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Project Presentations

Use of Hand-held Laser Scanning and 3D Printing for Creation of a Museum Exhibit.

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Abstract
Biological anthropology as a discipline continues to be holistic in both its approaches to understanding research problems and its borrowing of methods from many related disciplines. More and more, digital imaging is becoming an integral part of data acquisition and analysis in biological anthropological research. With many new emerging technologies, however, these techniques are also now contributing even more to research dissemination. One of the newest tools in anthropological research is 3D object printing. Stereolithography has seen limited use, but the costs are often prohibitive. New developments in 3D object printing have begun to make this technology more available to osteological studies. Here we discuss the use of 3D laser scanning and 3D printing to re-create human skeletal remains for a museum exhibit. A Polhemus 3D laser scanner is used to capture the geometry and shape of the individual bones. The point clouds are then edited and exported as STL files for printing on a Z-Corp Z406 3D printer. The recreated bones are then incorporated into the exhibit, yielding an accurate and realistic depiction of the original skeleton. An overview of the challenges associated with the project and its successful completion are discussed in the context of the role of 3D printing in bioarchaeological research.

Categories and Subject Descriptors (according to ACM CCS): J.2 [Archaeology]: Repatriation and digital archiving

1. Introduction

New technologies allow researchers in anthropology to overcome some of the challenges of working with ancient human remains. Virtual archaeology, including 3D visualization and modeling, is rapidly becoming integrated into the mainstream dissemination of archaeological research [Weber 2001; Weber et al. 2001; Zollikofer and Ponce de Leon 2005]. Additionally, these new methods are helping to improve communication between researchers and the public.

In 2005 the Mennonite Heritage Village (Manitoba, Canada) opened a new museum exhibit on the 'Funeral as a Rite of Passage' in Mennonite communities. The exhibit was to include a display presenting an archaeologically recovered human burial of a Russian Mennonite woman who lived in the late 1800s and early 1900s in the former Schoenfeld village in southeastern Manitoba. Due to the culturally sensitive nature of the display of human remains, a replica of the skeleton was created for the exhibit. A non-invasive method to replicate the remains was employed in order to avoid unnecessary damage. This paper presents an overview of the challenges encountered in successfully creating the replica using a hand-held laser scanner and 3D printer.

2. Laser Scanning

The shape and geometry of the human skeletal remains was acquired using the Polhemus Fastscan handheld 3D scanner. The scanner uses a laser, camera and motion-tracking system to accurately record a 3D point-set of the original object surface. The laser and range-finding camera are contained in a portable handheld wand (Figure 1).

A fan of laser light is emitted from the wand as the user scans the object's surface using a motion similar to spray painting. The range finding optics calculate the distance from the object to the scanner and record the position as a point in 3-space. The motion tracking system establishes these points relative to a single datum identified as the transmitter 0,0,0. The motion tracking for the Fastscan is based on the Fastrak system marketed by Polhemus. The Fastrak system tracks the position of a receiver (in the wand) in relation to the transmitter (0,0,0) through a low frequency magnetic field generated by the transmitter. The result is the ability to scan objects with accurate six degrees of freedom (X,Y,Z, Azimuth, Elevation and Roll).

Figure 1: *Polhemus hand-held laser scanner.*

Resolution of the scanner decreases as the distance between the object and wand increases. Resolution is also affected by the scanning rate (i.e. the speed at which the user passes the wand over the object). Average resolution is 0.5mm at 200mm, where line to line resolution is 1mm at 50mm per second (pers. comm. Dan Ratta, Polhemus). Since the motion tracking system is based on a field generated from the transmitter, accuracy depends on wand-object range in relation to the transmitter. Accuracy for the Fastscan is 1mm at 200mm (pers. comm. Dan Ratta, Polhemus).

