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Pottery Goes Digital.
3D Laser Scanning Technology and the Study of Archaeological Ceramics

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Abstract: Most frequently brought into play for documentation purposes, 3D technologies are highly precise measurement tools, providing high quality three-dimensional archives of an object's surface. However, the possibilities offered by 3D technologies have not been fully explored in archaeological research so far. Pottery studies, in particular, have paid greater attention to develop sophisticated methods of visual recording and to build typologies, largely overlooking other applications. To bridge this gap, we will present the preliminary results of a pilot study carried out on experimental bodies of pottery, in which systematic ceramic analyses have been coupled with 3D technology. In so doing, we argue that the full potential of 3D technology applied to ceramics goes beyond accurate documentation. In receiving the complete account of surface topography, 3D models provide valuable information on the very process of making a pot, shedding light on manufacturing methods, technological choices and potters' motor habits.

Keywords: 3D scanning technology, Pottery analysis, Computational geometry, Shape analysis, Detection of manufacturing methods

Introduction: 3D technology beyond recording systems

Over the last fifteen years, the 3D recording of both structure and objects has received considerable scholarly and public attention, as the proliferation of literature on the subject may well demonstrate (Andreetto, Brusco, Cortelazzo 2004; Callieri, Ponchio, Cignoni, Scopigno 2006; Forte and Pietroni 2009; Stylianou 2009; Remondino, Barazzetti, Nex, Scaioni, Sarazzi 2011; Kampel and Sablatnig 2006; Meyer 2007; Pop and Bucksch 2007; Ter Haar, Cignoni *et al.* 2005; Limp, Payne, Simon, Winters, Cothren 2011). Initially, great emphasis has been placed on the description of methods and workflows, their weaknesses and strengths, giving full account of a range of deployment efforts. Only recently, the focus has shifted from the small to the wider picture in order to understand the implications, strategies, and consequences of the application of 3D imaging technology for reconstructing the past. From the acquisition of data to the creation of a digital archive, through digital object discovery, citation, analysis, study, and reuse, the complex process of 3D recording must be considered as part of a comprehensive and interconnected research infrastructure (or digital ecosystem; see Forte 2008; Limp, Payne, Simon, Winters, Cothren 2011). All the aspects belonging to 3D digital ecosystems need therefore to be approached as a whole and in an interdisciplinary manner, in order to assess most effectively the long-term value of these new techniques, as well as to address more consistent research questions.

1 Research questions and aims

It is exactly towards this direction that we have undertaken our research project, which has at its core the systematic integration of 3D recording methods within pottery analysis. One of the main aims of this ongoing project, carried out in joint forces by the 4D Research Lab and the Petrographic Lab of the University of Amsterdam, is to move beyond the current 3D documentation practices in order truly to explore where this technology can lead us. It is our belief that, although 3D documentation represents a valuable undertaking, it is too often an end in itself. Clearly, digital archives are powerful sources, 3D models are fun to play with as well as effective educational tools (Fig. 1), but more work needs to be done to embed 3D technology more firmly in our research practices and to evaluate what kind of archaeological questions we can answer with it.

As noted earlier, pottery studies have been mainly concerned with 3D techniques in order to accelerate the traditional practice of documenting potsherds. In particular, greater attention has been paid to the development of increasingly sophisticated methods for deducing from 3D outputs the most accurate artefacts profiles, with the ultimate aim of building automated typologies, but there is much more to be gained beyond this. Studies conducted on other types of artefacts, such as lithics, metals, or bone remains, have already started

