

Virtual skeletons: using a structured light scanner to create a 3D faunal comparative collection

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ABSTRACT

Appropriate comparative animal skeletons are not always available to faunal analysts for use in identifying archaeofaunal remains. This is especially pertinent when working in locations where no comparative collections are available locally, and the archaeological assemblage cannot be transported to another facility. In order to fill this gap, we are building a virtual comparative faunal collection using a structured light scanner to scan modern skeletal material in 3D. The resulting high resolution 3D color models are a valuable resource for identifying fossil specimens. Scan data can be converted into a variety of formats for viewing and can be transported on a portable digital device for use at field or laboratory localities. In addition, scans can be printed three dimensionally to produce a replica of the scanned skeletal part. A particular advantage of this digital technology is that we can eventually create a complete 3D representation of a taxon's skeleton from scans of several components of what are incomplete skeletons of one animal taxon in a museum collection. The results of our project thus far are available to other researchers and educators by means of the internet. A variety of interested parties could benefit from such a collection, including zooarchaeologists, paleontologists, biologists, teachers and museum curators.

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1. Introduction

For both research and educational purposes, zooarchaeologists depend on access to high quality comparative faunal skeletal collections, which ideally contain a diversity of species represented by multiple aged animals of both sexes. Unfortunately, we often have to work with less than ideal collections or in some instances, none at all. While most faunal analysts have assembled vast packets of drawings and photographs to fill the gaps, these somehow never seem to capture the right angle or feature. Short of having a comparative specimen to hold, we would like to have a model that we can rotate to just the right position, and even magnify for a closer look. Fortunately, 3D scanning technology provides a way to produce models that can be rotated and enlarged in 3D, allowing zooarchaeologists to create a virtual comparative collection. Such a collection can then be easily transported in a computer, external storage device or stored on a digital server, and the data can be

accessed and distributed anywhere in the world. Scan data can also be printed (i.e., prototyped) as replica skeletal elements.

We present here the methods and results of a project that scans modern animal skeletons in 3D in order to create a virtual reference collection. Generating models that are accurate to the submillimeter and include color, structured light scanning is an exceptional technology for such a study. Following four years of testing, we have established an efficient and successful protocol for scanning animal bones and processing the data into formats for viewing and prototyping. This paper discusses the equipment and methods necessary to undertake such a project, the potential challenges involved, and the benefits of such a study. We also discuss the application of the 3D models in our current laboratory analyses and excavations.

Although 3D models cannot ever replace true skeletal specimens, a virtual comparative faunal assemblage nonetheless has numerous benefits that will surely become more valuable as genuine specimens become harder to access. Museums and institutions holding such collections are continuously facing budget cuts and restrictions on storage space, resulting in collections being sold or given away. Obtaining animal carcasses for processing is also difficult due to the threat of biological hazards such as disease (e.g., rabies, mad cow disease), while processing carcasses or parts

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thereof presents problems if there are not adequate facilities that are properly ventilated and can dispose of biological hazardous waste. Although the skeletons of some domestic animal species can often be acquired for purchase or loan, those of wild animals are more rare. Moreover, domestic and wild species from other continents are extremely difficult to obtain, even for an institution or museum. Finally, endangered or extinct species are unavailable. Therefore, the ability to build a virtual comparative skeletal collection might make it feasible for institutions as well as individuals to access these much-needed research tools.

Three-dimensional surface scanning, either by laser or structured light scanner, has proven a valuable tool in anthropology, paleontology and related fields. Laser scanners have been widely used for fossil and modern hominin or faunal skeletal material (e.g., Dawson and Levy, 2005; Hennessy and Stringer, 2002; Kappelman et al., 2000, 2001; Larson et al., 2009; Lyons et al., 2000; Motani, 2005; Pfisterer et al., 2007, 2008; Plyusnin et al., 2008; Smith and Strait, 2008; Strait and Smith, 2006; Wood et al., 1998), with applications such as morphometric analyses and comparative anatomical research, archiving specimens, or cultural preservation. Structured light scanners are particularly suited for use in laboratory and museum conditions, where one has been used on pottery (Karasik and Smilansky, 2008), lithics (Grosman et al., 2008), and sculpture (Breuckmann, 2008). However, both types of scanners can be packed and transported relatively easily for use elsewhere. A good example of the structured light scanner's portability was its use in documenting *in situ* archaeological features in the field (Gernat et al., 2008; McPherron et al., 2009), where it made high resolution scans of excavated ground surfaces and their associated artifacts.

