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3D Imaging in Cultural Heritage

A Conservators Point of View

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The purpose of this study was to investigate the use of 3D imaging applications in conservation in a manner accessible to conservators. In order to do this, the basics of 3D imaging, as it applies to conservation, had to be discussed and explained and the history of 3D imaging in cultural heritage and conservation examined. Case studies were used as examples of the most relevant applications for this technology in conservation. Finally, a theoretical look was taken at the broader meaning of 3D imaging in the conservation field.

The study found that a wide variety of applications are available in the conservation field, namely those of documentation, analysis, and monitoring. Some applications are currently accessible, while others will become more appropriate as costs are established and developments made.

Conservation theories were examined to place 3D imaging into the broader context of conservation and to push for more cooperation and resources spent on the adoption of 3D imaging into the conservators' toolbox.

Keywords	3D Imaging, 3D scanning, Conservation, Cultural Heritage, Digital Documentation, Digital Analyzation, Digital Monitoring

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Tutkimuksen tarkoitus oli pohtia 3D mallintamisen sovelluksia konservoimisen puitteissa tavalla, joka tukisi konservaattoreiden työtä. Jotta tämä olisi mahdollista, 3D mallintamisen perusteet ja historia kulttuuriperinnön ja konservoimisen työkaluna piti käsitellä ja selittää. Tapaustutkimuksia käytettiin esimerkkeinä siitä, miten tätä teknologiaa voi soveltaa konservoinnin kannalta. Lopuksi 3D mallintamisen laajempaa merkitystä konservoinnissa tarkasteltiin teorian kautta.

Konservoinnin teorioita tutkittiin, jotta 3D mallintamista voitaisiin tarkastella konservoinnin laajemmassa kontekstissa ja jotta yhteistyö ja resurssit tällä saralla lisääntyisivät niin, että 3D mallintamista pidettäisiin yhtenä konservaattoreiden työkaluista.

Avainsanat	3D kuvannus, 3D skannaus, konservointi, kulttuuriperintö, digitalien dokumentointi, digitalien analysointi, digitalien monitorointi

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Contents

1 Introduction

The object of this thesis is to explore current and developing 3D imaging technologies and their applications in the conservation field. This is a relatively new field in conservation. Although the technology has been available for a number of years, its quality and cost has made it prohibitive for use in the conservation sphere. The rapid development of these technologies means that their relationship to conservation is in constant flux, always moving towards greater accessibility and affordability. Case studies have been relatively few, and limited in scope, meaning that up to date information is limited. Further research into current technologies must happen to be able to adequately orient ourselves to their applications in the conservation and cultural heritage arenas. Additionally, active participation in the field means that conservators can have a greater effect on the development of the technologies and their suitability to their needs (Wachowiak & Karas, 2009). Besides a lack of case studies and participation, there is also a lack of texts meant to guide and instruct conservators in the field of 3D imaging. Much of the research and development is going on in the entertainment industry and the practical usage of the technologies is happening in the industrial sector. The goal of this thesis is to help orient conservators to adopt the terms and principles of 3D imaging as well as initiate the process of bringing these topics into general discussion as it applies to conservation.

This thesis will discuss the basic concepts and vocabulary of 3D capturing and imaging as well as the hardware and software involved in creating three dimensional representations of museum objects. It will also give a brief history of the technology in the cultural heritage and conservation fields. The discussion on the applications of the technology will specifically focus on technologies that can be used as documentation, analytical, and monitoring techniques in conservation and offer case studies as examples of their usage in the discipline. After detailing the possible applications in the field, this thesis discusses the future development of the technology as well as the theoretical basis for expanding the technology into broader acceptance.

2 3D Imaging Basics

To understand the technology discussed in the following sections, it is necessary to give a brief description of what the desired end result is. The goal is to make a 3D representation, or 3D model, of a physical object. A 3D model is a digital representation of "a physical body using a collection of points in 3D space, connected by various geometric entities such as triangles, lines, curved surfaces, etc." (Wikipedia c.2016f, para. 4). This can be done in a number of ways, however, this paper will focus on those made through 3D scanning.

When building a 3D model, you can create two types: a solid model or a shell/boundary model. A solid model represents the surface shape, also referred to as geometry, as well as volume. A shell model is one that represents the boundary of the physical surface but not the volume (Wikipedia c.2016f). Shell models are easier to work with and are the type normally produced with 3D scanning. Scanning produces only the surface shape. Interior details and volume can be achieved using special tools with some scanners. To produce a one-to-one accurate 3D model, it needs to be textured. Texturing can include, but is not limited to, color, microstructure, reflectance, and gloss (Russell 2015). This is a complex process with its own research, software, and algorithms. A section will be dedicated to briefly discussing the issues associated with this topic.

To make a useable 3D scan you need the following: a scanner, the appropriate hardware and software, a computer, and a computer program designed to compile the scanned data and display it in a readable way (Cignoni and Scopigno 2008). For each of these technologies, there are a number of different options. The following will describe the technologies most used in conservation and discussed in this paper.

2.1 3D Scanning Hardware

To begin the process of acquiring a 3D image, you must start with the imaging hardware. This is the hardware that produces the raw data, in this context we are referring to a scanner. The 3D imaging hardware discussed here can be broken down into a few categories. These are non-contact active imaging, non-contact passive imaging, and structured light scanners. In the past, the most common technology used in cultural heritage and conservation were non-contact active scanners. Currently structured light scanners are becoming more common and are on the forefront of the field. Non-contact passive imaging, in the form of Polynomial Texture Mapping or PTM, is also an emerging technique. Volumetric techniques, namely medical CT scanning, has been in use in the cultural heritage fields for many years. Photogrammetry refers to the use of digital cameras to capture images of an object from multiple angles and merged, using software, into a 3D-like image. Photogrammetry can also be used to record color and texture. This paper will not deal with CT or Photogrammetry techniques as they do not address the goals of this thesis.

