

# The Traveling Optical Scanner – Case Study on 3D Shape Models of Ancient Brazilian Skulls

Camilla Himmelstrup Trinderup<sup>1</sup>, Vedrana Andersen Dahl<sup>1</sup>,  
Kristian Murphy Gregersen<sup>2</sup>, Ludovic Antoine Alexandre Orlando<sup>2</sup>,  
and Anders Bjorholm Dahl<sup>1</sup>(✉)

<sup>1</sup> DTU Compute, Technical University of Denmark, Lyngby, Denmark  
abda@dtu.dk

<sup>2</sup> Natural History Museum of Denmark, University of Copenhagen,  
Copenhagen, Denmark

**Abstract.** Recovering detailed morphological information from archaeological or paleontological material requires extensive hands-on time. Creating 3D scans based on e.g. computed tomography (CT) will recover the geometry of the specimen, but can inflict bimolecular degradation. Instead, we propose a fast, inoffensive and inexpensive 3D scanning modality based on structured light, suitable for capturing the morphology and the appearance of specimens. Benefits of having 3D models are manifold. The 3D models are easy to share among researchers and can be made available to the general public. Advanced morphological modelling is possible with accurate description of the specimens provided by the models. Furthermore, performing studies on models reduces the risk of damage to the original specimen. In our work we employ a high resolution structured light scanner for digitalizing a collection of 8500 year old human skulls from Brazil. To evaluate the precision of our set-up we compare the structured light scan to micro-CT and achieve sub-millimetre difference. We analyse morphological features of the Brazilian skulls using manual landmarks, but a research goal is to automate this, fully utilize the dense 3D scans, and apply the method to many more samples.

## 1 Introduction

Being vital for understanding of our past, archeological specimens are a part of natural and cultural heritage which enjoys a broad professional and public interest. In this paper we discuss the benefits and challenges of scanning archeological specimens, propose a suitable data acquisition system, and demonstrate the use of our system in a small case study with a subsequent analysis of the data.

The case study involves human skulls, approximately 8500 year old, recovered from the Sumidouro cave in Brazil by the Danish scientist Peter Wilhelm Lund around 1843 [11]. These skulls are important for understanding the peopling of the Americas, and are of interest for research both now and in the future, where new technology might reveal secrets not available today. However, the skulls from

the Brazilian collections are fragile, and each handling of the skulls increases the risk of deterioration. Many of such handlings can be avoided by having accurate 3D models of the specimens.

Maximizing the preservation of the archeological and paleontological items, so as to make them available to future generations, is a general concern for the curators of museum collections. In this respect, one of the main advantages of 3D scanning techniques is to be compatible with objects of any size, including biological remains as well as cultural artefacts. Through 3D structured light surface scanning the shape and appearance of the artefact is documented, easily shared between researchers, and made available to the general public [4]. However, there are considerations specific for archeological specimens, which put additional requirements to the scanning system.

The first issue is accuracy. To be of use in studies of cranial morphology, the 3D skull models need to be highly accurate. The scanning system should therefore have a well documented and high precision.

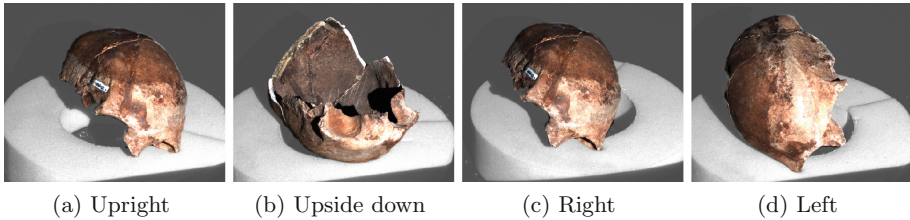
Furthermore, material alteration needs to be considered when scanning archeological specimens. In case of our Brazilian skulls, it has not yet been possible to extract any DNA from the bone tissue. However, this might be made possible in the future. Despite being classified as non-destructive, scanning techniques based on electromagnetic radiation including light sources like laser scanners, but especially penetrating ionizing radiation used in e.g. CT, may potentially lead to DNA damage [3,8].

