for many projects they do their 3D scanning internally (Smithsonian Science, 2014).

Turkana Basin Institute

The Turkana Basin Institute used Artec 3D scanners (Thilmany,_2015). They have also made use of a Faro ScanArm and, for a few test models, a method of photographic 3D scanning that utilized the software programs AutoDesk 123DCatch, AutoDesk ReCap 360, and GeoMagic Studio. The 3D models they created are available online at africanfossils.org, where they are viewable through an Autodesk-powered web-viewer very similar to the one used by the Smithsonian Institute. For this project, fossils from the Turkana Lake Basin that were too fragile to be transported to Nairobi for analysis were digitized to enable study of the objects offsite (Geggel, 2014).

The Museum of Nature

The Museum of Nature in Ottawa, Ontario has been involved in 3D scanning since 2002 (Museum of Nature, 2015). They use an Arius 3D scanner, created by a Canadian company called Arius. In addition to the Arius 3D scanner, the Museum of Nature has also used 3D Studio Max to help finish and animate 3D models, and Adobe Flash to display these models online. The objects they have focused on digitizing are fossils, birds and animals (Canadian Museum of Nature, 2005).

Google Cultural Institute

Google's cultural arm, the Google Cultural Institute (Burns, 2015), has recently moved into 3D scanning. They have a large number of museums working with them, including The Israel Museum and the Los Angeles County Museum of Art. For their 3D scanning projects they rely on their own proprietary, unreleased, 3D scanning technology and post-processing software. They have 3D scanned a diverse range of objects including art, sculptures and antiques.

Threeding and Artec 3D Scanning Service

The 3D printing company Threeding has recently partnered with Artec and begun using Artec's Eva and Spider line of 3D scanners to digitize a number of objects from museum collections. The purpose of this digitization is to allow Threeding to resell 3D printable versions of these 3D models online through their website (Artec, 2015). The main museum mentioned in relation to this project is the Stara

Zagora Regional Museum of History in Bulgaria. Together, Threeding and Artec have 3D scanned figurines, helmets, swords, jewelry, coins and many other objects.

Peabody Museum

In 2013, Harvard's Peabody Museum made use of an Aicon3D structured light 3D scanner (Aicon3D, 2015) to digitize inscriptions from their Corpus of Maya Hieroglyphic Inscriptions collection. Low resolution versions of these models were then made downloadable online, but are no longer accessible through: www.peabody.harvard.edu/3dscan

Hampson Museum

In 2009 the Hampson Museum created a virtual museum collection using, like the Smithsonian, a Konica-Minolta Vivid-based 3D scanning system. Once the 3D models were created these models were made available online in both the VRML and OBJ formats, and also as 3D PDF files (Hampson Museum, 2015). For the project, an extensive array of pottery from the pre-Columbian Nodena Village was 3D scanned.

London Natural History Museum

The London Natural History Museum has made use of a Creaform HandyScan 3D scanner for a recent 3D scanning project (Design Engineering, 2009). They have also made 3D models available for visitors to view inside their museum using virtual reality technology (British Broadcasting Corp, 2015). They have publicized the digitization of dinosaur fossils, including an entire set of stegosaurus fossils (Halterman, 2015).

Metropolitan Museum of Art

New York's Metropolitan Museum of Art (MET) has been involved in a crowd-sourcing campaign that encourages their visitors to utilize Adobe's 123D Capture photographic 3D scanning software. In this campaign they ask visitors to use their phones to take pictures of museum objects, turn these photos into 3D models using the 123D Capture software, and then openly share these 3D models online through the 123D app website: www.123dapp.com/Gallery/catch. They recommend both MeshLab and Netfabb as tools to help their visitors repair their 3D models (MET, 2013).

University of Pennsylvania

The Digital Archaic Heraion Project, undertaken by researchers at the University of Pennsylvania (UPenn), used a Creaform 3D scanner and GeoMagic software to digitize a small collection of objects. The freeware program MeshLab was also used, but the limitations of this program as compared to GeoMagic were noted as making it inefficient. Objects digitized included wooden and stone tiles, and architectural fragments (UPenn, 2015).

Milwaukee Art Museum

The Milwaukee Art Museum used a Creaform scanner to digitize a number of significant objects in its collection. For a large part these objects consisted of 'face jugs' – distinct works of pottery from the region of South Carolina (Mooney, 2012). GeoMagic software suite was used turn the 3D scanned point clouds into 3D models (Cramblitt, 2013).

TABLE 1. TECHNOLOGY AND SOFTWARE USED BY MUSEUMS

Organization	3D Scanner	Post-Processing	Formats	Objects Scanned	Display
Smithsonian Institute	Konica Minolta	GeoMagic	STL, OBJ	Fossils, sculptures, antiques	Downloadable and viewable online
Turkana Basin Institute	Artec, 123D Catch	GeoMagic	STL	Fossils	Downloadable and viewable online
Museum of Nature	Arius3D	N/A	Flash	Fossils, birds, animals	Viewable online
Google Cultural Institute	Google-developed	Google-developed	Google 3D Viewer	Art, sculptures, antiques	Viewable online
Threeding and Artec 3D	Artec	N/A	STL	Figurines, armor, jewelry, coins	For sale on 3D model marketplace
Harvard's Peabody Museum	Aicon3D	N/A	N/A	Stone inscriptions	Downloadable and viewable online
Hampson Museum	Konica Minolta	N/A	VRML, OBJ, PDF	Pottery	Downloadable and viewable online
London Natural History Museum	Creaform	N/A	Virtual Reality	Fossils, dinosaur fossils	Viewable inside museum through virtual reality technology
Metropolitan Museum of Art	123D Capture	MeshLab, NetFabb	N/A	Entire collection	Models hosted on 123D Catch website
University of Pennsylvania	Creaform	GeoMagic	N/A	Wood/stone tiles, architectural fragments	Viewable online
Milwaukke Art Museum	Creaform	GeoMagic	N/A	Pottery	Museum installation

II. 3D SCANNING METHODS AND 3D SCANNERS

OVERVIEW OF 3D SCANNING METHODS

There are four significant methods of 3D scanning: laser scanning, white light scanning (sometimes referred to as structured light scanning), Computer Tomography (CT) scanning, and photographic 3D scanning.

Laser Scanning

Laser scanning is further divided into time of flight and triangulation 3D scanning. Time of flight is best for building-sized scanning, and has low accuracy, on the order of 2mm. Triangulation scanning is the opposite, it's better for scanning smaller objects very accurately, on the order of 0.2mm and smaller.

Laser triangulation scanning is done using laser emitters and cameras. Cameras detect the laser light at varying angles depending where the reflecting surface is in x, y, z space. The contribution of millions of these (x, y, z) coordinate points leads to the creation of a point cloud. Using Radial Based Functions the surface of an object is interpolated and a mesh is created.

