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A VIABILITY STUDY OF STEREOLITHOGRAPHY AS A MEANS FOR THE REPRODUCTION OF FRAGILE ARTIFACTS

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Abstract

This project details the ways in which the technologies of 3D scanning and stereolithography can benefit the National Museum of Denmark. Furthermore, it the explores various technologies, many of the companies dealing with these technologies, different machine models, the types of artifacts that are best suited for reproduction, and the many applications of these technologies in a museum setting. Recommendations for acquiring and utilizing these technologies are also given within this document.

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1. Executive Summary

In order for museums to attract new visitors and retain previous ones, they have to update current exhibits as well as create new ones. Traditionally this meant acquiring new and interesting artifacts for display. However, more recently, technology has been woven into museum programs and exhibitions, and thereby enabled museum administrators to rejuvenate current exhibits without the costly effort of starting a new exhibit from scratch.

Two technologies with great potential for the National Museum are those of 3D scanning and stereolithography. Both 3D scanning and stereolithography are relatively new technologies and are continually improving. 3D optical scanners are much like popular desktop scanners that record all of the information from a sheet of paper or a picture and convert it into a digital file. 3D scanners do the very same thing as desktop scanners, but rather than scanning pieces of paper, they scan a three-dimensional image. This image is stored in a digital format that can be manipulated using special software.

Once an object has been scanned and a digital representation of that object exists, a physical, three-dimensional copy of the original object can be built. The newest, fastest and most efficient method of making accurate copies of original objects from digital representations is stereolithography. The initial step is to convert the digital file that was the created by the 3D scanner to a format that the SLA (Stereolithography Apparatus) can read. Then, with the use of a laser and photosensitive resin, the SLA is able to build a physical representation of the digital object, one layer at a time. After several hours, a plastic, nearly identical copy of the original (within 0.025mm) is created.

The focus of this report is to explore different ways 3D scanning and stereolithography can benefit the National Museum of Denmark. Data obtained from the many interviews with various museum administrators has proven to be the most valuable information within the investigation. The curators of several exhibits, the gift shop manager, museum security, and educational administrators all supplied ideas and information about how 3D scanning and stereolithography can benefit their work and further enrich the museum experience for all Museum patrons.

The technology of stereolithography is still new and, therefore, relatively expensive. If only a few departments were able to find applications for it, then it would be advisable to either wait until its price has decreased, or, until its demand in the museum has increased. However, through our interviews we have found that there is a widespread desire to utilize this technology for the greater good of the museum and all of its patrons, as soon as possible.

The main benefit of obtaining the optical scanning and/or stereolithography equipment is gaining the ability to scan and/or duplicate fragile artifacts that cannot be copied with traditional means. Optical scanning makes it possible to replicate an object entirely without contact. This is a necessity for delicate organic artifacts made of bone or wood, as well as painted surfaces that could be damaged if molding were attempted. This technology also allows objects to be modified, manipulated, or scaled to any size. Once the desired changes have been made, an SLA could then produce the redesigned object.

From an educational standpoint, a method that makes possible the creation of replicas of artifacts can be of great benefit. The children's museum already has many replicas with which children can play. Stereolithography would allow the children's museum to expand its collection of touchable artifacts, and thus offer a more educational museum experience. Furthermore, the museum experience at present is quite limited for the visually impaired patrons. By creating copies of various artifacts, the blind would be given a more complete sensory experience. The replicas would provide a sense of texture and shape that previously would have been received only through an audio description. This same hands-on approach would also be beneficial to all patrons, since a fuller sensory experience can make a museum visit more memorable and enjoyable.

Optical scanning, even without stereolithography, could find many uses in the National Museum. Once an artifact has been scanned and its digital image has been created, this data could then be used for several purposes. For example, a virtual museum could be created either on the National Museum website or in a form of CD-ROM. It would include all of the existing exhibits with most important artifacts. The three dimensional, color images of the artifacts could be supplemented with text captions describing their history and importance. Furthermore, the users would be able to manipulate these images by changing their size, zoom level, and orientation on the screen.

The digital images acquired with 3D scanners could also be used by curators to learn about artifacts. In excavations, many of the discovered artifacts are often in fragments. Often the fragments are so old and fragile that they cannot be pieced together to create the original, as the process would damage them. 3D scanning, however, would be able capture all of the fragments and allow the curators to piece the artifact back together as well as to experiment on the digital copy without jeopardizing the original. This technique has already been successfully used by other museums, thus proving that technology can be of tremendous help to historians and archaeologists. In the same way, these technologies could help to improve the National Museum of Denmark.

The museum gift shop currently sells many recreations of artifacts on display at the museum. Most of these reproductions are made of metal due to the ease of casting metal without damaging the artifact. However, many artifacts on display at the museum are made of materials that cannot easily be reproduced by traditional means. But, with the use of stereolithography and 3D scanning, the museum shop would be able to make both digital and physical copies of most of these artifacts. By expanding the selection of artifacts, the gift shop would undoubtedly increase its revenue, as well as provide a tangible memory for museum patrons that will last a lifetime.

Interviews with museum employees offered useful suggestions about the multiple needs for technology within the museum. Our contacts with numerous companies that both sell and use this technology reinforced the vast potential for stereolithography at the National Museum. In the field of stereolithography, a single company owns all of the patents and has nearly complete control over the market. This company is 3D Systems, based out of Valencia California, USA. Its equipment has resolution accuracy of up to 0.025mm in resolution and prices as high as $800,000 USD. Although the technology of stereolithography can be implemented in the museum's daily works, this technology is evolving at a rapid pace. Within the next decade the same machines will cost a fraction of their current cost and will have many more capabilities. Therefore, the most viable option for the use of stereolithography within the museum is to outsource. There are multiple companies that offer the service of creating physical copies of objects using stereolithography for a reasonable fee. All that they require is the 3D digital representation of the desired object.

The use of a 3D scanner in the National Museum can find many more applications than that of an SLA. There are many factors to be considered in making a decision about 3D optical scanners. Therefore, it is necessary to consider all possible applications in order to determine which features are necessary to allow the museum the most freedom and use. It is also necessary to balance the cost, resolution, color, and size limitations. The ideal situation would involve buying a customized scanner from Cyberware, Inc., which would be capable of 0.005mm resolution, 24-bit color, and of scanning objects without size considerations. Such a scanner would cost approximately $200,000 USD, including training and a one-year warranty.

Stereolithography and 3D scanning are complex processes that are relatively new and are in a constant state of refinement. Along with each refinement come new capabilities and cheaper prices. Consequently, the decision of when to buy technology is always a difficult one. If one decides to wait for the decrease in price, one will also pass by on the immediate benefit of using the most recent technology. In this case we suggest that the Museum waits on purchasing an SLA, but seriously considers purchasing a 3D scanner within the next 5 years.

2. Introduction

Hundreds of museum visitors pass through the National Museum of Denmark everyday, viewing and reading about the many artifacts on display. Although museum patrons are standing right in front of the artifacts, their experience is only a visual one as the patrons are separated from the artifacts. In most situations patrons cannot be afforded the opportunity to pick up and handle the artifacts on display, yet a recreation would give museum visitors a physical sense of what they are viewing. The traditional physical separation from the artifacts make museum visits seem less interesting, and therefore less educational for the patrons.

The main focus of this study is to find a way to make a visit to the National Museum more enjoyable and beneficial for everyone. A popular theme among museums today is attempting to make the entire experience more hands-on. This hands-on approach is very effective, because manipulating objects gives the patrons a sense of empowerment, and consequently makes the experience more worthwhile. The challenge facing museums is that many of the more interesting artifacts do not lend themselves to reproduction by traditional means due to their fragility. The National Museum has a desire to reproduce various wood and bone artifacts that fall into this category.

As museums and education are closely related topics, any improvements made in the Museum will have a positive effect on education. One such example of an improvement to the Museum is the addition of reproductions of museum artifacts. With reproductions, more of the population will be attracted to the Museum, and in turn learn more at the Museum. Children, a group that benefits the most from hands-on approaches to learning, will be able to experience history and gain significantly more knowledge about historical topics simply by playing with and studying the replicas. The visually impaired represent another group of museum patrons who would greatly benefit from a hands-on learning environment. In addition to audio descriptions of the various artifacts, they would also have physical artifact reconstructions available for them to examine by touch. The technologies of stereolithography and 3D scanning would facilitate these reproductions.

In addition to educational purposes, the Museum could benefit from the technologies of stereolithography and 3D scanning in several other ways. By being able to reproduce artifacts quickly and flawlessly, the Museum would be able to improve significantly its methods of cataloging. Currently this is done through mere written descriptions and photographs, which do not provide as faithful of a representation as a 3D model. Also, replicas could be created for security purposes, i.e., reproductions could be displayed or even loaned out to other museums, while the originals would be safely stored. In addition, stereolithography could be used to make replicas of various historically important objects, which in turn could be sold at the museum gift shop. While other reproduction methods are possible, they all involve touching the object. These technologies, however, are beneficial because they are able to reproduce extremely fragile objects that cannot be touched.

Stereolithography is one of the most remarkable technological advances of our time in the area of replication. This technology is so versatile that it can find an application for itself virtually in every field. Through this project, the group will attempt to reveal its potential and its applications for the National Museum of Denmark. The process of making a copy using stereolithography and 3D scanning, though technical, is analogous to that of a photocopier. The first step is to choose an object to duplicate. The process of using a 3D imaging system to scan the artifact is similar to when a photocopier uses bright light to scan over an original document. The second process is transforming the digital information of the scan into a physical copy. The photocopier makes an exact replica of the original document, just as the stereolithography apparatus makes an exact replica of the original artifact; however, with this process the replica is created in three dimensions instead of two. A more detailed account of this process can be found in the background information chapter.

The goal of the project is to educate the museum administration about the technologies of stereolithography and 3D scanning, and to suggest new applications of these technologies that would benefit the museum. In order to meet this goal, the group conducted background research on the processes of stereolithography and 3D scanning, on companies associated with these technologies, and on applications of these technologies, both directly and indirectly related to the area of museums.

A methodology was created and followed based on the research done for the background information section. This methodology includes interviews with different companies and museums, both in the U.S and abroad, along with the examination of artifacts in the museum's holdings. Through the interviews the group received valuable advice and feedback on the techniques, benefits, and drawbacks of stereolithography and 3D scanning. By examining the artifacts, the gruop learned what the needs of the museum were, and what limitations of the technologies might come into play.

Finally, an analysis of the most efficient, cost effective, and available methods for reproducing the objects was conducted, using the procedure detailed by the methodology. In this investigation the factors of cost, time, space constraints, training, and mass production viability were examined. This information, along with information about the museum's resources, was used to decide what methods of scanning and reproduction best suited the museum's needs. These decisions are outlined in the recommendation section.

3. Background Information

This chapter contains information about the technologies of stereolithography and optical scanning. In addition, it provides information about companies involved in these technologies, and current applications. Technical terms and jargon are italicized the first time they appear in each section. Please refer to the glossary in section 7 for a complete definition of these words.

3.1 Education and Museums

For many decades education and museums have been closely related topics. A member of Executive Council of the International Council of Museums, Ulla Olofsson, stated :

> Museums, which aim basically at the preservation of artifacts, have at their disposal means of illustrating historical, scientific and artistic phenomena which may - and should - be used in education in order to provide an idea of what life was like in the past and perhaps also to give us some clue as to what things will be like in the future.

Thus, museums should be looked at as educational tools that can be used to gain more knowledge about the past, the present and the future (Olofsson 3).

In teaching, it is essential to go beyond the classroom setting with mundane lessons through reading, discussion and occasional pictures used as visual aids. Another authority on education in museums, a curator at the Skoletjenesten in Denmark, Tage Hansen, wrote in one of his articles entitled "The Educational Use of Museums, the Natural Environment and 'Reality'": " Teaching should be seen as a discovering activity, where the pupils use their school as a base from which to go exploring the surrounding society to find out how the world is put together. The knowledge acquired should then be used to make new connections in the future." Even with new remarkable technological advances and other societal progress, it may be very difficult or nearly impossible for the new generations to understand different aspects of life in the past that have long since disappeared. A short trip to the museum can change that significantly by actually demonstrating the past with the aid of tangible, three-dimensional objects used by people centuries ago.

Museums have over the years proven themselves to be invaluable educational tools. Still, the populations of visitors involved are relatively limited. It is possible to expand involvement in museums and capture the interest of more groups: for example, young children, teenagers and the visually impaired.

The National Museum in Copenhagen is ahead of many other museums, as it has already created and opened the "Please Touch" exhibit, where visitors can touch all objects. Also, the Children's Exhibit has many replicas of various museum artifacts with which the children can play. This exhibit has not only proven to keep the young ones entertained, but to also to excite them about the artifacts and their history. Further, because this type of learning is enjoyable, the exhibit has boosted their desire to do so.

3.1.1 Interactive Exhibits

It has been proven that an experience is much more memorable when several senses are stimulated simultaneously. For example, being able to touch an object as well as observe it is a much more intensive method of studying it, and therefore will result in a more complete understanding of the object and its function. The National Museum of

Denmark has opened a hands-on exhibition that encourages museum visitors to touch artifacts in addition to viewing and reading about them. This exhibition comprises many objects that are recreations of items found in ancient Eskimo cultures, such as furs, igloo models, bones, furniture, toys, and among other artifact replicas.

Along with the hands-on exhibit in which patrons are allowed to touch the objects that they are examining, there are exhibits in which patrons can use their sense of smell to experience yet another aspect of the rich ancient cultures. This is an exhibit that displays some of the materials ancient civilizations came into contact with regularly. In this exhibit, there are a number of plastic boxes with strong smelling objects in which museum visitors can look at and also smell. This is an enjoyable activity for all of the visitors that helps the learning process via multiple senses.

Although the museum has several creative exhibitions, it is eager to expand in new directions and increase the amount of interactivity with the patrons. Now, with the possibility of reproductions created by the process of stereolithography, the museum exhibitions have an even greater potential to become more useful and educational for all patrons.

3.1.2 Tactile Learning

Stereolithography has already been used in several museums world-wide, and it has improved the effectiveness of education in various ways. For the National Museum this technology may be used to produce exact replicas of important artifacts. Museum exhibits can be supplemented with such objects in order to allow the museum visitors to touch and to examine the artifacts more closely. Udo Liebelt, an educational officer at

Kunstmuseum in Germany, pointed out: "In order to understand the form and structure. . . we use our sense of sight. In many cases, however, the sense of touch plays a more meaningful, perhaps the most important role" (Liebelt 41). By touching the artifacts, visitors will understand the objects and the object's purpose more sharply and completely. In addition, such physical interaction makes for a more authentic experience, which in turn increases the level of enjoyment and interest.

3.2 Overview of Rapid Prototyping and Materials

In today's busy and continuously advancing world of technology, inventors and companies are simply unable to put new products out on the market fast enough. Brilliant ideas for new products are generated daily, but the only way that these ideas can survive is if they are brought to life. *Prototypes* are needed to present these new ideas, to make them tangible, to make them real, to make them valuable. If an idea is truly original and expedient, it will be recognized and it will undoubtedly gain demand on the market. The problem is not in generating ideas, but in quickly and efficiently realizing them and producing the actual product. Approximately twenty years ago, producing prototypes was a very slow and costly process. Since then, substantial advances in prototyping have been made. Most manufacturing companies now use *rapid prototyping* techniques to produce prototypes and advance their products to the production lines in record time.

3.2.1 Rapid Prototyping

Rapid prototyping is a popular term in the world of manufacturing. Before any production process can begin, it is necessary to have a physical *prototype* of the part being made, in order to make sure that there are no critical design flaws and that it functions as intended. However, often, prototypes cannot be produced fast enough. Manufacturing of the prototype itself may delay projects for weeks and may have prohibitively high costs. The solution to this problem that so many manufacturers have turned to is rapid prototyping.

The idea of rapid prototyping is very attractive to most companies because the process is so efficient, and professionals from their desktop computers can usually perform the entire procedure. All of the Computer Aided Design (*CAD*) editing of the desired object, the required programming of the peripheral output device, the mechanism that actually produces the product, as well as all of the laser scanning devices can now be accomplished with the same computer (Marks 11).

Rapid prototyping is separated into three categories of fabrication processes: subtractive, compressive, and additive. In a subtractive process, material is carved away, while shaping the desired object, as in lathing, grinding and milling, etc. Such processes were first to be subjected to computer control. Some drawbacks of subtractive fabrication are the limitations in the shape of the object being produced, the accuracy of its dimensions and also of the inevitable wear of the cutting tools that result in additional errors that can be very difficult to predict and compensated for in CAD. The second category of fabrication processes is compressive, which includes molding and casting. These procedures are generally efficient and are still used widely. However, their one drawback is the additional cost of the molds and extraction mechanisms. The third, and most recently developed in fabrication processes is the additive method, during which objects are "grown," layer by layer. This is a complicated process in which *photopolymers* or *thermoplastics* are solidified in individual layers by way of exposure to a powerful, computer-controlled laser beam. Manufacturing processes that fall under the additive category are *Selective Laser Sintering* (SLS), *Fused Deposition Modeling* (FDM), Three-Dimensional Printing, and *Stereolithography* (Burns 3).

The concept of rapid prototyping is dynamically evolving. All over the world scientists are researching new ways to create larger and more complicated designs and at the same time to reduce the amount of effort and the length of time that it takes to convert from a concept or a drawing to a flawless finished part. Several efficient rapid-prototyping techniques exist, each with very specific applications. In this report, however, stereolithography will be the primary topic of discussion.

Stereolithography is the most widely known and used method of rapid prototyping. Charles Hull, a co-founder of 3D Systems, Inc, developed the process of stereolithography in 1984. He originally scanned an ultraviolet laser beam over a surface of some liquid *photo-curable resin* that under the exposure turned into a solid shape of a layer. He, along with Ray Freed, led 3D Systems in perfecting this method, which was finally patented in 1986 (U.S. Patent # 4,575,330) (Burns 56). Their first product, the *Stereolithography Apparatus*, now more familiarly known as *SLA*, was introduced at a tradeshow in 1987 as the first commercially available rapid prototyping system (hkumea 2). The process of stereolithography will be discussed throughout the report, but the simplified overview of the machine's function is as follows.