To meet these requirements we propose a setup with a structured light scanner [6]. The scanner we use is highly portable, and scanning can take place at the museums, which is important for further reducing the handling damage to specimens. As an additional advantage, our structured light scanner is assembled from off-the-shelf parts, making it a low-cost scanning modality, with a price in the range of €10,000–15,000, compared to a metrology CT scanner starting at €500,000. Furthermore, the surface appearance e.g. color is captured. The first part of this paper, Sect. 2, contains a thorough description of our scanner, and evaluates its accuracy compared to a micro CT scanner.

The second part of this paper, Sect. 3, deals with the morphological analysis of the skull data. In an investigation by Neves et al. [11] morphology of the skulls from the Brazilian collection is established by measuring certain distances following standard procedures. It is our ambition to replicate those measures on 3D models. Ideally, the measures would be automated, which requires establishing a correspondence between the skulls. This would open a possibility of constructing a unified 3D model of cranial morphology.

However, the Brazilian skulls are all incomplete in some way – an inevitable factor when dealing with ancient specimens. The most complete skull has approximately 96% of its original mass left, whereas a big part of the collection has less than approximately 60% left. Consequently, handling the partial data is an important concern when choosing data processing methods.

One way of addressing this issue involves building a statistical 3D model of a human skull which incorporates specific shape priors. The priors might be



**Fig. 1.** Photographs of the four different positions used while scanning. One of the less complete skulls is shown. The background is made gray to make the skull appearance clearer.

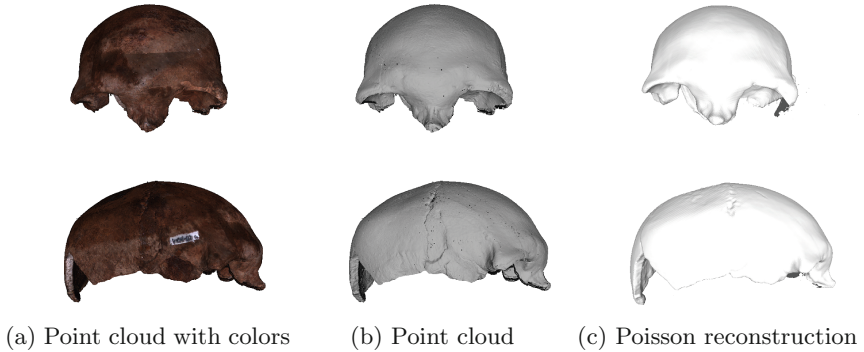
obtained from scans of complete skulls of modern man. Such a model could reconstruct the missing parts of an incomplete skull with a certain statistical significance. Our initial results, presented in this paper, are based on manually annotated landmarks, which is the typical approach for shape analysis. However, using all points in the scan would provide more information, but this requires finding corresponding points on the different scans.

In a longer-term perspective, automating data acquisition and processing of skulls would allow us to extend the model with other and diverse specimens. This leads to a statistical shape model of a skull, which can be employed for analyzing the shape variation within a set of skulls, and comparing it against variations of subgroups from the model. Furthermore, estimators for age, gender, ancestry, and race, could be provided by the model. If extended with scans of ancient skulls along the entire temporal range of human evolution, including archaic hominins, our model would be a full evolutionary model of human skull, opening for a better understanding of the phylogenetic relationship of the multiple hominin groups that existed in the last 6 million years.

## 2 Data Acquisition

Efficient and accurate data acquisition is essential for creating 3D models of archeological specimens, and is a prerequisite for advanced shape modeling. In this section we describe the data acquisition of the skulls from the Brazilian collection using an optical structured light scanner. The structured light scanner is based on visible light, which in practice is harmless to the specimens. In this section we also validate the accuracy of the scanner.

*Scanning Skull Specimens.* Our scanning setup, called SeeMaLab, is assembled at the Technical University of Denmark and is described further in [6]. It includes a rotation stage which allows for a  $360^\circ$  acquisition, where we chose to acquire structured light images in steps of  $20^\circ$ . The setup is calibrated such that it provides a single point cloud for a complete  $360^\circ$  scan. The cameras used are 9.1 megapixel color cameras providing highly dense point clouds. One  $360^\circ$  acquisition takes about 2 min and with moving the sample, a single scan can be acquired



**Fig. 2.** Assembled point clouds with and without texture information and an example of a surface reconstruction of the skull presented in Fig. 1.

in about 10 min for an experienced user. We used phase shift encoding [12] with 64 projections for all scans. The texture of the objects is obtained from the captured color images. To ensure high accuracy the scanner is calibrated on a daily basis and each time it has been moved. This is possible since the calibration procedure is fully automated and easy to perform.