The virtual fauna project described here is another useful application of structured light scanning technology to anthropology and paleontology. Although a small number of online 3D databases of human, non-human primate and animal skeletons are currently available (e.g., Kappelman et al., 2000, 2001; Smith and Strait, 2008; Strait and Smith, 2006), we add to this archive, via the internet,¹ models of taxa that are commonly found in our zooarchaeological assemblages. Our current goal is to focus on those species found in Late Pleistocene faunas from Africa and Europe; thus far, we have scanned an adult horse (*Equus caballus*), subadult reindeer (*Rangifer tarandus*) and adult gazelle (*Gazella gazella*). The next stage of this ongoing project will include rarer species, such as large carnivores. Ultimately, it would be ideal to scan individuals of different ages and of both sexes from multiple populations to encompass as much within-species morphological variation as possible.

One advantage that scanning technology offers is the possibility of printing actual replica bones using a 3D printer. Known as rapid prototyping, this printing technology is well established in areas such as engineering and industry, where prototypes of intricate mechanical parts or products are needed in the early stages of design and manufacture. Recently, it has become more common and widespread for a variety of specialized fields and has proven quite valuable for paleoanthropology. For example, 3D printing has allowed researchers at the Max Planck Institute of Evolutionary Anthropology to produce replicas of human teeth that were printed 20 times their natural size, which facilitated the analysis of their cusp morphology. Such prototypes are also useful for museum displays, teaching, and research.

2. Methods and materials

To create the virtual comparative collection, we are scanning modern animal skeletons with a Breuckmann triTOS-HE structured light scanner (Fig. 1). Two main elements make up this scanner: a digital camera with 1384 × 1036 pixel resolution and a projector, which are both mounted on a horizontal frame and whose positions can be adjusted according to the size of the object being scanned. Objects ranging from ca. 1 cm up to 90 cm can be scanned using the appropriate lens, although the camera resolution is never adjustable. For larger objects, when the scanner's field of view necessarily increases, the resolution of the scanner accordingly decreases. The majority of our scanning utilized the 100–675 mm lenses, with accuracy between 12 and 80 μm.

The following lenses offering various fields of view can be used on this structured light scanner (Fig. 2):

- 060 mm (use with smallest objects up to 6.0 cm)
- 100 mm (use with objects 6.0–10.0 cm)
- 325 mm (use with objects 10.0–35.0 cm)
- 675 mm (use with objects 35.0–67.5 cm)
- 950 mm (use with objects 67.5–95.0 cm)

Because the animal skeletons we are scanning vary in size depending on the species and element, these different sizes of camera lenses are necessary. Generally, only one size of lens is used in scanning a bone, e.g., 100 mm lens for the smallest elements and 675 mm for larger long bones, although in the case of the skull, both the 325 mm and 675 mm lenses were required to capture all of the details. If we were to scan a skeletal part that did not fit completely in the field of view of the largest 950 mm lens, the scanning process would be similar except that more scans of only part of the bone would be needed, and these would be aligned into a composite final product.

Skeletal elements are scanned singly, one at a time, and they can be scanned either with or without a color image overlay. Including the true color of the object may not be necessary in cases where the goal is to see the bone's general morphology, and in many cases the black and white model is sufficient as a representation (Fig. 3). However, the addition of color renders the bone more realistic and visually-pleasing (Fig. 4). If color is to be included, the first step in scanning involves acquiring a color image of the skeletal element. This is accomplished by saturating the field of view with external photographic lamps and the camera taking an image. Once these data are saved, the scanner software uses them to create color for the 3D polygon mesh (triangulated point-cloud) of the digitized surface. Because the structured light scanner obtains data on the geometry and color of an object through a single camera lens, the object's color can be accurately mapped to the 3D data. Regardless of whether color is included, the next step of scanning entails the projector's 100 W halogen lamp projecting a series of patterns consisting of vertical stripes of alternating black and white onto the skeletal element. The camera then acquires images of the patterns, whose deformations created by the shape of the scanned object are subsequently measured by the scanner. These measurements form the points of the 3D point cloud.