A stereolithography apparatus is equipped with a powerful ultraviolet laser that generates a beam, which is pointed at a vat of photopolymer resin. As the laser beam is moved over the surface of the photopolymer, a very thin layer of the photopolymer is solidified. Usually, there is an elevator directly underneath the solidified area that descends once a single layer of the object is complete. This scanning and lowering process continues until the entire object is solidified.

Information about what a machine can do is best supplemented with an explanation of how it does it. The SLA has several controls that allow it to function as it does. Most, if not all of these controls are concentrated in a single computer. The production of an object by way of stereolithography is a multi-step process. First, the SLA should be informed of what it is about to make. A previously made and formatted CAD file needs to be programmed into the SLA. Then, the special stereolithography software "slices" the CAD drawing of the object into thin layers. Now the SLA "knows" what layer shapes it will make and in what order. The laser beam is then directed at the surface of a vat of a photopolymer and the layer-solidification process begins. After the whole object is solidified, it is put through a second system, the *Post Curing Apparatus*, which generates a long-wavelength of ultraviolet light and provides the final cure for the object.

3.2.2 Resins

One of the key issues of *stereolithography* as well as in some other types of *rapid prototyping* is accuracy of the produced *prototype*. Materials, namely *resins* in stereolithography, which are used to create the product, play a critical role in impacting the quality of the finished product. Considerations such as speed of curing, viscosity, toxicity, photosensitivity, susceptibility to distortion such as warping, shrinkage and swelling after curing, as well as shelf-life must be considered for every application, in order to choose the most suitable resin (Bezdicek 35).

In stereolithography, lasers are used to cure resins. These lasers vary in speed and intensities, as well as in the point-area of exposure. All these factors, in addition to some chemical properties of the resin, determine the speed of fabrication of a product.

3.2.3 Photopolymers

A *photopolymer* is a material that originates as a liquid *resin*, but under the influence of light at a particular wavelength undergoes a chemical reaction, which transforms the liquid resin into a solid. Dupont invented photopolymers in the 1950's; however, they were not used until decades later. This unique chemical finally found the application that made it so valuable to the world of manufacturing in the 1980's, when a small company Chem-Form developed a process of using laser beams to solidify 2-D patterns in a vat of photopolymer resin. A few years later, 3-D Systems, another small start-up company at the time, perfected the technique of *photopolymerization* by using similar methods and concepts of applying ultraviolet laser beams to the resin to solidify 3D objects and finally patented. This technique is known as stereolithography (Burns 4).

3.3 Overview of Optical Scanning

As mentioned earlier, multiple steps must be taken to produce a finished object using *stereolithography*. As always, before the production process can begin, a specification of the object is required, in this case in the form of a *CAD* file. This type of file is required because a computer, which can only read a digital file, controls the *SLA*. This file, which contains the information needed to build the object, can be generated in one of two ways. An engineer can actually draw the object in CAD, but depending on the level of complexity of the object, this task can be very tedious and time-consuming. Thus, the better alternative is one that requires no physical drawing, but rather is a scanning method. The appropriately named *optical scanning* process is a much easier method of getting the complete dimension and shape data of any object into a CAD file.

A photocopier is used to make copies of paper and other two-dimensional objects. Optical scanning does the same thing for 3D objects; however, the result only initially exists in a computer. The procedure uses lasers and reflection to calculate a series of points that would exist on the object. The result of the procedure is a file containing the set of these points. This information is then fed into a processing program, such as Laser Design's DataSculpt, that can create a CAD file from the collection of points (Laser Design 1). This CAD file is the digital representation of the physical object, and consequently will be used to recreate the physical object later.

Any shape can be digitized using the three-dimensional coordinate system. Further, most systems allow for computer controlled rotational system in which the part is rotated as it is scanned so that every surface can be imaged. Also possible is blending images. In this process, multiple views of the same object may be taken and then blended into one file (Roberts 45).

3.3.1 Laser Design's Optical Scanners

While there are many companies that do work in the area of *optical scanning*, Laser Design's commercial scanners offer a good example of what is generally available. "Laser Design's Surveyor family of 3D Optical Scanners makes use of a laser sensor that is mounted to a 3 - 6 axis computer controlled positioning system" (Laser Design 1). In order to scan an object, it is put on the bed of the scanner, and then software moves the lasers and the sensor around the object. The precision of the scan has a directly inverse correlation to the speed of the scan, i.e., the slower the scan the better the quality. The speed of the machine is controlled by software (Laser Design 1).

3.3.2 Technical Description of Optical Scanning

The *optical scanning processes* use the principle of *triangulation*. A dual camera probe is the core of this technology. This probe emits a *diode based* laser beam from the center, and then the beam is split into a plane of laser light. This light comes out of the probe and shines below onto the surface of the object being scanned. The reflected light from the profile on the surface of the object is captured by one of the probe's two cameras (Roberts 32-33). The reason for having two sensors instead of one is that if for some reason the view of the profile on the surface of the object is blocked for one sensor, there is always the second sensor that can pick up the same profile. A user can toggle between the two sensors, that is, he or she can choose which camera to use, but only one is active at one time (Roberts 35).

The shape of a single two dimensional profile is recorded by the camera and subsequently, based on the calibration and look up tables of the lasers, a position in 3D space is determined and stored for each pixel value by the software (Roberts 35). This location along with the machine axes positions are used to compute the X,Y,Z coordinates of the points along that profile. Hundreds and thousands of similar profiles are thus collected as the probe scans over the object and the software stores this information into a *database* for later retrieval (Roberts 37). Each profile comes into the database as a single *polyline* entity with points distributed along the length of the line. Conceptually, this is like taking an object and a marker and drawing the straightest line possible from one end of it to the other, keeping track of the positions of the dots on the line. These *polylines* are displayed graphically on the computer screen as they are gathered (Roberts 37). Finally, once the entire object has been traced, the operator can look at the object on the computer screen to remove any abnormalities before it is converted into a CAD file.

3.3.3 Accuracy of Optical Scanning

Laser Design's scanners come in standard *resolutions* of 0.0004" and 0.0008" (Laser Design 5). The latest technological advances in the design of such scanners now allow for resolution as fine as 0.00006" (Roberts 43). However, resolution does not directly relate to accuracy. In this context resolution relates to the smallest change that in distance of the sensor is able to detect. Accuracy, on the other hand, relates to the correct reproduction of the object being scanned.

The determining factor for the accuracy of the reproduction lies more in the object itself than the optical equipment. If the object's surface is a matte finish, then resolution and accuracy will be nearly the same (Roberts 43). If the object has a glossy surface, there may be some incidental reflections that are displayed as noise on the subsequent image. The software can take care of this to some extent, but there are cases in which there is simply too much noise. This means that glossy surfaces cannot be accurately scanned in some cases (Roberts 43). Conversely, there exists the opposite to this condition, the fact that the object doesn't return enough light, so there are places where no readings exist. A solution to this problem is to coat the object with a powder or paint, but this is not feasible when dealing with artifacts such as those found in museums (Laser Design 5).

In any machine there are inaccuracies in reference to movement, and construction imperfections. However, these machines are individually and carefully calibrated, which virtually eliminates inaccuracies due to the operation of the machine itself (Laser Design 4).

3.3.4 Speed of Optical Scanning

As related in the section dealing with accuracy, the machine has to be calibrated with exposure settings much like a camera. Unlike a camera this is not due to ambient light but is contingent on the shade of the object being scanned. Light objects scan faster than dark ones because the dark objects need greater exposure settings. It is possible to sample at the same speed regardless of the object, but quality and accuracy degrade with darker objects (Roberts 44-45). The amount of detail that is desired also determines the speed of the process. Therefore, if measurements are taken after moving only a very small distance, then the process will be slower. On average, a scan with good accuracy has a speed of 3000 to 4000 points per second (Laser Design 6). There is some deviation as some situations may do the scanning at the full speed of 14,400 points per second and in other cases the speed can be reduced to 1000 points per second or lower (Laser Design 6). In comparison with *mechanical tracing systems* it is moderately faster, but it is much faster than *coordinate measuring machines*.

3.3.5 Using Optical Scanners

All of Laser Design's scanners possess software called DataSculpt, and scanners from other companies would similarly possess proprietary software to control their machines (Laser Design 1). Since this is the case, this software may be examined and its capabilities may be tested.

The DataSculpt Software has two main functions. The first function is to collect the data from the probe. The second function is to move the probe so that the data can be collected. After the data is collected, it is formatted and stored on the hard drive. This software controls all aspects of the process. While this enables the user great control, it does not necessitate a degree in Computer Science to use. The layout of the software is a menu system with a point and click interface (Laser Design 3). In this way the user sets up the system with tolerances and exposure times along with other configuration aspects. The user either sets the machine to perform the scanning automatically, or allows the user to control the scanning by the use of a joystick. If the process is set to automatic scanning, the defined path may be saved, and used again later (Laser Design 3). The system does not require code to be written, or any other type of involved computer programming. However, experience with CAD is encouraged because in this way the scanning can be done in a way that will be of the most benefit and will provide the best representation of the model (Roberts 45).

3.3.6 Safety Concerns of Optical Scanning

Class II lasers are generally used by optical scanning systems, such as those used by Laser Design, Inc (Laser Design 5). This class of lasers is very low power and is red to the naked eye. The laser has a built in beam spreader that does not contain any moving parts. The greatest concern is damage to the eye that may occur with prolonged exposure to the laser. While this is a concern, the span of time that it would take to damage the eye is much longer than the Class III lasers that were previously used (Roberts 44). In general, the machines are completely safe if used in accordance with their instructions. Moreover, even if the technician does look directly at the laser, the possibility of damage to the eye is very small given that they do not prolong the exposure.

3.3.7 Advantages of Optical Scanning

Features such as the design, speed, and accuracy of *optical scanners* illustrate how efficient, and therefore, valuable they are. However, these mechanisms possess other advantages over alternative techniques.

The first and foremost advantage of optical scanning is its non-contact nature (Roberts 41). This is extremely important when dealing with fragile objects such as museum artifacts. Further, since this process was designed with *CAD/CAM* applications in mind, it is well suited to the task and allows the files to be modified in CAD. This is a benefit because no additional software needs to be learned (Roberts 40).

Secondly, an image that can be created by use of optical scanning is of higher resolution than conventional *mechanical tracing systems*. This stems from the fact that the laser has a thinner beam than the probe so it can pick up finer details. Moreover, the method of optical scanning is superior to that of mechanical methods because in some cases the mechanical process creates false attributes due to incidental forces such as wind (Roberts 41).

Finally, the result of the process is a set of points that represents the surface of the object in question. Since this data is not automatically specialized by the procedure, it allows it to be used for a variety of applications such as CAD/CAM, archiving, and *tool paths* for machining (Laser Design 2).

3.4 Computer File Types Used in Stereolithography

As previously mentioned, *stereolithography* is a technology for which all controls are concentrated in a computer. It is this computer that communicates to the *peripheral device*, the *SLA*. Standardized conventions of information storage and exchange make communication possible between the computer and all other machines. This standardization is achieved through *file formats*. In this proposal two essential file formats will be discussed: *CAD* files and *STL* files.

3.4.1 CAD Files

Computer Aided Design (CAD) is the mainstay of the mechanical engineering community. CAD allows the user to specify a series of points and then allows the user to specify how those points are to be connected. While the creation of a file is not necessarily faster than creating it by using a piece of paper and a pencil, the product that is created is infinitely more versatile. This versatility stems from the fact that multiple views of the same part may be created from one drawing, a 3D representation may be created and displayed on the computer screen, and changes to the part can be made without having to redraw the entire part. For the purpose of this project, however, we will concentrate on CAD's ability to serve as the source of information for a *stereolithography apparatus (SLA)*.

CAD was chosen to act as the source of information for stereolithography machines because the format is already widely used, and provides an accurate representation of an object in 3D space. This is not to say that it provides an absolute answer, as there are problems that arise. Some of these problems stem from the fact that there are many different "flavors" of CAD. Some of these "flavors" are *VDAES*, *IGES*, and *STL* (Dolenc and Makela 18). The problem with multiple "flavors" is that the object can be scanned and saved in one format, but the people who are actually making the stereolithographic model may be unable to read the file on their computers. A second problem deals with the scanning process more than the file itself. If a part is scanned, accepted, and then saved in CAD, in some instances it is no possible to later correct the file should a problem be found. The only way to resolve this issue may be to rescan the entire part (Dolenc and Makela 19).

SLAs cannot read information straight from CAD files. This is because the SLA needs information about each layer that it needs to create, and this information is not directly available from the CAD file. Therefore, the information must be "sliced" into horizontal layers, as that information is used in the actual creation of the physical part. The two most popular choices are using software that slices directly from a CAD file for a particular machine, and using the CAD file to create a STL file.

3.4.2 STL Files

The *STL* file format was created by 3D Systems in 1987 and is the current standard for the input file of *stereolithography apparatuses (SLA)* (Donahue 222). Unlike *CAD* files, STL uses a triangular mapping method that is popular in most graphical modeling programs. In this method, the surface of the object is mapped with triangles of different sizes, shapes, and orientations instead of using other geometric shapes (Dolenc and Makela 21). These triangles that cover the surface are called *facets*. A facet is simply a triangle and its normal (perpendicular) vector (Donahue 224). The object modeled must be a solid because the format of the file does not represent internal geometry or structure. From this solid representation the object may be sliced into the layers and from that information, the SLA machine can create the part. If the part is large, it has to be divided into smaller sections so that it can be created. It is at this point that the part will be digitally broken up into parts that can be manufactured and later attached together (Donahue 224-225).

The STL format is by no means the perfect solution in all cases. One problem is during the transition from a faceted model (CAD) to a STL file, the conversion loses some attributes of the original representation (Dolnec and Makela 20). While this has become less of a problem of late because of better software, there are other file formats emerging that are attempting to address this problem.

Currently there is no one format that seems to be strong enough to overtake the popularity of the STL format. Nonetheless there are other emerging formats, such as *CLI* and *SLC*, that are attempting to creep in to the market. These formats, however, are marked with problems of their own in addition to the data loss issue of the STL files, and it is doubtful that they will take over the STL format anytime soon (Dolenc and Makela 22).

3.5 Stereolithography in Business

The technology of *stereolithography* was invented and to this day is being perfected by Research and Development departments of several companies all over the world. As more and more people in the industry are discovering this innovative method of rapid prototyping, they want to invest in it, and improve its efficiency, quality, and cost. Since 1984, the year stereolithography was born, many more people beside Charles Hull acquired similar interests in this process and started their own companies to either manufacture stereolithography devices, improve the necessary laser scanning, perfect the *CAD* and *STL* software, enhance various qualities of resins, etc. This list is endless.

Nowadays, stereolithography has innumerable applications in the business world. Whether to design, manufacture, or sell a product, stereolithography can prove to be a most valuable tool. For engineers alone, it is a great advantage to be able to have a physical representation of a part that was just designed to better see if it will fit with existing parts as intended. The manufacturing and production process is greatly enhanced with the use of SLA technology. With SLA prototypes, the production process can foresee any problems on the production line after changing a part or template. Likewise, the Sales division will have an immeasurable advantage over any competitor when they can present a tangible object that is a copy of the finished product. This can also help to eliminate any future conflicts dealing with misinterpreted design ideas between customers and clients. In the past, engineers have relied on CAD drawings to help see what they were designing, producing, and selling. Now they can pick up what they had only been able to see on the computer screen.

Figure 3.1

On the left of figure 3.1, a part created directly from a CAD file using stereolithography is shown. The part on the right is the manufactured part at the final stage from a manufacturing plant. It can be easily seen how creating the part in less than an hour could save much time and trouble if it is decided that the part is not what it should be. In another short increment of time, the part can be redesigned and speedily reproduced by way of stereolithography. The following sections deal with companies that are involved with processes of optical scanning and stereolithography.

3.5.1 Companies that Sell Machines

Even though the number of people involved in the area of stereolithography is rapidly growing, still there are relatively few successful companies in this market. The following are overviews of a few examples of leading companies selling machines used in the stereolithography industry.

3.5.1.1 3D Systems

In researching *stereolithography* machines, one name appears time and time again. This name is 3D Systems, inventors of the *stereolithography apparatus (SLA)*, based in Valencia, California with foreign offices in Germany and France (3D Systems

1). This company created the process of stereolithography and holds many patents relating to the process. While it does have competitors, there is no one that is even remotely as well known and well respected in the area or even comes close to its market share. This respect and market power comes from a legacy of quality machines, innovations, and total package solutions (3D Systems 1).

3D Systems has a product line of 7 machines. These machines are the ThermoJet solid object printer, the SLA 250, the Viper si2 SLA System, the SLA 500, the SLA 3500, the SLA 5000, and the SLA 7000. The SLA 7000 is the top of the line, and the quality and speed of the machines decrease from there. The SLA 250 is being replaced by the Viper si2, and the 250 is on clearance sale for $170,000 USD until the company sells its remaining inventory (3D Systems 3).

The Viper si2 is the company's first *solid imaging system* to combine standard and *high-resolution* part building in the same system. This makes the machine highly versatile as at the standard resolution it provides the best balance of *build speed* and part resolution, while the high resolution (HR mode) provides extremely high detail for small parts and features. The resolution of the standard setting is 0.10 mm and the resolution of the HR mode is 0.06 mm. The software that accompanies the machine has been updated to be more effective and easier to use. Objects that are 250 x 250 x 250 mm now can be made directly by the machine, but larger objects must be created by building them in sections and then assembling them in the *postproduction* process. The price of this system is $200,000 USD excluding import taxes and tariffs (3D Systems Sales Rep.). This price includes the machine, set-up, the *Post Curing Apparatus* (PCA), and the warranties.

At the other end of the spectrum there is the SLA 7000. Priced at $800,000 USD, excluding taxes and tariffs, it seems very expensive (3D Systems Sales Rep.). However, with the increased cost comes increased benefits. These benefits include a speed that is 6 times faster than the Viper, and an ability to make objects that are 508 x 508 x 600 mm directly from the machine. Also the resolution of the machine is configurable by the users to suit their needs (3D Systems 7). The fastest *build style* has a resolution of 0.127 mm, while the most accurate build style has a resolution of 0.025 mm.