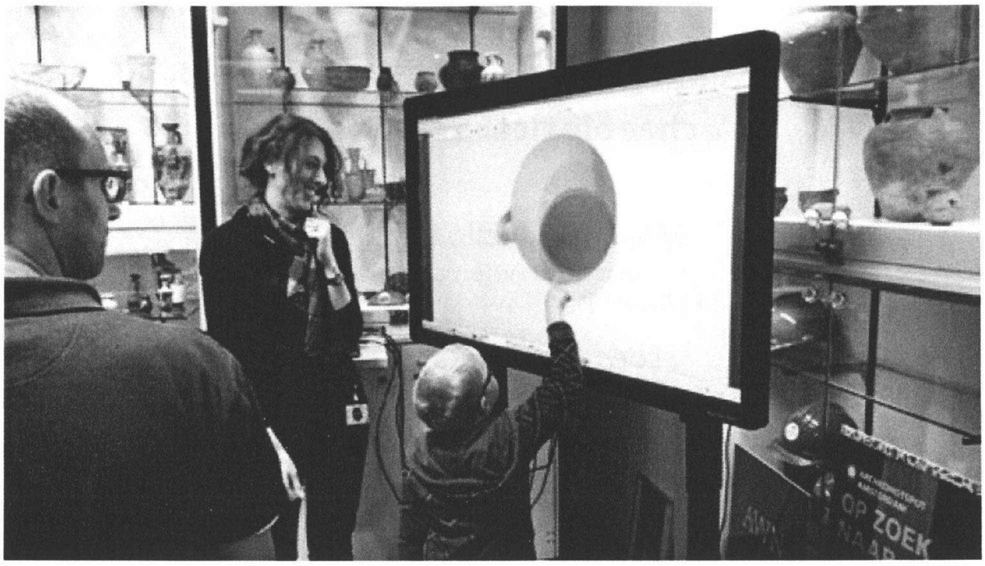


FIG. 1. THE PROJECT 'POTTERY GOES DIGITAL' PRESENTED TO THE VISITORS OF THE ALLARD PIERSON MUSEUM (AMSTERDAM).

to explore different research paths, successfully applying 3D data for use-ware analysis or for studying post-depositional damage, proving that 3D techniques are not only highly precise recording tools, but are also valuable (though under-explored) research tools.

What does it mean to use 3D recording methods as a research tool when it comes to the ceramic record? Or, to take up Martin Millet's invitation (Millet 2015, CAA 2015 opening lecture), what type of questions can 3D data help to address? A survey of the current literature indicates the following as the most common applications of 3D data to pottery analysis:

- So far, studies on axial symmetry focusing on uniformity and deformation of wheel-thrown vessels and potsherds, have addressed the issue of ceramic variability and scale of production, opening an important line of inquiry into the *chaînes opératoires* that characterize specific manufacturing processes, workshops, or even the work of individual artisans (Gilboa, Karasik, Sharon, Smilansky 2004; Saragusti, Karasik, Sharon, Smilansky 2005; Karasik 2008; Gilboa, Tal, Shimshoni, Kolomenkin 2013).
- Following the same path, other works focusing on metrics associated with wall thickness, height, diameter, and estimated volume of pots provided greater depth to the discussion on ceramic variability. In fact, research applying 3D morphometric analysis to pottery may also include coil-built and handmade vessels, while studies focusing on axial symmetry are limited to wheel-thrown objects (Selden, Perttula, O'Brien 2014).

In this paper, we argue that the potential of incorporating 3D data within ceramic analysis is still largely untapped. In receiving the complete account of surface topography and texture, 3D technologies can lead to most accurate analysis of features such as grooves, spiral ridges, cracks, etc., which are of pivotal importance for assessing different shaping techniques, technological choices, as well as potters' motor habits. Remarkably, this is one of the most promising yet least explored application of 3D data to pottery analysis and will therefore be the focus of the remainder of this paper.

2 The analysis of surface macrotraces and the identification of pottery forming techniques

Since the pioneering works of Valentine Roux and Marie-Agnes Courty (Roux 1994; Courty and Roux 1995; Roux and Courty 1998), who have called into question the criteria traditionally used for identifying pottery-forming processes, ceramic analysts have spent much energy in the study of the surface macrotraces that enable us to distinguish better between different manufacturing techniques. For instance, the integration of ethnographic and experimental data with material science and macrotrace analysis on fine decorated proto-geometric Greek pottery clearly pointed out that most of the vessels previously considered as simply wheel-thrown were actually coil-built and finished only at a later stage with the aid of the wheel (Berg 2013; Ruckl and Jacobs, forthcoming). The combination of these two forming methods, also known as wheel coiling, can be considered as the intermediate ceramic technology between hand-building and wheel throwing (Fig. 2). Current research demonstrates that wheel-coiling was a common practice in many different geographical and chronological frameworks from 3rd-millennium Mesopotamia and India, to Middle Bronze Age Aegean and Mycenaean Greece, and has called for a reassessment of our ideas concerning the spread of the potter's wheel in the Mediterranean and beyond (Knappett 1999, 2004; Jeffra 2011, 2015; Berg 2013).