2.1.1 Non-contact Active 3D Scanning

Non-contact active scanners require no contact with the object and "actively" emit radiation. The radiation emitted is usually in the form of light, and its reflection from an object, or its radiation through an object is detected by the scanner (Wikipedia c.2016a). There are two major types of non-contact active scanners, time-of-flight and triangulation. Time-of-flight scanners measure the time it takes the light to reflect back to the scanner. Using the speed of light the distance is then calculated from the scanner to the object scanned (Payne 2013; Wikipedia c.2016a). Time-of-flight scanners are more suited to large objects, sites, or environments (Cignoni and Scopigno 2008). Triangulation scanners use a laser emitter, a camera, and a laser dot (on the object) to form a triangle between the three. Since the measurement of the distance between the laser and the camera are known and the angles of the laser emitter and the laser dot, in relation to the camera are known, it is a simple calculation to determine the length of the side of the triangle that represent the distance from the scanner to the object (Payne 2013; Wikipedia c.2016a). Triangulation scanners are suitable for small or medium objects (Cignoni and Scopigno 2008). Once the object is scanned all the measurements are gathered as a "point cloud", a cloud of points that create a map of the object (Payne 2013). These are then further processed to connect the dots and create shapes which create the 3D image.

2.1.2 Non-contact Passive 3D Imaging

Non-contact passive imaging also requires no contact with the object, but instead of emitting its own radiation it relies on detecting the ambient radiation from an object (Wikipedia c.2016a). As stated above, Polynomial Texture Mapping (PTM), also known as Reflectance Transformation Imaging (RTI), is the non-contact passive imaging technique currently being used in cultural heritage fields. This technique is where multiple digital images are taken under different lighting conditions, digitally merged and processed, and then virtually lit in the computer (Payne 2013, Wikipedia c.2015). The object's geometry, three dimensional characteristics, are calculated from the “normal” values of the photograph. “Normal” values is a term used to describe the reflective data captured, in a photograph or scan, representing an object’s shape (Payne 2013). Since this type of image originates from digital photographs the color information is stored as well. This allows for recreation of an object’s shape and surface texture in the computer, creating an “interactive 2D images that appears 3D” (Payne 2013). This technique also allows for details, normally obscured or hard to view, to become visible under the digital lighting.

2.1.3 Structured Light 3D Scanning

Structured Light scanning, or white light scanning, is an emerging technology and still being actively researched (Wikipedia c.2016a). This is a technique that projects patterns of light, usually stripe patterns, onto an object and reads the deformation or displacement of the pattern from one or more cameras (Cretté et al. 2013, Wikipedia c.2016a). Multiple scans are taken and processed in the computer and a highly detailed 3D image is produced (personal communication with Bjarte Aarseth on February 26th, 2016). The software attached to these scanners can record tracking points, enabling the computer to instantaneously merge multiple scans based on point coordinates. This allows for much more rapid scan merging, an ability that is put to use on tools, with tracking points attached, that allow for the tracking of smaller, hard-to-reach details of objects (personal communication with Bjarte Aarseth on February 26th, 2016). This technology is found mainly in an industrial setting where it is used as a quality control measure.

2.1.4 Computer Hardware

After the raw data is acquired, it must be merged into a usable, readable, manipulatable digital object. This is the job of the computer hardware and software. The hardware refers to the physical components of the computer that are responsible for its computing power and memory. The main components of a computer are the CPU (Central Processing Unit), and Memory (data storage) (Wikipedia c.2016b). For computers working with 3D imaging, you can also have a dedicated GPU (Graphics Processing Unit) that specializes in the types of calculations needed for building and rendering 3D images. The more advanced these three components are the more data the computer can handle and at faster speeds. This will be discussed more in depth later.

2.2 Software

No matter how advanced the computer hardware is, it would be impossible to merge the raw data from the scanners without the use of computer software. In this instance, computer software refers to the programs designed to handle and calculate the raw data and create a digital representation of the object (Cignoni and Scopigno 2008). The software uses algorithms and formulas to aid its procedures. Software can also include programs for lighting and manipulating the object. The main goal of the software is to take the data and create a “polygon mesh”. A polygon mesh is simply a collection of edges, faces, and vertices that create a solid 3D model. The polygons are usually made up of simple shapes. Those made only of triangles are called triangle meshes (Wikipedia c.2016e). The more polygons you have, the more detail is represented in the final image. This is similar to image resolution in a digital photograph: the greater number of pixels per area, the higher the resolution of the photograph. The same applies to a polygon or triangle mesh: the greater number of shapes per area, the higher the resolution and the greater the detail in the resulting 3D model. Once the model has been created, a number of other software programs can be used to color, texture, light, or display the 3D model.

2.3 3D Model Material Properties

As stated in the introduction of this section, a basic 3D model is only a representation of the surface shape. For it to be a one-to-one representation, its material properties need to be defined. This can either be done by acquiring textures through different methods of photography and scanning, or by digitally painting them. For cultural heritage objects, acquiring the photographic representations of the material properties is the preferred method. The goal with this type of photography is to capture photos that represent an isolated material sub-property (i.e. color or reflectance). This can be achieved through careful manual setup of camera and lighting or through specially made light stages (Tunwattanapong et. al 2013) and post processing.