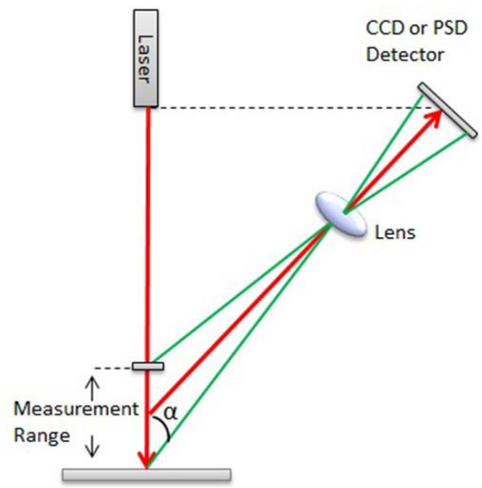

FIGURE 1

Laser triangulation scanning is currently the most accurate method of creating point clouds based on physical objects. Points are typically gathered at a rate of 750,000 points per second. Laser scanning is ideally suited for measuring complex geometries that require a high number of points to ensure accuracy, or objects whose surface is difficult to capture through the 3D scanning process, such as objects made of reflective surfaces like glass and polished metal, or objects that are extremely dark, such as black leather (Laser Design, 2015).

White Light Scanning

White light scanning uses a combination of photography, light and shadows to convert a physical object into a 3D model (ShapeGrabber, 2012). Light is projected onto an object's surface in a patterned design that becomes distorted. Cameras capture this distortion from multiple angles, and a method of triangulation is then used to calculate the distance of specific points on the object. These points are then in turn used to create a point cloud that illustrates an object's surface (Q-Plus Labs, 2014). White light scanning is ideal for larger objects, such as cars or furniture, objects with fixed mobility, or objects with simple, low-curvature surfaces, such as porcelain vases (ShapeGrabber, 2012). However, white light scanning does not capture points as rapidly as laser scanning does. On average white light scanning captures points at a rate of 10,000 to 100,000 points per second (Creaform, 2012).

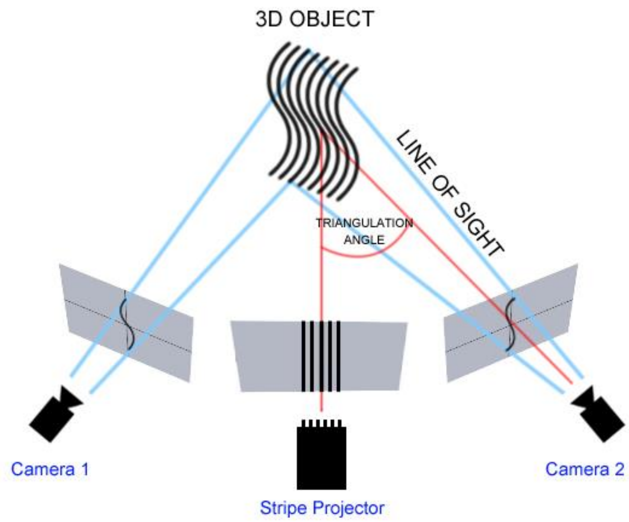

FIGURE 2

Computed Tomography Scanning

Computed Tomography scanning, most often referred to as CT scanning, uses an X-ray emitter and X-ray detector to create a point cloud of the interior structure of an object (Medical News, 2015). The typical CT scanner uses an X-ray generator and receptor which rotate around an object and capture 360 degree perspectives of a single cross section of the object. A computer combines the images of that cross section and calculates what the real object's shape and density distribution is. The object is then typically repositioned to capture a new cross-section. Once the scanning process has finished the resulting cross sections are viewed in 2D or can be can be superposed to create a 3D point cloud that represents the object's interior structure (National Institute of Biomedical Imaging and Bioengineering, 2015). CT scanning is ideal when an objects' structure needs to be non-destructively analyzed, for example with fossil samples within rock or unwrapped mummies.

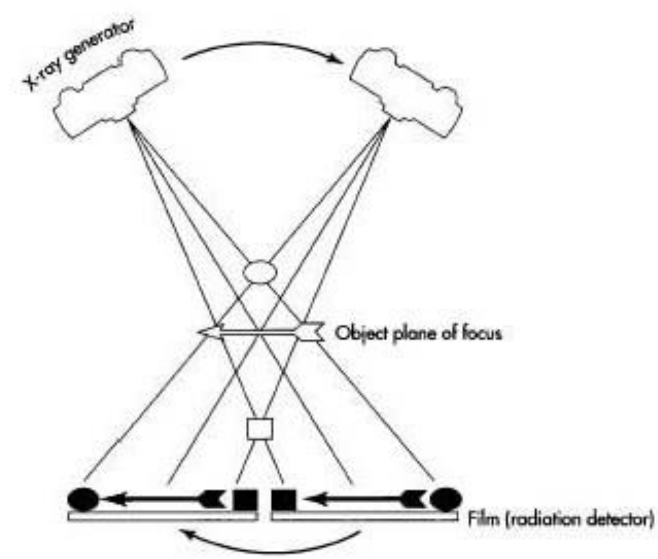

FIGURE 3

Photographic Scanning

Photographic 3D scanning (also known as photogrammetry) is the process of using cameras to take a series of photographs of an object (Photo Modeller, 2015). Using a number of different methods, such as analyzing the shadows, location of common reference points, or different angles of an object in a photograph, these photos are assembled together to create a point cloud, with the number of points in this cloud increasing as the number of photos and perspectives increase (Photo Modeller, 2015). Photographic 3D scanning can use one or multiple cameras. Single camera photogrammetry is ideal for low cost 3D scanning projects, or projects that require only low levels of accuracy.

Factors to Consider when Comparing 3D Scanners

When comparing different 3D scanners it is important to note the accuracy of the scanner, as this represents how well the 3D scanner is able to capture the intricacies of the original object. The scanning range is also important, as this can limit how large of an object can be 3D scanned. A 3D scanner fixed to a certain location, for example, being limited to a set scanning area, won't have the same flexibility for shape of objects that they can scan, or for the locations that they can be used in (Creaform, 2015). It is also important to note whether or not a 3D scanner captures an object's color. Lastly, how well a 3D scanner captures the surface texture of an object must also be considered. For objects with complex surfaces where every small detail is significant, such as fragmented bones, a scanner that captures surface texture very well will be required.