The handheld scanner provided a number of advantages for scanning the skeleton. It can be difficult to capture surface geometry from skeletal material due to the complex and variable nature of the bone surfaces. Archaeological skeletons are also more difficult since they can broken and shattered in various ways, making a uniform scanning process impractical. The handheld wand allows for the manipulation of the data acquisition device to suit the variable surface quality of the object. In this case, the researcher is capable of adjusting hand position to best record hidden areas of the skeleton. Archaeological skeletons can also become stained by soil and exhibit erosion of the hard boney surface over time exposing the more porous bone structure difficult to scan with conventional devices. Laser intensity can be adjusted on the handheld wand, allowing for differences in surface quality to be compensated for through laser intensity settings. Adjustment of laser intensity can be done on the fly during the scanning process.

The skeleton had intermittent staining from the soil and heavily eroded surfaces in a variety of localized areas. In order to capture detail from all the surfaces, the bones were scanned in an upright fashion with one end secured in a bed of sand. The bone was then turned 180 degrees, exposing the opposite end for scanning. A black felt cloth was draped over the table and sand box, with the skeletal element lying on top of the felt. 'Noise' occurs from the reflection of laser light from nearby surfaces such as the counter top or sandbox. The corrugated surface of the felt absorbs excess light yielding a better initial scan. Overhead lights were dimmed slightly, although they are not a source of significant error under normal conditions (e.g. indoor florescent lighting). Laser intensity was best at the lowest setting for long bones such as the Femur, Tibia and Humerus. Higher settings increased noise from other objects. The transmitter needed to be moved closer when scanning the Femur. Higher intensity settings were used for stained and eroded surfaces. Very high settings increase noise by including data from other nearby surfaces and/or excess reflection from the bone surface. Optimal range was between the first and third settings. All scans were saved as both ASCI text point cloud files (.asc) and stereolithography (.stl) files. Each bone had at least two files associated with it, representing the opposite ends. More complex bones were scanned from multiple angles.

3. Image Processing

Image processing of the scan data was undertaken using RapidForm software by Inus Technology Inc. Multiple scans of objects were registered to create 3D models of each skeletal element. STL files are easier to register since the format gives a visually understandable surface for the registration process. Using point files often leads to picking the wrong points since the depth cues are not as visually apparent. The editing process followed a specific pattern: Registration, Simplification, Detailing and Cleaning.

3.1 Registration

The individual scans were registered using the "Initial Registration" command in RapidForm. This command requires the user to input three or more points in common between the two scans, and matches the scans using the curve equations between the similar areas as landmarks for the registration process. It is important to include a recognisable common area between the scans for registration. The fine register command was then executed to increase the accuracy of the registration process. The initial registration yields an effective averaging of common surfaces, but the fine registration matches the scans more accurately. Finally, the "Combine Shells" command is executed to

turn the individual scans into one complete model. This command deletes some of the redundant and overlapping areas and makes a single model file. The result is a single STL file for each bone.

3.2 Simplification and Detailing

The simplification process is necessary for accurate, clean model files. Since skeletal material has a very complex surface morphology, it can be difficult to produce an accurate clean model using standard procedures. The new registered STL file is exported to the proprietary Rapid-Form point file (.pts). This file is then reloaded under a new project window. An exact copy of the point cloud is made and reduced several times and re-triangulated. The surface of the reduced point cloud is therefore very simple and represents the basic shape of the original, while reducing the number of boundaries and incorrect normals. Incorrect normals and excessive boundaries develop from errors in the triangulation process with complex objects such as bone. The simplified surface is then fit to the original high detail point cloud. This brings out the surface detail by increasing the triangle data without introducing new boundaries. This process produces a detailed and accurate representation of the original object without errors and unwanted holes. RapidForm recommends this approach when generating complex surfaces from point data in the help manual for the software.