Scanning takes place inside the confines of a photographic light tent. This consists of a cube with walls 120 cm in length, constructed from a lightweight, permeable fabric through which the light is dispersed evenly and without shadows around the object being scanned. Two halogen photographic lamps (26 W) are then placed either outside of both sides of the light tent or between the scanner and object, with the third standing behind the scanner (Fig. 5). Using the light tent means the scanned object retains all of its color with no shadows, resulting in significantly less time

¹ Please consult the internet site for the Max Planck Institute of Evolutionary Anthropology, Department of Human Evolution and follow the appropriate links to downloads, scanning equipment and projects: <http://www.eva.mpg.de/evolution>.



Fig. 1. (left) The setup for using the scanner: the technician controls the scanner, lamps and rotation table from the computer; (right) structured light scanner on tripod in preparation for scanning a horse skull on the rotation table.

needed for processing the data as well as final products with higher quality.

Objects to be scanned lie on a rotation table (20 cm diameter) covered with black cloth that sits on a black ground surface. These are non-reflective and thus help to eliminate shadows, which in turn helps the scanner and software differentiate the scanned object from the background. In addition, the black background saves time during the data processing steps, since the software masks out anything black so just the color element needs to be processed. Most bones can be placed directly on the rotation table lying flat. These elements, such as long bones, carpals and tarsals, would then be scanned from 4 to 6 different angles (e.g., lateral, medial, etc.). Other less geometrically-shaped elements require modeling clay for support on the rotation table in order to facilitate additional scans from other angles. Examples of this include the skull, vertebrae and sacrum, all of which contain foramina and uneven surfaces that are not captured in the initial scans. Flat elements such as the scapula and ribs also need modeling clay for

standing them upright on the rotation table, the most efficient position for scanning bones with thin edges.

Scanning a single bone involves between 4 and 20 rotation steps resulting in a full 360° scan of an object. After the first two rotation steps, the scanning software automatically conducts a basic alignment of the second scan to the first “base” scan. Each subsequent rotation step scan is then aligned to the base scan until the 360° rotation is finished. Following the completion of the first round of scans, the technician stops the process to adjust the angle of the bone on the rotation table. The first scan of the second round is then made but the scanning interrupted once again for the technician to align this first new scan to the initial set of scans. The alignment is made by manually choosing 4–6 points on the scanned bone data to which the other scans are aligned. After the alignment, the technician tells the software that the direction of the rotation axis of the bone has changed so that it can proceed with the rotation steps followed by automatic alignments until the 360° rotation is completed. This process continues until all angles of the bone are

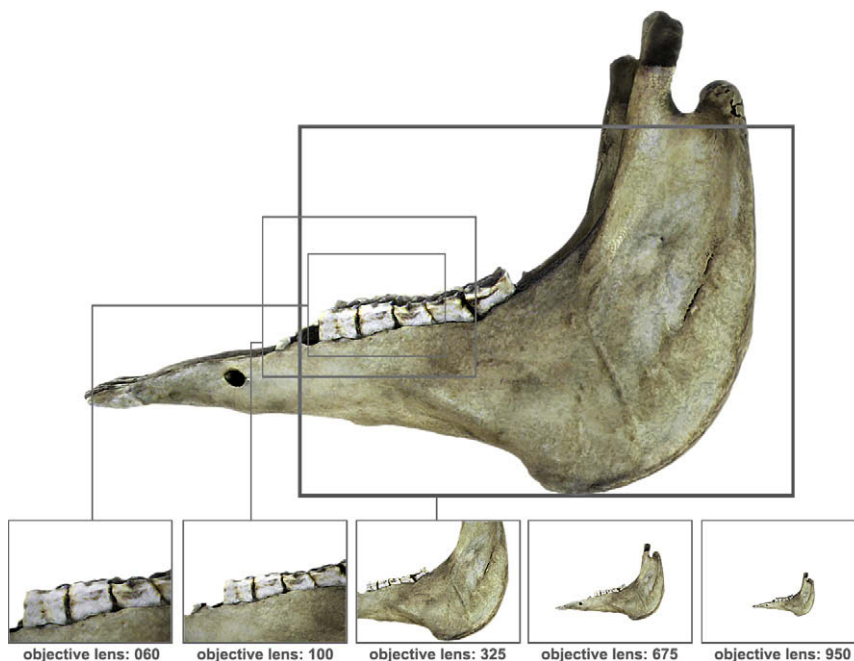


Fig. 2. Examples of the fields of view (in millimeters) for each lens used on the structured light scanner.