3D SCANNER COMPARISON TABLE

Product Name	Price (USD)	Scanning Type	Range	Accuracy	Texture Quality	Color	Thin	Reflective	Transparent	Dense Black	Stone	Metallic	Suitability for Scanning Objects
Structure Sensor	379	photography	0.4m	4mm	low	√					√	√	Simple objects where only low levels of accuracy are needed. Combined with mobile device can capture color.
Kinect 3D Scanner	500	laser	low	low	low	√					√		Simple objects where only low levels of accuracy are needed.
NextEngine 3D Scanner	3000	laser	0.15m	1.13mm	low	√					√		Simple objects where only low levels of accuracy are needed.
Range Vision 3D Scanner	10000	structured light	2m	0.16mm	medium	√	√		√	√	√	√	Simple, small to medium sized objects
Faro Freestyle 3D	11500	structured light	3m	1.5mm	high					√	√	√	Simple objects where color is not a requirement
Artec Eva Lite	14200	structured light	1m	0.1mm	low					√	√	√	Simple objects where color is not a requirement.
Artec Eva	19800	structured light	1m	0.1mm	medium	√	√			√	√	√	Complex objects with easy to scan surfaces
Creaform Go!Scan 20	25000	structured light	0.38m	0.1mm	medium	√	√		√	√	√	√	Small to large objects requiring medium accuracy levels
Nikon Metrology ModelMaker MMCX	25000	laser	1m	0.16mm	medium	√	√		√	√	√	√	Small to large objects with difficult to scan surfaces

Artec Spider	27000	structured light	0.35m	0.1mm	high	√	√		√	√	√	√	Objects with easy to scan surfaces, but where high levels of accuracies are needed
Faro 3D X330	40000	laser	330m	2mm	high	√	√	√	√	√	√	√	Smaller objects where high levels of accuracy are needed
Creaform MetraScan 70-R	60000	laser	0.15m	0.085mm	medium	√	√	√	√	√	√	√	Small to large objects requiring high accuracy levels
Faro ScanArm	60000	laser	0.15m	0.025mm	high	√	√	√	√	√	√	√	Smaller objects where high levels of accuracy are needed
Creaform MetraScan 2010-R	70000	laser	0.3m	0.085mm	medium	√	√	√	√	√	√	√	Small to large objects requiring high accuracy levels
Konica Minolta VIVID 9i	90000	laser	12m	0.02mm	high	√	√	√	√	√	√	√	Small to large objects with hard to scan surfaces, where high levels of accuracy are required
Konica Minolta Range 5	---	laser	0.75m	0.04mm	hight	√	√	√	√	√	√	√	Small to large objects with hard to scan surfaces, where high levels of accuracy are required

OVERVIEW OF SIGNIFICANT BRANDS OF 3D SCANNERS

Creaform

The Go!Scan 3D and the HandyScan 3D are Creaform's main lines of mobile, hand-held 3D scanners, while the MetraScan 70-R and MetroScan 2010-R are Creaform's main brands of fixed-location 3D scanners.

CREAFORM GO!SCAN 20

Go!Scan 20

- Structure light scanner
- Retails for $25,000 USD (Falconer, 2013)
- Accuracy level of up to 0.1m
- Range of 0.38m
- Texture resolution of 50 to 250 dots per inch (DPI)

HandyScan 300

- White light
- Price of $42,900 USD.
- Accuracy level of up to 0.04mm
- Range of 0.3m
- A reportedly high texture resolution

HandyScan 700

- White light
- Accuracy level of up to 0.03mm
- Range of 0.3m
- High texture resolution

MetraScan 70-R

- White light
- Price of $60,000 USD (Aniwaa, 2015)
- Accuracy level of up to 0.085mm
- Range of 0.15m
- No listed texture resolution

MetraScan 2010-R

- White light
- Price of $70,000 USD
- Accuracy level of up to 0.085mm
- Range of 0.3m

Faro

Faro's main hand-held 3D scanner is the white-light based Freestlye3D. They also sell two fixed-location 3D scanners, the Focus 3D X330 and the ScanArm HD.

FARO FREESTYLE3D

Freestlye3D

- Laser scanner
- Retails for $11,500 USD
- Accuracies of up to 1.5mm
- Range of up to 3m
- Does not capture color

Focus 3D X330

- Laser scanner
- Fixed-location
- Retails for $40,000 USD
- Accuracy of up to 2mm
- Range of up to 330m, which is much larger than the range offered by other 3D scanners

ScanArm HD

- Laser scanner
- Fixed-location
- Retails for an average of $60,000 USD (Laser Scanning Forum, 2015)
- Accuracy rate of up to 0.025mm
- Range is not listed but, due to the length of the scanner's arm, would be within 0.15m
- Texture resolution is reported to be high (Skabek & Kowalski, 2009)

Nikon Metrology

NIKON MODEL MAKER MMCX80

Nikon Metrology offers twelve different, industry specific 3D laser scanning solutions. Their entry level, hand held laser scanner is the Model Maker MMCx80.

Model Maker MMCx80

- Laser scanner
- Retails for $25,000USD (iReviews, 2015)
- Accuracies of up to 0.16mm
- Range of up to 1m
- Difficult to scan surfaces very well

Artec

ARTEC EVA

Artec's two main brands of 3D scanners are the Eva and the Spider. The Spider uses blue light rather than white light for its scanning process, which allows it to capture an object's color and texture with much greater detail.

Artec Eva (lite and full)

- White light scanners
- Lite version costs $14,200 USD, full version costs $19,000 USD
- Both offer accuracies of up to 0.1mm
- Both have ranges of up to 1m
- The lite version does not record the color of objects

Artec Spider

- Blue light scanner
- Retails for $27,000 USD
- Accuracy up to 0.1mm
- Range of up to .35m
- Texture resolution of 1.3 mega-pixels

Range Vision

Range Vision 3D scanner

- Retails for $10,000 USD
- Accuracy of up to 0.16mm
- Range of 2m
- Ability to capture texture reviewed as mid-range quality (iReviews, 2014)

RANGE VISION 3D SCANNER

Konica Minolta

The Vivid 3D scanner is Konica Minolta's main line of 3D scanners. Within the Vivid line there are the Vivid 9i and the Vivid 910 scanners.

KONICA MINOLTA VIVID 9I

Vivid 9i

- Retails for $90,000 USD
- Accuracy of up to 0.02mm
- Range of roughly 12m
- Faster capture rate than the Vivid 910
- Reviewed as being the best choice for cultural preservation projects (3DscanCo, 2015)

NextEngine 3D Scanner

NextEngine 3D Scanner

The NextEngine 3D scanner is a low cost 3D scanner similar in cost and performance to other low-cost options such as the MakerBot Digitizer, the Rubicon 3D, the Fuel3D, and the Matter and Form 3D scanner.

NextEngine 3D scanner

- Retails for $3,000 USD
- Accuracy of up to 0.127mm
- Range of 0.15m
- Surface texture capture low (Polo and Felicismo, 2012)

Microsoft's Kinect 3D Scanner

Microsoft's Kinect 3D scanner can be used as a low-cost laser scanning option if paired with the appropriate software.

Microsoft Kinect

- Retails for $300 USD
- Must be paired with software such as Skanect
- Retails for $200 USD
- Accuracy of 2-3mm

Structure Sensor

Similar to the Kinect, the Structure Sensor is a device that can be paired with an iPad in order to create quick, rapid 3D scans at a relatively low cost.