2.1 Tracing wheel-fashioning techniques

V. Roux and M.A. Courty distinguished four different methods of wheel-coiling depending on the stage at which the rotative kinetic energy (i.e. the wheel) is used for shaping the clay (Fig. 3). Based on their experimental material, they were also able to set a number of criteria for recognizing the four methods on ancient ceramics (Courty and Roux 1995; Roux

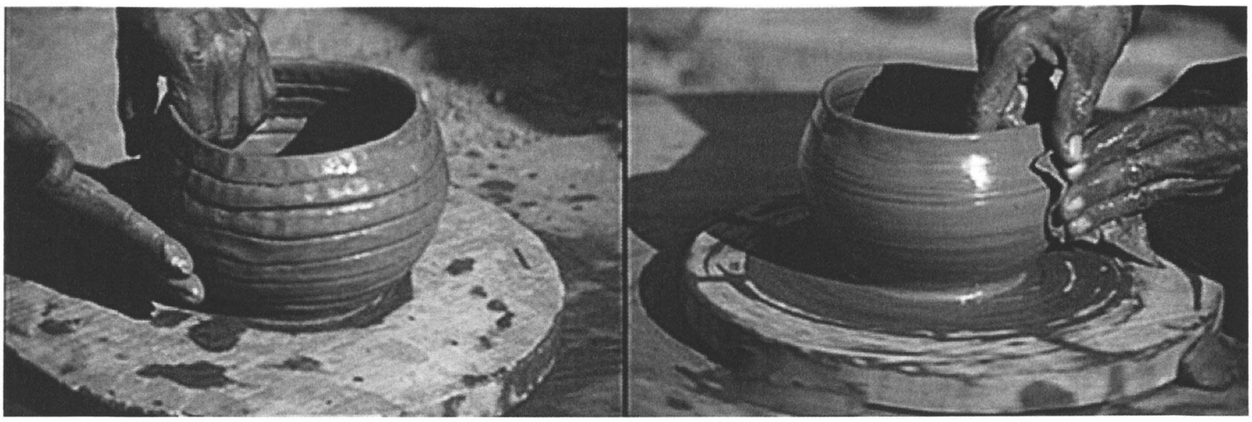


FIG. 2. WHEEL COILING TECHNIQUE: ROUGH-OUT MADE OF ASSEMBLED COILS AND THEN SHAPED AND THINNED WITH ROTATIVE KINETIC ENERGY (AFTER BOILEAU 2009).

and Courty 1998). Without going into a detailed description of the different wheel-fashioning techniques, which would stray from the purpose of this paper, suffice to say that when dealing with ceramics, assessing manufacturing methods is a far more complex task than just choosing between hand-building or wheel-throwing. In particular, the identification of mixed techniques requires experienced ceramic analysts and closer macroscopic examination of surface features.

Despite substantial differences between wheel throwing and wheel coiling, the resulting appearance of the finished products may be quite similar. This similarity relates to features such as parallel horizontal striations and rilling, axial symmetry, and string-cut marks at the bases of ceramic vessels (Courty and Roux 1995). In particularly favourable conditions, however, the two techniques can be distinguished by closer examination of macroscopic surface features, such as coil-seams (often not parallel to the rilling), variation in wall thickness due to discontinuous pressure while shaping the pot at its initial stage — when it is assembled from coils — or significant undulations on compression zones due to the deformation of stiff coils. The presence and form of these traces will not only depend on the particular wheel-coiling method, but also on the skill of the potter (for a detailed description see Jeffra 2015).