Once textures are acquired, they are mapped over the 3D mesh to represent different material properties over the whole object body. The basic properties for a photo realistic portrayal are diffuse/albedo, gloss, and reflectivity. Other properties can be captured and represented as well. For instance, glass, leather, clay, or other light permeable materials can include refraction and subsurface scattering in the representation. Jeff Russell in *Basic Theory of Physically-Based Rendering*, 2015, describes the basic properties in the following ways. A diffuse map is used to describe the objective colors of an object. This can also be called an albedo map. A reflectivity map depicts how reflective the surface is, for instance, a mirror versus a rock. A gloss map, also called smoothness, or roughness, describes how the light reacts with the surface and its micro texture. In essence, whether that reaction creates a blurry or sharp reflection. A refraction map represents how light bends when passing through and object. A sub-surface scattering map depicts the effect of light entering into a material, interacting with it, and then being reflected back out at a different angle (Russell 2015).

Technology for acquiring photo realistic textures and rendering them, like others described in this paper, is advancing all the time. Consequently, making one-to-one representations of cultural heritage objects is closer to becoming a reality.

3 Timeline of 3D Imaging in Cultural Heritage

The timeline for 3D imaging in cultural heritage fields follows a similar pattern to other technological research and is intrinsically related to the evolution of computer power. Without the advancement of computer processing power, the development of 3D imaging would not have happened. Computers as we know them began in the late 1950's with the development of transistors that could fit onto chips (Lammers 2015). The first transistors were small, but not small enough or powerful enough for computers as we know them. The invention of integrated circuits in the early 1960s meant that more transistors could fit onto a chip. With this development, more processing power could fit into a smaller space, creating a computer chip (Lammers 2015).

Research continued into minimizing the size of the circuits, and therefore the chips. In 1965, Gordon Moore, a businessman and founder of Intel, predicted that the number of transistors able to fit onto a chip would double every year. In 1975 he revised his prediction to double every two years (Wikipedia c.2016). This prediction is called Moore's Law and became a standard goal in the chip manufacturing industry. For this reason, it is unknown whether his prediction was correct or it just became a self-fulfilling prophecy (van Lente & Rip 1998, 206). It is better to think about Moore's Law not as a physical law, but more as a projection of where the technology is headed. Either way, the processing power of computers has doubled every year or two for the last 50 years, leading to more available power at a lower cost of production (Franco 2015).

This rapid evolution of technology has allowed for innovation in the fields of 3D imaging, as both the hardware and software used in creating 3D images is based on a computer's ability to process information. As this ability progresses, so does the capability of the hardware and software used for 3D imaging. For instance, a 3D scanner can scan information, but to make it readable the scans are transferred onto a computer. The computer's CPU (central processing unit), or its GPU (graphics processing unit) does the necessary calculations to render the object and put the scans together into an image. The more calculations the computer's CPU or GPU can handle, the faster and more detailed a scan can be. In the next sections, we will take a look at the past, present, and future of 3D imaging in the cultural heritage and conservation fields.

3.1 Past: 1995-2005

Experiments in 3D imaging in cultural heritage fields have been happening for about twenty years. One of the first instances of a scan done to investigate a cultural heritage object was The Digital Michelangelo Project in 1998-1999, although there were other smaller scale projects around the same time (Levoy et al. 2000). The Digital Michelangelo Project lasted for a year and its goal was to scan as many of Michelangelo's sculptures as it could in that time. In the end, it scanned 10 statues, including David, two interiors, and all the fragments of the Forma Urbis Romae. One of its main goals was to scan the objects with a large enough resolution that the tool marks left on the surface were visible and represented in the 3D model (Levoy et al. 2000, 1). They used a non-contact active triangulation-based style scanner. The results were quite impressive for the time and they achieved their goal of a high enough resolution to identify Michelangelo's tool marks. At the time, the 3D image of David was by far the largest scan ever done (Levoy et al 2000, 11). They pushed the boundary of technology at the time and had to create their own solutions, as many did not exist.

Another early project was also done on a statue of Michelangelo, The Florentine Pietà. Fausto Bernardini and his team at the IBM Research Center scanned the statue and published their results in 2002. The team partnered with an art historian who helped guide them in what he felt would be valuable from a 3D image. It was felt that this statue, because of its complex geometry, would benefit from a 3D scan because it would capture areas traditional techniques, such as photography, would not be able to capture (Bernardini et al. 2002, 2). The technique used in this project was different from the Digital Michelangelo Project. The type of scanner used was also a non-contact active scanner, but instead of laser triangulation it used structured light and a stereo system to capture multiple photos that were generated into a 3D mesh. Again the results were quite successful and the art historian found benefits from working with a 3D scan, as well as the original sculpture (Bernardini et al. 2002, 9).

3.2 Present: 2006-2016

Investigation into 3D imaging for cultural heritage objects is still ongoing. The methods described above are still being used, but they have improved in quality, speed, and affordability over the last decade. For example, the previously mentioned structured light method is being used in the Saving Oseberg project at the Museum of Cultural History in Oslo. In a conversation on the 26th of February, 2016, with B.E. Aarseth, Senior Engineer at the Conservation section of the museum, described how a state of the art, structured blue light scanner was being used to scan the ships and artefacts at the Viking Ship Museum in Oslo. Mr. Aarseth explained how the improvement in the software and hardware over the years has made it a much faster and precise process than ever before. Today's software and scanners can almost instantaneously produce a 3D image. The advancement of computing power has also made the merging of hundreds of scans into an integrated 3D image much faster.

Besides the above mentioned methods, new methods have also been adopted into the cultural heritage field. For instance, universities in the UK have used PTM (Polynomial Texture Mapping) as an analytical technique for a variety of objects (Payne 2013). The Universities of Oxford and Southampton have used PTM imaging on cuneiform tablets, statues, and ceramic objects with great analytical results (Payne 2013). This technique was also used in the British National Gallery and Tate Museums to document condition changes as opposed to the traditional method of using rake lighting (Payne 2013).