STRUCTURE SENSOR

Structure Sensor

- Retails for $379 USD
- Mainly intended to scan rooms
- Uses open sources software
- Requires a free app called ItSeez3D for object scanning
- Accuracy of up to 4mm
- Range of 0.4m

123D Catch

123D Catch is a free Autodesk app that allows for the generation of 3D models from photos. While this technology has the potential to open 3D scanning technology to a much larger audience – essentially anyone with a smart phone – the process of creating a 3D model is fairly difficult, and the results are often poor, as can be seen browsing the newly submitted models on the 123D Catch website: http://www.123dapp.com/Gallery/catch

III. PROCESSING 3D SCANS

WHY 3D SCANNING POST-PROCESSING SOFTWARE IS NEEDED

The 3D scanning process creates a point cloud. This point cloud consists of millions of separate points that, taken together, map out the surface of an object. While it is fairly easy to create a point cloud, to turn the point cloud into a fully formed 3D model requires much more work (ShapeGrabber, 2012).

Problems can often emerge when converting point clouds into 3D models. During the 3D scanning process overlapping points are commonly recorded, which can create issues when building a 3D model. 3D scanning can also record irrelevant points, or fail to record points for a certain area of an object, which can create undesired holes in the object's surface when the point cloud is converted into a 3D model (ShapeGrabber, 2012). To create a 3D printable model, this process is even further complicated, as the 3D model needs to have a perfectly formed surface – which is commonly referred to as being "water tight".

Following the 3D scanning process, post processing software offers many different tools to help turn point clouds into finished 3D models. These tools include subsampling, where the data contained in the point cloud is reduced to make it more manageable. This is followed by a reconstruction process, whereby triangles are drawn between sets of three points, after which the triangles are joined together to build the surface of the model. If the model's color was recorded, the color is then mapped back onto the corresponding vertices of the model (Meshlab, 2009).

Post-processing software programs will usually offer a tool that will use a mathematical function to create an average of the points in a point cloud that match a model's surface, and then remove any points that fall too far outside of this average. Many programs also provide tools for both the automatic filling of holes in a model's surface, and manual tools for more precise surface reconstruction, or for further repairing the surface after it has been automatically constructed (GeoMagic, 2015). Post-processing software commonly offers a tool for decimation as well, which eliminates triangles in a 3D model to reduce the overall file size. The appearance of the 3D model is supposed to be left unchanged, but how well the original appearance of the model is preserved will depend on the program (Shapeways, 2015).

Post-processing software programs commonly export completed 3D models into a wide variety of file formats, including formats related to CAD design, 3D animation and, in some cases, 3D printing.

Factors to Consider when Comparing Post Processing Software

When comparing different post-processing software programs the most important feature to consider is how accurately the program can create a 3D model, based on a point cloud, which best matches the original object. This refers not only to the program's automated process of converting point clouds into 3D models, but also the tools the program provides to allow the user to further repair any inaccuracies and ensure that the 3D model is as close to the original object as possible.

POST-PROCESSING SOFTWARE COMPARISON TABLE

Name of Program	Price (USD)	Filling holes in scans	Fixing scan surfaces	Aligning texture to surface	Filling in missing data
Meshlab	0	Low	Low	Low	N/A
Memento	0	Medium	Low	Low	Low
NetFabb	299	Medium	Medium	N/A	N/A
3D Reshaper	800	Medium	High	Medium	Medium
GeoMagic	15000	High	High	High	High
Polyworks Modeller	20000	High	High	Medium	Medium

OVERVIEW OF SIGNIFICANT SOFTWARE PROGRAMS FOR 3D SCANNING POST-PROCESSING

GeoMagic

GeoMagic is a powerful software suite that helps users turn point clouds into fully formed 3D models. Within the GeoMagic suite, the program directly related to the 3D scanning process is GeoMagic Wrap. GeoMagic wrap offers a number of tools for cleaning and perfecting 3D scan data.

- Retails for $15,000 USD
- Automatic re-meshing tools to turn points clouds into 3D models
- Automatic removal of points or triangles too far from the model's surface
- Polygon editing tools to fill holes in the surface of 3D models
- Tools to ensure 3D models are 3D printable
- Highly regarded for maintaining the texture of objects (Laser Scanning Forum, 2013)

3D Reshaper

3D Reshaper offers many features similar to GeoMagic Wrap. These features include the cleaning of point clouds to remove unwanted or unrelated data. The program can also be used to fill holes in the surface of a point cloud, and to repair surfaces that have not been properly scanned.

- Retails for $8,000 USD
- Automatic re-meshing tools to turn point clouds into 3D models
    - Reported as being less accurate than GeoMagic for this (Laser Scanning Forum, 2013)
- Automatic or manual hole repair for 3D model surfaces
- Removing of unwanted points or triangles

Polyworks Modeler

Polyworks modeller has a number of plug-ins that allow it to work directly with many common 3D scanners, such as those produced by Creaform and Artec. The program's features allow users to clean and smooth the surfaces of 3D scans, and better ensure that a 3D model's surface texture matches that of the original object.

- Retails for of $20,000 USD (Direct Dimensions, 2015
- Clean and smoothing 3D scan surfaces
- Surface texture repair
- Generate meshes for 3D models

Meshlab

Meshlab is a free, open-source program with many powerful features for cleaning point clouds created through the 3D scanning process. Meshlab allows users to remove excess data captured by a 3D scanner that is not meant to be part of the completed 3D model. Meshlab also allows users to merge multiple, incomplete scans into a single 3D model, creating a more complete result.

- Free
- Automatically creates meshes for 3D models
- Automatically removes scan data not part of the original object
- Repairs the surfaces of 3D models
- Reduces overall polygons within a 3D model
- Does not provided the same level of point cloud repair or accuracy as GeoMagic and 3D Reshaper (Landes, T., et al., 2013)

NetFabb

Netfabb is a software program used primarily for closing holes in 3D models and preparing 3D models for the 3D printing process. While NetFabb is available for free, there are a number of restrictions attached to the free version. Besides the free version, two professional version exist: NetFabb private and NetFabb professional. The private version retails for $299 USD while the professional version retails for $1799 USD. The main difference between them is that NetFabb professional, in addition to processing 3D models to ensure that they are 3D printable, also allows users to break models into different pieces that can be 3D printed separately and then assembled afterwards to create a larger object.

AutoDesk Memento

AutoDesk Memento is a software program intended to simplify the process of cleaning and repairing 3D scans. It is able to generate 3D models based on photos, using the photogrammetry scanning process and also by using scan data captured by 3D scanners. AutoDesk Momento aids in the process of perfecting 3D scan-based models, and helps users optimize 3D models for 3D printing, web displays and mobile phones.