3.3 Cleaning

The last step for each 3D model is to double check that the model is free of errors and a manageable size. The detailing process can add a significant amount of triangles, producing an excessively large file. The decimate function reduces the number of triangles at a minor cost to the amount of surface detail. This function is applied during this final step along with the clean function to double check the absence of crossing faces, bad normals and non-manifold faces. These along with excessive boundaries can cause problems with the physical model when the STL file is printed.

4. 3D Printing

The virtual models were then printed using a Z-Corp Z-406 3D printer. This printer is capable of printing in both colour and monochrome, but was restricted to monochrome for this project. This printer uses plaster-based material and binder solution to recreate 3D objects. A layer of plaster is first spread onto the build chamber floor. A layer of binding solution is sprayed onto the powder surface in the shape of a 2D cross-sectional slice of the original object (Figure 2). This process is repeated until a 3D object is produced and contained within the build

chamber. The object is then removed from the build chamber and excess powder is cleaned from the model with a conventional brush and then an air-brush.

The orientation of bones was a significant point of consideration in the building process. To save time multiple bones are loaded in a single build. The speed of the printer is mainly limited by the number of times the gantry can move across the build chamber, so the most efficient use of time and space involves limiting the z-axis depth of items as much as possible in the build chamber. Additionally, the z-axis is where the greatest amount of printing error and the lowest amount of part strength occurs. Therefore, it is important to print long thin bones to maximize the x-y plane. Thus, the femur is oriented lengthwise on the x-y plane. The printed object needs to be left for several hours before removing. This allows for the binding solution to dry and become hard. While in theory, objects can be removed immediately, for this project objects were left for at least 5-6 hours but model strength for large bones was best left in the chamber for approximately 12 hours.
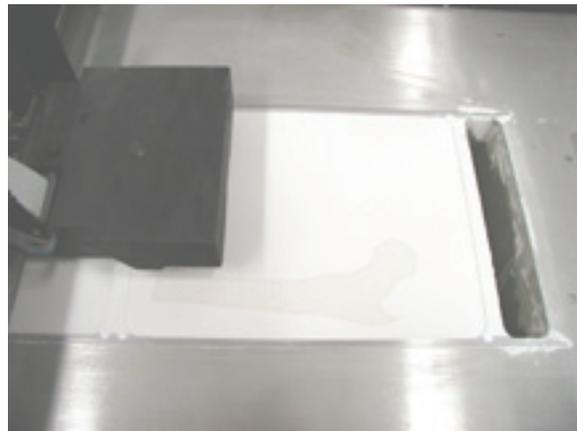

Figure 2: *3D printing.*

Large bones, such as the femora and tibia, were be printed as two segments due to the limited size of the build chamber. This meant that these elements also needed to be glued together prior to display. This was the most challenging component of the printing process. The best technique for this involved bevelling the circumference of the adjoining surfaces to provide a channel for the cyanoacrylate (CA) glue. The CA was applied to both adjoining surfaces, and held together until slightly firm. Additional glue was applied through the channel to increase the seal. The original models were bisected on an angle to increase the surface area for gluing. A putty was made with the plaster and binder solution and applied to the channel (Figure 3). The rough edges were sanded. This process was repeated until the seam was barely visible. Excess CA changes the surface colour of the model and must be covered appropriately to hide the gluing process.

The final stage for all the models is submersion into a paraffin wax bath. This makes the models slightly

stronger and yields a nice finish that seals the powder. The result is a solid off-white model that visually represents the shape of the original bone.

Figure 3: *Attaching two halves of a long bone model.*

5. Putting it all together

After all physical models were completed, they were integrated into a display representing the partially excavated burial (Figure 4). The purpose of the display was to help communicate to the public aspects of the daily life of the individual, as revealed by an osteological analysis of her remains. This display formed part of the larger exhibit that taught about early Mennonite settlers and their beliefs about death both spiritually and philosophically.