The scanned specimens include 24 skulls from the Brazilian collection at the Natural History Museum of Denmark in Copenhagen [11]. All skulls have missing parts, and 9 skulls are very incomplete and consists of mere bone fragments.

In order to capture their entire shape, we placed each skull in four different positions as shown in Fig. 1. The resulting point clouds were assembled using the iterative closest points (ICP) algorithm [2] implemented in the MeshLab tool.

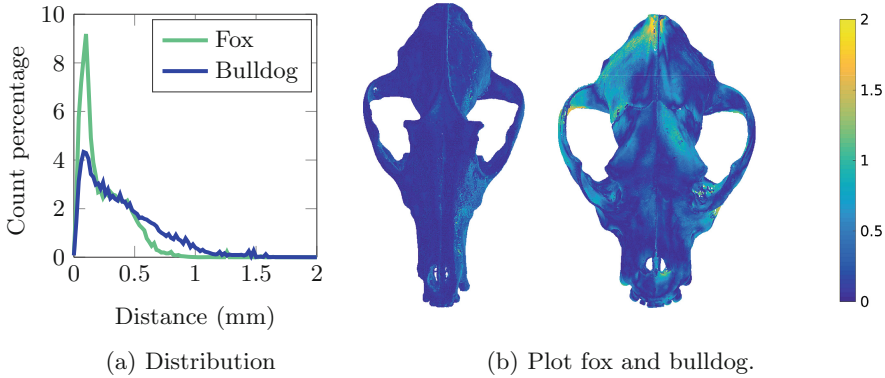
Structured light scanning is limited to surfaces that primarily scatter light from the object surface, which rules out transparent or reflective objects. Luckily skulls have good reflective properties. However, there are some black regions that are hard to capture resulting in small holes in the point clouds.

We obtain a point cloud density of up to 300 points per  $\text{mm}^2$  because of overlapping viewing positions giving up to 30 million points for the most complete skulls. This leaves us with excellent representation of the surface allowing us to compute an accurate and highly detailed 3D surface model using Poisson reconstruction [9] from MeshLab. An example of the point clouds obtained by the optical scanner is shown in Fig. 2 along with a Poisson reconstructed surface.

*Scanning Accuracy.* The standard approach for assessing the accuracy of a surface scan is established as the deviation of individual reconstructed points. In case of SeeMaLab the accuracy is down to 10  $\mu\text{m}$  and it therefore meets industry standard VDI/VDE 2634 (Part 2) [1]. To investigate how the point clouds compare to a metrology scanner, we provide a distance measure between point clouds obtained using SeeMaLab and CT scans. For this experiment we used a fox and a bulldog skull.

**Table 1.** Mean and median of the distances between points from a CT scan and a structured light scan.

	Fox	Bulldog
Mean	0.2425 mm	0.3957 mm
Median	0.1777 mm	0.3277 mm

**Fig. 3.** Left: Histogram of point-wise distances from CT to optical scan for the fox and bulldog skull. Right: Illustration of point-wise distances on the skulls.

CT scanning is valuable in metrology science [13] and had it not been for potentially harmful effects, it would be an excellent choice for scanning ancient specimens, when high accuracy is a priority. CT scanning produces volumetric data and the accuracy of a CT scanner is expressed in terms of voxel size. The scans we used have a voxel size of  $190.8 \mu\text{m}$ . They are acquired for this experiment using a Nikon XT H 225 micro-CT scanner at the Imaging Center at the Technical University of Denmark<sup>1</sup>. The dog skull is a bulldog specimen from the Zoological Museum of Denmark at Copenhagen University and the fox skull belongs to one of the authors.

In order to compare a volumetric CT scan with the point cloud, we need to establish surface of the skull in the CT scan. This is done by thresholding voxel intensities and extracting the surface mesh using marching cubes algorithm [10] and considering the vertices of the mesh as a point cloud. The point clouds are hereafter aligned using the ICP algorithm.

There is a significant differences in the representation of the shape for the two scans. To cope with these differences we estimate a surface point cloud from the CT scans and consider point-wise distances between the scans.

