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An Application of Structured Light Scanning to Documenting Excavated Surfaces and *in situ* Finds: Examples from the Middle Paleolithic Sites of Jonzac and Roc de Marsal, France

Abstract: This paper describes an attempt to create digital 3D representations of excavated surfaces and profiles at two Middle Paleolithic sites in southwest France using a Breuckmann triTOS-HE structured light scanner. One major challenge we faced while applying this scanner in the field was to create a lighting environment that would allow us to obtain high quality 3D and color data about the archaeological surfaces. Another major challenge was to setup the scanner so that it would have good visual access as well as approximately the same distance to different sections of the surfaces and could be moved quickly. In total we performed more than two hundred scans during the fieldwork. We will discuss some of the post-processing issues that arose from our data acquisition methodology and from hardware and software limitations. Furthermore we will present workarounds for these limitations and suggest possible improvements for data collection with a triTOS-HE.

Introduction

In 2006 we began a project to build a high resolution virtual faunal comparative collection using a Breuckmann triTOS-HE structured light scanner. Based on experience with digitizing bones under laboratory conditions, we knew that this scanner was a technology that while perhaps not appropriate for daily use on an excavation, could be appropriate if we encountered an extraordinary archaeological find. Because we anticipated problems applying our scanner in the field, we designed this test project to ascertain in advance whether it could be usefully applied to documenting finds in their archaeological context. The overall goal of this project was therefore to test whether our structured light scanner could be used in the field to collect data on objects *in situ*. Additionally, we wanted to estimate how much excavated surface could be digitized per unit of time. To this end, we selected two Middle Paleolithic sites in southwest France: Jonzac (co-directed by J. Jaubert from the University of Bordeaux I and J.-J. Hublin) and Roc de Marsal (co-directed by S. J. P. McPherron, H. L. Dibble, A. Turq, and D. Sandgathe) (see Fig. 1).

Jonzac is an open-air site with a deep Middle Paleolithic sequence (AIRVAUX 2004; AIRVAUX / SOR-ESSI 2005). Of particular interest is a one meter thick bone-bed deposit covering several square meters. The bones are densely packed or jumbled together

and mixed with stone tools. The state of preservation is quite good. Thus, at Jonzac, the goal was to capture the complexity of this deposit.

Roc de Marsal is a cave site known primarily for the discovery of an intact skeleton of a Neanderthal child (LAFILLE 1961; BORDES / LAFILLE 1962). New excavations here have revealed a number of well preserved hearths and a pit like feature not far from where the skeleton was found. At Roc de Marsal, we wanted to capture the complex spatial relationship between these fire features, the underlying bedrock, the newly discovered pit, and the original location of the skeleton. However, after the experience at Jonzac, it was clear that this was too ambitious given our time constraints. In the end we digitized the fire features in section, overlying sediment, and portions of the bedrock surface.

Equipment

We used a Breuckmann triTOS-HE scanner, consisting of a separate controller and a sensor unit that is usually mounted on a tripod. The sensor unit is equipped with a projector and a single 1384 x 1036 pixel color camera. This camera acquires information about both the color and the geometry of an object, thus allowing for an accurate mapping of object color to 3D data. The projector uses a 100 W halogen lamp and combines gray code and phase



Fig. 1. Overview of the Middle Paleolithic sites of Jonzac (left) (photo by Jacques Jaubert) and Roc de Marsal (right) (photo by author).

shifting methods to generate the fringe patterns typical of structured light scanners (BREUCKMANN 2003; BREUCKMANN GMBH 2007).

A notable feature of the triTOS-HE is the modular design of its sensor unit. The lenses of the camera and projector and the base connecting camera and projector are interchangeable. Depending on the set of lenses and the length of the base, the size of the field of view and the resolution limits of the scanner change. When a small field of view is used, small volumes can be digitized at a high resolution. Successively larger fields of view allow increasing volumes to be digitized at decreasing resolutions (BREUCKMANN GMBH 2006; BREUCKMANN GMBH 2007).

To reduce the number of scans and thus the time necessary to create a digital 3D representation of an excavated surface, we fitted our scanner the biggest possible field of view available to us. With this field of view the maximum volume that could be digitized during one measurement was bounded by $x=560$ mm, $y=410$ mm, and $z=300$ mm. The lateral resolution limit was 0.45 mm, meaning that details smaller than this could not be resolved with this setup. The optimal working distance to the object was 1120 mm.