Fig. 3. Examples of scanned *Equus caballus* (horse) calcanei with color (left), without color (middle) and in wireframe view (right). The wireframe image is in low resolution and illustrates the network of polygons (the small triangles in the mesh) that construct a scanned bone.

scanned; simple bones such as carpals require fewer rounds of rotation steps, while more complex bones such as the skull or vertebrae might need 8–10 rounds.

Finally, when the scanning is completed, all scans (point clouds) are merged into a final mesh. Despite the alignment actions being done throughout the process, each single scan must be aligned in this final step. Accuracy of the mesh alignment is decided by the technician from a range offered by the software. Any examples of overlap are automatically repaired by the software during this process. Lastly, the more scans that were involved, the more time the mesh alignment requires.

The final merged scans are saved in .PLY (polygon file) format. This file format stores all of the properties constituting a 3D object, which facilitates viewing or printing a scanned object as well as converting to other data formats, depending on the desired end product. In this project, the .PLY data are 1) stored in high resolution for archival purposes; 2) converted to .STL (stereolithography) format in middle resolution, which serves as the “blueprint” of the object for printing replicas; and 3) converted to .OBJ (3D object) format at low resolution for further conversion to .PDF (portable document format), graphic formats such as .JPG or .TIF, and .AVI for video. The resolution of the scans can be adjusted at this point, and changing model resolutions essentially means merging polygons. For example, the reindeer astragalus at high resolution contains one million polygons (600 MB), then gets merged to medium resolution with a half million polygons (100 MB). The maximum/minimum side length of polygon changes in this process from its high resolution size of ca. 0.008–0.016 mm to medium size ca. 0.05–0.1 mm, although these changes vary between edges and planar surfaces.

The software Optocat 2007 is used for controlling the scanner and rotation table as well as for processing the scan data. The scanner can be run with either a desktop or laptop PC (e.g., we have used a Pentium-M CPU 1.6 GHz with 1 GB RAM). However, unless the scanner is being used at a field or museum location, a powerful desktop computer is the most economical choice for scanning and faster data processing (McPherron et al., 2009). Depending on the size of the computer’s hard drive, an external storage device is often a necessary addition.

In order to print replica bones, we have used a Spectrum Z510 color printer from the Z Corporation, USA. The resolution of this printer is 600 × 540 dpi and the maximum size a prototype can be is 254 × 356 × 203 mm. Using inkjet technology, the 3D printer creates prototypes by depositing multiple, fine layers (1–2 mm) of

nylon-based powder, resulting in an accurate physical reproduction of a specimen. The replica can be actual size or scaled up or down depending on its intended use.

3. Results and discussion

Instead of scanning every bone in the animal skeleton, this project scanned all left-sided elements and one representative from each of the following element sets: cervical vertebrae 3–7; thoracic, lumbar and caudal vertebrae; ribs; sternum; phalanges 1–3. Nonetheless, it takes 50–60 h to scan and process the data (Fig. 6). The largest investment of time is required for the data processing and subsequent export into various file formats. To most efficiently accomplish this work, we use two computers



Fig. 4. Examples of scanned skeletal elements. Top: *Equus caballus* (horse) skull; bottom: *Rangifer tarandus* (reindeer) humerus. Note: shadows were added for visual effect.

