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Structured light scanning for high-resolution documentation of *in situ* archaeological finds

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ABSTRACT

Archaeologists strive to document the process of excavation and discovery as completely as possible. Over the past several decades archaeologists have incorporated a growing number of computerized techniques for documenting archaeological finds. Scanning is one such technique. There are a number of technologies that now allow archaeologists to scan structures, excavation surfaces and *in situ* artifacts to create high-resolution, 3D data sets. We report here on a trial application of one of these, a structured-light scanner, to create 3D representations of excavated surfaces and associated artifacts at two Middle Paleolithic sites in southwest France. In each instance, surfaces of approximately 2.5 m^2 were scanned in approximately 1 day. The resulting data sets are very good representations of the originals in terms of colors and spatial details, and as such provided an important piece of archaeological documentation. To use this equipment successfully in the field, however, required solving a number of logistical issues, and the amount of time required to learn to use this equipment was significant. Once these issues are addressed, this technology is appropriate for documenting extraordinary, unique finds where time and costs are offset by the importance of good documentation.

1. Introduction

The basic tools of archaeological documentation allow archaeologists to easily capture the location of objects in 3D space (e.g. total stations) and to capture what those objects look like in their primary context (e.g. photography). In recent years, the technology to merge these two kinds of data into a spatially accurate, 3D, photo-realistic representation of an object and its archaeological context has greatly improved. There now exist a number of possibilities including digital photogrammetry, laser scanners, and structured light scanners (see Beraldin et al., 2004; Pavlidis et al., 2007; and Pieraccini et al., 2001 for more details and comparisons).

In general, the application of 3D scanning in archaeology tends to fall into two broad categories, which in turn dictate or at least influence the type of technology that is employed. One category of archaeological remains is large-scale, expansive, typically at least partially outdoor, structures that range from collapsed and fragmentary ruins to complete buildings and landscapes the size of castles, cathedrals and even small towns (e.g. el-Hakim et al., 2004; Lambers et al., 2007). A second category consists of objects stored in museum collections that range in size from small ornaments to large statuary (e.g. Borgeat et al., 2007; Godin et al., 2002; Karasik and Smilansky, 2007). In the former case, centimeter accuracy on any given point may be sufficient and the spacing between points might be relatively large so as to keep the total number of points manageable. In these situations the object itself cannot be moved meaning that the scanner has to be repeatedly re-positioned to collect data from the entire scene. Importantly too, environmental variables such as lighting are difficult to impossible to control. In the latter case, point accuracy may have to be sub-millimeter and point spacing will be correspondingly small. Often times the object itself can be rotated in front of the scanner or at a minimum positioned so that the scanner can easily move around it. Finally, if the work is being done in a museum, it is often possible to control the lighting to achieve the best result.

What we wanted to do, and what is presented here, is to test the feasibility of using a 3D scanner, designed to achieve high accuracy under well controlled conditions, as one finds in a museum, to scan archaeological surfaces and *in situ objects* with similar accuracy under field conditions (cf. Godin et al., 2002). Similar efforts have been made to scan surfaces and *in situ* objects in detail, particularly rock-art, using laser-scanners (e.g. Brown et al., 2001; Díaz-Andreu et al., 2006; Doneus and Neubauer, 2004; Freitas et al., 2007). Structured light scanning produces sub-millimeter accurate 3D representations with color information and for the last few years we have been using this technique to scan hominin fossil material and a paleontological reference collection housed at the Max Planck

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Institute (Leipzig, Germany). The question was could we obtain similar results in, for instance, a Middle Paleolithic site where we anticipated that we might encounter human fossil material for which it would be important to document in great detail and in three dimensions the context of the find. To this end, we used the structured light scanner to document two archaeological surfaces with exposed artifacts at two Middle Paleolithic excavations in southwest France.