2.2 Surface macrotraces in 2D

The recent work of S. Ruckl and L. Jacobs, who kindly shared their research with us as well as providing a large part of the material processed for this pilot study, well illustrates the importance of a correct interpretation of surface features for ascertaining pottery manufacturing techniques. In particular, Ruckl and Jacobs's analysis focuses on the identification of macrotraces related to the wheel-coiling technique, and uses as a case study protogeometric fine decorated pottery from Mitrou, Lefkandi, and Halos compared with experimental pots created in the Laboratory of Ceramic Studies in Leiden (Ruck & Jacobs, forthcoming). The latter body of pottery (the experimental material) lies at the core of our pilot project, providing an ideal opportunity to build a 3D reference collection of surface macrotraces based on pots for which the manufacturing technique is known, as they have been especially made for this purpose.

According to Ruckl and Jacobs's thorough analysis, the following are the most important surface features (or macrotraces) usually taken into account by specialists to ascertain different wheel-fashioning techniques, and on which we have focused our attention:

- Coils: the most evident features to identify coiling or wheel-coiling technique; in most cases imperfectly flattened coils largely retain their original shape and might be visible on the vessel's internal surface, often in the form of horizontal rilling (Fig. 4a).

- Coil seams: coil seams/joins can be observed on wall surfaces in the form of a narrow horizontal groove between two convex features, when two coils are not completely joined (Fig. 4b).

- Preferential horizontal breakage along the coil-joins: imperfectly joined coils may constitute fragile parts on wheel-coiled vessels, which will most probably break horizontally, along the two assembled elements (Fig. 4c).

- Compression undulations: usually due to the assembling of stiff coils, compression undulations are oblique irregularities in the form of restricted but prominent swellings (Fig. 4d).

- Overall, wheel-coiled vessels do show an irregular topography of interior surfaces (especially visible on the bases of large closed shapes), differential wall thickness on a horizontal plane, and small irregular cracks on the surface (Fig. 4e)

3 Surface macrotraces in 3D

3.1 Exploring 3D scanning methods

So far, we have seen two-dimensional representations of surface macrotraces re-elaborated by a professional photographer in order to make the features more evident, under the guidance of a ceramic specialist (Fig. 4). The result is effective, but is not metrically exact or easily achieved. For this reason we decided to run a test on the same experimental sherds in order