IV. 3D MODELLING SOFTWARE

3D MODELLING SOFTWARE

3D modelling software is commonly used to both modify and manipulate 3D models created through the 3D scanning process. Common tasks performed with 3D modelling software are the enhancing of models (such as emphasizing certain features or traits), animating 3D models, and creating backgrounds or renderings that allow a 3D model to be better visualized (PC Mag, 2015). An example of this would be an animation that takes various 3D models based on a set of dinosaur fossils, assembles these fossils, and then animates the completed object in order to illustrate how the dinosaur might have moved.

3D modelling software is typically divided between CAD-based modelling software, such as Autodesk or SolidWorks, and animation-based software such as 3D Studio Max, Maya 3D and Rhino3D. For CAD-based software there is a focus on functional design, whereas for animation based modelling software the focus is on presentation, such as creating scenes and animations. While both types of software can be used to better visualize 3D models created through the 3D scanning process, it is the 3D animation software that will likely have the most applications for museums and other cultural heritage institutions (AutoDesk, 2011).

3D MODELLING SOFTWARE COMPARISON TABLE

Program Name	Price (USD)	Animation	Scene Rendering	Web presentations	3D Printing
Blender3D	0	√	√	√	
Rhino3D	395			√	
Wirefusion	399			√	
Unity	1500	√		√	
3D Studio Max	3675	√	√	√	
Maya	3675	√	√	√	
AutoCAD	6295				√
SolidWorks	10000				√

OVERVIEW OF 3D MODELLING SOFTWARE PROGRAMS COMMONLY USED WITH 3D SCANNING

3D Studio Max

3D Studio Max retails for a one time purchase of $3,675 USD or an annual fee of $1,470. Monthly and quarterly fees are also available. 3D Studio Max is a 3D modelling and 3D animation program used by a large number of animators and designers. It allows for the creation of 3D models, the customization of 3D models, and the ability to animate 3D models and render them in various scenes. 3D Studio Max also allows for models to be exported into a variety of file formats, including formats that would be suitable for web animations.

Maya

Maya retails for a one time purchase of $3675 USD, but is also available for time-limited licenses, such as a $185 per month license. While Maya is similar to 3D Studio Max, it is especially notable for its use in 3D animation. It has many powerful features to bring 3D models to life, either through rendered scenes or full animations. It also has much to offer in terms of web displays or in-person displays utilizing technologies such as video screens and holographic projection (Digital Tutors, 2015).

SolidWorks and AutoCAD

SolidWorks and AutoCAD are both Computer Aided Design (CAD) based programs commonly used for 3D scanning projects. SolidWorks retails for a $10,000 USD professional license, while AutoCAD retails for $6295 for a one-time purchase, with additional charges to upgrade to newer versions.

In terms of visualizing and modifying models, since CAD software is focused on design rather than presentation (AutoDesk, 2011), they offer little in terms of rendering 3D models, and nothing in terms of animation. CAD programs such as SolidWorks and AutoCAD can be very useful in ensuring 3D models are 3D printable, but this is something that can also be done through similarly priced 3D scan processing software such as GeoMagic.

Rhino3D

Retailing for $395 USD, Rhino3D is as a lower cost alternative to 3D Studio Max. Like 3D Studio Max, it has a number of 3D modelling features that allow users to improve and manipulate a 3D model, or place a 3D model within a larger scene. In terms of animation, however, Rhino3D does not have nearly the same number of features as 3D Studio Max or Maya do, and so would be less suitable for projects involving animation related work.

Blender3D

Blender is a free, open source program created as an alternative to 3D modelling programs like Maya and 3D Studio Max. As a free product, Blender does not have the same support or range of features as Maya or 3D Studio Max. It has a fairly large user base, however, and is becoming increasingly comparable to these professional programs.

Unity, Wirefusion, and Autodesk A360 Viewer

There are a number of software programs available for simplifying the process of displaying 3D models on webpages. Notable programs include Unity, Wirefusion and the AutoDesk A360 Viewer. These three programs all offer a fairly smooth, simplified process for presenting 3D models on websites and allowing users to interact with them. These programs are fairly limited in comparison to what programs like 3D Studio Max and Maya are capable of, but excel at creating engaging web-based presentations. Unity Pro is available for a single purchase of $1,500 USD or $75 per month. Wirefusion professional retails for $399 USD. The Autodesk A360 Viewer, as it is still a beta product, does not yet have a listed price.

Other Web Display Methods

Besides Unity, Wirefusion, and the Autodesk A360 Viewer, there are several other methods of displaying 3D models online. One of these methods is through the use of Adobe Flash, the downside of Adobe Flash being that users need to have the Flash plug-in installed (Adobe, 2009).

WebGL is another common method of displaying 3D models online. WebGL is essentially a set of java libraries that can be used to display 3D models within web browsers. The downside of WebGL is that it requires HTML5 in order to work properly, which is not support by all browsers, and that 3D models displayed through WebGL can be slow to load (Bourke, 2013). WebGL has been used by museums previously, including the Smithsonian Institute's X3D project (Smithsonian Institute, 2015)

A third method of displaying 3D models online is iframe, or inline frames, which allow for the embedding of web based 3D model viewers within a webpage (Mozilla, 2015). With iframes, a 3D model could be hosted using a secondary website such as SketchFab.com, and a link to the SketchFab-hosted 3D model then embedded within an iframe. The downside to this is that the 3D models would need to be hosted on an external server, which may not always be possible.

V. DESCRIPTION OF 3D MODEL FILES FORMATS

Different 3D model file formats allow for 3D models to be used by different programs. File formats typically vary in terms of their file size, the level of detail they are able to store, and whether or not they support textures (McHenry and Bajcsy, 2008). Additionally, some 3D model file formats are designed for specific purposes, such as for 3D printing or for web displays.

In terms of cultural preservation, it is important to consider the life time of a file format and whether or not the format is suitable for archival purposes. A file format used by only a small number of people has less chance of still being supported fifty years into the future. A 3D model intended to be preserved for a long period of time could become unusable, such as has been the growing issue with VHS tapes, and the data could eventually become unrecoverable economically.

When a 3D model is being made available to researchers, it is also important to consider the level of quality that a file format provides. Researchers typically require a very high level of quality in order to benefit from viewing or analysing a 3D model (Bennett, 2015). An example of this is the difference between models stored in the PLY and OBJ formats. The PLY format is much smaller in size, and so would be easier to store and share. The OBJ format, however, allows for much greater detail. In a case where a 3D model is being used by researchers, despite its much larger file size, the OBJ format would be preferable as it would offer researchers much more detail to analyze.

When choosing a file format another consideration is whether the format is open-source or proprietary. For proprietary formats, these can typically only be used by a small number of expensive software programs. Open-source formats, on the other hand, are useable by a wide range of software programs, including many free options. This factor makes open-source formats the preference for 3D models being shared with a large number of users.