The other machines that are sold fall somewhere in between the Viper and SLA 7000 in their abilities and price. However for all the machines in addition to buying the equipment, the purchaser must provide a small air conditioning unit. This is because there are environmental conditions that must be met for the build process to be successful. Furthermore the buyer must have a PC as one is not provided with the system. The warranty for all the systems is one year from the installation date and includes parts, labor, and 3D Systems' software upgrades. The laser is under a separate warranty and is specific to the machine that is being purchased (3D Systems Sales Rep.).

3.5.1.2 Solidscape

Solidscape, a privately held company incorporated in February of 1994, designs, develops, manufactures, and sells rapid prototyping hardware and software. The company primarily sells two products: the PatternMaster and the ModelMaker, which make patterns and molds respectively. These systems combine *thermoplastic ink jetting* technology with high precision *milling* to build models or patterns that have a maximum accuracy of 0.025 mm. Products from this company use the ink jet technology similar to plotters but with two heads that deposit different material to achieve the desired part. In layman's terms, the machine places heated drops of two types of material one might think of it as wax and plastic. When the drops cool, a new layer is then added. After the completion of the build process, the wax is melted away leaving only the plastic part (Solidscape 2).

The *thermoplastic* only comes in green, but may be painted using certain types of paint. While the limited material color choice is not different from SLAs, the idea that the machines use ink jet technology means that one day coloring may be able to be added to the thermoplastic before it cools. A significant feature of this future enhancement would be that the part would already have the correct color when it sets, and there would less post-production work.

While the results sound similar to 3D System's SLA machines, this process takes the user several steps closer to the final part. SLA models are only usually used for conceptual models. However, with these machines, the products may immediately be used to make casts and molds, which would then allow masters to be made using whatever material is desired. The cost of these machines is in the range of $60,000 - $80,000, which is much less than an SLA machine of comparable quality (Solidscape 5). However, the drawback of these machines is the speed, as they are very slow compared to the SLA machines.

3.5.1.3 AAROFLEX, Inc.

ARROFLEX, Inc. is a company that is attempting to provide an all in one solution for people that want to both scan objects and then reproduce them using *stereolithography*. Based in Fairfax, Virginia, the company offers products that it claims are comparable to the competition's products at a much cheaper price. However, the company is currently involved in litigation with 3D Systems for alleged patent infringement so it is not currently selling its products. The company does expect to win the suit and stated that it would be more than happy to serve the needs of customers after the conclusion of the suit.

3.5.1.4 Laser Design, Inc.

Laser Design, Inc. is a company that specializes in machines that scan 3D objects and then creates a computer representation of them in a desired format, usually some flavor of CAD. While not the only company that sells such machines, it is known for having quality products at affordable prices. The company, established in 1987, is based out of Minneapolis MN, and also has offices throughout the world with its European office located in Genova, Italy (Laser Design 1). It sells lines of scanners that specialize in scanning objects with complex geometry (Laser Design 1).

Laser Design carries three types of scanners. These scanners have the product name of Surveyor, and the different series are the DS-Series, the RE-Series, and the PS-Series (Laser Design 2). The DS-Series (Dual Scan) is the top of the line scanner, and is set up with a scanning table, and a separate computer station. It is used for ultra precise imaging of parts with applications in the mechanical engineering field (Laser Design 7). The RE-Series (Reverse Engineering) is a cheaper, less precise version of the DS series, because in reverse engineering tolerances do not have to be as tight as in full-scale production (Laser Design 8). The PS-Series is the most practical and well suited to scanning artifacts. The unit itself is portable and provides an economical, and highly accurate scanning of objects. Further, it has a color scan mode in which the texture of the product can be captured (Laser Design 9).

3.5.1.5 Cyberware

Cyberware is a company that specializes in the scanning of 3D objects. It was incorporated in 1982 in Monterey, CA, and is owned and managed by members of the Addleman family. It holds many key patents on this technology and consequently is a market leader (Cyberware 1). At its inception, the company focused on building custom machines, and digitizing objects for various firms. However, as applications grew to include the fields of art reproduction, medical uses, movie special effects, *rapid prototyping*, and research, the focus of the company changed. The focus moved to primarily selling a standardized line of scanners, but still building custom systems on a need basis (Cyberware 3). The company has international resellers located in Japan, Hong Kong, Europe, Australia, Korea, and Israel.

The standard product line of scanners includes the following machines: Head & Face Color 3D Scanner, Model Shop Color 3D Scanner, Mini Model Shop Color 3D Scanner, Desktop 3D Scanner, and the Whole Body Color 3D Scanner (Cyberware 5). For the specific applications of museums, the scanner recommended by the company is the High Resolution Model Shop Color 3D Scanner Bundle. This scanner would be able to scan objects of a diameter of 450mm to 1 meter. Bone and wood are typically ideal surfaces for scanning, and the ability to move most objects simplifies the scanning and post production process considerably. The price of this scanner is $90,500.00 (USD, C.I.F. Port of Entry), and it includes scanning hardware and software, on-site installation, and training as well as technical support and warranty (Cyberware 7). With this system multiple scans, and sets of scans, can be automatically aligned and merged to create a complete 360 degree 3D model in about one hour per part. However, for larger objects a custom system would be required. Custom systems are more expensive than the standard ones because of the engineering time required (Cyberware 4).

Cyberware has many customers that have used either their standard machines or custom machines for museum work. These customers include: Stanford University, The Smithsonian, The Tech Museum of San Jose, and The American Museum of National History. A more detailed account of these projects can be found in the applications section (Cyberware 4).

3.5.1.6 ShapeGrabber Incorporated

ShapeGrabber Inc. was created on November 1, 2000 and its offices are located in Ottawa, Canada. The company is a wholly owned subsidiary of the VITANA Corporation and derives its name from VITANA's ShapeGrabber product line (ShapeGrabber Inc. 1). The CEO and president of the company is Marc Bisson, and the goal of this subsidiary is to take advantage of the growing market by expanding the existing product line and improving the quality and speed of the existing products. The company boasts that its scanners provide a choice of scan platforms enabling parts of virtually any size to be scanned, fast user-friendly data acquisition, powerful and easy to use software, and interchangeable scanning heads with variable scan width and range (ShapeGrabber Inc. 2) .

Currently the company has three models available: The ShapeGrabber Tabletop 3D Scanning System, The ShapeGrabber Portable 3D Scanning System, and The ShapeGrabber Gantry 3D Scanning System. One aspect of these scanners that stands out is their accuracy. For example the accuracy of the tabletop system is 0.025 mm, which is the best in the market, according to the corporation (ShapeGrabber Inc. 1). This is of interest because one of the concerns of any reproduction is the accuracy of the reproduction, and in a museum application, faithfulness to the original artifact is very important. Furthermore, the price is less than that of competitors, as the tabletop system sells for $48,000 USD. This price includes on-site training for the museum staff as well as a 1-year warranty (ShapeGrabber Inc. 4).

For museum applications, the Gantry or the Tabletop system would be adequate for most applications, but for large artifacts the Portable linear platform would be the best solution. The platform is a 300mm high precision linear stage mounted to an industrial tripod. The tripod is mobile and the user would place the stage in from of the area that is being scanned. The platform is fairly lightweight and portable. The only problem with this scanner is that it could take dozens of scans to completely digitize an object. Then once all the scans are complete, someone would have to manually align the images so that they combine to form the actual object. The price of this system is $54,000 USD, and the price of the alignment software is $7,590 USD. The systems come with on-site installation and training, and a full 1-year warranty (ShapeGrabber Inc. Sales Rep).

The technology that these scanners use is based on the BIRIS system developed by the National Research Council of Canada (NRC). An example of an application of this technology is the Sphinx reproduction at the Canadian Museum of Civilization. In this application the large artifact was scanned using the BIRIS system and then reproduced using the process of stereolithography. Because the data is stored in a computer, it is relatively easy to scale the object down, and this made it possible to create smaller replicas that are now for sale in the gift shop at the museum. A more detailed account of this reproduction is described in a later section on stereolithography applications (ShapeGrabber Inc. 5).

3.5.2 Companies that Specialize in Scanning Objects

A number of companies cater to the 3D imaging needs of other companies and organizations. There are essentially two different varieties of 3D imaging companies, the ones that sell the systems to clients and those that scan an object that is sent to them. The decision of outright ownership vs. outsourcing is decided by the needs and capabilities of the institution requiring the 3D imaging.

There are a few factors to be weighed before arriving at a decision to outsource or to acquire all of the necessary equipment and software. If an organization's budget permits and the constant need of this technology is present, then ownership should be seriously considered. But if money is tight, the technology will only be used a little of the time, or waiting a few days for the digital images isn't going to inconvenience the task at hand, outsourcing might be the better alternative.

3.5.2.1 Scansite

Scansite is the leading provider of 3D scanning technology being sold on the market. It is on the cutting edge of the technology, offering full service 3D scanning equipment among the fastest and most accurate machines in the business. The company also offers fast and affordable high quality 3D laser and optical scans at their facility in Northern California within a tolerance of .05 mm (Scansite 1). It offers onsite scanning in the customers' facility for large or high security projects. Clients of the company range from The Smithsonian, NASA, Disney, Warner Brothers, Nike, and The Denver Museum of Natural History to name a few (Scansite 1). Scansite supplied the technology to the Smithsonian and helped to develop the first ever, complete 3D image of a Triceratops.

If the decision to buy the 3D technology has been made, then Scansite should also be considered for the purchase. Scansite has a variety of 3D scanning models that it currently offers on the market (Scansite 2). It currently sells models that will both capture shape and color. The company also has models big enough to accommodate the scanning of an entire person, or small enough to cater to images 0.25 meters in super high detail. Scansite will send a technician to the location of the newly purchased equipment and set up the equipment as well as train the new owners of the technology (Scansite 4).

3.5.2.2 Scantech3D

Scantech3D is a company specializing in high quality 3D images. Yet, it only performs its services from a facility in Norton, MA (Scantech3D 1). This would require that the object one desired to be scanned in would first have to be shipped to Norton, MA and then get scanned in at their facility, and then be returned. The company advertises a three-day scanning time upon receiving the object to be scanned (Scantech3D 1). It also offers many computer formats, which would easily enable someone to use the 3D digital images on any type of *SLA* machine or *CAD* package (Scantech3D 1). For larger objects they do offer onsite services for an additional fee.

3.5.3 Outsourcing Solutions for Stereolithography

If buying a machine outright is not feasible, there are many companies that provide cost-effective outsourcing solutions. The following section describes a few of the companies currently in the service field of rapid prototyping.

3.5.3.1 Mack Prototype

Mack Prototype is a division of a larger company called Mack Molding, whose headquarters are located in Arlington, VT (Mack 1). Mack Prototype is located in Gardner, MA and specializes in rapid prototyping and rapid tooling. For *SLA* applications, it has a SLA 350 machine produced by 3D Systems (Mack 3). The approximate cost to replicate a part is determined by height of the part and its volume, as that determines the amount of resin and time that is required to create the part. The company does not possess the capability to scan objects, as it is more involved in the physical reproduction side of the process, and will produce the best results with files that are submitted in either the *IGES* type of *CAD*, or a *STL* file (Mack 4).

3.5.3.2 Shared Replicators

Shared Replicators is a company based in Tulsa, Oklahoma that specializes in "high volume, world-class quality solid imaging services" (Shared 2). It uses 3D Systems' SLA 7000 machines. It is different from other outsourcing companies in that it sells a fraction of a machine that it houses, starting at 10% ownership and moving up in 5% increments (Shared 1). Sharing the machine opens a new realm of pricing options as the National Museum could buy only the amount of time that they needed, and do the work themselves if it wanted. The obvious problems are distance and shipping concerns.

Shared Replicators is also unique because it has been involved in some work in this area already.

> Recently, the company delivered to the Smithsonian Institution's National Museum of Natural History, the first full-scale silicon mold pattern of a Triceratops dinosaur skull and lower jaw fabricated in plastic using 3D scan data and stereolithography. We take great pride in assisting our client in its efforts to create and exhibit near perfect cast replicas of these national treasures so that the actual fossils, damaged through nearly a century of continuous exhibition can be preserved for future generations of scientific study (Shared 3).

The fact that the company was involved in such a large conservation effort and the result of that effort speaks very highly about its work.

3.6 Current Applications of Stereolithography

Even though this technology is just a few decades old, its applications have expanded into many different directions. There are various applications of the technology being used today that can be seen throughout the world. For example, Hollywood has created a $1 billion business with art reproduction, and stereolithography has just started catching its attention. Museums have also just begun to see the benefit in producing accurate replicas of an artifact, without disturbing the artifact being observed. Finally, the greatest use of stereolithography is in engineering firms, where it is now possible to get quick and accurate visualization of prototype designs.

3.6.1 Hollywood Applications

There are now companies in Hollywood, California that are using the *SLA* technology to make models and props for various movies. One such company, Gentle Giant Studios in Burbank, California, owns the popular SLA-250 (Gentle Giant Studios 3). The company had begun without any rapid model prototyping systems, but now use their SLA-250 nonstop. It mainly uses its SLA machine to make prototypes of the creatures that it creates in *CAD* (Gentle Giant Studios 3).

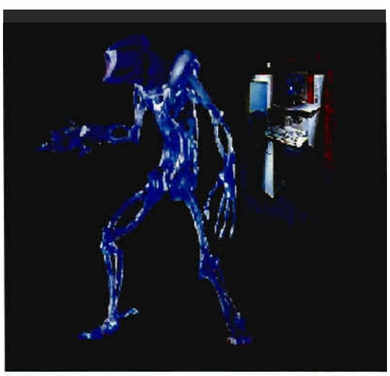

Figure 3.2

Art reproduction in movies is big business, bringing in more than a billion dollars per year. Many of the 3D prototypes that are produced are finished with a coat of paint and are used in the movies (Hollywood 1). Figure 3.2 is a creature that Gentle Giants created using stereolithography.

3.6.2 Museum Applications

Stereolithography has just begun to enter into the museum would. Due to the immense startup costs and expensive operating costs, it will probably only be affordable for large museums. Two museums have already begun to examine the possibilities of stereolithography in their museum activities. The various possibilities are endless and an excellent start is underway.

The Canadian Museum of Civilization began the use of stereolithography in order to make a scale replica of a Sphinx. The replica was then turned into a mold, and smaller versions of the sphinx are currently being sold in the gift shop. The 3D capturing software can automatically take the scanned object and create a digital mold that can be produced with an SLA machine. The three statues in figure 3.3 are all products of the digital scanning process. The biggest one was created from a mold that was made using stereolithography, while the smaller two were created using stereolithography as a means to create the end result (Canadian Museum 1). This application has been recorded as the first time a museum has made a replica of an artifact without disturbing or even touching the original (Canadian Museum 1). The smallest of the three statues are sold at the museum gift store. An 11.5in. polyester resin model is $69.99 and a 4.5in. polyester resin replica is only $9.99 (Canadian Museum 3).

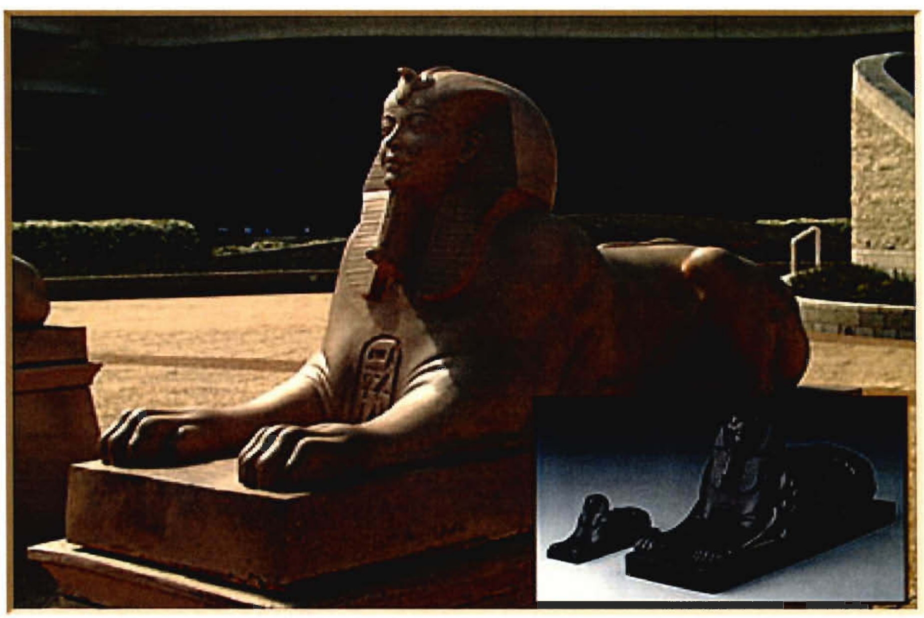

Figure 3.3

The Smithsonian museum needed to repair a Triceratops that had been on display for nearly 100 years in its museum. It invited 3D specialists to individually scan every bone from the Triceratops. This application of 3D scanning brought forth the first full digital representation of a triceratops. This digital dinosaur allows the scientists to reposition the newly constructed bones before they do any of the physical labor. Scientists have now created a scale model of the dinosaur in order to assess the degrees of freedom for all of its bones, in the hopes of understanding how the animal moved, ate, ran, and fought while it was living.

Figure 3.4 below shows how the Triceratops looked in the Smithsonian Museum for the last 100 years (Smithsonian 1). Figure 3.5 shows a digital recreation of the Triceratops' skull. Figure 3.6 is the actual skull created using stereolithography. The skull was unveiled at the Smithsonian in August of 2000. The entire recreation is scheduled to be up and ready for a Winter 2001 unveiling. The original Triceratops was pieced together using the bones of 15 different animals (Smithsonian 1). The digital recreation will be anatomically correct and an even more accurate representation than the pieced together original, say scientists at the Smithsonian.