2. Methods and materials

For this project we used a Breuckmann triTOS-HE structured light scanner (Fig. 1) (see also Gernat et al., 2008 for additional technical detail). The scanner itself consists of a small projector, which displays a structured light pattern on the object, and a separate 1384×1036 pixel resolution color, digital camera (cf. Karasik and Smilansky, 2007). These two components are mounted at opposite ends of a tubular frame with an interchangeable middle segment such that the distance between the camera and the projector can be modified. By changing the length of the middle segment and the focal length of the lenses on both the projector and the camera, the size of the area to be scanned can be changed. Thus depending on the configuration of the scanner, it can capture 3D information at scales ranging from a single tooth to an area approximately 75×55 cm. Of course since the camera resolution remains fixed, the effective resolution of the scanner decreases as the field of view increases. Because we were interested in scanning large surfaces, we configured the scanner for the largest field of view available to us, which, under controlled conditions and with the best calibration, yields an area of 0.23 m^2 at 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.

Structured light scanners are able to acquire information about both the color and the geometry of an object through a single camera lens thereby allowing a very accurate mapping of the object color to the 3D data. In the first step of the scanning process, the scanner projector uses a 100 W halogen lamp to project a series of patterns, consisting primarily of vertical stripes of alternating black and white, onto the object. In effect, by measuring the deformation of these patterns the scanner is able to calculate *XYZ* coordinates for each pixel captured by the camera. This step requires just a few seconds. The second step is to flood the scene with the projector lamp or optionally with external lamps to capture a color image. Lastly, these data are passed to a computer via a controller box, pre-processed, and saved. This is the most time consuming step, and it is greatly influenced by the speed of the computer used to run the scanner. In our case, we used an average laptop (Pentium-M CPU at 1.6 GHz and 1 GB RAM) to run the scanner and as a result all steps combined required about 90 s/scan.

Fig. 1. The Breuckmann triTOS-HE structured light scanner setup in a lab with controlled lighting. The inset shows the front face of the scanner with the projector on the left and the camera on the right. The bone inside the light tent is resting on a turntable controlled by the computer. This scanner communicates with the computer via an external control (the black box sitting next to the computer) (photo by SPM).

The software used to operate the scanner was Optocat 4.01, which was provided by the scanner manufacturer. In conjunction with a triTOS-HE, it produces quality-annotated data where the quality of a 3D data point is an estimate of the precision of the measurement of this point. This software was also used to calibrate the instrument prior to going into the field (see below) and for post-processing (aligning and merging the individual scans).

We scanned an archaeological surface at two different Middle Paleolithic sites in southwest France. At Jonzac (Airvaux, 2004; Airvaux and Soressi, 2005; Jaubert et al., 2008) an approximately 2.5 m^2 bone-bed deposit was scanned. This surface was roughly horizontal and contained a single archaeological horizon consisting of a dense accumulation of overlapping and jumbled bones with some stone tools (Fig. 2). The excavation methodology used here was *décapage* meaning that the artifacts are left in place until an entire surface is uncovered. At that point a standard 2D photo mosaic is done and 3D, total station coordinates are recorded as the objects are then removed (Dibble, 1987; McPherron and Dibble, 2002). The 3D scan was done at the end of one of these *décapage* when the artifacts and bones were most visible, and the goal was to capture the complexity of this rich deposit.

The situation at Roc de Marsal (Turq et al., 2008) was a bit different. Here the original intent was to use the scanner to document the complex, 3D, spatial relationship between the original find location of a Neandertal skeleton, a pit like feature in the bedrock approximately 1 m from the skeleton, the incised floor of the cave, and the relationship of these features to the stratigraphy of the current excavation which includes a number of fire features (Fig. 3). However, after the experience at Jonzac, it was clear that the work would have to be scaled back and only a scan of the section with the fire features and the bedrock was attempted. This scan differed from the Jonzac situation primarily in that it emphasized a vertical surface and secondarily because in this case it was very important to capture accurate color information to reveal the extent of the fire features.

3. Results

The final 3D mesh of the digitized surface at Jonzac represents an area of about 2.5 m^2 and consists of more than 10.3 million vertices (Fig. 4). It was computed from 75 overlapping point clouds (scans), generated within 1 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 m^2 and consists of slightly more than 9.9 million vertices (see Fig. 4). This mesh was computed from 146 overlapping point clouds generated within 2 days. Roc de Marsal required more time, somewhat ironically, because of the increased three-dimensionality of the surface. It was far more difficult in this case to position the scanner in a systematic way to cover this surface. Subsequent experience with the scanner on archaeological sites has shown this to be the more typical case.