3.3 Future: 2016 and Beyond

So far Gordon Moore's prediction has been an accurate projection of growth for computer power and performance. If this is sustained, future computer hardware and software will continue to advance. All indications are that the trend is set to continue. In 2014, a number of chip manufacturers presented their new innovations that allowed the next generation of chips to hold double the number of transistors in the same area compared to the previous generation (Lammers, 2015). As processors pack more transistors into the same amount of area, more power can be had at a lower cost. This means that hardware and software previously too expensive to be accessible to the cultural heritage field will become increasingly available. Another outcome of the boost of computer power is the advancement of the software used in creating the 3D images. The direction in imaging software has been a reduction of the need for user input in creating the final image, therefore reducing the need for specialized training and allowing conservators to get more involved. Needing less user input also decreases the amount of interpretation needed in creating the 3D image, resulting in more accurate final images. All of these outcomes have the additional effect of bringing down overall costs of the scanning process, thereby making it more affordable to cultural heritage institutions.

4 Applications of 3D Imaging in Conservation

3D imaging has been used in cultural heritage and conservation for a wide variety of reasons. Most of the early case studies have revolved around the suitability of this technology in the field. As the technology has advanced, more and more projects are using it as a bonafide tool in the study and conservation of objects. The acquiring of the raw data and its processing into a digital object is just the first step. Once a digital object is made, a multitude of different applications are available for its use. This thesis will focus on the use of 3D imaging as a documentation, analytical, and monitoring technique in cultural heritage because these three applications of 3D imaging are the most relevant to a conservator’s everyday work. They allow for the possibility of more detailed analyses, condition reports, and object files, as well as for preservation in the form of a digital object. Much of the actual work of conservators revolves around documenting the objects in their care. Finding clear and concise ways of presenting and preserving an object’s information is essential in the continuation of their work. For those in the field working directly with the physical objects, on their repair or study, new analytical techniques are always welcome. Better methods of monitoring changes and damages to objects or collections can be invaluable in the efficient use of resources.

This section will present a selection of case studies representing the documentation, analytical, and monitoring applications of 3D imaging technology in conservation. The 3D imaging field is developing and advancing all the time. In its current state it may not be plausible for use on all objects and in all situations, but as the case studies below will show, there are major benefits to including this technology into wider usage.

4.1 3D Scanning as a Documentation Technique

Documentation is the bread and butter of conservation work. Every detail known, every action taken, every object's location, etc. needs to be recorded. Documentation is, in its own way, an act of preservation. While other methods preserve the physical object, documentation helps preserve the intangible aspects of an object. These aspects might be inaccessible, undetectable, or just plain gone. They include aspects like an object's history, method of production, or previous conservation work. Documentation helps preserve as much information as possible. 3D imaging can act as a documentation technique instead of, or accompanying, other 2D visual methods along with the conservators' notes.

In 2012 a trial project was undertaken in the Victoria and Albert Museum in England to use a 3D scanner as a documentation technique for their collections. A structured white light scanner and its accompanying software was used to create the scans (Stevenson et al. 2012). A variety of different objects made of different materials were chosen to gauge the effectiveness of the scanner. Some examples of these were a stone bust, a pair of shoes, a metal box, a ceramic figurine, and a textile figure (Stevenson et al. 2012). Not all the materials proved suitable for scanning, but a majority worked well. The project found that the museum's staff were greatly interested in the results and began thinking about how to use this technology to their benefit (Stevenson et al. 2012). The end result of the project was that more development in hardware and lower costs would be necessary to implement this technology full time.

Another study focused solely on documentation was done by researchers Brunsch, Guzowska, and Sitnik (2012) of the 3D scan of the King's Chinese Cabinet in Wilanow Palace Museum. The cabinet was due for conservation and it had been altered greatly since it was first made. The decision was made to restore it to its original design. It was agreed that a 3D scan of the cabinet would be made, documenting the colors and three dimensional properties of the cabinet to preserve the history of its change. Since the layers of paint and additions were being removed, photographs and the scans were the only way of preserving the cabinets alternate design (Brunsch et al. 2012). These scans could then follow the object and be displayed with it, allowing a deeper understanding of its history even though it is otherwise "lost". One very useful point described in the paper is how a 3D scan can allow you to very precisely mark sample areas on an object. This is a great advantage to conservators, as the precise location of a sample may be needed for an accurate interpretation of the results. On objects with extensive conservation work, traditional means of documenting sample areas, either removals or chemical tests, can become illegible and bulky (Brunsch et al. 2012). In these cases, digitization can allow for a much more accessible condition report.

There have been many other projects where scanning became a useful or intricate part of the conservation of an object. Colin Macgregor mentions his work in scanning outdoor Aboriginal sites in Australia (2013). 3D imaging on sites of this kind is essential since the art is under the effect of constant weathering. One could also argue that these types of artworks can only be properly documented in the physical environment in which they were made. This is made possible with a 3D scanner. Another project of this kind was Marcus Abbott's 3D scan of Stonehenge (2012), creating an entire digital representation of Stonehenge and its surroundings. As a collection of large objects in an environment, 2D documentation techniques cannot fully represent the scale of the site. Another interesting example is Francoise Rutland and Annemarie La Pensée's project on scanning a Roman Helmet at the British Museum (2011). The helmet had already been removed in a soil block from the main site and was being excavated in the lab. They were asked to scan the helmet before, during, and after excavation to make a complete three dimensional record of the process. This allowed the spatial relationship of all the finds to be recorded exactly (Rutland and Pensée 2011).