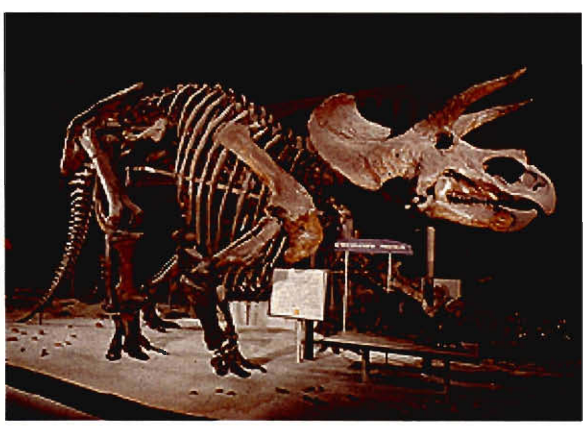

Figure 3.4

Figure 3.5

Linda Spillers/AP

Figure 3.6

There are many advantages of producing reproductions with stereolithography. The main advantage is the preservation of the original artifact, which takes precedence over all other goals. Stereolithography allows the scientist to make near perfect replicas with amazing accuracy in minutes, without disturbing the original artifact. Even with a sculptor trying to do his best at making a copy of an artifact, it will never come out as close to the original, and it cannot be resized nearly as easily as using an SLA machine. Although the technology is expensive, an individual use is much cheaper than having a skilled sculptor come in to make his best representation of the artifact. Lastly, using the 3D modeling software, one can get new angles and new insights on ancient tools and bones that might have not been possible before.

The future for stereolithography in museums is a bright one with many potential applications. The Canadian Museum of Civilization has made significant progress on the marketing aspects, and the Smithsonian has worked well with the technology and informational aspects, but it will undoubtedly be a number of years before stereolithography becomes a part of every museum. When it does, though, it will be an invaluable tool that will be used everyday.

Professor Marc Levoy of Stanford University has been researching the different methods of digitally capturing three-dimensional objects. In 1997 Professor Levoy and about 30 graduate and undergraduate students designed, built, tested, and implemented technology for scanning statues. The goal of their project was to scan a large collection of Michelangelo architecture and sculptures. This was the first time that anyone had ever attempted to scan an entire collection (Cyberware 3).

The technology behind this tremendous feat was complex, and the equipment was designed and created by Levoy and his students for this task. Due to the size of the objects that they would be scanning, the demands were very high. The goal was to be able to capture a chisel marks smaller than 1 mm. They also had to take into account that the famous David statue is almost six meters tall while on its pedestal. The statues could not be moved; therefore the equipment that was designed had to be far away enough that it took big enough pictures while at the same time mobile enough to move from angle to angle. The last challenge faced by Levoy and his colleagues in this project was to find a way to capture not only the physical data of the object but also its color.

After 2 years of planning, building, and scanning, Levoy's team came home with a scan of 10 of Michelangelo's masterpieces. For the statue of David alone, they had captured over 2 billion *polygons* and 7000 color images. The total collection encompassed over 250 *gigabytes* of information (Cyberware 3).

3.6.3 Medical Applications

Stereolithography has seen its way into the hospitals over the past few years. In Denmark three years ago, surgeons took x-rays of a young girl's skull prior to an operation. They took the results of the x-rays and using an SLA machine created a physical model of the skull allowing the surgeons to see what they needed to do to the

Figure 3.7

little girl (Air Force News 1).. In dealing with bones, x-rays combined with stereolithography prove to be a valuable model when x-rays alone can't give a doctor or surgeon the entire picture. Figure 3.7 to is the model that the doctors used as a practice tool before the surgery (Air Force News 1).

Another notable medical miracle, which owes its success to stereolithography, is a case dealing with conjoined twins. In 1995 at Wilford Hall Medical Center, Lackland Air Force base, Texas, a 28 hour surgery took place to split a pair of six-month-old girls. The girls were joined at the hip and shared a middle leg. It took a 29-member team of both air force and civilian surgeons to make the historic surgery a success. The surgeons had used stereolithography to make a copy of the shared hips (Air Force News 1). The most important part of the operation, if the girls were ever going to walk again, was getting the hips cut correctly.

Figure 3.8

The surgeons planned out and practiced the procedure on the artificial hips before working on the girls. With the help of prosthesis, both girls are now walking on their new legs. Figure 3.8 shows the two girls at six months joined from the chest through the hips (Air Force News 1).

Professor H. F. Sailer has so well incorporated stereolithography into the medical field that it seems cranial surgery should not be contemplated without using this new technology. The Maxillofacial Surgery clinic at the Zurich University Hospital is the setting for Professor Sailer's. The purpose of using models in medicine is to give the patient and surgeon an exact representation of body structures.

The digital imaging data of the bones is collected via computerized *tomography*, *magnetic resonance tomography*, or *ultrasound tomography*. The tomographic images are produced by a number of digital cross sectional images. These images are then laid in order one on top of the other until a true three-dimensional picture is completed. The image contains all bone structures and also gives an impression of the organs and fatty tissue in different color. Through this 3-D image, rapid prototyping takes hold and a true physical representation is made for the surgeons to use. (Cyberware 6)

The main advantage of this treatment is for the doctors and radiologists to have actual practice with what they will encounter on the operating table. This process has been used recently in a *hypertelorism* operation. In this operation, the patient's eye sockets needed to be repositioned. This surgery was performed by removing the patient's eye sockets and repositioning them towards the center of his face, while at the same time adjusting the height of the sockets (Cyberware 7). Planning for an operation of this magnitude is very important as the smallest error can cause the patient to loose his sight completely.

A standard hypertelorism operation usually takes around 23 hours to complete. With the implementation of rapid prototyping, the surgeons are able to cut that time down to somewhere between 8 and 12 hours. Cutting down on operation time saves money, minimizes blood loss during the operation, and cuts down on organ exposure time which stops infection. Furthermore, a shorter surgery allows the surgeon to be more alert during the end of the operation thereby giving better a chance for a successful operation (Cyberware 9). Along with helping the doctors prior to an operation, rapid prototyping and 3-D imaging help the patients to better understand what it is that they are about to go through. A better-informed patient and a better-prepared doctor give any operation a better chance of success (Cyberware 9).

3.6.4 Museum Applications for the Blind and for Children

Although libraries, museums and other public recreational centers are becoming more sensitive to the needs of their visually impaired visitors by adding Braille text or audio descriptions, still even more can be done and stereolithography can help. In addition to having Braille descriptions and audio commentaries of the artifacts, life-like replicas, produced by way of stereolithography, can be appended to the exhibit. The visually impaired would have the opportunity to feel the object and examine all of its detail, weight and texture - something that can never be sufficiently conveyed with a text description alone. These replicas will allow for a more fulfilling museum experience for the visually impaired. Furthermore, children will be able to benefit from this technology as well. Since stereolithography objects are safe and durable, an entire children's exhibit can be added to the museum, where children can touch and play with the objects and naturally become more interested and involved in their history and applications.

3.7 Improvements in Stereolithography

It is true that stereolithography is a process that is much more efficient than many other methods of prototyping. However, there is always room for improvement. Over the past decade, new, even more innovative techniques in stereolithography have been developed and perfected.

One of the major improvements in the process of stereolithography was achieved at the close of the decade of the 1980's. A new *Weave* method was adopted. Developed by 3D Systems, the *Weave* method drastically improved the accuracy of stereolithography, by using two separate passes perpendicular to each other, with very small cross-hatch spacing. Until this technique was applied, the primary source of distortion was post-curing stress. The *Weave* method reduces the distortion by curing more of the part in the vat. When the *Weave* is not used, up to 60% of the part remains liquid resin, trapped inside the cured walls. When the *Weave* method is applied, however, approximately 96% of the part is solidified in the vat. This, in turn, reduces the post-cure distortion, also known as warpage, resulting in a twenty times more accurately dimensioned part than with the previous method. Also shrinkage could be as much as 20 mils/inch, but with the *Weave* it is reduced to at most 2.5 mils/inch.

Yet an even more recent improvement is called the *Star-Weave*. When a company uses the *Star-Weave* method, as much as 99% of the resin is cured in the vat during laser exposure. This, in turn, significantly increases dimensional accuracy of the system to approximately 0.002in/in. Moreover, new improvements in the software, which will be further discussed, can compensate for nearly all of the remaining distortion, yielding a virtually flawless product.

The new software releases contributed greatly to the improvements in stereolithography. These software packages are now more logical, require fewer keystrokes, and are more user friendly. In some cases the file sizes were reduced and the software was regenerated to support laser control, improve cure depth calculation, vector drawing and beam profiling (Medler, 67).

New materials are constantly being developed and improved. Fresh modifications targeted improvements in strength, susceptibility to shrinkage, swelling and warpage and flexibility. Also, lower viscosity resins have been developed to minimize recoating time.

Finally, the accuracy with which the laser can lay down its traces is continuously improving, and much research has been devoted to choosing the appropriate laser intensity to minimize the time of the curing process.

4. Methodology

The previous chapter provided background information on the topics of stereolithography and optical scanning. It also dealt with several companies now using those technologies. In addition, it provided an overview of applications of those technologies in many fields, including their relevance to museums and artifact preservation. This chapter focuses on the evaluation and examination procedures used to evaluate the usefulness and practicality of these technologies, as applied specifically to the National Museum of Denmark.

4.1 Interviews

Throughout the course of the project, the group, either in part or in whole, conducted a series of interviews. The interviewees fell into one of two main categories: museum personnel or rapid prototyping companies. These broad categories comprised more specific subcategories: museum personnel and companies. The museum personnel categories included administrators, gift shop employees, curators, and visitors. The companies included firms that sell machines, and companies that perform tasks.

These interviews were essential to the project because they provide insight into problems that are not evident from published research alone. In addition, they were the best way of obtaining the quantitative information needed to draw conclusions for the applications of these technologies.

4.1.1 Interviews with Museum Administrators

The group conducted semi-standardized interviews with museum administrators. The scope of the questions concentrated on learning their desires and ideas for the project, and on learning the exact constraints that exist in the areas of space, time, and money. To record the information, the interviewer taped the interview and took notes about important points. This ensured a detailed record of the information at all times.

The rationale for interviewing museum administrators was straightforward: they are the primary audience for the project. Therefore, it makes sense to understand fully what they perceive as the goals of the project and what they would like to see result from the project. Further, the administrators had knowledge about the museum budget, private sponsorship, available space, and time constraints so it only makes sense to get this information from the source instead of a third party.

4.1.2 Interviews with Museum Gift Shop Employees

The group conducted both semi-standardized and unstandardized interviews with gift shop employees. The semi-standardized interviews targeted the upper level employees, such as managers, while the unstandardized interviews targeted the lower level employees, such as checkout clerks. The reason for the two categories relates to the information that we sought from the respective interviewees. Interviewers took notes during the semi-standardized interviews to record the information obtained. For the unstandardized interviews, the interviewer wrote summaries after the interview.

The information procured from the managers relates to the popularity of current items for sale, and the price that people will pay for an item. This information was important for evaluating what kinds of artifacts to reproduce. It was also valuable in deciding if the technology provides a cost effective and marketable solution for the gift shop. Consequently, this type of information gathering lends itself to specific preconceived questions.

The checkout employees possess knowledge of what they see people buying first hand, and what people look at but may not buy because of the price. This information supplemented the information gathered from the upper-level gift shop employees. Further, it gave the group insight into the preferences of the store customers. These interviews did not follow an exact script, and thus they were organized as unstandardized interviews.

4.1.3 Interviews with Museum Curators

The group conducted semi-standardized interviews with museum curators. The interviews developed an idea of which artifacts in the museum are the most historically significant to the Danes, and gauged the fragility of artifacts. Some of these interviews entailed the curator showing the group around the museum, i.e., providing a tour. In the case of a private tour, the group did not tape the interview. The group taped the interviews when they occurred in a more formal setting, and took notes as well.

The reason for interviews with curators was that they understand the historical significance of each artifact. This information provides data for determining which artifacts are more historically important than others, and helps to gauge public interest in touching or owning a copy of the artifact. Moreover, the curators know the physical properties of the artifacts and this information serves to show which artifacts might endure the reproduction process.

4.1.4 Interviews with Museum Visitors

The group had planned to interview museum visitors to get a sense of which artifacts are most interesting to the visitors, and why these artifacts hold said interest for them. However, because the museum was running another survey during the time that we were performing our investigations, we were unable to administer our survey. Nevertheless, this information has been gleaned from the interviews with administrators and curators, an alternative for gathering this information. Curators and administrators have extensive experience with the museum and they have observed which exhibits are the most popular over the years, and the survey that we purposed would have only examined a small population during a short span of time.

4.1.5 Interviews with Companies that Sell Machines

The group conducted semi-standardized interviews with companies that sell optical scanning or stereolithography machines. The goal of these interviews was to learn about the price, accuracy, overhead, speed, and efficiency of these machines. The interviews were over the phone, and accompanied by notes.

The information obtained from the companies was of interest because it provided insight into which company offers the best total services for a given price, the benefits of owning the machines as opposed to outsourcing, and the constraints of the machine relative to materials, space, operation, and maintenance. In addition, it allowed us to establish a rapport with the companies. This rapport might be of use to the museum later, should they decide that they would like to make a purchase, as they would already have the a contact in the business world.

4.1.6 Interviews with Companies that Perform Tasks

The group conducted semi-standardized interviews with outsourcing companies with the goal of learning about the price, accuracy, speed, and efficiency of outsourcing. These interviews were on the phone and in person, and accompanied by notes.

The information obtained from the outsource companies was of interest because it provided insight into the precautions necessary to preserve the integrity of artifacts. In addition, it allowed us to see if companies could produce accurate reproductions more cheaply than via the purchase of a machine.

4.2 Group Interviews

We used group interviews to supplement the material gathered in the individual interviews. The interviewees consisted of members from different subgroups, i.e., curators and administrators. The group acted as the moderator, and held the interviews in an open-ended semi-standardized format, addressing qualitative issues. The interviews were recorded by notes.

The rationale for group interviews is that the interviewees fed off, and responded to, the responses other members elucidating various trade offs and conflicts. The group was then aware of these conflicts and sought to find compromises that satisfied all parties involved. This, however, was not be feasible in many cases, as the group has limited time and such meetings were hard to coordinate among the different members of the staff.

4.3 Artifact Examination and Evaluation

Besides learning from the interviewees, the group ventured into the museum to look at the artifacts themselves. During this process, the group used the information gathered from the interviews and other sources to evaluate the reproducibility of artifacts in the museums holdings. The group evaluated the artifacts using the following criteria: historical importance, size, shape, detail, marketability, and reproduction survivability. The group took notes about and pictures of each of the previously mentioned criteria, and that information determined which artifacts the group recommended for reproduction.

4.4 Cost Estimates

After performing artifact examination and conducting interviews, the group examined and analyzed the data to arrive at cost estimates. The group looked at different combinations of machines, outsourcing companies, artifacts, reproduction methods, and applications. Then the group organized the gathered information to arrive at combinations of attributes that offered varying degrees of benefit to the museum.

From the organized information, cost estimate scenarios were developed. For example, three such scenarios for initial expense were as follows: the museum uses outsourcers, the museum uses a machine-sharing program, the museum buys the machines outright. From these categories we see that the initial costs associated with buying the machines would be the greatest, using outsourcers the least, and the machine-sharing program somewhere in between. After creating and evaluating a number of these scenarios, the group made its conclusions as to which options would provide the best solution for the museum.

5. Analysis and Recommendations

This chapter provides an analysis of artifacts in the museums holdings that currently cannot be reproduced by conventional means. In addition, applications for these reproductions specific to the National Museum are presented and discussed. Also, the companies involved with the technologies of optical scanning and stereolithography are analyzed in light of the machines that they sell. Based on this information, recommendations are given as to which objects should be scanned and/or reproduced, and how that goal should be accomplished.

5.1 Artifact Analysis and Recommendations

Through much research and the interviewing of museum officials from various departments in the National Museum of Denmark, we were able to select twenty items from the museums holdings and evaluate each one according to the following criteria: historical significance, marketability and educational purposes, and reproduction feasibility. A complete listing of the artifacts that were examined, along with our findings, can be found in Appendix B. To arrive at our findings, we attentively qualified each object, taking into account issues such as size, detail, material, fragility, purpose, appearance, and all possible methods of its reproduction. By outlining both advantages and disadvantages of each selected artifact, we were able to determine which objects would be best suited for the use of both optical scanning and stereolithography. Furthermore, in analyzing the artifacts we found that the replicas could serve many different purposes. For example, some of the reproductions could be used by the museum for education, whereas others would be primarily beautiful decorative pieces that people would be able to buy in the gift shop.

5.1.1 Artifacts Best Suited for 3D Scanning and Stereolithography

Optical scanners, as mentioned in previous sections, are the means for obtaining valid data to be used in stereolithography. Although this technology is capable of acquiring data from objects of various sizes, materials, and colors, it can present some severe limitations. These limitations stem from the fact that a laser beam is used to scan the surface of the object, so the reflective properties of the object determine its scanibility. This technique is fully effective as long as the color of the object being scanned is not too dark or too glossy, the scanner's resolution is high enough to detect the object's smallest detail, and the size of the object does not preclude the object from being scanned in its entirety.

Some artifacts found in the museum are ideal for both scanning and stereolithography. Of the twenty chosen objects, three examples were chosen to illustrate qualities that would work best for optical scanning and stereolithography. The first artifact is a small statue St. Barbara, one of the five Saints on display in Room 112 in the Middle Ages Exhibit. This is an ideal candidate due to its relatively small size and lack of intricate details. Also, this figure is made out of well-preserved wood, is not very fragile, and has a surface of easily reproducible texture. Although it does have a painted finish, only a few colors were used and those would not be difficult to match.

Another wooden artifact that would be best suited for scanning and reproduction by way of stereolithography is the crucifix from the Tirstrup Church on display in Room 102 of the Middle Ages Exhibit. The crucifix is made out of oak with mostly large details and a surface of medium-dark brown color, a shade that is light enough for an optical scanner to detect. Though it is quite large, its size would not be a major factor in the scanning or reproduction processes. Intricate details on objects of such a size matter little whether the object is reproduced in full size or scaled down several times.

A third artifact that would be ideal for optical scanning and stereolithography is an ivory carving for a portable altar that can be found in Room 104 of the same exhibit. Although this object has much surface texture, the details are large enough to be detected by the scanner. In general, ivory is a perfect material to be scanned since most of the surviving ivory artifacts tend to be very fragile and probably cannot be touched. Furthermore, even aged ivory usually has a smooth surface, which is not too shiny, nor too dark, and naturally weighs and feels much like plastic. Therefore, very little post build procedures are required to finish the replica.