Data post-processing took approximately 95 h for Jonzac and 205 h for Roc de Marsal. About one-third of this time was spent on manual pre-alignments and color corrections. Manual pre-alignment entails identifying at least three points in common on two overlapping scans. Once these points are identified, a best-fit algorithm can be used to improve the alignment before merging the scans. The merge process is obviously required to make

Fig. 2. The surface scanned at Jonzac (left) and the scaffolding constructed to move the scanner at a fixed distance over the surface (right). Subsequent to this photo a tarp was placed over the scaffolding to darken the area scanned (photo by SPM and Steffen Lätsch).

a complete 3D representation, but one beneficial effect is that redundant data from overlapping scans are discarded thus reducing the size of the overall data set. As mentioned above, this particular scanner assesses the quality of the 3D data at each point in the scan. Thus when the scans are merged the software is able to discard lower quality data in overlapping areas. Fortunately, once pre-alignment points are identified by hand, the rest of the merging process can be done without supervision meaning that a substantial portion of the data-processing time does not require a human presence.

4. Discussion

The two main challenges we encountered in this work were (1) the positioning of the scanner and (2) controlling the light. As for the light, in each case, we were obliged to use black tarps to completely or nearly block the ambient light. In bright light the scanner simply does not work because it is unable to accurately identify and measure the projected pattern on the archaeological surface. The instrument likely would have been able to collect 3D data in the reduced light of Roc de Marsal, where we were inside a cave. Even in the cave, however, the light was variable over the course of the day, and, given how long it took to do this work, eventually we were working at night. This meant it would have been very difficult to adjust the speed and aperture of the camera to maintain a constant exposure across all scans we conducted on each surface. As a result, when we merged the scans we would have had additional difficulties avoiding obvious, visible lighting differences across the final merged imaged which, in the worst-case scenario, can result in a kind of quilt work of varying light intensities. Thus at both Roc de Marsal and at Jonzac we took special steps to reduce the ambient light to nearly complete darkness. At other sites this might be difficult to achieve, and it can certainly have an impact on the rest of the excavation. By far the simplest solution is to work at night.

Fig. 3. The surface scanned at Roc de Marsal. The scan included the short section crossing the photo with the dark layers, the bedrock immediately in front of this section, and a portion of the surface above it. The black plastic in the background is reducing the amount of light that entered the cave (photo by SPM).

Positioning the scanner both compounded lighting issues and created problems on its own. In laboratory situations, small objects can be placed on a turntable in front of the scanner and rotated multiple times to get a complete image. Alternatively, large objects can be positioned such that the scanner can be rotated at a fixed distance around them. In the field, the scanner had to be repositioned to capture all visible surfaces and, depending on the physical layout of the excavation surface, this was not always possible. The end result is holes in the mesh. Just as challenging, however, are two related points: the scanner must be positioned a fixed distance from the surface, and the instrument has a limited depth of field. For instance, at both sites, with the lenses we used, the instrument had to be between 105 and 135 cm from the surface. Parts of the surface that were substantially closer or further from the lens were ignored by scanner. Thus at times the scanner appeared to be positioned to capture a large portion of the scene we were digitizing, but because of the depth of field in the scene only a small portion was actually captured.