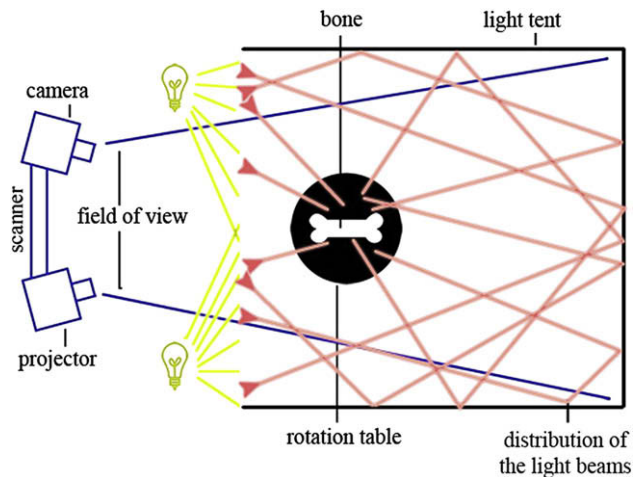


Fig. 5. View of the scanning arrangement from above, illustrating the benefits of using a photographic light tent to evenly distribute light for optimal scanning with minimal shadows.

simultaneously (one to scan, one to process data while the other is scanning), although one computer is sufficient.

For viewing scanned bones, .PDF files are the most practical for identifying faunal specimens in the field. These files can be viewed in 3D in Adobe Acrobat Reader 7.0 or higher or Acrobat Professional 8.0 or above, which allows the user to zoom in and out, or rotate the specimen in any speed or direction. This is the primary advantage of the 3D scans over traditional 2D drawings or photographs of bones. Short video clips can also be created in any 3D program and are useful for academic lectures and classroom teaching. Viewed in any player, these videos present a rotating skeletal element, showing all of the possible angles.

The 3D models of animal bones in .PDF have been put to good use by L.N. and T.E.S. in both field and laboratory conditions as part of ongoing excavations and analyses in Europe and Africa. Actual comparative skeletal material is limited or not available in our current research projects due to factors such as space and transport costs. Therefore, we found the 3D models of horse, reindeer and gazelle to be valuable additions to our zooarchaeology kits during several months in the field. The .PDF files in medium (15–30 MB) resolution offer excellent quality and detail, and in cases where either downloading time and speed are limited or data storage space are issues, low resolution .PDFs (3–5 MB) are perfectly adequate. Because of their large file size (ca. 200–600 MB), high resolution .PDFs are not advisable as they are awkward when opened and extremely slow to operate in Acrobat. If a highly detailed view of the bone is desired, opening the high resolution

.PLY file with 3D software is an option that allows better manipulation of the model despite the large file size. We also found that the 3D models containing color were the most visually realistic and provided the best views for comparisons. Color provides better-defined details on surface features or landmarks such as muscle attachments, nutrient foramina, and suture lines, which aids in the identification of archaeofaunal specimens. For our purposes, scanning with color is essential, though cases in which bones (e.g., Larson et al., 2009; Pfisterer et al., 2007, 2008) or archaeological artifacts (e.g., Grosman et al., 2008; Karasik and Smilansky, 2008) are being analyzed morphometrically, black and white models suffice and have much smaller file sizes.

Although we are satisfied overall with the .PDF models for use in faunal identification in the field, we should emphasize that these 3D models will never serve as a perfect replacement for actual comparative skeletons; we doubt that any zooarchaeologist would deny that genuine skeletons are preferred, especially when one has fragmentary archaeofaunal material to identify. Similarly, some knowledge of skeletal anatomy is essential before using 3D models (or 2D images of any kind) as the sole source of comparative material for faunal identification. However, our intention is not to replace comparative skeletons with 3D versions but instead, to provide a portable alternative for researchers to use when actual comparative bones are unavailable.

Three-dimensional prototypes of the reindeer calcaneus were printed in low, medium and high resolutions. The goal of this was to evaluate the degree of differences in detail, if any, between the three replicas in order to make recommendations to other researchers for 3D printing. Although there was no difference between the medium and high replicas, the lowest resolution prototype was somewhat poorer in detail. The high resolution data file is extremely large (>600 MB) and cumbersome for the computer and printer to process. At this point, we tentatively propose that medium resolution files (50–100 MB) are the best option for 3D printing, although as 3D printers become more powerful and capable of prototyping at higher resolutions, the high resolution data files will undoubtedly be preferable. Because .STL data do not contain color information, replica bones are printed in neutral ivory color. Printing with color is possible, though the color reproduction is poor and somewhat distracting as a result. Overall, the quality of printed bone specimens is indeed good enough for making a replica comparative skeleton for use in the lab, field, or classroom. The opportunity to reproduce skeletal parts of rare or extinct animal taxa is an additional benefit of this technology.