5.1.2 Artifacts Best Suited for the Museum Gift Shop

The National Museum of Denmark contains thousands of artifacts that are not only historically important, but beautiful as well. Currently, relatively few of such artifacts are being reproduced since the methods used to create the replicas are complicated as well as time consuming. Moreover, there are many objects that are simply too fragile to be touched, making it impossible to make a mold. However, with recent technological advances, such as stereolithography, it is possible to scan and produce exact copies of many more desirable artifacts and make them available at the museum gift shop for visitors to buy and enjoy at home.

Several aspects should be considered in selecting artifacts to be replicated and sold in the gift shop. Since the gift shop's success depends entirely on the interests of its visitors, the primary concern should be determining what is important and valuable to the public. Another important issue is the feasibility of producing replicas of chosen artifacts according to the budget of the museum as well as the budget of its visitors. If both these issues can be successfully resolved, the museum and its patrons will benefit greatly from the gift shop.

While examining the artifacts in all of the exhibits in the National Museum, we found several examples of artifacts that would be ideal for stereolithography and sale in the gift shop. The first item is the Gunhild Cross, displayed in Room 104 of the Middle Ages Exhibit. This item has not yet been reproduced with conventional methods due to its age and fragility. However, if optical scanning and stereolithography were used to reproduce it, this item would be a great success in the gift shop because of its appearance, and its historical and religious significance. This elaborate walrus ivory cross was made for a princess in 1160 A.D. and centuries later was owned by Sophie Brache. Its Biblical significance lies in its symbolism of the balance of life and death, as well as in the transition from the Old Testament to the New Testament. The rich history and beauty of the Gunhild Cross is bound to attract many visitors not only in the Exhibit but in the gift shop as well.

A second item that would be ideal for sale in the gift shop is a Japanese No-Maske on display in the Japanese room of the Ethnographic Exhibit. This wooden, well-preserved mask is very attractive because of its compact size and colorful authentic Japanese make-up. This decorative piece exemplifies ideal Japanese beauty of its era and at the same time preserves that part of the ancient culture.

Another example of an artifact that would be perfect for reproduction and sale is the crucifix from Tirstrup Church. This object is unique, beautiful, and most of all intriguing, as it combines several different styles of various eras, provoking much thought and discussion about its origin and meaning. Reproductions of the crucifix of various sizes would serve as great decorative pieces in peoples' homes, and they might make fine gifts.

5.1.3 Artifacts Best Suited for Educational Purposes

There are thousands of artifacts on display in the National Museum of Denmark that represent historically significant time periods and cultures from all over the world. However, often, their importance and meaning cannot be fully conveyed from behind the glass of the display. The museum already makes additional efforts to expose people to more artifacts, and to enhance their interaction with them. Stereolithography can help broaden the museum's educational purposes. By making replicas of various artifacts, visitors, including the visually impaired patrons, would be able to examine the objects by touch and to study them from different angles. Also, children would be able to play with the object and enhance their understanding and interest.

An example of an artifact that would be best for educational purposes, if reproduced using stereolithography, is a large wooden panel, found in Room 124 of the Middle Ages Exhibit. This beautiful object has elaborate surface designs which in some areas are very dark could be studied closely, i.e., by touch. It holds much historical and religious significance, as it depicts the resurrection of Christ using carving techniques characteristic of the 17^{th} century.

Another extremely interesting artifact is titled "St. George Defeats the Dragon," displayed on a large pedestal in Room 111 of the Middle Ages Exhibit. This figure is large, complicated and mounted so high that it is nearly impossible to entirely grasp. A smaller reproduction is needed to allow the opportunity to study it more closely, examine the ancient clothing, weapons and such, in order to gain a better understanding of that time period, its culture and its artistic styles.

The African chairs displayed in Room 255 of the Ethnographic Exhibit would also make great educational supplements to the museum. One or more of these beautiful wooden pieces of various sizes, shapes and styles could easily be reproduced using stereolithography. They can be added to the existing reproductions in the Children's museum, serving as another useful historical and potentially educational object for children. These chairs may also be displayed in the "Please Touch" Exhibit for all museum patrons to test and enjoy.

5.1.4 Artifacts Best Suited for Miscellaneous Museum Purposes

Replicas of museum artifacts can be used for many more purposes besides the gift shop and improving museum's educational strategies. For example, the Tirstrup Church has asked the museum to return the crucifix. However, since it is not possible to give the original back to the church, an exact replica of the crucifix can be produced and given to the church, thus eliminating concerns such as security and possible damage to the artifact. Another very important possible application of stereolithography is cataloging, as mentioned in a previous section. Cataloging for many small artifacts, such as Kleinkunst in the Ethnographic Exhibit, can be simplified tremendously by making reproductions of the small figures and women's finery rather than relying on a two-dimensional, single-view picture. Also, some objects are simply too fragile to be put on display. A stereolithography replica can be created and displayed in place of the perishable original.

5.2 The Use of 3D Scanning to Improve National Museum of Denmark

The need for a three dimensional scanner in the National Museum spans many departments and includes multiple purposes. With all of the various uses of a three dimensional scanner in one institution, the problem soon arises of which scanner would suit all of the museum's needs while at the same time fit within a specified budget. There are many aspects of a scanner that need to be explored and evaluated before reaching a decision. After research on many scanning companies was completed, it soon was evident that the outstanding companies in the business are Shape Grabber, LDI, and Cyberware. This section focuses on these three companies and on their respective scanners.

5.2.1 Educational Benefits of 3D Scanning

Museums offer ways for the general public to learn about their past as well as other civilizations. Traditional museum exhibits comprise display cases in which visitors can observe ancient artifacts and read short synopses of each one. The National Museum, in keeping with its strong conviction to educate patrons to the best of their capabilities, has established such programs as the children's museum, the hands-on "Please Touch" exhibit, and the audio tour for patrons to get an audio description of artifacts. These programs strive to make the museum more interesting to the public, and thereby stimulate interest in the history of Denmark.

With a 3D scanner, the museum would be able to scan and reproduce objects that previously could not be reproduced by traditional means. The reproductions could then be placed in the children's museum for the young to work and play with, used as a tangible artifact in the "Please Touch" exhibit, or even be placed beside the original artifact for patrons to examine more closely. The educational aspect also has many possibilities in the realm of helping the visually impaired to experience the museum and all of its holdings more fully.

3D scanning, even without actually reproducing an object once it has been scanned, could be of use to the museum. Once an artifact has been scanned, it is only a digital file and if uploaded to the Internet, could be viewed from any location. These files could be compiled to create an online database of the museum\s holdings. People could click on an artifact that they would like to see, and on their computer monitor that object would appear. Then, using their computer, they could turn the

3D model enabling them to see an artifact from all angles, zoom in or out to get a better view of details, or print a picture of the artifact for whatever use they desire. Along with the 3D pictures of the artifacts, various text boxes or even audio guides could be provided in order to further educate the public. The possibilities of an online museum are endless, and would give the whole world a chance to visit Denmark and its National Museum.

5.2.2 Archaeological Benefits of 3D Scanning

Besides educating the public through displays and exhibitions, a museum has curators who attempt to piece together the past with clues such as artifacts from excavations, or the excavation sites themselves. Many of the artifacts uncovered from expeditions are extremely fragile and in most cases need to be pieced together. With the use of 3D scanning, a curator could easily scan all of the pieces of a delicate artifact and piece them together using current editing software. At this point, a curator or scientist could manipulate the digitalized artifact and create what he believes to be what the original might have looked like. Archaeologists are already using X-Ray scanners to see through rust and corrosion of metal objects, giving them a clear view of what a metal object once was. Scanning seems like the logical next step in helping to discover more about the past.

5.2.3 Gift Shop Benefits of 3D Scanning

The museum gift shop currently sells replicas of artifacts such as jewelry, glass, pottery, and artifacts of other materials. Items not easily reproduced are objects made of bone, wood, ivory, or other artifacts that have a high degree of fragility. Besides having an artist create a replica by hand, scanning and stereolithography are really the only ways in which most of the museum\s holdings can be copied. Another possibility is creating a CD-ROM in which the artifacts are displayed as 3D images and supplied with text or sound to provide a narrative of the artifacts displayed.

5.2.4 Security Benefits of 3D Scanning

Within the museum's walls, there is a small army of people dedicated to making sure that artifact theft does not occur. Despite the excellent job that is done deterring theft, museum theft is still a problem. Often times when an artifact has been stolen, it is later recovered and returned to the museum. One of the difficulties faced by museums is confirming the authenticity of the returned artifact. Although pictures of the artifacts are taken and kept for such cases of identification conflicts, pictures alone can't help to eliminate the return of a very good fake. Only with an exact copy or a three dimensional digital copy of such an artifact can scientists truly determine with very little doubt weather the artifact is genuine or not. This exactness is directly related to the exactness of a scan. An object is scanned .005mm of accuracy, is able to pick up all of the fine details, which can then be used as a good representation of the original. If this technology was implemented in a museum setting, museum officials would have little difficulty in determining a returned artifact's authenticity.

5.3 Scanner Recommendations

Once the various needs for a scanner are determined, the next step is to find a scanner to fulfill these needs. Two charts are displayed in Appendix C, which show the various characteristics of 8 different scanners, thus providing a comparison of their capabilities.

For the educational needs of the museum, a scanner that will be able to capture very fine physical details and imperfections is necessary. High resolution is a must if patrons are going to be holding and touching the recreations in order to get an accurate appreciation for the original. If the museum staff preferred to have digital representations of the artifacts online, or on a CD-ROM, it is imperative that the artifacts are captured and displayed in color. Also, unless people are able to see an artifact as it appears in real life, the educational benefit might be lost.

The National Museum also contains many statues and artifacts that are large and bulky. A smaller reproduction would be of value because it would be easier to examine. The size of the artifacts to be scanned is a serious consideration in determining which scanner would best capture all artifacts large and small. Some of the more interesting artifacts such as "St. George vs. the Dragon" would be prime candidates to be scanned and then shrunk in order for the gift shop to sell smaller copies. For the purpose of security, accuracy is key. Also, because these objects are so big, unless a scanner with exceptional speed is acquired such a venture would be impossible.

Along with the scanner, choosing a company with whom to establish a rapport is very important. In choosing a company, there are a number of questions that need to be considered. Does the company provide a warranty with their products? It is important when making such an investment to make sure that the company providing the scanner will fix it if the equipment does not work correctly or breaks. The three companies previously mentioned that offer the best products and value all offer a 1-year warranty on all of the machines that they sell. Another important question is training. With a sophisticated piece of equipment such as a 3D scanner, it is imperative that the company provides some sort of training for the people who will be using the scanner. ShapeGrabber Inc. and Cyberware both offer on-site training, while LDI offers an optional on-site training session that costs extra. In terms of service and training, the three previously discussed companies seem reputable and professional; therefore no conclusion on which company offers better service can be determined.

After careful examination of the products of the leading companies, the three scanners that should be considered are ShapeGrabber's Gantry, LDI's PS-3300C, and Cyberware's high resolution model. Shape Grabber does not offer any scanners in color, yet they offer the best resolution. However, in order to get the highest resolution of 0.0025mm, the maximum size of the scanned object must be no greater than 50mm x 50mm x 50mm. The price for a Shape Grabber unit is steeper than that of the LDI. Thus, because of the lack of the color option, limitations in size and higher prices, ShapeGrabber products may not measure up to products of its competitors.

The LDI Surveyor offers a very competitive price for a machine that has many of the key options that the museum needs. The specifications for these options however, are not quite as attractive as the options offered by its two competitors. The resolution of the Surveyor is at 0.0075mm, and the color option is by no means photo quality, paling in comparison to the Cyberware color scanner.

The Cyberware model is the most expensive, yet by far the best scanner on the market. The resolution is variable from 0.02 – 0.005mm, which allows the user to choose between high resolution and slower speed or lower resolution and a rapid scan. The color is 24-bit RGB quality, which is an exceptional color quality comparable to the quality one would expect from a professional photograph. The only drawback with the Cyberware model is that the maximum volume of the object being scanned is 1m x 1m x 450mm. With a scanner that can only capture objects of less than 1m cubed, many of the museum's statues and larger artifacts will not be suitable for scanning. Cyberware does custom make scanners and for more money, would be able to customize a scanner for the museum, enabling the machine to scan in artifacts of all sizes.

Finally, it should be noted that further costs will accrue such as the cost of buying computers to run the scanner, as well as computers to hold all of the information once artifacts have been scanned. A generous estimate of all of the add-ons would be somewhere around $20,000 U.S.

5.4 Comparison of 3D Systems' SLAs

Though the technology of stereolithography has only existed for a few decades, it has already intrigued many scientists and engineers in several companies. However, the originator of stereolithography, 3D Systems, Inc., still holds most of the SLA patents and, therefore, has control over nearly the entire stereolithography market. Consequently, we will be analyzing only 3D Systems equipment in this report.

Currently, there are 5 different models of stereolithography machines being produced by 3D Systems. These machines vary in price, accuracy, and size; therefore, a closer analysis of each one is needed to determine which machine is best for museum purposes. In this report we consider three of the five models, since they represent the entire spectrum of the SLA machines.

The Viper si2 SLA (See Appendix D) is the least expensive machine produced by 3D System at this time. Priced at $180,000, this SLA comes with the PCA, as well as all the necessary software. It has programmable variable resolutions of 0.06 mm, 0.10 mm, and 0.15 mm, the smallest of which may be used to produce museum replicas of sufficient accuracy. One drawback of this SLA is the size limitation. It will only be able to build objects of maximum dimensions of 250mm x 250mm x 250mm. A model of such speed and accuracy would best be suitable for producing replicas for the gift shop. The resolution is high enough to produce objects of sufficient resemblance to the original. Also, since most of the items available in the gift shop are small, the size of the vat in this SLA will also be appropriate.

The next best stereolithography apparatus is the SLA 3500. This machine is 2.5 times faster than the Viper series with the build speed of 2.5 m/sec. It is capable of producing objects with maximum resolution of 0.05 mm and maximum dimensions of 350mm x 350mm x 400mm. The price, however, is more than twice that of the Viper si2, totaling $400,000, including PCA and software. This machine would be a great asset to the National Museum because of its accuracy and efficiency. SLA 3500 would be suitable for educational purposes in the museum. Produced items of various dimensions and high accuracy may be used as supplements to the existing museum exhibitions.

The most recent, accurate, efficient, as well as most expensive SLA that 3D Systems has to offer is the SLA 7000 model. This machine has four programmable resolutions, the best of which is as low as 0.025 mm. The largest size capabilities are approximately a cube of half a meter on each side. The *build speed* was almost quadrupled to 9.52 m/sec. The price, however, was doubled as well to the prohibitively high $800,000. This SLA will surely satisfy most of the museum's criteria for accuracy, but the price might not be so attractive at the present time. If purchased by the museum, however, there will be virtually no limits to the uses of this machine. Its four programmable resolutions would produce replicas of various accuracies. The highest resolution settings would be used to produce replicas for cataloguing and educational purposes, where the lower resolutions would suffice for sales in the gift shop.

5.5 The Past and the Future of Stereolithography

Since 1984, the year stereolithography was invented, there have been major advances in this technology. Until recently, stereolithography was still considered to be an emerging method of rapid prototyping. In 2001, however, after nearly twenty years of improvements, designs and redesigns, stereolithography has finally been established as one of the fastest and most efficient methods of three-dimensional object creation and reproduction. Many modifications have been made to virtually all aspects of this process, starting from improvements in software and ending with perfection of resins to be used for different purposes.

Within the past ten years many exciting breakthroughs have been made in the field of stereolithography, optical scanning and other accompanying processes. The resolution of optical scanners has improved over 200% during the past decade. Current scanners can now detect hundreds of colors, something that was deemed impossible just five years ago. Similarly, the resolution of the SLAs has significantly improved from approximately 0.5 mm to 0.025 mm. 3D Systems is not stopping there, however, as it continuously keeps redesigning and improving its equipment. The techniques of actual build have also been improved with the addition of first the Weave method and later the Star Weave, which drastically boosted the accuracy and quality of the finished product. Also, the computer industry has made unprecedented advances over the past decade. This, in turn, positively reflected on the quality of stereolithography and optical scanning. Recent software improvements have made it possible to save scanned data in dozens of different file formats, i.e. CAD, STL, OBJ, 3DS, etc., thus opening doors for more applications. Other software improvements have greatly simplified the user interface, allowing for easier and faster programming/control operations of both the optical scanner and the SLA.

Though both optical scanning and stereolithography have greatly advanced within the last two decades, their progress still continues and will continue in order to avoid becoming obsolete like so many other underdeveloped technologies. Following recent technological growth rates and trends, technological advances are not bound to slow down any time soon. On the contrary, they promise to continue at an exponential rate. Since both optical scanning and stereolithography are caught up in this wave, they will continue evolving with the rest of the world of technology. In the near future, the resolution of SLAs should at least double. The optical scanners will be able to detect any shade of color and objects of virtually any size and shape. Also, the cost of owning stereolithography and optical scanning equipment should drastically decrease within the next few years, making it possible for more companies and organizations to use them.

5.6 Summary of Recommendations

Although stereolithography is a more technologically advanced method of rapid prototyping than the conventional methods, such as tooling, milling or molding, it still has many flaws that need to be resolved. Currently, the resolutions of any of the SLA's are not yet comparable to the atomic level accuracy of silicon molding. Also, their costs are almost always prohibitively high. Furthermore, though stereolithography is a fast and nearly effortless method of reproduction, additional time will be needed to finish the final product. It would require post build processes of sanding, possibly an elaborate and time consuming surface finish, as well as a paint finish. In addition to stereolithography, new technologies such as 3-D printing and 3-D ink jetting are evolving. These technologies combine building a three dimensional object from a set of data acquired with an optical scanner and, in the same step, coloring the surface of the object being produced to match that of the original. All of the prototyping methods mentioned are simultaneously rapidly improving. Their quality and capabilities are also continuously improving, while their costs are reducing. In the future, and perhaps in the next decade, all these methods will be affordable, as well as capable of atomic level precision and much more.