One of the factors greatly influencing the time needed to digitize using a triTOS-HE is the speed of the computer pre-processing and storing the data generated by the scanner. Consequently, we took with us a powerful PC but were unable to use it with our field generator. Instead, we made all scans with our backup system, an IBM T41 laptop equipped with a 1.6 GHz Pentium-M CPU and 1 GB RAM. To connect this laptop to the controller of the scanner we installed two PCMCIA cards; one card

emulating a serial interface and the other emulating a FireWire interface. For post-processing we used a standard PC with a Pentium 4 CPU at 3 GHz and 3.25 GB RAM.

For calibration, 3D data acquisition, and post-processing we used Optocat 4.01, a Microsoft Windows based application provided by the scanner manufacturer. The Optocat user interface consists of an area for visualizing 3D data and various toolkits that can be customized and extended using a built-in scripting language. Using this software, scanner calibration is performed by scanning a calibration plate from multiple distances and angles. After this, quality annotated 3D data can be acquired either with or without the help of index marks. Additionally, the scanning process can be synchronized with the rotation of a turntable. This simplifies scanning smaller objects, because successive scans are automatically aligned by an iterative closest point algorithm. If no rotation table is used, this algorithm can also be invoked during manual alignment. Further Optocat functionality includes, but is not limited to merging point clouds, measuring and manipulating 3D data, and data import and export in a variety of standard formats (BREUCKMANN GMBH 2006).

Data Acquisition

The main challenge in digitizing the bone-bed in Jonzac was to capture its complexity without disturbing the site. To digitize the artifacts in the bone-bed from all sides, we had to position the scanner so that there would be a direct line of sight between the artifacts and the scanner. However, the



Fig. 2. Frame made from scaffolding tubes with wooden sledge holding the sensor unit of the scanner over the bone-bed (left). The opaque tarp used to block daylight from the bone bed (right) (photos by Steffen Lättsch).

density of the deposit made it impossible to place the tripod with the scanner sensor unit in the bone-bed itself. Additionally, because of a pit and a steep slope at the western edge of the excavated surface, we could not position the sensor unit next to the bone-bed and move it along its edges (see Fig. 1).

One way to work around this issue was to suspend the scanner sensor unit above the bone-bed with the lenses looking straight down. To this end we built a wooden “sledge” to hold the sensor unit and constructed a frame above the bone-bed to support the sledge (see Fig. 2). The height of this frame was chosen to keep the scanner at approximately correct working distance from the bone-bed. This setup allowed us to move the sensor unit quickly by a given distance along the two horizontal tubes of the frame, which was important because we intended to move the scanner often during data acquisition. However, it did not render every artifact completely visible; especially difficult were a few artifact depressions parallel to the line of sight of the scanner.

A first test scan with the described setup resulted in a sparse, slightly distorted point cloud because the ambient light was too bright for the projector to generate a high contrast pattern on the bone-bed. To solve this problem we put an opaque tarp over the frame, thus blocking most of the daylight. When the tarp was in place, we were able to acquire good 3D data. To also get constant lighting conditions for acquiring color data in this now dark environment, we illuminated the bone-bed with the projector of the scanner.

We started digitizing the bone-bed at its southern edge. From that position we slid the sensor unit along

the horizontal tubes of the frame, stopping to scan at 10 cm intervals (first pass). The idea behind moving the sensor unit by a short distance was to maximize the overlap of successive scans so that a region of an artifact not covered in one scan would be covered in the next. The first pass across the bone bed captured data on its eastern side. At this point, we turned the sensor unit by 180°, thus switching the positions of the camera and the projector. We then moved the sensor unit back to its starting position, again making a scan every 10 cm (second pass). Because of the changed positions of the camera and the projector, we were now able to acquire data about the western part of the bone-bed with the overlap needed to link these scans to the first pass.

During the first two passes we realized that we were not getting enough data about the eastern vertical edge of the bone-bed. In order to get better data on this area, we turned the sensor unit by 90° in its sledge and additionally tilted it by 20°. We then repeated the first pass over the bone-bed, but this time stopping halfway along the horizontal tubes of the frame (third pass).

To summarize, at Jonzac, by constructing a frame to support the sensor unit and to help structure movement of the scanner, we were able to carefully control the data acquisition much like one does in a laboratory situation except that in this case, rather than doing controlled rotations of an object on a turntable in front of a stationary scanner, we did controlled movements and rotations of the scanner above the stationary object being digitized.