All of the aforementioned studies show how a scan can serve in a generalized way, similar to a 2D photo or map, in documentation. The advantage of a scan being that it can make the three dimensional aspects of an object or site more accessible. Other studies have shown how a 3D image can help document interesting and essential data for the object in a more specific way. In a study done in 2007 by Guidi, Beraldin, and Atzeni, 3D scanning was used on small areas of wooden statues in Italy to document damages and fluctuations due to environmental factors. The study mentions how an entire scan need not be done on an object. Instead, smaller scale scans of damages could be just as informative in a condition report (Guidi, Beraldin, and Atzeni 2007).

A more recent development has been the scanning of painted artworks to capture the three dimensional properties of the paint on the canvas (Tim Zaman 2013; Zaman 2013). This is a new documentation technique that allows the small details in brushwork and impasto to be seen and recorded extremely accurately. In a conversation on February 26th, 2016, Bjarte Aarseth of the Saving Oseberg Project at the Oslo Museum of Cultural

History stated that a digital documentation record of all the Viking ships, and all their associated objects, were being created. The ships and their objects were being scanned with a structured light scanner, normally used in industrial quality control, creating incredibly detailed scans. Although the process was still lengthy, the software used sped up the merging of multiple scans and resulted in some of the most detailed and accurate scans of any cultural heritage object. This advanced scanner was able to handle objects that would normally cause problems, i.e. shiny objects, high contrast, and textiles. Although far from perfect, this shows the technology's capability to advance to a near one-to-one representation of an object.

4.2 3D Scanning as an Analytical Technique

Once a 3D model of an object is constructed, there are a number of different ways in which that model can be used to investigate the object further. What may have been a scan for the purpose of documentation, can also be used as an analytical technique. Analyzing by using three dimensional models can complement traditional techniques, as well as give new insights unavailable before. As the field grows, a wider variety of analytical techniques may become available.

As mentioned previously, the scans done on the King's Chinese cabinet by Brunsch et al. were helpful as an analytical technique, as well. The scans allowed for detailed area measurements and the precise calculation of the gilded surface area (Brusch, Guzowska, and Sitnik 2012). This was very helpful for the conservators whose job it was to restore the gilding, as they could more accurately calculate the materials needed. Their project also involved scanning a Roman Age tombstone. These scans were able to identify tool marks as well as motifs that were difficult to discern using the naked eye (Brunsch 2012). By controlling the lighting on the digital object, it can reveal details that are otherwise obscured. During their examination of this tombstone, the authors discovered that a 3D model is a huge asset when dealing with multiple experts. When foreign experts needed to be consulted, they could do so without having to be physically present. The 3D model was detailed enough to allow examination without having to travel or risking the transportation of the object (Brunsch 2012).

Michael Nieß of Uppsala University recently published a study of 3D modeling in the analysis of Viking Age brooches. By scanning the brooch fragments, he was able to reconstruct what the original would have looked like (Nieß 2014). These detailed 3D models allowed for analysis of motifs, calculations of material weight, and tool marks. In fact, the detailed measurements allowed him to compare brooches housed in different museums and to come to the conclusion that they were most likely made with the same tools, meaning they were made in the same workshop (Nieß 2014). This type of analysis would be very difficult to achieve without the highly detailed model, the extremely accurate measurement capabilities of the software, and the ability to compare objects normally located countries apart. Another benefit described in the paper is how different elements can be isolated and viewed separately from the object once in 3D (Nieß 2014). This is a highly valuable technique for complex objects that may be difficult to analyze and view using traditional techniques because the object must be viewed in full.

On a larger scale, the previously mentioned scan of Stonehenge by Marcus Abbott, also allowed for new analytical work to be done on the site. The exceptionally detailed scans of the stones were examined through software that allowed the viewer to manipulate the lighting conditions. This revealed new undiscovered details on the stones (Abbott 2012). In addition to prehistoric carvings, new tool marks were discovered. In fact, Abbott describes the marks as “layers of tooling” (Abbott 2012, 2). The scans were so accurate that the layers of markings were able to be seen, giving an unprecedented look into the creation of these objects. Another interesting and valuable application for the conservator was the ability to see previous conservation work by looking at the scans (Abbott 2012). The detail being so great that the conservator was able to tell the difference from the original methods of productions and later works.

A number of other studies have found digital lighting of a 3D model beneficial in the analysis of tool marks and production techniques (Levoy et. al 2000, Rutland and Pensée 2011, Abbott 2012, Zaman 2013). Emma Marie Payne describes in her paper the technique of PTM which, as previously described, creates 2D images that react like 3D (2013). This is essentially a form of digital rake lighting and can be used with a multitude of different objects. These digital lighting techniques reveal details not visible under other lighting conditions. These could be tool marks, as stated before, details that have been badly weathered, or writing that is indecipherable.

4.3 3D Scanning as a Monitoring Technique

Besides documentation and analysis, 3D imaging can act as a monitoring technique. This is perhaps the most useful application of this technology currently available to conservators. Much of the work revolves around preventative conservation, attempting to find the ideal environment, storage solution, or display option. Identifying changes or damages before they become a serious threat is essential in the long term care of an object. It is also the best use of resources, as preventative conservation can take less time and money than active conservation. While the limitations of 3D imaging technologies means that other applications may need more time to fully develop, monitoring applications are now at a stage where they surpass most traditional measuring techniques. The following case studies will show the benefits of this type of application.