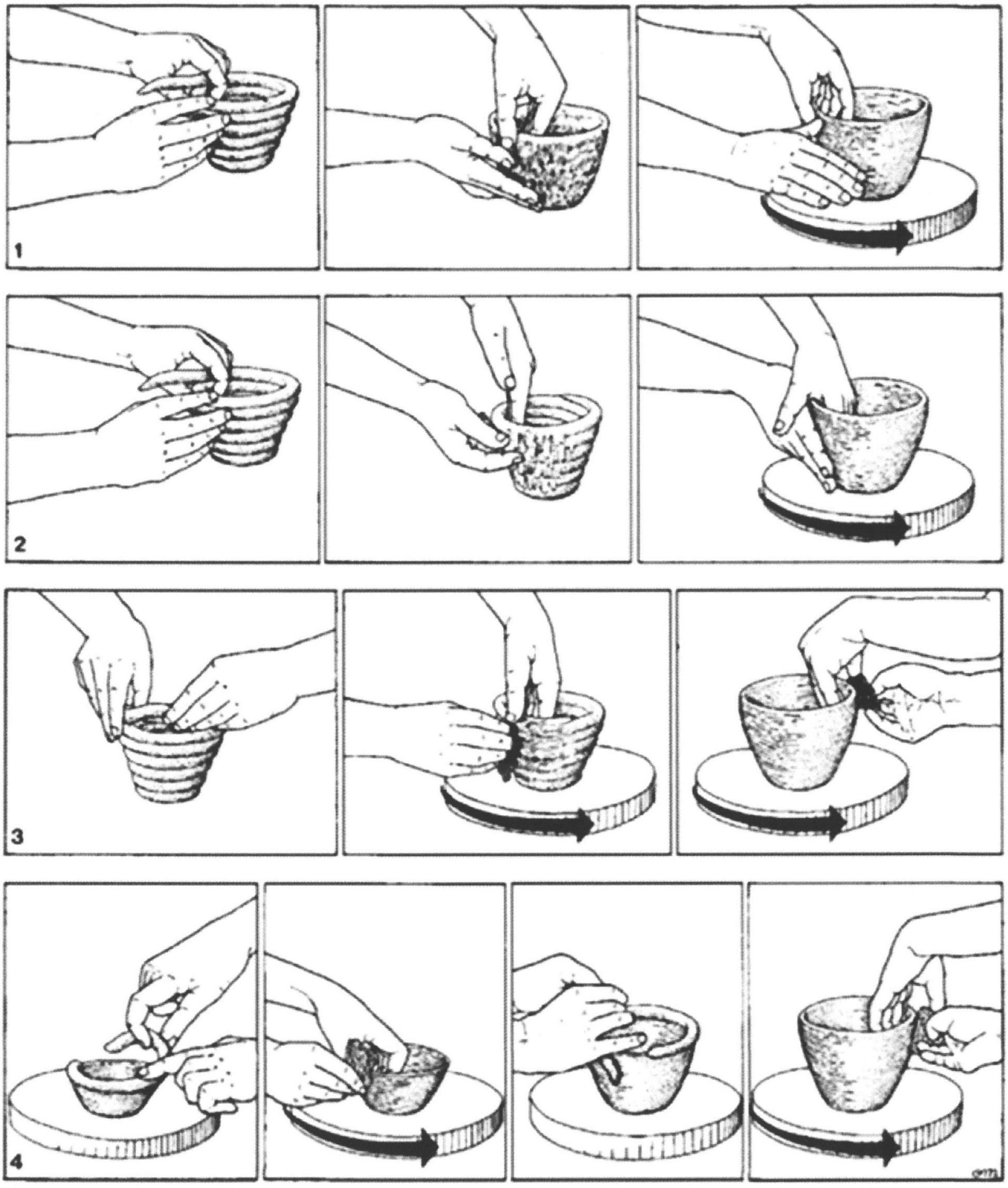


FIG. 3. FOUR WHEEL-FASHIONING METHODS (AFTER ROUX AND COURTY 1998: FIG. 1).

to evaluate to what extent 3D recording might ease the process of identifying and representing surface macrotraces and if so, whether it might also add information beyond the macroscopic level because frequently, wheel-coiled features are not visible to the naked eye. As an ultimate goal, we will try to establish whether the application of 3D technology might eventually lead to the development of an automated system for identifying ceramic forming processes and ancient manufacturing techniques.

The formulation of the above research questions has clearly determined the level of detail of our analysis. To set up the workflow, first we had to assess the techniques required and whether they were available at the 4D Research Lab. The 4D Lab has already extensively worked with the DAVID SLS-1, a low-cost structured light scanner. A few months ago, a relatively low-cost NextEngine Ultra HD laser scanner was added to the equipment at our disposal to explore further the possibilities of laser scanning. Lastly, the Lab has very recently