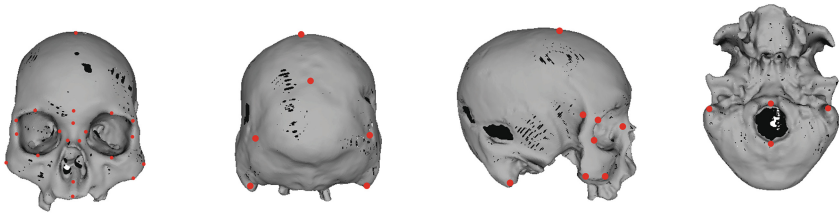
The results of accuracy validation are summarized in Table 1 and Fig. 3. The larger deviations occur at the areas that are most likely to be occluded. This is e.g. seen in the inner corners of the cheekbone. Our results obtained in this

<sup>1</sup> <http://www.imaging.dtu.dk/>.

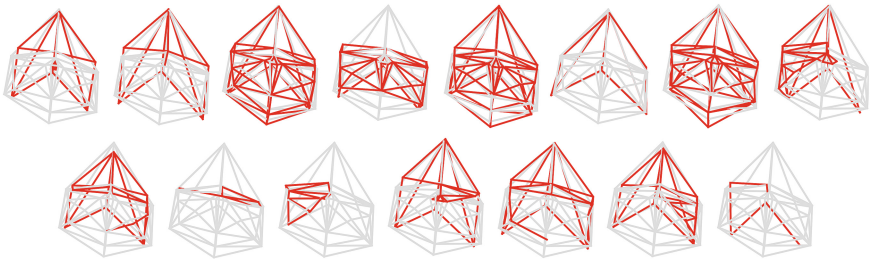
analysis clearly demonstrate that our optical surface scanning is an option for obtaining accurate 3D scans of fragile cultural heritage specimens. We obtain higher accuracy than reported in [7].

### 3 Shape Analysis

It is our ambition to use and analyze the 3D scans of ancient skulls in a statistical shape model. This would require a larger number of complete scans than we could obtain from the Brazilian collection. So, in order to initially demonstrate the use of our data we include it in a model based on the publicly available 3D-ID.org<sup>2</sup> dataset. Hence we build a model based on anatomical landmarks.



**Fig. 4.** Placement of the anatomical landmarks on the skull.



**Fig. 5.** Landmarks (shown as mesh vertices) for the 15 skulls from the Brazilian collections compared to the mean shape from 3D-ID.org.

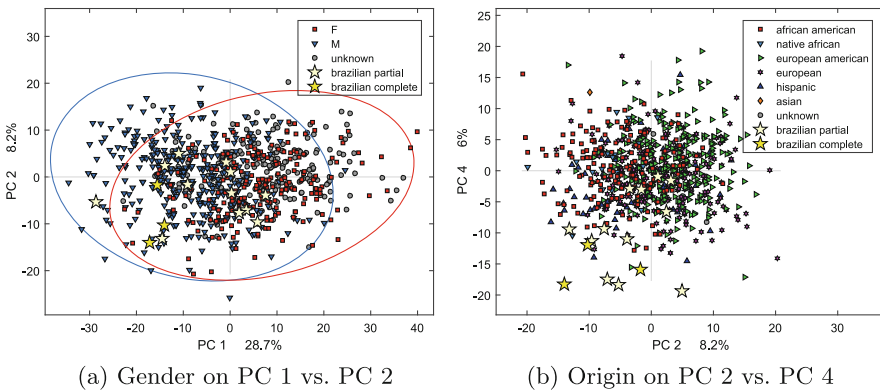
*Shape Model.* The forensic database 3D-ID.org contains data on 889 skulls including up to 34 landmarks per skull. For building the active shape model [5] we use 759 most complete skulls and 23 landmarks. We follow the conventional approach with aligning the shapes using Procrustes analysis (translation and rotation, but not size), and performing the principal component analysis to identify the variation within the shapes. The largest contributor to the shape variation is the size of the skull, describing nearly 30% of the total variation.

<sup>2</sup> [www.3d-id.org](http://www.3d-id.org).

We chose the 15 most complete scans of Brazilian skulls to include in the shape model. We manually placed anatomical landmarks equal to those from 3D-ID.org on the skulls. The landmark setting was repeated three times, and the final positioning of the landmarks is an average of the three. In the case of the Brazilian skulls, it is not possible to locate all landmarks on every skull.

Figure 4 illustrates placement of the landmarks on a skull, while Fig. 5 shows landmarks for the 15 skulls from the Brazilian collection compared to the mean skull shape obtained from the shape model.