Many museums have begun to experiment with 3D scanning as a monitoring technique. The Smithsonian National Museum of American History has created a 3D scan of the Gunboat *Philadelphia*, a Revolutionary War ship. This allowed them to mix scans with photographs to get “real-time feedback of minute areas of erosion and other structural change” (Waldemar n.d., para. 9). In a conversation on February 26th, 2016, Bjarte Aarseth stated that in addition to documentation, the Saving Oseberg Project has found the 3D scans a useful monitoring technique. Scans of the main ship have been compared, leading to discoveries regarding fluctuations in the ship's shape and displaced parts. The rudder had moved significantly. It was investigated and found that although the ship had been roped off, visitors had been the cause of these changes. The museum staff were then able to create a Plexiglas shield for the rudder to avoid any more damages. In this same conversation, Mr. Aarseth explained that the scanner used during the project has a number of tools that allow for very precise scanning of cracks, holes, and even interior details. This kind of tool would make small detail scans possible to help monitor damages in types of objects that could not be scanned or accessed previously. Another method of monitoring with 3D scanning, is creating a model and overlaying a succession of different photos of the object onto the model. These can be photos from past projects, photos created at the time of the scan, or photos taken sometime in the future (Brizzi et al. 2006). This allows for a more interactive comparison of changes and can possibly allow for easier detection of damages and vulnerable areas without having to rescan an object.

Similar to overlaying of photos on a 3D model, another helpful application of this technology is the ability to compare scans to one another. Scans taken at different times could be laid over each other on the computer and differences marked (Guidi, Beraldin, and Atzeni 2007, Happa et al. 2009, Ritland and Pensée 2011, Macgregor 2013). This could allow for highly detailed comparisons such as those before and after, those concerning conservation or damages, or comparison with similar objects. This technique was found to be very useful, for example, in measuring the success of consolidation treatments in two different studies on archaeological waterlogged wood (Bandeira et. al 2013, Cretté et al. 2013). Shrinkage is a major problem in the conservation of water-logged wood and traditional measurement techniques cannot always measure changes in fine detail. Scanning allowed for more detailed measurements and comparisons than that of traditional techniques. Cretté et al. specifically noted in their paper on the conservation of waterlogged corks how the structured light scans they made were able to record changes in size and shape that were undetectable by photographing or other traditional measurement techniques (2013). Other studies also mention the benefit of using 3D scans to monitor damages, shape and color change, or variations, and material loss (Cignoni and Scopigno 2008, Happa 2009, Payne 2013).

4.4 Further Applications

Once the 3D model is created, there are a number of other applications that are available for its use. One utilization of this technology in conservation would be that of building support or display structures for an object. A 3D model of an object can give exact measurements and allow for a virtual support or display option to be built and tested before the actual construction. Transportation or carrying the equipment could also be constructed for fragile objects using a 3D model (Happa 2009). It could also allow for a 3D print of the structure to be made. All of these options could save time and materials. Cignoni and Scopigno discuss how future technological development could allow for simulations of conservation tasks, weathering, or deterioration on virtual objects (2008). These could be tested on the virtual objects to help conservators make the best decisions for the physical objects (Cignoni and Scopigno 2008).

There are other uses for a 3D model that do not specifically relate to conservation but rather to cultural heritage in general. A 3D model is a flexible product. It can be transferred from one computer program to another, allowing for a multitude of possibilities for its use. A 3D model can also be used as a learning tool in museums by being displayed alongside the original object to present a fuller understanding. It can be placed, perhaps with other related objects, into a virtual setting recreating its place/time/culture of origin. A 3D model can be used to create a virtual or augmented reality display for museum guests. If an object or site is inaccessible because it has been loaned, conservation work is taking place, or it has become too fragile to display, a digital representation can be displayed until it is available (Brizzi 2006). It can also be used to 3D print a version of the object for display, to repair, or replace damage to the original object, or for visitor accessibility, allowing guests to handle otherwise fragile objects. Rutland and La Pensée give an example of a rare diptych whose two parts were held in different museums, one in Cardiff, Wales, and the other in Liverpool, England (2011). They were only recently discovered to be a pair and the Liverpudlian half was loaned to the Welsh museum for a period of time. The Welsh museum obtained permission to scan and 3D print the loaned half so that when the original returns to Liverpool, the copy can be displayed alongside the original to allow for the diptych to be seen as it was intended (Rutland and La Pensée 2011).

These are all options currently available and more are being created all the time. The subject is much too broad to further comment on here, but the applications for 3D imaging technology and its products are far reaching into the cultural heritage sphere.

4.5 Issues for Consideration

As 3D imaging technology is constantly developing, the most appropriate, affordable, and available technique for a conservation or cultural heritage project needs to be researched. The type of scanner needed depends on the project undertaken and what the final scans will be used for. If physical geometry is required, to monitor change of shape or losses, then most of the technology available today is appropriate and an affordable option can be found. At present, 3D models are available as an analytical technique. Current technology allows for greater analysis of objects than can be done with traditional techniques alone. This will likely continue to improve and more analytical applications could become available.

If creating a one-to-one accurate representation of an object's shape and material is the desired end result, then that is a more daunting task. The technology is available to create a one-to-one representation, however, it is expensive and still requires a large amount of expertise. Further research and development will most likely make this possibility more readily available. As for now, a nearly perfect model is available for documentation purposes with a little research into the appropriate technology.

Another issue to consider is file management. The naming, cataloging, viewing, and storage of digital files is a whole topic unto itself and resources need to be placed at its disposal. Furthermore, the file size of a virtual object is a concern. A virtual object is not made of just one file, many interim files are created in the process (Cignoni and Scopigno 2008, Groenendyk 2013). These can be quite large and the file type may not be one widely available. Storage space and its cost is not currently a deterrent to the use of 3D imaging. Costs per gigabyte of storage have gone down rapidly and many cloud services offer storage on servers for free. The field of 3D imaging does not currently have a standardized file type, so conversion and program compatibility may be an issue. If 3D imaging files are to become a part of an object's documentation or a museum's collection, thought needs to be given to the way in which the files will be stored and made usable in the future.