Now, however, we do not feel is the appropriate time for the museum to invest in a Stereolithography Apparatus. The greatest current benefit would come from acquiring an optical scanner. This versatile device will find innumerable uses in the museum. It can be used by the National Museum to scan various fragile, priceless artifacts internally, without having to worry about security and other issues. In cases where actual reproductions are desired, it would be more cost efficient to send the data obtained with the scanner to an outsourcing company that specializes in stereolithography. The acquisition of an optical scanner would prove to be a highly beneficial addition to the museum. Virtually all departments in the museum will be able to use the optical scanner for various purposes.

The scanner that we recommend depends on the budget that is available for its purchase. If a budget of $50,000 were available, we would recommend LDIs Surveyor PS-3300C. This scanner is a very versatile scanner with decent resolution, the ability to scan objects of all sizes, and the ability to capture color. For a budget of $100,000 we would recommend Cyberware's High Resolution Model Shop 3D Scanner bundle. While it does have a limitation in relation to the size of the object to be scanned, 1m x 1m x 450 mm, its other features are excellent and it would offer outstanding results. However, for a budget of $200,000+, we would suggest a custom system from Cyberware. While this is an expensive option, it would be tailored to the needs of the National Museum and would provide the single best solution.

6. Epilogue

The Interactive Qualifying Project (IQP) is a unique graduation requirement at Worcester Polytechnic Institute, an engineering college in the state of Massachusetts, USA. This project attempts to broaden the educational experience for all WPI students, taking it beyond the strictly technical curriculum. Its objective, best stated in the WPI Program of Studies, is "to enable WPI graduates to understand, as citizens and professionals, how their careers will affect the larger society of which they are a part." These projects are designed to address realistic issues such as environmental, safety, educational concerns, etc., and require students to use their technical knowledge as well as problem-solving skills to produce viable solutions and useful recommendations for a particular problem or situation.

In our time, technology has become a gigantic and a constantly-increasing force in societal progress. Technology, in all its forms, has been permanently woven into our daily lives. Therefore, several IQPs composed in the past few years have been centered around the most recent technological issues, in attempts to relate the complicated world of technology to society and to the ever-evolving human needs. Our project at the National Museum of Denmark falls under this category. Its purpose is to explore one of the most recent and technologically advanced methods of rapid prototyping, stereolithography, namely its applications in the museum. An equally important task is to educate the museum officials about the benefits of this technology in several specific areas of the museum. This IQP attempts to integrate a new, highly sophisticated technology into a traditional museum setting with a mission to enhance educational fulfillment for the patrons, boost the gift shop revenue, as well as aid with internal work in several museum departments.

The introduction of stereolithography is just one example of technology positively interacting with society in the National Museum. Other currently used technologies such as recorded films, virtual and audio tours of several exhibits, and various special props and effects, just a few years ago were deemed new and highly advanced. These additions to the museum enhanced the educational and aesthetic sides of the exhibitions, simplified programs and improved communication with the patrons, as well as added new and exciting elements to the solid, traditional institution that is the National Museum of Denmark. The established technologies as well as the latest editions of the rapidly evolving technological progress now hold a permanent significance in the museum and in our society as a whole. They continually refresh our view of the world, both complicate and simplify our lives, and provide valuable insight into the infinite possibilities of the future. Further, by using technology to gain a complete understanding of history, we can truly improve society by learning from the mistakes of the past in an effort to create a future that does not repeat them.

7. Glossary

A

ASCII — American Standard Code for Information Interchange. A file format that uses character codes to describe the file content.

B

Binary — A file format in which data is represented as a series of ones and zeroes.

Build speed — The speed with which a machine makes an object.

Build style — The accuracy with which a machine makes an object.

C

CAD — Computer-Aided Design or Drafting. CAD is the "front-end" to rapid prototyping systems.

CAE — Computer-Aided Engineering. CAE software offers engineering analysis such as evaluating structural integrity or heat transfer.

CAM — Computer-Aided Manufacturing. Refers to software systems that use CAD data to generate tool paths for CNC equipment.

CNC — Computer Numerical Control. Machine tools that are driven (controlled) by computers and computer programs. CNC is a replacement of manually operated or tape driven equipment.

D

DXF — Drawing Exchange File. File format that allows transfer of CAD data amongst dissimilar systems. Originally devised by Autodesk for the AutoCAD software program.

E

F

Facet — A three or four-sided polygonal element that represents the smallest unit of a 3D mesh. These meshes represent an approximation of the actual geometry. Three-sided (triangular) facets are used in STL files.

FDM	Fused Deposition Modeling, a rapid prototyping process offered by StrataSys Inc. The process extrudes material and deposits it on a layer-by-layer basis.
FFF	See free-form fabrication
File Format	A standardized way of storing and exchanging digital information.
Free-Form Fabrication	An alternative description of rapid prototyping. Intended to describe a broader base of applications where components are generated directly from digital data.

G

Gigabyte	A unit of storage capacity equal to one billion bytes.

H

High Resolution	The fineness of detail that can be distinguished in an image, as on a video display terminal.
Hypertelorism	Abnormal increase in the inter-orbital distance; in other words, the eye balls are set too deeply in the eye sockets.

I

IGES	Initial Graphic Exchange System. An industry standard format for the exchange of CAD data between dissimilar systems.

J

K

L

LOM	Laminated Object Manufacturing. The rapid prototyping system offered by Helisys Inc. A laser is used to cut a cross-section from sheet materials. These cross-sections are stacked to create a prototype.

M

Magnetic Resonance Tomography	A tomography technique which uses magnetic resonance to obtain images (See "Tomography").
Mechanical Tracing Systems	The process of taking measurements of a 3D object by tracing the surface with a probe.

Milling	A rapid prototyping technique that involves grinding, pulverizing or breaking down a piece of solid material to create a 3-D object of desired shape.

N

O

Optical Scanning	The process of taking measurements of a 3D object without touching the object.

P

Photopolymer	A polymer that reacts with natural (ultraviolet) light. (See *polymer*)
Photo curable Resin	A resin that hardens when exposed to natural (ultraviolet) light. (See *resin*)
Polymer	Any of numerous natural and synthetic compounds of usually high molecular weight consisting of up to millions of repeated linked units, each a relatively light and simple molecule.
Polygon	A closed plane figure bounded by three or more line segments.
Polyline	A line made up of any number of distinct points that is not necessarily straight.
Post Curing Apparatus (PCA)	A computer-controlled device that is used after stereolithography in order to finish solidifying and completely cure the photopolymer.
Post Production	Any of several processes, e.g. assembly, additional surface finishes, that follow stereolithography in order to complete the prototype.
Prototype Tooling	Molds, dies and other devices used to produce prototypes; sometimes referred to as soft tooling.

Q

R

Rapid Prototyping	A reproduction process driven by computer model data that uses liquid, powder or sheet materials to create 3D objects in plastic, wood, metal or ceramic.
RP	See Rapid Prototyping.

Rapid Tooling — Digitally-driven tooling that decreases time and expense in securing prototypes created in production intent materials. An industry-wide definition of rapid tooling has yet to be adopted.

Resin — Any of numerous physically similar polymerized synthetics or chemically modified natural resins including thermoplastic materials such as polyvinyl, polystyrene, and polyethylene and thermosetting materials such as polyesters, epoxies, and silicones that are used with fillers, stabilizers, pigments, and other components to form plastics.

Resolution — The fineness of detail that can be distinguished in an image.

RT — See Rapid Tooling.

RTV Molding — Room Temperature Vulcanized molding.

S

Selective Laser Sintering — Rapid prototyping process that uses a CO2 laser to fuse powdered materials.

SLA — See Stereolithography Apparatus.

SLS — See Selective Laser Sintering.

Solid Modeling — 3D CAD modeling technique that accurately represents all physical characteristics of a component, including volume, mass and weight.

Solid Imaging System — any of several systems used to produce solid objects directly from computer data with no intermediate steps.

Stereolithography — Rapid prototyping process that uses an ultraviolet laser to cure (harden) a liquid polymer.

Stereolithography Apparatus — A machine that performs the process of stereolithography.

STL — Neutral file format used as input to rapid prototyping equipment. The file contains point data for the vertices of the triangular facets that combine to approximate the shape of an object.

Surface Modeling — 3D CAD modeling technique that accurately represents all physical characteristics of a component, including volume, mass and weight.

T

3D Printing — A low-cost variation of RP that is faster, easier to use, less expensive and office-friendly.

Thermoplastic — A resin that becomes soft when heated and hard when cooled. Such as polystyrene or polyethylene.

Thermoplastic Ink Jetting — A rapid prototyping technique that produces 3-D objects with exact shapes as well as surface colors.

Tooling — Molds, dies and other devices for applications such as plastic injection molding and die-casting.

Tomography — Any of several techniques for making detailed x-rays of a predetermined plane section of a solid object while blurring out the images of other planes.

Triangulation — A surveying technique in which a region is divided into a series of triangular elements based on a line of known length so that accurate measurements of distances and directions may be made by the application of trigonometry.

U

Ultrasound Tomography — A tomography technique which utilizes ultrasound to create images (See "Tomography").

V

W

X

Y

Z

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Appendix A

Introduction to the National Museum of Denmark

The National Museum of Denmark, located in the Crown Prince's Palace in the center of Copenhagen, was established in 1807. It contains eight permanent exhibits with artifacts dating back to as far as 13000 BC: Danish Prehistory, Middle Ages and Renaissance Denmark, Seventeenth-century Denmark, The Royal Collection of Coins and Medal, The Collection of Egyptian and Classical Antiquities, the Ethnographic Collection, "Please touch" exhibition from Greenland, and the Children's Museum. In addition, there are several temporary collections, which change throughout the year. The National Museum not only appeals to the Danish public with its vast collection of Danish Prehistory, but rather to all people, as in addition to ancient Danish artifacts, the museum holds thousands of artifacts from various geographical areas and historical periods.

The National Museum tries to appeal to its patrons not only by expanding, reorganizing and perfecting its exhibitions, but also through other means, such as the cinema, the Children's Museum and the gift shop. The cinema offers additional, more in depth, information about various artifacts and related topics. The Children's Museum allows young visitors to experience history by allowing them to touch and play with various reproductions of artifacts found in the museum, as well as old toys. This exhibit can also be enjoyable for adults, as they can read about the toys, games of their parents' childhood or perhaps even their own. The gift shop is also a vital part of the National Museum. The purpose of the gift shop goes far beyond merely earning money for the museum. More importantly, it is there to reach out to the public, to advertise various artifacts in order to spark further interest in their history, as well as to communicate. As the manager of the museum shop, Anders Holm stated: "... the museum shop is recognized as a new medium for dialogue with the public." The items in the National

Museum gift shop reflect thousands years of history displayed in the Middle Ages and Renaissance, Collection of Egyptian and Classical Antiquities, the Ethnographic Collection and the Royal Collection of Coins and Medals. The shop contains many meaningful replicas - samples of the museum that the public can bring home with them, as well as much literature about various items, significant historical events and eras. Such literature further educates the museum visitors about what they have just seen (Holm 217).

Appendix B

Artifact Evaluations

The Saints (Room 112 #2, #3, #5)
#2: St. Barbara
#3: St. Catherine
#5: St Eustace

- ***Historical Significance***

The above group of saints was honored around the time of 1450AD. These particular saints were especially revered during this time period due to their miraculous assistance in warding off disease, death, and helping to solve particular life problems.

- ***Marketability/ Educational purposes***

Artifacts of this type are not of the type that would sell very well in a gift shop. Newer versions of these saints' statues are readily available and the above group have no particular historical significance that sets them apart from more modern religious icons aside from their age. Copies may be better suited in an educational environment in which patrons may feel hold the statues and get a sense of the craftsmanship that went into creating them. A possible marketing application could be to sell replicas to religious institutions in the market for replicas.

- ***Reproduction Feasibility***

The objects would be ideal for scanning and copying due to their size and also due to the fact that they are made of wood. The artifacts however would both be costly and time consuming to paint and would require tedious attention in order to acquire the correct texture.

The Wooden Panel (Room 124)

- ***Historical Significance***

This was a panel carved by Hans Gudeworth the Elder in the early 17th Century. The carving is a large panel depicting the resurrection of Jesus Christ. Elaborate Renaissance ornaments fill the frame of the panel.

- ***Marketability/ Educational purposes***

A wooden panel replica would probably sell reasonably well in the museum shop. The panel could be reproduced either as a full size copy or a smaller scale replica and be used as a wall or door ornament. For the educational aspect of reproducing such an artifact, it would probably be helpful to get a sense of the intricacy of the artifact if museum patrons were allowed to feel all of the small pieces and get a better look at the detail of this piece.

- ***Reproduction Feasibility***

The object is made of wood, which is easily scanned. The color is consistent, making it easier to add color without having it professionally painted. On the other hand, the object is somewhat large and would have to be scanned in sections. It may also loose some of the intricate detail while being scanned and even more once being reproduced, since there are many small details.

Sandstone capital with animal figures (Room 102 #D345)

- ***Historical Significance***

Although capitals such as these are quite common in France and especially prevalent in Italian columns, they are quite rare in Denmark. These columns were built around 1150 AD and were from a church in the Roskilde area.

- ***Marketability/ Educational Purposes***

A reproduction of this artifact could be a good idea if it were to be used for a specific purpose. The artifact itself is rather large, extremely heavy and not interesting enough to require an exact replica in ones home. Although, the object could have market appeal if a scale model were created in plastic. Such lighter and scaled copies could be used for any number of applications, including but not limited to a bookend or candleholder. Since it is made of stone and not likely to fall apart in the nest few hundred years, visitors can probably feel it if they so desired. This particular artifact probably couldn't justify having a reproduction made from an educational standpoint.

- ***Reproduction Feasibility***

The object would be rather easy to scale down and the details are such that a scanner would give a near exact copy. The object is also a solid color making the color more easily reproduced for a replica. The artifact is extremely heavy and for that reason might require special scanning measures.

Crucifix from Tristrup church near Ebeltoft
(Room 102 #D5100)

- ***Historical Significance***

This unique oak figure is mounted with gilt copper plates and has much in common with earlier crucifixes from other regions. First, there is a technical resemblance between this crucifix and some slightly older ones from Aby, Lisbjerg, and Odder. The design and a few of the features of this Christ figure also bear great resemblance to earlier pieces. Although the details of his suffering with the crown of thorns, closed eyes, and the position of the arms indicate a slight influence from the Byzantium region, numerous factors indicate that the artifact must have been made around the time of the Lisbjerg altar. One big factor leading to this conclusion is the depiction of Christ with his feet side by side, as most artifacts of the Byzantine era depict Christ with crossed feet. This artifact is believed to have been created in about 1150-1175 AD and for it's intriguing features makes it of the utmost historical significance.

- ***Marketability/ Educational Aspects***

This artifact along with a small booklet explaining the different design techniques and its artistic influences could provide a lot of capitol to the gift shop. The color would be important to capture correctly and the object would reproduce well in either plastic or ceramic. The object could be sold either to museum patrons or even full size to churches with an interest in a replica.

- ***Reproduction Feasibility***

The crucifix is moderately detailed allowing an easier scan with a high resolution. A possible problem could come from the object reflects light making it hard to scan. The object is also big and will probably need to be scanned in sections. Lastly, the object would need to obtain the correct colors, which shouldn't provide too large of a challenge yet needs to be factored in.

The Odder Crucifix (Room 102)

- ***Historical Significance***

This Crucifix dates back to around 1150AD and was crafted from Oak. The crucifix is different from most due to the shortened arm span of Jesus. This shortened span was probably necessary to fit into a particular area of the church.

- ***Marketability/ Educational Aspects***

This artifact might not be a prime candidate for the use of a gift shop, yet churches with a need for a particular sized crucifix or just in the market for a unique crucifix may be interested in a recreation. There aren't any major foreseeable educational benefits in reproducing such an artifact, yet it is unique and may generate special interest for visually impaired patrons to feel.

- ***Reproduction Feasibility***

The crucifix is not very complicated and scanning should be able to capture all of the details. The glare however may pose a problem to the scanner and the artifact may need to be coated in a fine powder in order to be scanned properly. The color might be tuff to match and the replica would have to be produced in sections in order for the whole object to be reproduced using stereolithography.

The Gunhild Cross (Room 104)

- ***Historical Significance***

This beautiful cross dates back to around 1160AD and was crafted from walrus ivory. The cross symbolizes the balance between life and death as well as the transition from the Old to the New Testament. The cross was created for the daughter of a king and before being acquired by the state, was owned by Sophie Brache in 1646.

- ***Marketability/ Educational Aspects***

The cross is very beautiful and would probably sell very well in the gift shop. The cross is reasonably sized and wouldn't need to be scaled down in order to be marketable. There may be a market within the religious community to acquire replicas of this artifact for display in local churches. The original is very detailed and looks fragile, making the replica a prime object to be picked up and handled in order for the patron to get a sense of the detail and labor that went into creating such a masterpiece.

- ***Reproduction Feasibility***

The Gunhild Cross would be difficult to reproduce without loosing at least some of the amazing detail. The object is made of Ivory, which should have no problems getting scanned, but the details are such that only with a good SLA machine and scanner, will there be a minimal loss of sharpness and detail. The size of the cross is small enough to be produced all in one piece making the prototyping job easier in that respect, and the cross shouldn't take very long to scan.

Ivory Carvings For Portable Alters (Room 104)

- ***Historical Significance***

These small folding figurine displays were created in the mid 14th century. The wealthy set these Ivory carvings upon a portable alter for prayer and meditation while they traveled. The style originated in France in about 1330 and soon after was being imitated. Some of the museums holdings of this style are undoubtedly from France while others were German and Scandinavian imitations.

- ***Marketability/ Educational Aspects***

This type of artifact is in a style that may sell very well in the museum gift shop. They are nicely detailed and pleasant to look at. They are relatively small and could probably be produced inexpensively allowing more patrons to buy them. These objects probably wouldn't be necessary to reproduce from an educational standpoint as there are other ivory carvings which would be more interesting for patrons to handle, yet in the children's museum, children might find it fun and educational to play with replicas due to their moving parts and ornate designs.

- ***Reproduction Feasibility***

Some of these Ivory figurines are painted which could pose somewhat of a problem in reproducing the artifacts. However, if the purpose of the reproductions is for sales and or education, the objects probably would not need the small painted details that the originals contain. The artifacts would be relatively easy to scan, yet would need to be reproduced in parts and working hinges would have to be added to them. Due to Ivory's smooth nature, a reproduction of this artifact wouldn't loose much in the way of texture or detail and therefore make a good candidate for stereolithography.