At Jonzac, where we were digitizing a nearly horizontal excavation surface, we solved the positioning problem by building a set of rails 120 cm above the surface. We then mounted the instrument on a sledge and pulled it along these rails at fixed intervals that provided the required overlap between successive scans. Because the only relief in the surface was provided by the objects themselves, for each scan nearly the entire surface visible to the camera could be digitized. At Roc de Marsal, where the surface was mostly vertical but also contained horizontal elements at the top and bottom, we were unable to build a rail system. Instead, large portions of the surface had to be digitized with the instrument mounted on a tripod. While initially the idea of using a professional grade photo tripod seemed appealing in that it would allow a great

Fig. 4. The resulting images for Jonzac (left) and Roc de Marsal with close-ups of each.

deal of flexibility in positioning the instrument, in fact repositioning the tripod for each scan, finding secure footing for the tripod legs on an uneven cave floor while maintaining a fixed distance from the surface, turned out to be an incredible time consuming process (particularly in contrast to the rail system used at Jonzac). At one point we attempted to speed the process by pivoting the instrument in the tripod rather than moving the tripod. While we were able to collect 3D data faster in this way, it had a disastrous affect on the lighting for when the color information was captured. Because the light was no longer striking the surface perpendicular and was instead raking across the surface at variable angles, the brightness was no longer constant across the image and when merged the individual scans produced the kind of quilting pattern mentioned above.

One additional difficulty with this equipment in the field is the need to calibrate the instrument prior to digitization. Calibration is required to re-adjust the scanner after changing lenses and to correct for small changes in the positions of movable parts, due to, for example, shock or big temperature differences. The flexible design of this particular model, which allows for the lenses and spaces tubes to be changed due to circumstances, also means that calibration is more frequently required. Calibration involves running a series of scans with a calibration plate (Fig. 5) that contains a pattern that the software is pre-programmed to recognize and analyze. By comparing the expected pattern with the measured pattern, the program can calculate correction factors that are used to calibrate the instrument to within acceptable limits. The acceptable limits vary according to the lenses and, therefore, the size of the field of view. Ideally the instrument will be calibrated each time it is transported and installed in a new context. This is fairly easily done in museum contexts were the objects to be digitized can be positioned on the same table or surface where the calibration plate was previously placed. In other words, careful repositioning of the instrument is required after it is calibrated. At Roc de Marsal and Jonzac, however, we had to calibrate the machine, pack it into the transport boxes, transport it by car to the sites, and then re-install the instrument as described above at the two sites. This is likely to have had an impact on the calibration of the scanner and thus on the accuracy of the instrument. One way of dealing with this problem is to use the calibration plate to re-check the calibration after returning from the field.

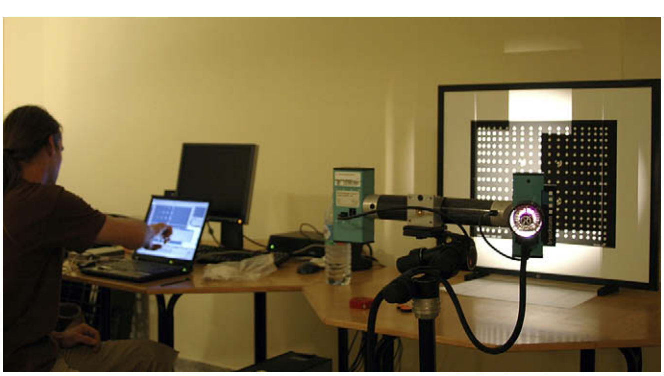

Fig. 5. Calibrating the scanner. The scanner is in the foreground on the right. It is projecting a structured light pattern on the calibration plate which is set at a fixed distance and angle from the instrument (note paper guide under the calibration plate). The calibration process is controlled by the software running on the laptop shown on the left (photo by Steffen Lätsch).

A hidden or at least easily overlooked aspect of the calibration process is that it also adds considerably to the volume and weight of the equipment that must be transported to the field. As can be seen in Fig. 1 the instrument itself is quite small and fits in a padded box, along with the cables and controller box, about the size of a normal suitcase. The calibration plate for the lenses we used, however, is approximately 86 by 70 cm, requires its own metal frame stand, and comes in a separate padded box. Add to this a high quality tripod and, in our case, a backup desktop computer plus flat-screen monitor, and the result was two metal boxes each measuring $120 \times 80 \times 50$ cm.