While the focus at Jonzac was a horizontal surface, the primary goal at Roc de Marsal was to digitize fire features in vertical section. Because a

preliminary alignment of some of the scans made in Jonzac looked promising, we approached digitizing the fire features in a similar way. We first blacked out the cave by putting an opaque tarp across the cave entrance. Then we built a low bench from a long wooden board and sand bags in front of and parallel to the fire features. Digitizing the fire features consisted of moving the scanner sensor unit along the bench and scanning at 10 cm intervals. Additionally, we took some extra scans to better get the sides and the back of two large holes in the fire features that resulted from taking geomorphological samples (first pass).

For digitizing the bedrock and the overlying sediment, we experimented with other methods. For the bedrock we mounted the sensor unit on a tripod, letting it look straight down. We then positioned the tripod next to the area of bedrock we wanted to digitize and moved it along one of the edges of this area, making a scan approximately every 20 cm (second pass). Digitizing the overlying sediment differed from scanning the bedrock in that we took a sequence of 5 scans for each position of the tripod, tilting the sensor unit horizontally by -20° , -10° , 0° , 10° , and 20° in each instance. In doing this, we digitized more ground per position of the tripod. Therefore, we moved the sensor unit by a distance of about 40cm after all scans for a position had been taken (third pass).

Post-processing

At both sites we produced three sequences of overlapping point clouds. Each sequence represented one pass over a surface. Merging all point clouds from a single surface would have required more memory than available on our computer. Therefore, we first defined groups of successive point clouds within each of the sequences of point clouds. We then aligned and merged each group independently from all other groups. In doing this, Optocat discarded redundant points in overlapping areas of the point clouds in a group, keeping points measured with higher precision in favor of points measured with lower precision as indicated by the quality score of the points. Thus, the amount of memory needed to represent a group was reduced. This reduction allowed us to define new groups of successive point clouds and to repeat the described process until only three point clouds per site remained.

In order to merge the remaining point clouds, the amount of memory required for this task still had to be reduced. To achieve this, we down-sampled these point clouds as little as possible but enough to make them processible. In the end, we set a threshold of 0.05 mm for the maximum surface error during down sampling. After merging the down sampled point clouds, the resulting point cloud was saved as a PLY formatted file.

Results

For all scans we used the projector light of the scanner to acquire color data. Since the projector is oriented to best illuminate the center of the field of view of the camera, areas farther away from the center received less light during data acquisition. This resulted in a light falloff at the left and right edges and especially at the corners of our color data. An additional but comparatively small contribution to this effect also came from light falloff that is inherent in the design of the wide angle lenses we used.

When looking at the colored 3D mesh from a single scan, the described brightness differences were almost invisible to the human eye. However, when we aligned and merged point clouds representing a complete pass over a surface the individual problems of each scan were reinforced and became clearly visible. For example, after aligning the point clouds representing the first and second pass over the Jonzac bone-bed, areas of the surface that were less illuminated during the first pass overlapped areas brightly illuminated during the second pass and vice versa. This resulted in two dark stripes along the whole length of the aligned point clouds. In order to obtain final 3D meshes without stripes while retaining as much 3D data as possible, we deleted by hand those parts of the point clouds that were too dark and overlapped with well lit areas of another point cloud before merging the point clouds representing a whole pass over a surface.

While analyzing the data from the overlying sediment area at Roc de Marsal, we observed another unwanted effect of using the projector light for acquiring color data. We discovered that because we tilted the sensor unit of the scanner, any given area of the sediment was illuminated at a different angle and from a different distance multiple times. This in turn resulted in an irregular pattern of well illuminated and darker areas in the point cloud representing the whole of the overlying sediment. As

we could not easily predict from which point cloud the darker areas originated, we were not able to easily correct for this effect.

The final 3D mesh of the digitized surface at Jonzac represents an area of about 2.5 m² and consists of more than 10.3 million vertices. It was computed from 75 overlapping point clouds, generated within one day, including scanner calibration and setup. The final 3D mesh generated from data acquired at Roc de Marsal also represents an area of about 2.5 m² and consists of approximately 9.9 million vertices. This mesh was computed from 146 overlapping point clouds generated within two days. One of the reasons why digitizing 2.5 m² at Roc de Marsal took twice as long as in Jonzac was that the excavated surface had a more complicated topology. Another reason was that positioning the tripod mounted scanner took easily twice as long as compared to a setup like the bench or the frame-and-sledge combination at Jonzac.

Data post-processing took approximately 95 hours for Jonzac and 205 hours for Roc de Marsal. About one third of this time was spent on manual pre-alignments and color corrections. The remaining time went into automatic alignment optimization and the merging of point clouds and required no human presence. The final meshes for both test sites are shown in *Fig. 3* and can be downloaded from <http://www.eva.mpg.de/evolution/files/sls.html>.