Ivory Chess Pieces (Room 107)

- ***Historical Significance***

These old Icelandic chess pieces were carved somewhere between 1100 – 1500 AD. The pieces were originally created to represent the different members of society, ranging from the peasant (pawn) to the nobility (King and queen). The game of chess is over 1000 years old and still one of the most popular games throughout the world.

- ***Marketability/ Educational Aspects***

These pieces might not move very well in the museum gift shop unless there could be a complete set of chess pieces and a board created. With the prospect of using the same style chess pieces as nobility used in the early medieval period, patrons could be coaxed into buying an entire set. The individual pieces would provide a fun interaction for children and adults alike allowing them to hold and play with these medieval game pieces.

- ***Reproduction Feasibility***

The chess pieces are small enough to reproduce quickly, yet the details are big enough to be captured by a scanner. There are no tricky colors to deal with since the artifacts are made of Ivory, and the material lends itself very well to scanning. Some of the finer details may get smoothed out during reproduction, but with a good scan, this should not pose a threat.

The Preetz Altarpiece (Room 109)

- ***Historical Significance***

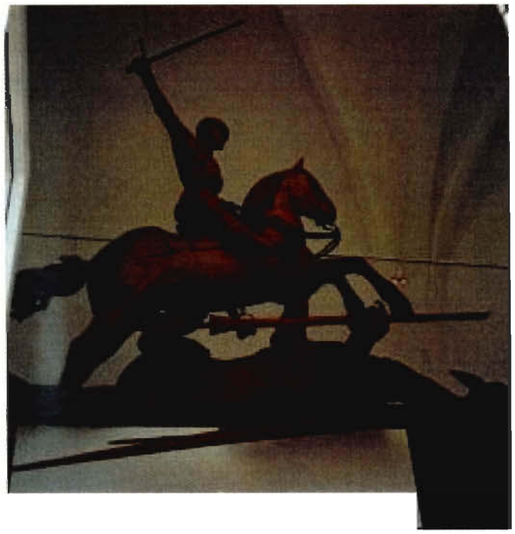
This huge altarpiece had originally been a display behind the altar at Preetz Abbey and contained 2 wings of displays. At the present time, only one set of wings (Doors) remains on the piece. All of the figures still contain their original well-preserved colors and gilding. The altarpiece was made around 1435AD by a Pupil of master Franck's workshop, in Hamburg, Germany.

- ***Marketability/ Educational Aspect***

The value of this piece in a gift shop environment probably isn't very high. The piece is rather large and even if the figurines were sold separately, they don't individually hold enough intrigue and historical significance to warrant many patrons buying them. This artifact may be nice for patrons to touch yet probably closer to the bottom of the list in terms of tactile appeal. It is very pleasing to look at on the whole, and the main purpose that could be obtained by reproducing such a massive piece is for sales to churches or a private collector.

- ***Reproduction Feasibility***

An artifact such as this Altarpiece would be very difficult to scan because of the many hard to reach areas and small details. The paints and colors that this artifact possesses are complicated and intricate, and reproducing such colors would be expensive and time consuming. The piece is so large that it would need to be scanned in many sections and built in even more sections.



St. George Defeats the Dragon (Room 111)

- ***Historical Importance***

  Back in medieval days, the dragon symbolized all evil, and this wooden statue symbolizes the knight St. George fighting off evil. The statue originally stood 3 meters high at the Husum church, yet in 1807 the church was torn down and the piece was moved. The figure was carved in 1520 by Hans Brugemann, where it was placed in front of the East window at Husum church.

- ***Marketability/ Educational Aspects***

  Although the artifact is very large, a scaled down version would probably sell very well in the museum shop. People have always been fascinated with dragons and knights, and this piece being very pleasing and interesting to look at would probably become a big seller. A scaled down version would also play a nice role in the children's museum for young people to touch and admire.

- ***Reproduction Feasibility***

  The major problem with reproducing this figure is its size. The statue would have to be scanned into many sections and there are many fine details that only a good scanner can pick up. If the desire of scanning this object was to later scale it down and reproduce it, than reproduction could be a very feasible venture. Since the object is only stained wood and not painted, there shouldn't be any severe difficulties in adding the color during reproduction. This object would be a challenge to scan, but the fruits of a good reproduction would make it worthwhile.

Royal Bracelets (Room 154)

Finger Ring (Room 154)

- ***Historical Significance***

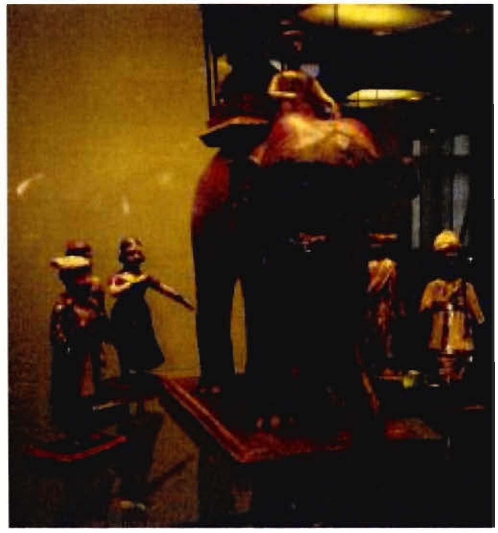
Both of these items are Aftrican ornaments that were used not only for aesthetic purposes, but were also indicative of the owner's tribal identity. Such pieces of jewlery, when closely examined and studied, provide information about the owner's age, sex, wealth, religion, marital and social status, as well as any outstanding achievements honored by their tribe.

- ***Marketability/ Educational Purposes***

Ancient African articles of jewelry are very important items, as they are not only beautiful, but they also speak much about the culture and the history of the tribe to which it belonged. It may be interesting to touch them and study their details, in order to better understand their purpose and significance. However, if reproduced and were made available for sale in the gift shop, due to their rather large size, aged and sometimes damaged appearance such items probably will not be acquired in order to be worn for decorative purposes.

- ***Reproduction Feasibility***

Both the bracelet and the ring are items that have a convenient size and shape for the use of stereolithography. Their colors, as well, are quite suitable for this technique, as these artifacts are not too dark and both have color finishes that will not be very difficult to reproduce. In addition, the bracelet and the ring do not have much detail. However, there are some aspects that can be potentially problematic. Even though there are relatively few details on these items, some of the details are very fine, thus, making it impossible to exactly reproduce them. Also, the finger ring is made out of metal. Other rapid prototyping techniques may be more suitable for reproducing metal objects.



Elephant (Room 157)

- ***Historical Significance***

The Elephant, along with several other Ancient Indian items made in the 1500's, were products of Indian handcraft of making toys and other decorative figures. Artists received their inspiration from their beautiful surroundings, both man-made and natural. This unique craft was based on highly developed and perfected living techniques, as well as strong Indian religious traditions.

- ***Marketability/ Educational Purposes***

The Elephant is a significant historical figure, as well as an attractive decorative item. Such an item may prove to be a great success at the gift shop. By studying it more closely, it is possible to learn about the techniques used to produce it, as well as to be inspired to learn more about its significance in the Ancient Indian culture.

- ***Reproduction Feasibility***

This item is a suitable candidate for the use of stereolithography, as it is made of wood and does not have very much surface detail. However, it is large, intricately painted and has some interior details that would be difficult to both scan and reproduce.

Netsukes (Room 163)

- ***Historical Significance***

The common dress attire in Japan in the 18th and 19th centuries was the kimono. This garment had no pockets, therefore people had to carry small purses suspended from their belts; i.e. tobacco pouch, writing set, small medicine box, etc. The string from these pouches was secured under the belt by a small toggle, or netsuke. Although the people were not allowed to wear gaudy clothes, their wealth and social status was shown through designs on their purses and netsukes.

- ***Marketability/ Educational Purposes***

Netsukes are important items in the Japanese culture as they have been used for several centuries and can tell much about the person to whom it belonged. These items are very attractive, and because of their relatively small size, they will probably be sold for a small price in the gift shop. Also due to their small size, it may be beneficial to be able to examine these items more closely and from different angles.

- ***Reproduction Feasibility***

These items are small and usually made out of ivory. They are also unpainted, which would simplify the process of its color reproduction, as there are relatively few shades of a uniform color. Some of the drawbacks of some of these items would be that the surface might be too dark in some areas, making it impossible for the scanner to detect data. Also, some of the netsukes have a large amount of intricate detail that would be impossible to reproduce with the current stereolithography technique.

No-Maske (Room 163)

- ***Historical Significance***

A few centuries ago in Japan women did not wear any jewelry. They decorated their heads by other means. For example, they styled their hair in high, luxurious dues and wore decorative combs, hairpins, and such. Decorating the face was another very important part of the woman's appearance. The ideal beauty, for which especially the upper class society reached, had a white powdered face with blackened teeth and red lips. Preserved images and items such as the No-Maske illustrate such cultural details.

- ***Marketability/ Educational Purposes***

This mask is a beautiful item with bright colors that currently attracts much attention on display in the museum. This type of artifact would surely prove to be a success in the gift shop as well. The No-Maske also has a strong historical significance, as it demonstrates how women looked, and beyond that, it speaks of what was considered beautiful and refined during that era.

- ***Reproduction Feasibility***

This mask is made of wood and has a relatively smooth finish. It has a suitable size for both scanning and stereolithographic reproduction. In addition, it does not have many fine features or details. Once reproduced, however, the object will require a paint finish of several colors.

The Japanese Abbot (Room 164)

- ***Historical Significance***

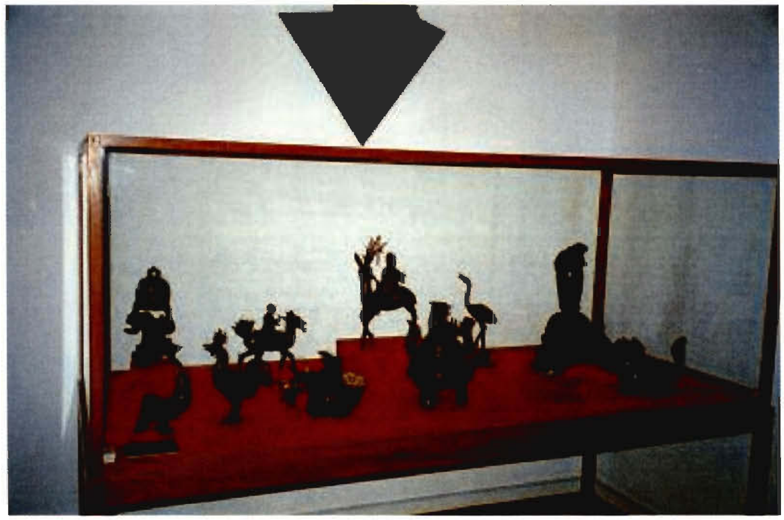
  This figure of an abbot is just one of the many thousands of Mahayana Buddha that originated in East and Central Asia in the 1600's. The Mahayana Buddhists believe that there exists many potential Buddha, spiritually advanced beings, who help to enlighten mankind. The Japanese Abbot portrayed in the wooden figure was believed to be such a being.

- ***Marketability/ Educational Purposes***

  Such an item, if scaled down to a much smaller size, may prove to be an item of great interest at the gift shop as it is quite attractive due to its bright colors. It can also be used for educational purposes as it holds great historical significance in the history of Buddhism.

- ***Reproduction Feasibility***

  The Japanese Abbot is a suitable candidate for stereolithography as it is made out of wood with few small details that would be potentially problematic. However, the size of this artifact may play a negative role, as it could be difficult to scan. Also, it is painted with many colors some of which may be difficult to reproduce.



Japanese Censers of Bronze (Room 267)

- ***Historical Significance***

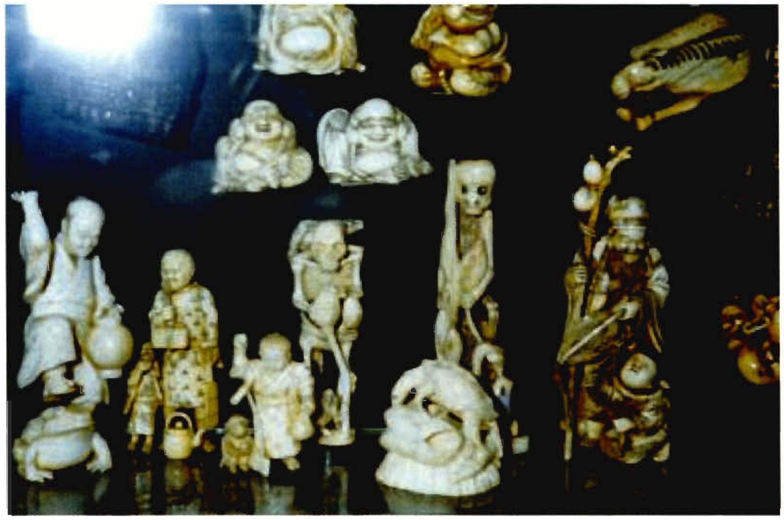
These decorative statuettes in the shape of various birds, dragons and animals came from the Edo period (1603 - 1867) and the Meiji period (1868 - 1912) in Japan. Some of these items were used for practical purposes such as storage, while others were simply decorative additions to Japanese homes. These bronze objects demonstrate the artistic skills and techniques of the two eras, as well as show the cultural and technological progress.

- ***Marketability/ Educational Purposes***

These items, if scaled down, would be tasteful additions to the gift shop in the museum. People would be interested in them for both their unique, distinctly Japanese look, which speaks volumes about the ancient culture in which they were conceived, as well as for their elegance and the beauty of their intricate details.

- ***Reproduction Feasibility***

The Japanese censers are of convenient size for both the scanning and reproducing processes. Although these objects have a very dark surface, they do not appear to be easily susceptible to damage, and therefore, could endure light surface powdering in order to make optical scanning possible. Some of the objects may not be possible to accurately reproduce due to their intricate design and detail.



Kleinkunst (Room 266)

- ***Historical Significance***

These small decorative items, figures of Buddhas, as well as women's finery can be found in the Japanese displays of the Ethnographic exhibit. They were created and used between the years of 710 and 1912.

- ***Marketability/ Educational Purposes***

The small decorative statues are very beautiful and complicated pieces that would attract much attention in the gift shop. The objects and people carved out of ivory, stone, or wood tell a lot about the Japanese culture, and of its influences and main concerns.

- ***Reproduction Feasibility***

The small decorative figures, as well as the hairpins and combs, though beautiful, are small and very complicated pieces with many details and nooks that the optical scanner would be unable to detect and/or reproduce with a desirable accuracy. Also, some items are very dark as well as fragile making scanning one of a very limited selection of options for reproduction. Other items have complicated painted finishes, which would be painstaking to reproduce.

Red Japanese Plates (Room 263)

- ***Historical Significance***

These plates were made and used during the Ming period, between the years 1368 and 1644. They were made with uniquely Ming era Japanese techniques and have designs, which reflect the culture and art of that specific era in Japan.

- ***Marketability/ Educational Purposes***

These items are very beautiful and at the same time indicative of an important time in Japanese history. These plates show more than just the skill of the artist. They give insight into the techniques used to make these plates, about the tools that were available, about the needs of the people, the atmosphere, as well as various artistic influences at that time. Reproductions of these plates will allow people to study the intricate designs on the plates much closer and establish a deeper understanding.

- ***Reproduction Feasibility***

The Japanese plates are not very large, therefore making the processes of scanning and reproducing easier. The color of these items is a deep red color, with some areas that may be too dark for the scanner to detect. Also, the plates are so finely detailed in some areas that it may be impossible to scan/reproduce all of the surface texture accurately due to the limitations in resolution of scanning/reproduction devices.

Emalje (Room 263)

- ***Historical Significance***

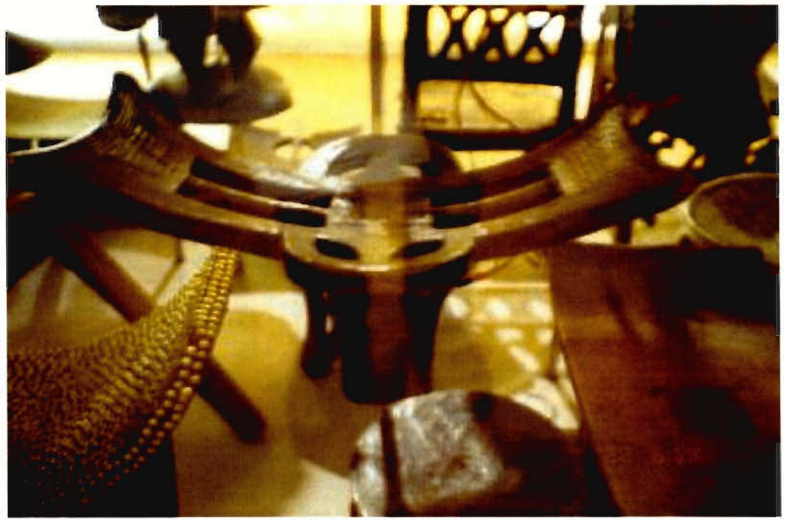
  These Japanese plates, bowls, vases, small statues and other decorative items illustrate the traditional Japanese artistic styles, as well as the available materials and skillful techniques used to produce them.

- ***Marketability/ Educational Purposes***

  Items such as small vases and small attractive figures would sell best in the museum gift shop. These artifacts tell the story of ancient Japan and of its cultural progress, as well as serve as a decorative object.

- ***Reproduction Feasibility***

  The plates, bowls and vases are of ideal size for scanning and stereolithography, however, they would require a painted surface finish with various colors and elaborate patterns. The small figures may be too dark and difficult to scan, as they have much intricate detail.



African Chairs (Room 255)

- ***Historical Significance***

There are hundreds of different sizes and styles of chairs that originated in ancient African cultures. Depending on the owner's social status, the size and height of the chair varied. For example, a wealthy man used tall and wide chairs, where as his servants used very small chairs, sitting only a few inches above ground.

- ***Marketability/ Educational Purposes***

These items are a great gimmick for the ancient African culture. Some of them are quite beautiful and will surely attract attention. These chairs will be especially successful if they can actually be used rather than merely looked at.