The handheld scanner presented a number of challenges and rewards for this project. The portable nature allowed for the equipment to be easily transported to the location where the remains are curated. Since the body is far more precious than the equipment, this approach makes gaining access to remains for scanning easier and fosters better relations between researchers and curators. The Polhemus scanner was also effective for dealing with the fragile and variable nature of the remains. The ability to manipulate both the scanning apparatus and the bones to achieve a more complete scan yielded excellent overall results.

Some skeletal elements were unfortunately too small for the resolution of the scanner. Tiny finger and toe bones from the hands and feet were impossible to capture. The bones that were imaged from these regions were accurate in shape but lacked fine detail. Additionally, the skull was particularly difficult due to multiple thin boney fragments within the orbits and nasal regions. The skull detail needed to be significantly reduced in order to create a pleasing model. The scanner also had a difficult time capturing the subtle changes in rib end shape, therefore detail needed to be compromised and some rib elements were estimated from basic geometry.

Most CAD/CAM software is developed for the engineering market, therefore programs are designed to work on tidy surfaces such as CAD drawings or scans of inanimate objects. Anatomical material is highly variable in shape, texture and size. The complicated nature of biological surfaces presents significant challenges for the creation of anatomical models. The STL files produced from the scanning software are thus noisy, rough and full of holes and have other errors from the incorrect generation of the complex surface from the dense point-set. This was overcome by using the simplification and re-detailing process described above. This method was extremely effective for generating visually pleasing, "clean" model files suitable for the requirements of the museum. The accuracy of the original skeletal element to the replica has not been assessed for this method. Some precision may be lost during this editing process although it is certainly not apparent from initial visual inspection, nor does it impact the overall goal of this project - to recreate a believable replica of the original skeleton and not a replica that could be scientifically studied in lieu of the original.

What may look visually pleasing on-screen may not always be optimal for the 3D printing process. When looking at an STL file onscreen, the computer-aided rendering may cause a problem model to look good. When that same file is sent to the printer, it can have dramatically different results. It is important to eliminate boundaries, holes and other problems associated with generating surface models.

The application of rapid prototyping technologies to fields outside of manufacturing has been explored over the past decade or so. In particular, the role of RP in medicine has prompted a number of researchers to examine the use of stereolithography for anatomical modeling including surgical applications [e.g. Borah et al. 2001; Brown et al. 2003; Choi et al. 2002; Dolz et al. 2000; Perez-Arjona et al. 2003]. In addition, while less common, RP has also been explored by other disciplines including art [e.g. Chua et al. 1994], architecture [e.g. Giannatsis et al. 2002], paleontology [e.g. Clark et al. 2004; D'Urso et al. 2000] and anthropology. In 1995, Hjalgrim and colleagues imaged and printed an Egyptian mummy skull using stereolithography (SL) technology. This model took 40 hours to print and cost approximately $2500 USD [Hjalgrim et al., 1995]. The more recent development of the Z-406 3D printer makes experimentation and whole skeletal reproduction possible by overcoming the production cost and speed barriers of earlier SL equipment (Grimm 2004). As with any imaging project, editing and scanning time were the greatest costs to this project. Well over 200 hours was invested in editing individual skeletal elements in preparation for the printer, however this includes some time exploring different approaches to produce the best possible models. The printing process was relatively fast and highly affordable, taking about 20% of the time as standard stereolithography and less than 5% of the production cost. A project such as this could not have been reasonably undertaken using the technology described by Hjal-

grim and colleagues a decade prior. Continued perseverance and cross-disciplinary projects have made significant enough advancements to make this type of research possible. Researchers in anthropology now have an example of a non-invasive skeletal reproduction using non-contact laser scanning and cost effective 3D printing.

Figure 4: *Museum display.*

6. Conclusions

This paper has presented a project which describes the replication of human skeletal remains using a hand-held laser scanner and 3D printer for use in a museum exhibit. A variety of technical challenges were addressed, and this project demonstrates that the use of these technologies is both practical and economical for public presentation. Ultimately, however, the success of this project is in the experience that museum visitors take with them.

7. References

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