*Modelling results.* Figure 6 (a) shows the distribution of the population along the two first principle components direction (PC 1 and PC 2). The size of the skull is a chief contributor to PC 1, so PC 1 correlates largely with the gender distribution. The Brazilian skulls are not distinguishable from the general population.



**Fig. 6.** Placement of the Brazilian skulls in the principal component space. Brazilian complete have all 23 landmarks.

By further investigating the model, we conclude that the separation of the Brazilian skulls from the general populations is most evident for the fourth principal component (PC 4), illustrated in Fig. 6 (b) against PC 2. Investigating the fourth principal component further by looking at the magnitude of the landmark contributions, we see that the three landmarks at the back of the skull have higher values. This indicates that the Brazilian skulls are distinguished from other considered populations by the shape of the posterior portion of the skull.

## 4 Conclusion

In this paper we suggest using optical scanning based on structured light for obtaining 3D surface models of archeological artifacts and specimens. We have demonstrated a scanning system on a collection of ancient skulls and shown

that we obtain an accuracy very close to that of a micro CT scanner, using a fast, inoffensive, and inexpensive scanning modality. In addition we have shown the use of our data for shape modeling using a few landmarks. Landmark-based analysis is not ideal, because all data between landmarks are not included in the analysis. Our aim for future work is to include the full 360° point cloud, but we do see some exciting challenges for this work especially with point-to-point registration. We also wish to expand the collection of skulls obtained using our scanning system. Hereby, we will not only be documenting our cultural heritage, but potentially revealing new discoveries within evolutionary biology.

## References

1. Acko, B., McCarthy, M., Haertig, F., Buchmeister, B.: Standards for testing freeform measurement capability of optical and tactile coordinate measuring machines. *Measur. Sci. Technol.* **23**(9), 094013 (2012)
2. Bærentzen, J.A., Gravesen, J., Anton, F., Aanaes, H.: *Guide to Computational Geometry Processing: Foundations, Algorithms, and Methods*. Springer, London (2012)
3. Bertrand, L., Schöeder, S., Anglos, D., Breese, M.B., Janssens, K., Moïni, M., Simon, A.: Mitigation strategies for radiation damage in the analysis of ancient materials. *Trends Anal. Chem.* **66**, 128–145 (2015). <http://www.sciencedirect.com/science/article/pii/S0165993614002490>
4. Boochs, F., Trémeau, A., Murphy, O., Gerke, M., Lerma, J., Karmacharya, A., Karaszewski, M.: Towards a knowledge model bridging technologies and applications in cultural heritage documentation. *ISPRS Ann. Photogrammetry, Remote Sens. Spat. Inf. Sci.* **II–5**, 81–88 (2014)
5. Cootes, T., Baldock, E., Graham, J.: An introduction to active shape models. *Image Processing and Analysis*, pp. 223–248 (2000)
6. Eiriksson, E., Wilm, J., Aanaes, H.: Precision and accuracy parameters in structured light 3-D scanning. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* (2016, to appear)
7. Friess, M.: Calvarial shape variation among middle pleistocene hominins: an application of surface scanning in palaeoanthropology. *C.R. Palevol* **9**(6), 435–443 (2010)
8. Grieshaber, B.M., Osborne, D.L., Doubleday, A.F., Kaestle, F.A.: A pilot study into the effects of X-ray and computed tomography exposure on the amplification of DNA from bone. *J. Archaeol. Sci.* **35**(3), 681–687 (2008)
9. Kazhdan, M., Bolitho, M., Hoppe, H.: Poisson surface reconstruction. In: *Proceedings of the Fourth Eurographics Symposium on Geometry Processing*, vol. 7 (2006)
10. Lorensen, W.E., Cline, H.E.: Marching cubes: a high resolution 3D surface construction algorithm. In: *ACM Siggraph*, vol. 21, pp. 163–169. ACM (1987)
11. Neves, W.A., Hubbe, M., Piló, L.B.: Early holocene human skeletal remains from Sumidouro cave, Lagoa Santa, Brazil: history of discoveries, geological and chronological context, and comparative cranial morphology. *J. Hum. Evol.* **52**(1), 16–30 (2007)
12. Salvi, J., Pages, J., Batlle, J.: Pattern codification strategies in structured light systems. *Pattern Recogn.* **37**(4), 827–849 (2004)
13. Suppes, A., Neuser, E.: Metrology with CT: precision challenge. In: *Proceedings of the SPIE - The International Society for Optical Engineering* (2008)