- ***Reproduction Feasibility***

The African chairs are of various sizes and shapes, most of which are ideal for optical scanning and stereolithography. They are made of wood and do not have many fine details. These objects also have colors that would be easy to match, although some surfaces are especially dark and could prove to be problematic.

Appendix C

3D Scanner Product Information

Company	Product	Resolution(s)	Price	Speed	Max Object Volume
ShapeGrabber	Portable 3D Scanning System	.0075mm .02mm	$54,000+ $8,000	15,000 Points/Sec	None, Any size is able to be assembled from multiple scans
ShapeGrabber	Tabletop 3Dscanning System	.0025mm .0050mm .0075mm	$48,000	15,00 Points/Sec	132mm x 132mm x 211mm
ShapeGrabber	Gantry 3D Scanning System	.0025mm .0050mm .0075mm .0200mm	$75,000	15,000 Points/Sec	195mm x 132mm x 211mm
LDI	Surveyor PS-400	.05mm	$26,000	15,000 Points/Sec	None, Any size is able to be assembled from multiple scans
LDI	Surveyor PS-1100	.02mm	$33,000	15,000 Points/Sec	None, Any size is able to be assembled from multiple scans
LDI	Surveyor PS-3300/ PS-3300C	.0075mm	$39,000	15,000 Points/Sec	None, Any size is able to be assembled from multiple scans
LDI	Surveyor RE-810 with RPS-120	.00635mm	$51,000	14,400 Points/Sec	(20 x 500 x 108mm)
Cyberware	High Resolution Model Shop Color 3D Scanner bundle (3030RGB/HIREZ/MS) (Customization is possible but more expensive for this unit)	.005-.02mm	$90,500	14,580 Points/Sec	(1m x 1m x 450mm)

Company	Product	Color	Computer	Warranty	Instruction & Training
ShapeGrabber	Portable 3D Scanning System	No	Included; Credit if not needed	1-Year	On-Site for Staff
ShapeGrabber	Tabletop 3Dscanning System	No	Included; Credit if not needed	1-Year	On-Site for Staff
ShapeGrabber	Gantry 3D Scanning System	No	Included; Credit if not needed	1-Year	On-Site for Staff
LDI	Surveyor PS-400	No	Not Included	1-Year	Optional
LDI	Surveyor PS-1100	No	Not Included	1-Year	Optional
LDI	Surveyor PS-3300/ PS-3300C	No/Yes	Not Included	1-Year	Optional
LDI	Surveyor RE-810 with RPS-120	No	Not Included	1-Year	3-day training on site
Cyberware	High Resolution Model Shop Color 3D Scanner bundle (3030RGB/HIREZ/MS) (Customization is possible but more expensive for this unit)	24-Bit RGB (Good)	Not Included	1-Year	On-Site Training

Appendix D

3D Systems Product Information

SLA Model	Resolution	Price	Fastest Build Speed & Maximum Build Envelope	Warranty	Notes
250/50 HR	0.0625 mm	$175,000 (PCA & software *not* included)	0.635 m/sec 250x250x250mm	1-year (Laser under a different warranty)	Being phased put and replaced by the Viper system. Price reflects this.
Viper si2	0.06 mm 0.10 mm 0.15 mm	$180,000 (PCA & software included)	250x250x250mm	1-year (Laser under a different warranty)	-Dual resolution -Best value
3500	0.05 mm 0.10 mm	$ 400,000 (PCA & software included)	2.5 m/sec 350x350x400mm	1-year (Laser under a different warranty)	- 2.5 times faster than SLA250 - Bigger vat
5000	0.05 mm 0.10 mm	$ 625,000 (PCA & software included)	5.0 m/sec 508x508x584mm	1-year (Laser under a different warranty)	- 35% more power than SLA 3500 - Bigger vat
7000	0.025 mm 0.076 mm 0.100 mm 0.127 mm	$ 800,000 (PCA & software included)	9.52 m/sec 508x508x600mm	1-year (Laser under a different warranty)	- Smoothest finish - Fastest machine

Appendix E

Interview Summaries (Museum)

Poul Grinder-Hansen

Curator, Middle Ages Exhibit

The group met with Mr. Grinder-Hansen on Tuesday, March 27. He was very interested in the technologies of stereolithography and optical scanning, and how they could allow him to make reproductions of artifacts that he had previously been unable to reproduce. Further he currently was attempting to find a method to reproduce and object that he was having difficulty reproducing.

Mr. Grinder-Hansen brought up concerns about accurately matching the color of objects and their finishes. He justified this concern by saying that the surface finish and color are used to determine when an object was made, where the object was made, and in some cases, by whom.

In reference to the educational benefits of having reproductions available for the general public to touch, he thought that would be of enormous benefit. However, to be of the most benefit for the visually impaired, he suggested that there needed to be some sort of verbal description of the object so that the public would know what it is that they are touching. We suggested that perhaps there could be added information added to the existing headphone system, and in this way it wouldn't entail a brand new system, rather a modification to the existing one.

Poul Mørk
Curator, Ethnographic Exhibit

The group met with Mr. Mørk on Wednesday, March 28. He did not see a great need for the process of stereolithography in his department, as most of the artifacts in his department are reproducible by other less expensive and more established methods. Most of the objects in his exhibit were either not very complex, or were made in a style that is still practiced by some people today.

Mr. Mørk, however, did see a use for the technology of optical scanning. He suggested that optical scanning could be used for the purposes of archiving and cataloging the artifacts not only on display, but all the objects in the museums holdings. He further suggested that these scans could be used to check for imposters, be used for insurance purposes, and be used to keep a record of the object, should the unforeseen happen and an artifact was damaged or stolen.

Mr. Mørk was interested in making copies of some objects in materials that are more durable that the original, but have the same look. For example, he was interested in making a reproduction of a Native American robe that is made up of feathers. He thought it would be interesting to reproduce the rope in plastic. We explained that the robe would be difficult to scan, but not impossible, as there is precedent of scanning hair which is similar to feathers. The real difficulty would lie in the method of subsequent reproduction as stereolithography probably would not be adequate for reproducing all the intricate features of the feathers.

Peter Henrichsen

Conservation Department

The group conducted this interview on Tuesday, April 3. At first, Mr. Henrichsen did not think that either of the technologies of optical scanning or stereolithography were accurate enough to be of use to the museum. However, after the group explained the current capabilities of the technologies, he did see some potential uses for the technologies. First, he saw a use for security purposes as a copy could be put on display, while the original could be secured elsewhere. Second, copies could be used for foreign museums and for loans on either a permanent or temporary basis. This may not be a viable application because the reproduction may not be accurate enough. Also, in the past, when outside museums have been offered copies to exhibit, they have refused them because they desired the original and have offered many times the cost of a reproduction in an attempt to acquire it. Third, depending on accuracy, reproductions could be used for comparative analysis of tool marks and scratches in order to tell how the tools were made and used. However, in this case, high resolutions of the scanner and of the reproduction process would be necessary, as some small tool marks could be lost in the reproduction process. Lastly, Mr. Henrichsen echoed the sentiment of Poul Mørk in saying that optical scanning could be used as a method of cataloging and documentation, as a 3D model would be better than just a picture. Again, the amount of accuracy here would be important to be able to accurately describe the original.

Mr. Henrichsen then told the group about the methods that are currently used to make copies. The primary methods that are used are casting and molding. Material for these molds include silicone rubber, aluminum and galvanized steel, plaster of Paris, and resin. The master molds produced for the museum shop are made of silicone rubber and last for 8 - 10 years. Also, the lost wax method is used in some cases. In this process, the part is made in wax prior to being casted in plaster. Once the plaster has dried, the wax is heated and removed by a vacuum machine. In this process, when the mold is separated, there are no visible parting lines. During the reproduction process, the original may only be handled by the museum conservation staff. Under no conditions can the artifacts leave the museum.

The methods of casting and molding are not well suited for wooden, unfinished ceramic, or bone artifacts. The original would be damaged during the casting or molding process, as the casing material may be deposited on the artifact or the mold may remove material from the artifact. Mr. Henrichsen stated that in these cases stereolithography and optical scanning would be a good solution to this problem, as the entire process is touch-free, i.e., no material is added nor removed.

The topic of resins was also discussed. Mr. Henrichsen has experience in finishing epoxy resin. He showed us a Native American "Cherokee pipe" that he made of epoxy resin, which looked identical to wood to a non-expert. However, after handling the piece, it was clear that it had the characteristics of plastic, as far as weight was concerned. This showed that it was possible to finish epoxy resin to appear identical to wood with the inflections of different colors and the ring marks of the wood. According the Mr. Henrichsen, this process is easiest to do by making the resin "hit the base color" with the proper finish, either of matte or half matte. This is important for stereolithography reproductions, as resin is used which requires a finish, in order to match the copy to the original.

The pricing for an individual reproduction created by the conservation department, on average, is approximately 60,000 DKr, if the reproduction is made for the museum. If it is for an outside buyer, the reproduction costs twice that amount, 120,000 DKr. This price does not include the VAT of 25%.

Karl - Johann Hemmersam
Head of Educational Programs

We interviewed Mr. Hemmersam on Thursday March 29. This interview was brief as he was engaged in other activities at the time. During this interview were learned about past educational programs along with some of the hands on exhibits already located in the museum. He suggested for us to look at the "Please Touch" and children's museum to get an idea of the scope and the implementation of these programs. He also directed us to some literature on research done on the topic of the benefits of tactile learning and said that he would mention our project at his department's weekly meeting to see if there were any people that were interesting or had an immediate need for this type of reproduction for their endeavors.

Karin Andreasen
Public Relations

We met with Mrs. Karen on Friday, March 23. This interview was to discuss the possibility of arranging interviews with the public. She told us that currently that the museum was conducting a survey of their own until mid-April. We discussed the possibility of conduction of random interviews in the museum with visitors, but were told that was not desirable as people might feel like they were being harassed. Further, there exists a certain procedure for conducting interviews in the museum, to ensure that the surveys are not offensive and reflect the professionalism of the museum. Also, if the survey were to be conducted, it would have to be done through the information desk on a volunteer basis.

Appendix F

Interview Summaries (Companies)

Maria H. Garcia

3D Systems: Sales Representative

Ms. Garcia was our first contact with 3D Systems, and we contacted here through e-mails and phone conservations. She was very interested in assisting us with this project as 3D Systems is looking to expand its market, and using stereolithography for conservation purposes in museums is a relatively new market. She provided us with the initial information about the company along with the initial information about the capabilities of the machines. She was not able to provide us with information specific to Europe, but referred us to Deniz Okur in their Germany office.

Deniz Okur

3D Systems: European Sales Representative

A phone interview with Ms. Okur was conducted on March 26. During this interview, information about pricing specific to Europe was discussed. We learned that the SLA 250 was being phased out and replaced by another machine called the Viper si2. Also we learned, in general, about European pricing for the SLA machines. They were more expensive, as expected. Further we discussed the resolution of the machines. We learned that the resolution of the machines improved in relation to the model number, and price. Also that the Viper si2 had fairly decent resolution, but was slow. Ms. Okur suggested that this might be a good solution for the museum since the reproduction was not being used for rapid production, and that accuracy and price were more important than speed.

Ms. Okur described some of the applications in European museums. She described one such application in the Netherlands in which the skull of a mummy was reproduced without unwrapping it. To do this the mummy was put in a CT scanner which created a digital image of the skull underneath the bandages. Then, using that information, the skull was reproduced using stereolithography.

Ms. Okur then offered to send more information, along with having a representative from the pricing department get in touch with me so that more accurate pricing options for the National Museum could be discussed.

Ar Tulaj

3D Systems: European Pricing Specialist

A phone interview with Mr. Tulaj was conducted on March 26. During this interview, information specific to Denmark was discussed. We learned that because 3D Systems was coming out with a new machine, the Viper si2, the one that it was replacing, the SLA 250, was on sale to liquidate the remaining stock. Originally the SLA 250 cost on the range of $220,000 - $250,000, but now was on sale for $170,000. While this is a fairly significant drop in price, it doesn't mean that it is a deal. The new machine, which is faster and has better resolution, costs $180,000 according to Mr. Tulaj. The prices of the other machines were discussed during the remainder of the interview. Also we learned that the prices that were quoted to us includes the post curing apparatus (PCA). This machine is used to harden any resin that isn't completely hardened during the solidification process. However the price does not include the price of a small air conditioner that is needed because there are certain environmental conditions that must be maintained in order for the process to be successful. Also the price of a PC is included in the quote, but will be subtracted if a PC is provided by the museum. If the museum desires to have a specific quotation, that option is available.

Ron Jones

SharedReplicators: President

We contacted Mr. Jones through e-mail. During the course of our correspondences, we learned about SharedReplicators, and a little about the projects in which the company was involved. The project that was of the most interest to us was the reproduction of the Triceratops for the Smithsonian Institute in the United States. We learned that the reproduction process was only partially based upon stereolithography, and that the specific methods that were developed for the project were proprietary. Further that they would be interested to bid on the work or would "entertain a consultant arrangement." Should the museum desire to speak with them further, the company has a Confidentiality and Non-Disclosure Agreement that is required to be in place before more information can be given about it's methods.

Ric Perry

Mack Prototype, Incorporated: President

We contacted Mr. Perry through e-mail, and then took a tour of Mack Prototype before coming to Copenhagen. During the tour we learned about plastic injection tooling and molding. This is interesting to the project because it is the best method for reproduction if there are to be a large number of a specific object to be reproduced. Also, there are two ways to go as far as making copies, either molding or tooling. The tooling method is more expensive initially, as the cost of a tool is about $70,000. However, if there are a large number of artifacts to be made, it will be cheaper than the molding method as the molds do not work for large numbers of objects and long term is more expensive.

Mack Prototype also has a stereolithography apparatus (SLA). They have an SLA 250 that they run almost continually, and are able to do outsourcing work. The price for this work is in the range of \$500 - \$750 for an object the size of a coffee cup, depending on the detail of the object, the desired accuracy, and the amount of post production work that is needed. The company has foreign customers already, so doing business overseas is not new to them. Mr. Perry stated that their company would be eager to do work for the National Museum, should they decide that they would like to use stereolithography.

David Bothwel

Solidscape: President

The group contacted Mr. Bothwel via e-mail and phone. Through these communications, the group learned about the process of thermoplastic inkjetting and the advantages, and disadvantages, of this technology as compared to stereolithography. We learned about pricing, accuracy, and speed, and compared to stereolithography apparatuses (SLA), these machines are cheaper, about as accurate, but very much slower. Also this is a new technology, and there are limitations that exist in reference to part size and the detail of the objects along with other problems that have not arise as of yet.

One interesting aspect that was mentioned was future ability to color the object as it was created. This is not an option for SLAs, but could be possible for this technology at a later date. Currently the only color available for the thermoplastic is green.

Armando Alonso

Laser Design: Sales Representative

The group contacted Mr. Alonso through e-mail and by phone. He told us that their company is several similar installations with museums and anthropology departments at leading American universities. Also, based on the information we provided to him about the museum and the needs and requirements of the objects to be scanned, he provided us with recommendations of products that they sell. He suggested two series of scanners that they produce, the PS-series, and the RE-series. The PS-series is the most versatile and lowest cost option and works for object of all sizes. However, it does not have the best resolution. The RE-series was also recommended and is the scanner with the best resolution that they make. However, this scanner cannot accommodate the larger objects that were proposed for scanning. This system is also more expensive, and all the software needed is extra and is dependant on the specific requirements of the project. Mr. Alonso also offered to make a formal quotation, should the museum desire to obtain a specific estimate.

Mark Bisson

ShapeGrabber Incorporated: President

The group contacted Mr. Bisson through e-mail and by phone. He told us that their company new, and formerly was included in the Vitana corporation. Also, the technology that they sell is based on the BIRIS system that was developed by the National Research Council of Canada (NRC), but they now own the commercial rights to that technology. This technology was applied at the Canadian Museum of Civilization in the recreation of a Sphinx that they had in their possession.

In reference to specific scanners that they sell, he suggested their portable linear platform. The platform is 300mm high, and seated on an industrial tripod. The tripod is mobile and would be placed in front of the object that is being scanned, like any camera. The platform is fairly lightweight and portable. The only problem with this scanner is that it could take dozens of scans to completely digitalize an object and once the scans are completed they would have to be reassembled to form the 3D representation. Recently, this company has a system to an American university to digitalize small pieces of ceramic and bones. Lastly, Mr. Bisson offered to make a formal quotation, or to answer any other questions via either e-mail or phone.

Sue Addleman

Cyberware: Vice-President

The group contacted Ms. Addleman through e-mail and by phone. She informed us that Cyberware has sold its machines to various other museums including Stanford University, The Smithsonian, The Tech Museum of San Jose, and The American Museum of Natural History. In reference to the artifacts that the National Museum desires to scan, she stated that bone and wood are typically ideal surfaces for scanning, and the ability to move most objects simplifies the scanning and post production processes considerably. The main challenge for the objects that are to be scanned is their size.

According to Ms. Addleman, Cyberware's standard line of systems will not accommodate objects that are large, but they do possess experience building custom 3D scanning systems for large objects. Moreover, nearly half of Cyberware's annual business comes from custom hardware and software development.

Ms. Addleman did make a recommendation for the smaller sized objects. For the smaller objects, a maximum radius of 450mm, the companies standard Model Shop Color 3D scanner was suggested. The high-resolution model of this scanner was also suggested. The price quoted, $90,500.00 was the most expensive that was quoted by anyone, but the scanner also had the best features with the exception of the ability to handle objects of large size.

Also of interest was the offer to do a sample scan of an artifact. Our liaison, Mr. Holm, was interested in this demonstration, and currently is in the process of sending an object to the company to get the sample scan.

John Taylor
National Research Council of Canada (NRC)

The group contacted Mr. Taylor by e-mail. In contacting Mr. Taylor, we were interested in learning about the work that the NRC did in developing the BIRIS scanning system, and the use of the system for the Canadian Museum of Civilization. Mr. Taylor was, for the most part, unable to discuss the specific details of the technology as the commercial license was sold to the Vitana corporation, which later became the subsidiary ShapeGrabber. This information was useful in contacting ShapeGrabber.

Appendix G

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