Another issue to consider is that changing between different file formats creates a risk of losing information stored in the previous format. Thus, ideally, a 3D model should be saved in a format that makes it useable by the largest amount of users, without these users needing to convert the model into additional formats (McHenry and Bajcsy, 2008). If the model is intended to be used largely by animators, for example, it may be a good idea to provide the model in an animation-related format such as MAX.

OVERVIEW OF SIGNIFICANT 3D MODEL FILE FORMAT TYPES

3D Scan Based File Formats

Every 3D scanner will have a file format proprietary to the company that manufactures it. As such, there are an extremely large number of file formats that exist in this area. The problem with these formats is that, for them to be used, the user needs access to proprietary 3D scanning software. Thus the number of users who could use 3D models stored in these formats would be very limited. Contrary to this, the benefit of storing models in a 3D scanner-based format is that the highest level of accuracy for the original object would be preserved. Most software that comes bundled with 3D scanners will export 3D models to a wide variety of formats, including those used for animation and Computer Aided Design (CAD) design.

Computer Aided Design File Formats

Computer Aided Design (CAD) is a broad term used to represent file formats intended for manufacturing processes. Of the many CAD formats available, two of the most popular are the Initial Graphics Exchange Specification (IGES) and the Automation systems and integration — Product data representation and exchange (STEP) formats. As these formats are both open source they can be used by essentially all CAD programs and, as such, the largest amount of users. In contrast to this, other proprietary CAD formats such as the SolidWorks specific SLDPRT format, only allow users who own a specific – and often expensive – software program to interact with the model.

Animation Related File Formats

Animation related 3D model file formats have the same division regarding proprietary and open source as CAD models do. Thus the same general practice principal of using open source formats over proprietary formats is true for animation-based file formats as well. The Waveform Object (OBJ) format is the format most commonly used by museums to share 3D models online, the significant example of this being the Smithsonian Institute. There are a large number of software programs that can view models in the OBJ format, including many free programs. The 3D Studio Max specific format MAX, on the other hand, requires users to have access to this software program, which will only be possible in a smaller number of cases.

Web-Specific File Formats

The two main 3D model file formats used to share models online are the Virtual Reality Modelling Langue format (VRML), which typically ends in a .WRL extension, and the Extensible 3D Graphics format (X3D). VRML emerged in the 1990s while X3D is a newer development. In terms of preservation and long-term use, museums and archives are currently recommending X3D as the format that 3D models be shared under for web-based presentations (Web3D, 2014). The reason for this is that the X3D format is open source as well as the format currently being supported by the Web3D Consortium as the successor to VRML.

3D Printing File Formats

The file format most commonly associated with 3D printing is the stereolithography file format, or STL. CAD-based programs are especially well designed to export 3D models in the 3D printable STL format. Animation based modelling programs such as 3D Studio Max can also export to the STL format, but these programs do not verify that the model is actually 3D printable, which can result in problems when users attempt to 3D print it. Many free programs, such as MeshLab and NetFabb, are also able to convert models from a variety of formats into the 3D printable STL format.

Outside of the STL format, the VRML file format can also be used for 3D printing. There are a very small number of 3D printers that allow for the VRML format, however. Most notable of these is the full-color ZPrinter, which uses the VRML format to duplicate an object’s texture.

The Smithsonian Institute, for its current collection of online 3D scan-based models, provides STL files for every 3D model in its collection.

3D MODEL FILE FORMAT COMPARISON TABLE

Extension	Full File Name	Open Source or Proprietary	Web Displays	3D Printable	Animation	In Use by Museums
3DS	3D Studio Max Native Format	Open source			√	**√**
MAX	3D Studio Max Scene	Proprietary			√	**√**
PLY	Polygon File Fomat	Open source				**√**
3DM	Rhino3D File Format	Proprietary			√	
STL	Stereolithography File Format	Open source		√		**√**
OBJ	Wavefront Object	Open source	√		√	**√**
X3D	Extensible 3D Graphics	Open source	√			**√**
WRL	Virtual Reality Modelling Language	Open source	√	√		**√**
STEP	Product data representation and exchange	Open source	√			
MA	Maya File Format	Proprietary			√	
IGES	Initial Graphics Exchange Specification	Open source	√			

VI. SUITABILITY OF THE ABOVE HARDWARE AND SOFTWARE COMPONENTS FOR USE IN MUSEUMS PROJECTS

RECOMMENDATIONS FOR 3D SCANNERS

When selecting a 3D scanner it is important to note features such as the mobility of the 3D scanner, the ability of the 3D scanner to capture a model's surface texture and color, and how well the 3D scanner can handle difficult to scan surfaces such as glass or polished metal.

Whether or not a 3D scanner with a high accuracy range is required will depend entirely on what objects are being scanned. If the object has a complex surface with a number of curves or other intricacies, or if the object consists of a difficult to scan material such as glass, then it is likely that a highly accurate scanner, such as the Konica Minolta VIVID 910, will be required to capture the object in detail. Otherwise, for objects with simpler structures, such as a collection of clay pottery, a scanner with medium-range accuracies of around 0.1mm, such as the Artec Eva or Creaform Handyscan, will be all that is required.

For more specialized objects, such as a collection of glass sculptures or a room-sized object, more consideration must be placed into what 3D scanner will be needed. For the example of the room sized object, a scanner that can capture extremely large objects such as the Faro Focus 3D XX0 would be required. For the example of the glass sculptures, a scanner capable of capturing the complexities of their surface, such as the Konica Minolta VIVID 910, would be required. As such, what type of objects are being scanned is very important to consider when selecting a 3D scanner.

RECOMMENDATIONS FOR 3D SCAN POST-PROCESSING SOFTWARE

For 3D scanning projects where high levels of accuracy are needed, post-processing software such as GeoMagic or Polyworks will also be required. GeoMagic or a similar program will be especially important when 3D scanning transparent, highly reflective, or intricate objects, as these are the objects mostly likely to have errors in the point clouds created through the 3D scanning process.

For simpler objects, such as wood and stone carvings, the software that comes bundled with most 3D scanners should be suitable for 3D model construction. In a number of examples, such as the 3D scanning projects undertaken by the Smithsonian Institute and the Turkana Basin Institute, GeoMagic was relied on for cleaning and repairing scan data (see Table 4, Section 6.2).

While there are free options for cleaning 3D scans, most notably MeshLab, the inefficiency of these free programs to clean 3D scan data at the same level as programs such as GeoMagic has been noted by a number of researchers, including those at the University of Pennsylvania (UPenn, 2015

RECOMMENDATIONS FOR 3D MODELLING SOFTWARE

For 3D modelling programs, those that best relate to museum and cultural preservation projects are 3D animation related programs such as 3D Studio Max and Maya. These programs offer users not only the ability to clean and repair 3D models, but also the ability to animate these models, and better present them to their users.