5 Theoretical Basis for 3D Imaging in Conservation

As previously discussed, 3D imaging techniques can have a variety of different applications in cultural heritage and conservation. This technology is steadily advancing towards greater detail, accessibility, and affordability. This paper has shown that the use of this technology in the conservation field can be both practical and beneficial. Yet technology does not completely replace traditional techniques, and in certain areas it has yet to advance to a state where its use could be considered appropriate and convenient. Why should conservators then put effort into discussing, studying, and using this technology if it is not yet widely accessible? Why is this technology important to the study of conservation and objects? This section attempts to answer these questions by using Classical and Contemporary theories of conservation to investigate the usefulness of 3D imaging technology in conservation in a wider context than the applications discussed previously.

5.1 Classical Conservation Theories

In Classical Conservation theories "Truth" is the keyword. In *Contemporary Theory of Conservation*, Salvador Muños-Viñas describes these Classical theories as saying that "conservation should always be a truth-based activity." (2005, p.66). Once Scientific Conservation took hold, conservators saw that the "only way to establish objective truths was the way of science" (Muños-Viñas, 2005, p.67). Scientific Conservation is the prevailing theoretical basis for much of the conservation being done today. This theory focuses on the better understanding of materials and their deterioration processes (Muños-Viñas, 2005). The use of hard sciences in investigating objects meant that there was a focus on objectivity. Looking at an object's history, material, production, damages, and possible future conservation treatments in an objective way became a core principle for many conservators. Salvador Muños-Viñas referred to this as “conservation-as-research” (2005).

If 3D imaging techniques are looked at through the lens of Classical conservation theory, many arguments advocating its use as an “objective” research method can be found. Using the most advanced 3D imaging device as an example, together with material property acquisition techniques, the process of capturing a 3D image is scientifically objective. The scanner only scans the information belonging to the object without recording any other outside information. Lighting settings do not affect the end result, as it does with photography. Photography requires the conservators to make judgement calls on what the best lighting for the object is in order to show the object and its most defining features most clearly. This is a subjective act, as different conservators may have different opinions on the best lighting. Ideally, before and after shots should be taken under the same lighting conditions, but one style of lighting may not suit both. This could lead to a loss, or unclear presentation, of an object's physical information. As discussed in the section on material property scanning, the ability to digitally capture and record the original color of an object and the unique way it reflects and refracts light from its surface, is an objective way of documenting the material properties of an object. Textural scanning is another way in which this could be beneficial in order to better archive an object's attributes than the traditional methods.

Another interesting argument for the objective use of 3D scanning technology relates to collections overall. The choice of objects preserved in a museum's collection is a subjective one. Choices are made on which objects are worth preserving and which are not. How much time, space, and financial resources will it take to preserve, house, and display an object? Often these decisions are made with a cultural or historical bias. 3D images and scans of objects could allow for a type of digital preservation of a greater number of objects for public consumption. A larger amount of objects in collections, even digitally preserved, would mean less cultural bias as well as time, space, and money issues associated with housing a physical collection.

There are a few issues with these arguments. The “objectivity” of 3D imaging is based on the idea that it can capture a one-to-one three dimensional shape, color, and textural representation of an object. However, in some cases this is true, in others the technology has not quite reached this point yet. As discussed before, the rapid development of 3D imaging technology means that a one-to-one scan is not far from reality. The capabilities of the technology, in relation to conservation applications, need to be further developed and the more involved conservators are in the discussion, the more say they can have on that development. Another issue arising from this line of argument is with objectivity itself. Many conservation theorists and conservators themselves have begun to argue against the use of objectivity. In fact, they argue that objectivity is an impossibility and its pursuit is a detriment to the field (Muños-Viñas, 2005).

5.2 Contemporary Conservation Theories

Contemporary theories of conservation have moved away from the principle of objectivity. Salvador Muños-Viñas summarizes the main principles of decision-making in contemporary theories as “stress(ing) symbolism and communicative functions” over objectivity or aesthetic principles (2005). Šolas’s work in 1995 states that we do not collect objects merely for the objects themselves but for the “notions and ideas that these objects can convey” (English translation in Salvador Muños-Viñas, 2012, p. 44; from Spanish in Alonso Fernández 1999). A further principle set out in *Contemporary Theory of Conservation* by Salvador Muños-Viñas is that of the Stakeholder (2005). This is the idea that there are people who own a tiny part of an object, are affected by decisions made concerning that object, and therefore have a right to join the conversation about that object (Muños-Viñas, 2005). Sörlin suggests that conservators create a “trading zone” in which they step out of the experts-only mindset and begin negotiating with the Stakeholders of objects in their care (2001, in Muños-Viñas 2005). Before making conservation decisions, it should be asked “why, and for whom” they will be done (Muños-Viñas, 2005, p.170). Contemporary theories on conservation focus on negotiation, equilibrium, discussion, and consensus (Muños-Viñas, 2005).

Therefore if, as Šolas says, objects are collected and conserved to communicate ideas, then conservation techniques should support this principle. 3D imaging techniques can help to do just that. Many of the intangible properties represented by an object are not bound to the authentic object. These intangible properties, like history, culture, social practices, and traditional craftsmanship can also be expressed by a digital representation. An object communicates these properties by acting as an anchor, yet it is not the properties themselves. Consequently they can be represented in some cases by a 3D representation. The efficacy of digital representations ability to communicate may be up for debate, but the ability to do so is available. This is not to say that the original authentic object has lost its importance, but instead to recognize the capacity of digital representations to act as an anchor in modern culture. In today's society people interact with their world through digital means. The advent of the internet and the ease of digital communication has changed the way in which people relate to the world and gather information. Younger generations interact more and more in a mixture of real and virtual worlds. It would be wise to work with this trend allowing objects and collections to expand their accessibility into virtual spheres as well as traditional spaces. In fact, for some objects, being loosened from its physical boundaries can allow for its properties, tangible and intangible, to be conveyed more accessibility, as with the following examples of digital repatriation.