We have not yet conducted osteometric analyses of the scanned bones in the 3D models or prototypes produced during this project, though the positive results from research involving human skeletal specimens suggest that these methods will be equally suitable for fauna. For example, 3D data obtained on hominin crania with this

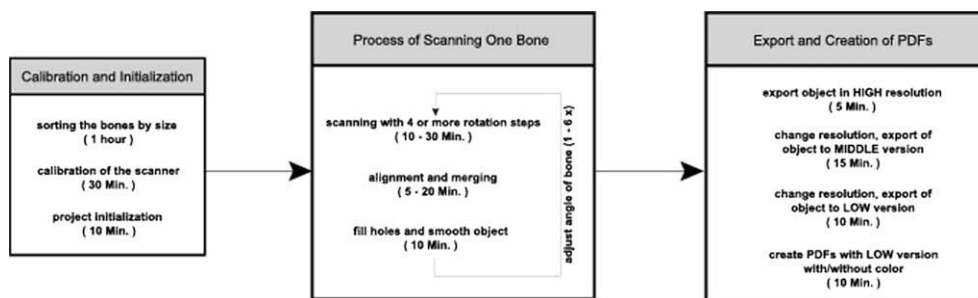


Fig. 6. Timescale of scanning one animal bone, processing the data, and exporting the data into a format such as .PDF. Note that in the middle box, the returning arrow refers only to cases in which additional scans of the bone from more angles are necessary. In these cases, the third step involving filling holes and smoothing the object gets omitted until the additional scans are completed.

scanner have been used to collect traditional linear and angular measurements as well as coordinate-based measurements for 3D geometric morphometric analyses (Gunz et al., *in press*). For such studies, a surface scanner is preferred over a CT scanner because of its submillimeter accuracy and ability to record bone surfaces in high resolution, facilitating easier identification of anatomical landmarks on the scans.

Despite our progress thus far, there are some disadvantages to undertaking such a project. These involve the initial costs in equipment; although a 3D printer is not necessarily essential, the costs of the scanner and software are still considerable. A significant time investment is also required to become proficient with the equipment and a sufficient amount of expertise with computers and 3D technology is a must. In this project, we have combined a team of people with expertise in 3D/computers or zooarchaeology, but not in both fields. Good communication between the teams is essential to convey each other's goals and expectations.

This project is currently focused on scanning of single skeletal elements of an entire skeleton, yet future plans will include the scanning of articulated element sets such as carpals and tarsals or a complete foot. Additionally, we hope to be able to rearticulate single elements to form a complete articulated skeleton, which would be a valuable tool both for faunal analysts and anyone wanting to learn animal skeletal anatomy. It would also be beneficial to compare 3D models of articulated bone sets between very different animals, e.g., canid versus ungulate, for teaching purposes.

4. Conclusions

After nearly four years' investment in this project, we have developed and refined an efficient method for scanning animal bones in 3D for the purpose of producing high quality models and replica specimens for a virtual comparative faunal collection. These virtual reproductions of animal skeletons are not intended to replace genuine comparative materials for zooarchaeological research, but instead provide an alternative resource for identification that is portable and therefore useful in remote field locations or in laboratory settings where comparative specimens are limited or unavailable.

The ability to create a virtual comparative faunal collection and make it available to the public via the internet (e.g., Kappelman et al., 2000, 2001; Strait and Smith, 2006) is beneficial to a wide range of researchers (Weber, 2001). First, it provides access to animal specimens that are difficult to find in museum collections, such as exotic taxa or very young individuals. Second, as museums and institutions holding skeletal collections are faced with budget cuts and restrictions on storage, animal skeletons will become more difficult to access; a virtual collection could ease these restrictions. Third, for researchers with limited or no access to genuine comparative material, due to location or other factors, 3D models and replica specimens could provide the valuable comparatives. Lastly, the museums or institutions whose skeletons are scanned benefit in terms of their educational and research objectives, as the scans are available to a diversity of researchers who may not have access to them otherwise. Three-dimensional technology and scans such as we have produced in this project will never replace genuine comparative faunal material for zooarchaeological and paleontological research but they do provide a research and educational source for much-needed realistic images to a broad spectrum of disciplines and researchers.

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