In terms of 3D printing, or 3D printing related projects, it is typically CAD software that best enables a 3D model to be successfully 3D printed, which is much more difficult to do when using 3D animation software. Creating 3D printable models could also be achieved using a post-processing software program such as GeoMagic, however.

Ultimately, unless a museum is entirely focused on 3D scanning models meant to be 3D printed, 3D modelling programs such as Maya or 3D Studio Max would be the best solution. Beyond cleaning and improving 3D models, these programs also allow for the creation of displays or animation featuring 3D models. 3D Studio Max has been used in a number of notable museum projects, including projects undertaken by the Museum of Nature in Ottawa, Ontario, and by the Smithsonian Institute (Smithsonian Science, 2014).

RECOMMENDATIONS FOR 3D MODEL FILE FORMATS

3D Model Archiving

For archival purposes, it is a good idea to store the 3D model in the format originally created by the 3D scanner, as this format will contain the highest level of detail. This original scan data may be used for the creation of new 3D models based on this original data at a later time, possibly with the addition of new scan data. If this data is not preserved, the scanned object would need to be re-scanned if there was a need for any new 3D models to be created.

Specialized File Formats

Once a 3D model has been created from a point cloud, the 3D model should be exported to the file format that best represents the needs of those who will be working with it. If the 3D model will be used by animators, it should be exported to the format that matches the software they will be working in. In terms of CAD software, this would be a format such as IGES, or in the case of 3D Studio Max, the MAX file format. If the 3D model is meant to be publicly downloadable, or to be shared with a large group of people, it should be stored in an easily accessible, open-source format such as OBJ, which is the format used by the Smithsonian Institute for this purpose (Smithsonian Institute, 2015).

File Sizes

When selecting a 3D model, it is also important to be aware of the file size. A file format such as PLY, for example, will have a relatively small file size, while the OBJ file format will have a much higher file size. As the file size increases the overall quality of the 3D model typically increases as well. If a 3D model is meant to be downloaded, or shared between users, an extremely large file with a size such as 1 or 2 gigabytes could make sharing the 3D model an issue, and could also lead to problems in terms of archiving the 3D model.

3D Printing

In cases where a 3D model is meant to be 3D printed, the format most commonly used is the STL format. Examples of this include the Smithsonian Institute (Smithsonian Institute, 2015), as well as the 3D scanning project undertaken by Threeding and Artec (Artec, 2015). The problem with the STL format, however, is that the object's texture is not captured. In cases where a full-colored 3D print is required, then the best option would be to store the model in the VRML file format in addition to the STL format.

Web Based 3D Models

In terms of web based 3D models, the format currently recommend by archivists for long-term preservation is the X3D format (Web3D, 2014). This format allows for 3D visualizations that can easily be rendered within a web browser, and has become a standard for 3D-based web displays.

Credits

This document was created for AureXus in collaboration with Michael Groenendyk.

References

123Kinect. (2010). Kinect's Accuracy Analysed. Retrieved from http://123kinect.com/kinect-forums/thread-3729.html

3DScanCo. (2015). Konica Minolta Vivid 9i / 910. Retrieved from http://www.3dscanco.com/products/3d-scanners/3d-laser-scanners/konica-minolta/

Aicon3D. (2015). Aicon3D. Retrieved from http://aicon3d.com/start.html

All3DP. (2015). Artec Eva 3D Scanner. Retrieved from https://all3dp.com/Artecs-eva-fastest-way-enter-3d-world/

Aniwaa. (2015). Compare 3D scanner. Retrieved from http://www.aniwaa.com/3d-scanners/compare-3d-scanners/

Artec. (2015). Threeding uses Artec 3D scanners to add historical museum of Stara Zagora relics to collection of 3D printable models. Retrieved from http://www.Artec3d.com/news/Threeding+uses+Artec+3D+scanners+to+add+historical+museum+of+Stara+Zagora+relics+to+collection+of+3D+printable+models_32797

AutoDesk. (2015). Comparison between AutoCad 3D modelling and 3DS Max. Retrieved from https://forums.autodesk.com/t5/autocad-2010-2011-2012/comparison-between-autocad-3d-modeling-and-3dsmax/td-p/3180250

Bennett, M. (2015). Evaluation the creation and preservation challenges of photogrammetry-based 3D models. Retrieved from http://digitalcommons.uconn.edu/cgi/viewcontent.cgi?article=1057&context=libr_pubs

Bourke, B. (2013). What is webgl and why should you be using it? Retrieved from http://wallblog.co.uk/2013/08/13/what-is-webgl-and-why-should-you-be-using-it/

British Broadcasting Corp. (2015). British Museum offers virtual reality tour of Bronze Age. Retrieved from http://www.bbc.com/news/technology-33772694

Bryce, E. (2015). The British Museum uses 3D scanning to bring artifacts to life. Retrieved from

Burns, C. (2015). Google expands online museum with 3D objects. *SlashGear*. Retrieved from http://www.slashgear.com/google-launches-online-museum-of-3d-objects-09378058

Canadian Museum of Nature. (2005). Annual Report. Retrieved from http://nature.ca/pdf/ann05-06nature_e.pdf

Crambliit, B. (2013). Recreating 19th-century face jugs with 3D scanning and printing technology. Retrieved from https://boingboing.net/2013/01/02/recreating-19th-century-face-j.html

Creaform. (2012). Short-range 3D scanning technologies: an overview. Retrieved from http://www.creaform3d.com/blog/2012/12/short-range-3d-scanning-technologies-an-overview/

Creaform. (2015). Differentiation of 3D scanners and their positioning method when applied to pipeline integrity. Retrieved from http://www.creaform3d.com/sites/default/files/assets/technological-fundamentals/differentiation_of_3d_scanners_and_their_positioning_method_when_applied_to_pipeline_integrity.pdf

Design Engineering. (2015). Creaform sells 1,000th laser scanner. Retrieved from http://www.design-engineering.com/general/creaform-sells-1000th-laser-scanner-10650/

Digital Tutors (2015). 3ds Max vs Maya: is one better than the other? Retrieved from http://blog.digitaltutors.com/3ds-max-vs-maya-is-one-better-than-the-other/

Direct Dimensions. (2015). Software. Retrieved from http://www.innovmetric.com/en/products/polyworks-modeler

Exact Metrology. (2015). Laser or white light 3D scanning? Retrieved from http://www.exactmetrology.com/3d-scanning-technology/white-light-scanning

Exact Metrology. (2015). High Resolution 3D Scanner Artec Spider. Retrieved from http://www.exactmetrology.com/metrology-equipment/artec-3d-scanner/spider

Falconer, J. (2013). Creaform's GO!Scan makes large-scale 3D scanning quick and easy. Retrieved from http://www.gizmag.com/creaform-goscan-hand-held-3d-scanner/27241/