For examples where negotiation and discussion are beneficial to conservation and cultural heritage, it is possibly more beneficial to take a look at instances where that principle was ignored and how 3D imaging may have provided a solution. Repatriation of objects is a controversial area all over the world. For instance, in the United States there has been a nearly decade long battle for the repatriation of the oldest known native skeletal remains, the Kennewick Man (Wilson, 2015). The Native population of the area they were found in wanted the study halted and the bones given back for reburial, citing them as ancestors, a right granted by the Native American Graves Protection and Repatriation Act (Wikipedia, c.2016d). Scientists claimed the remains were too old to be related to the local tribes and wanted them for further study. After several court battles and differing rulings, the skeletal remains were judged to be “unrelated” (Wikipedia, 2016). Yet in 2015 it was found that the remains were genetically related to Native populations (Wilson, 2015).

Digital repatriation is an up and coming topic in today’s technological world. This is where the digital representations of objects held in museum collections have been made available, either online or through portable computers, to the indigenous people whose culture the objects originated from (Hess et al. 2009; Macgregor, 2013). Many other similar projects have been done with photographic libraries, but having access to a three dimensional object can perhaps enhance the way Stakeholders are able to interact with these objects. The 3D scanning of disputed ethnographic objects may allow for the repatriation of some physical objects as well. If Stakeholders of the Kennewick Man had been able to obtain a more open “trading zone”, it is possible that a solution benefitting both parties could have been reached. 3D imaging in cases like these could provide a solution for disputed artifacts and remains to be studied and treated in a way that would comply with the ideals of their original cultures. The native peoples could have been respected and their ancestor's remains returned, while the scientists could have had a 3D representation for further study, increasing the Kennewick Man's accessibility for future generations.

The case of the covert 3D scan of the bust of Nefertiti in the Neues Museum in Berlin is another example of 3D scanning increasing the accessibility of an object in the "trading zone". Artists Nora Al-Badri and Jan Nikolai Nelles snuck a 3D scanning device into the Neues Museum and secretly scanned the bust of Nefertiti (Voon 2016). This object is a huge draw to the museum and no guests are allowed to photograph it. The Neues Museum has, apparently, created their own 3D model of the bust but have not released images or files to the public, in contrast to other similar projects (Voon, 2016). Nora Al-Badri and Jan Nikolai Nelles created a 3D model from their covert scans and released it online for public consumption, where a large amount of interest was shown. The artists were contacted by other museums and universities asking to use their model for study (Voon, 2016). The bust of Nefertiti is largely believed to have arrived in Germany underhandedly, if not outright stolen from the excavation where it was uncovered. Egypt has made numerous requests to have the bust returned to them (Voon, 2016). The artists claim that this project's goal was to bring attention to how the history of the bust has been rewritten, in part by failure to display it alongside the history of its arrival in Germany, as well as to highlight the modern day colonization of objects in Western museums (Voon, 2016). This is an amazing example of Stakeholders in an object making their voices heard, in respect to what they feel is best for the object, namely being more accessible to its homeland. Anger and disappointment over the bust's reinvention as a German symbol, as well as the refusal to acknowledge it as an important symbol for the Egyptian people, caused these artists to take action (Voon, 2016). This could have been a much more fruitful opportunity for all involved if negotiation and compromise had taken place between the different Stakeholders. It is important for conservators to remember, especially when working with ethnographic objects or objects with Stakeholders from opposing sides, that the decisions they make do not affect the object alone. People can have strong feelings, personal or national, towards certain objects, and in today's technological society they are finding more and more ways of speaking out. Open discussion, negotiation, and innovation can help solve or avoid disagreements between Stakeholders, as well as help provide better care for objects in conservators' trust.

6 Conclusion

For the last twenty years, cultural heritage fields have been experimenting in 3D imaging technology. In those twenty years, the field of computing has changed extremely rapidly. Many of the studies done earlier can no longer be relied on to give an accurate view of the current suitability of the technology in the field of conservation. As computing continues to advance, conservators need to keep up to date with its suitability as a resource for conservation. The trend seems to be heading towards more accessibility for cultural heritage institutions. More case studies need to be done and more cooperation with 3D imaging professionals needs to happen.

The thesis has shown that there are numerous ways in which 3D imaging can be applied to the field of conservation. Namely through documentation, analysis, and monitoring. These are currently available to the conservator at varying levels of accessibility. In the wider cultural heritage field, the applications for this technology is growing. 3D imaging could prove to be a massive shift in the way conservators/people interact with physical objects. Many scholars are still skeptical of its suitability in the field, much like with the beginning of color or digital photographs (Stevenson et al. 2012). Yet when viewed through the lens of developing technology and Conservation theory, this technology can have major benefits in the field. Instead of backing off and waiting for it to be suitable for their needs, conservators should begin to actively learn and engage themselves in the topic. This would allow them to determine where the technology will go and how it will be developed. In today's world, interdisciplinary cooperation is a great asset. Conservators need to reach out, not just to specialists in the 3D imaging field, but to all those involved with the objects cared for. Even if this technology does not produce any long-lasting benefits for the conservation field, the cooperation required to investigate it will. The interest 3D imaging can engender in the public can be a massive boost to the importance placed on people's cultural heritage and everyone's involvement in it.

Modern culture has merged the real and virtual into all aspects of life. Today's museum visitors are increasingly fluent in this newer style of interacting with the world. It would be wise for conservators to keep up and adapt to this trend, as it does not seem to be going anywhere anytime soon.

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