While it is possible to operate the scanner with a laptop computer, the increased computing power that can be attained less expensively with a desktop computer makes this a more attractive solution. Computing power makes the scanning process in the field go faster if the scanner can be re-positioned quickly between scans. At Jonzac, for instance, where we could quickly slide the scanner into position, a more powerful computer would have made the work go faster. At Roc de Marsal, however, positioning the scanner prior to each scan took enough time that increased computing time was proportionately insignificant. Even so, a fast computer is definitely an advantage after the fieldwork when the individual scans are merged. While it is not necessary to do the merges in the field, doing some preliminary alignments of adjacent scans allowed us to assess the quality of the data and, ultimately, the feasibility of the project prior to shipping the equipment home.

Similar computing issues are faced afterwards. The technology to obtain 3D data is outpacing the technology to display and manipulate these data. Currently, at our institute, we have no machines that can display the full data set at its full resolution while at the same time allowing for smooth user interaction (e.g. tilting or rotating the image). As a result, the data have to be down-sampled before they can be viewed in a user-friendly manner, which to a large extent contradicts the purpose of applying this high-resolution technology in the first place. Alternatively, portions of the image can be cut from the total image and displayed at their original resolution. These are, of course, only temporary problems in a field that progresses as fast as computer technology does. Thus we have archived the original, raw data in anticipation of a time when it is possible to treat the data set in its entirety.

We have presented here our work with the surface scanner separate from the other types of spatial documentation techniques that we use at these two sites, but clearly the goal is to integrate the data sets produced by the scanner into the geographic information system of the respective projects. The resulting 3D meshes are correctly scaled spatial data sets with their own origin and orientation. To georeference these meshes, meaning in this case to place them into the site's grid, involves scaling, shifting and then rotating them into place. This can be accomplished by measuring, with a total station, for instance, at least three control points in the scanned surface so that the coordinates of these points are known in the site grid. Once this is done the surface scan data can be aligned to the site grid and presented in their proper spatial context along with other kinds of archaeological spatial data including, for instance, point proveniences on artifacts or a topographic map of the site. This step is important too if the surface scan data are to be integrated with data from other automated 3D data acquisition systems such as laser scanners.

5. Conclusions

The application of structured light scanning to archaeological discoveries in the field is certainly possible and the results are impressive. Sub-millimeter accuracy can be obtained across many square meters of surface, and by carefully controlling the lighting a seamless high-resolution, 3D image of the scene is achieved. To accomplish this, however, a considerable number of logistical problems, particularly concerning lighting and camera positioning, must be solved and for a surface of approximately 2.5 m^2 approximately one full day of field time is required. Post-processing time in the lab takes at least another two weeks and can require substantially more depending on the how well the field conditions could be controlled.

Our use of surface scanning in this instance was not for analytical purposes but rather as a documentary tool and as such there are no objective measures of the resulting data set. We do not, for instance, have scans of the same surfaces using other technologies with which we can compare results. However, from the perspective of archaeological documentation, the results were quite satisfying. To our eye the resulting data set was a very good digital replication of the original. Strictly in terms of pixel resolution, individual photos taken with high-resolution digital cameras can exceed the results we obtained, but the three-dimensionality and seamless spatial extent of the structured light results have a tremendous archaeological value. We only wish a similar image was available for the Roc de Marsal skeleton, discovered in 1961 and known only from a few black and white photos that are very difficult to contextualize.

If we could obtain similar results on a daily basis by placing a scanner over each excavation unit we would be able to reconstruct sites in unprecedented detail that future generations would no doubt find useful as they attempt to understand what we have done. This would also make data sets that would facilitate the communication and instruction of the archaeological process and results to the general public and students. Terrestrial laser-scanners are already doing similar work for larger-scale archaeological finds. Structured light scanners are one more tool that archaeologists can use to document their finds along side total stations, laser scanners, digital photogrammetry and similar technologies. Based on our experience at two Middle Paleolithic sites, however, the logistical difficulties of structured light scanning are such that for now it is a technology best applied for extraordinary finds in need of extraordinary documentation. Our experience too indicates that substantial time and testing are required to learn the equipment sufficiently well to obtain good results. Thus, trial runs such as those presented here are highly recommended before attempting to document extraordinary finds.

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