Geggel, L. Giant fossils get renewed life with 3D scans. *Live* Science. Retrieved from http://www.livescience.com/49292-3d-fossil-scanning-turkana.html

GeoMagic. (2015). Key Features of GeoMagic Wrap. Retrieved from http://www.geomagic.com/en/products/wrap/features/

Griffiths, S. (2015). A glimpse beneath the bandages. Retrieved from http://www.dailymail.co.uk/sciencetech/article-3162711/A-glimpse-beneath-bandages-Egyptian-child-mummy-gets-CT-scan-bid-uncover-secrets.html

Halterman, T. (2015). Sophie the Stegosaurs 3D scanned for London Museum of Natural History Project. *3Dprint.* Retrieved from http://3dprint.com/45856/stegosaurus-3d-scanned/

Hampson Museum. (2015). The Virtual Hampson Museum. Retrieved from http://hampson.cast.uark.edu/about_models.htm)

Hoffman, V. (1998). A brief history of 3D scanning. Retrieved from http://vr.isdale.com/3DScanners/3d_scan_history/history.htm

Johnson, S. (2015). What is a point cloud? wiseGeek. Retrieved from http://www.wisegeek.com/what-is-a-point-cloud.htm

iReviews. (2014). RangeVision RV 3D Advanced. Retrieved from http://3d-scanners.ireviews.com/rangevision-rv-3d-advanced-review

iReviews. (2015). Nikon Modelmaker MMCX. Retrieved from http://3d-scanners.ireviews.com/nikon-modelmaker-mmcx-review

Landes, T., Waton, M. D., Alby, E., Gourvez, S., & Lopes, B. (2013). 3D Modeling of headstones of the 2nd and 3rd century by low cost photogrammetric techniques. *ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *1*(2), 397-402.

Laser Design. (2015). What is 3D scanning. Retrieved from http://www.laserdesign.com/what-is-3d-scanning

Laser Scanning Forum. (2013). GeoMagic Wrap. Retrieved from https://www.laserscanningforum.com/forum/viewtopic.php?f=122&t=6050

Laser Scanning Forum. (2015). Faro's new hand scanner. Retrieved from https://www.laserscanningforum.com/forum/viewtopic.php?f=21&t=8047&start=20

Levoy, M. (2002). What is 3D scanning hard? Retrieved from https://graphics.stanford.edu/talks/3Dscanning-3dpvt02/3Dscanning-3dpvt02.ppt

McHenry, K & Bajcsy, P. (2008). An overview of 3D data content, file format and viewers. Retrieved from http://www.archives.gov/applied-research/ncsa/8-an-overview-of-3d-data-content-file-formats-and-viewers.pdf

Medical News. (2015). CT Scans: How do they work? Retrieved from http://www.medicalnewstoday.com/articles/153201.php

Mendoza, H. (2014). Berlin's museums integrate 3D printing & scanning in several unique ways. Retrieved from http://3dprint.com/9323/berlin-museum-3d-printing/

Meshlab. (2009). Meshing Point Clouds. Retrieved from http://meshlabstuff.blogspot.ca/2009/09/meshing-point-clouds.html

MET. (2013). 3D Scanning, Hacking, and Printing in Art Museums, for the Masses. Retrieved from http://www.metmuseum.org/about-the-museum/museum-departments/office-of-the-director/digital-media-department/digital-underground/posts/2013/3d-printing

Mooney, C. (2012). From the chipstone collection – of ghosts and speculation. *Milwaukee Art Museum*. Retrieved from http://blog.mam.org/2012/07/03/from-the-chipstone-collection-of-ghosts-and-speculation/

Mozilla. (2015). <iframe>. Retrieved from https://developer.mozilla.org/en/docs/Web/HTML/Element/iframe

Museum of Nature. (2015). Arius3D Imaging Center. Retrieved from http://nature.ca/puijila/fb_3d_e.cfm

National Institute of Biomedical Imaging and Bioengineering. (2015). Computed Tomography (CT). Retrieved from http://www.nibib.nih.gov/science-education/science-topics/computed-tomography-ct

PC Mag. (2015). Definition of 3D Modelling. Retrieved from http://www.pcmag.com/encyclopedia/term/37074/3d-modeling

Photo Modeler. (2015). Photo Modeler Scanner. Retrieved from http://photomodeler.com/products/scanner/default.html

Polo, M & Felicisimo, A. (2012). Analysis of uncertainty and repeatability of a low-cost 3D laser scanner. Retrieved from http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3444090/

Q-Plus Labs. (2014). 3D scanning basics: how structured light scanning works. Retrieved from http://info.qpluslabs.com/blog/3d-scanning-basics-how-structured-light-scanning-works

ShapeGrabber. (2012). Optical 3D Scanning: Laser Beam or Structured Light. Retrieved from http://blog.shapegrabber.com/2012/06/optical-3d-scanning-laser-beam-or-structured-light.html

Shapeways. (2015). Polygon Reduction with Meshlab. Retrieved from http://www.shapeways.com/tutorials/polygon_reduction_with_meshlab

Skabek & Kowalski. (2009). Building the models of cultural heritage objects using multiple 3D scanners. Retrieved from http://www.researchgate.net/publication/228850822_Building_the_Models_of_Cultural_Heritage_Objects_Using_Multiple_3D_Scanners

Skanect. (2015). Skanect. Retrieved from http://skanect.occipital.com/

Smithsonian Institute. (2015). X3D. Retrieved from http://3d.si.edu/

Smithsonian Science. (2014). A mummy 'grows' with CT scans and 3D digital technology. Retrieved from http://smithsonianscience.si.edu/2011/08/video-a-mummy-grows-with-ct-scans-and-3d-digital-technology/

Terdiman, D. (2012). Smithsonian turns to 3D to bring collection to the world. *CNet*. Retrieved from http://www.cnet.com/news/smithsonian-turns-to-3d-to-bring-collection-to-the-world/

Thilmany, J. (2015). How do you resurrect ancient fossils? Try paleontology technology and a 3D laser scanner. Retrieved from http://lineshapespace.com/paleontology-technology-3d-laser-scanner/

UPenn. (2015). 3D Scanning at the Corfu archaeological museums. Retrieved from http://sites.museum.upenn.edu/monrepos/evidence/methods.html

Web3D. (2014). Cultural Heritage Preservation. Retrieved from http://www.web3d.org/example/cultural-heritage-preservation

Figure 1: "Inechopen." Intechopen.com. intechopen.com. Unknown date. 1. Web. http://www.intechopen.com/source/html/40008/media/image1.jpg

Figure 2: "3D scanning and Analysis." Clemson.edu. Restoration institution. Unknown date. 1. Web. http://www.clemson.edu/restoration/wlcc/equipment_services/equipment/3d_scanning_and_analysis.html

Figure 3. "CAT Scanner." Madehow.com. Unknown date. 1. Web. http://www.madehow.com/Volume-3/CAT-Scanner.html