Discussion

If a structured light scanner is used for 3D digitization, environmental light should be dim enough for the projector of the scanner to generate high contrast patterns. To acquire color data during a scan, comparatively bright, ambient and constant light is best. While both conditions can be easily achieved indoors, in the field environmental light is often too bright and changes throughout the day. Consequently, we used tools available to us at the sites to simulate indoor conditions. This included blocking the daylight from the surfaces we intended to digitize and illuminating these surfaces with the projector light to obtain color data.

Since the projector light is directed and focused to produce sharp patterns at the working distance of the camera, it is neither ambient nor constant over space. This resulted in brightness differences in our color data as described above. Future field applica-

tions of structured light scanners might be able to avoid this effect by using multiple light sources to illuminate the surface to be digitized from different angles and directions during color data acquisition. If multiple light sources are not workable and the projector has to be used, it might also be possible to compensate for brightness differences by applying a gradual grey software-filter during post-processing. This could be especially successful if a surface is scanned from just one direction and angle.

When we digitized the bone-bed in Jonzac and the fire features in Roc de Marsal, we performed a scan every 10 cm hoping that a greater number of overlapping scans would reduce the number and size of holes in the final 3D meshes. This was indeed the case. However, during post-processing we realized that once a given area was covered by two to three point clouds, additional coverage only rarely improved the final 3D mesh. To get a preliminary confirmation for this, we re-computed part of the Jonzac mesh, using only every second scan. The resulting 3D mesh showed no apparent differences from its counterpart generated from all scans, indicating that half the number of scans – and thus half the time for data acquisition and post-processing – would have resulted in very similar meshes.

For the project described here we fitted our scanner with lenses having a lateral resolution of 0.45 mm and a feature accuracy (the difference of the measured positions of index marks towards target values) of 0.068 mm. These values were determined by the scanner manufacturer under optimal conditions and after careful calibration. However, suboptimal environmental conditions at our sites and the need to transport the scanner several kilometers to the sites after calibration probably had an impact on the precision of the instrument. Furthermore, aligning and merging the point clouds from individual scans introduced noise. We thus assume the resolution of the 3D representation of the digitized archaeological surfaces to be lower than one would expect from the specification of the lenses, but estimates on this have not been calculated yet.

Conclusions

From a technical perspective, the project was successful. At both test sites we were able to create conditions allowing us to collect high quality data and to produce a 3D representation of the archaeological surfaces and the objects therein. Many of



Fig. 3. Screenshots of the final 3D meshes for Jonzac (left) and Roc de Marsal (right). The Jonzac detail shows a scapula, a tooth, and an articulation amongst other bones and stones of the bone bed. The Roc de Marsal detail depicts part of the fire features made up of light gray ash and dark gray charcoal.

the technical issues we encountered, such as slow pre-processing times on-site, lengthy post-processing times in the lab, and difficulties with memory limitations when merging will resolve themselves as computer technology in general continues to improve. Other issues, such as creating good lighting conditions on site, will remain an issue with this particular technique.

Ultimately, however, the results have to be assessed on their archaeological merit rather than strictly on their technological feasibility. In this regard, this test project was critical before we attempted to digitize an extraordinary, and presumably unique, archaeological find *in situ*. As described here, there were a number of logistical problems that had to be solved and both solving these issues as well as the scanning itself took time away from excavation. The net result was added costs. However, in our opinion, the final 3D meshes are very good representations of the archaeological surfaces. The color reproduction in particular is quite good given the care that was taken to control the lighting conditions. With regard to the level of detail in the final 3D meshes, it is clear that individual photographs with high resolution cameras could do better for individual objects or limited portions of the digitized surfaces. Nevertheless, the slightly lower quality of the final meshes was more than compensated for by their three-dimensionality and by the otherwise difficult to obtain seamless mosaic covering a very large surface at a still quite high level of resolution. If today we had a 3D representation of the original Roc de Marsal Neanderthal skeleton *in situ* it would be invaluable for further analysis of its burial context.

Thus, if a structured light scanner could be implemented more easily and if the costs of the system and its application were lower, we do not doubt that structured light scanners would become a part of the excavation documentation routine just as total stations and digital cameras are today. However, based on the experiences presented in this paper, we conclude that at the present time the system is only feasible and worthwhile for extraordinary finds where the fullest, most complete documentation possible of the archaeological context is required, and this is how we are currently using this equipment.

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