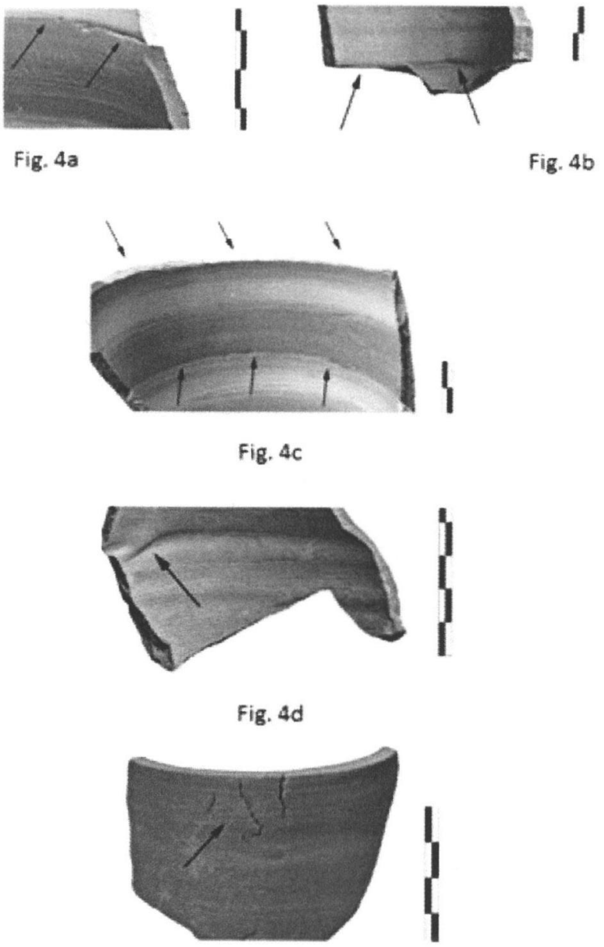


FIG. 4. SURFACE MACROTRACES, ARROWS INDICATE A) COILS; B) COILS-SEAMS; C) HORIZONTAL BREAKAGE; D) COMPRESSION UNDULATIONS; E) IRREGULAR CRACKS (COURTESY OF S. RUCKL AND L. JACOBS, AFTER RUCKL AND JACOBS, FORTHCOMING).

purchased a white light scanner, the HDI Advance R3x White Light Scanner, but unfortunately, we could only run a couple of tests with it, and therefore it does not have a central role in our current project.

Having defined our working strategy, we selected the ceramic material to be recorded and started the actual acquisition process.

3.2 NextEngine Ultra HD laser scanner

The first scanning sessions were devoted to finding the most efficient method to scan potsherds with the NextEngine on the highest resolution in order to register the most detailed geometry. We also tested for the number of scans needed to cover effectively all the relevant fragments parts: as mentioned earlier, breaks are important markers for identifying manufacturing techniques and should therefore be recorded in detail. After a difficult start, thanks to the support of NextEngine we discovered that both the alignment issues of batches of sherds and the divergence in the z-axis, were due to calibration problems that could easily be solved by the machine itself. Subsequently we were able to scan five to seven sherds in one batch (Fig. 5), each batch needing eight to ten scans, which takes from 48 to 51 minutes. The scanner was set on 'extended' mode.

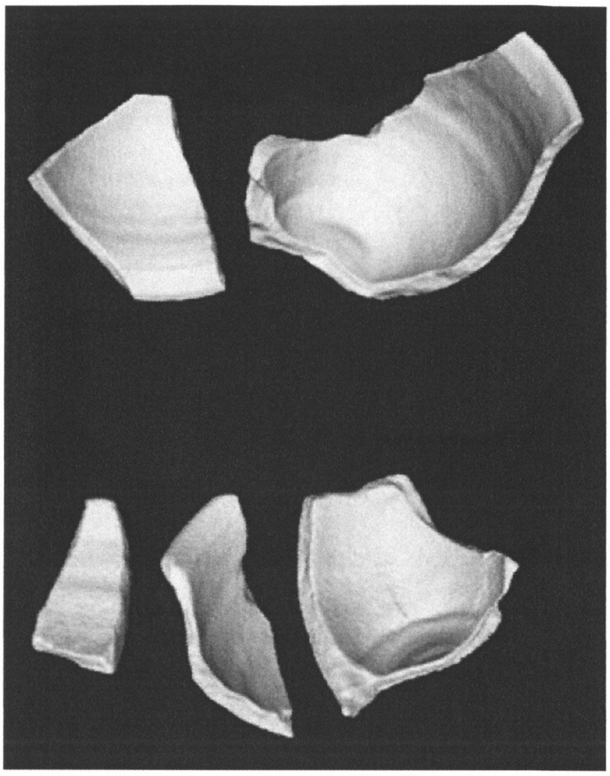


FIG. 5. BATCH OF MESHES CREATED WITH NEXTENGINE HD ULTRA LASER SCANNER.

The accuracy is around 0.003 to 0.005 inches after alignment (Fig. 6). Each point-cloud of a sherd is then cleaned and fused to a mesh in ScanStudio (the scan-software of NextEngine), producing files of 85-260 MB per sherd, leaving little post-processing time in Meshlab. Lastly, we decimated 25% of the total original faces (or points) considerably reducing the size of the file and making the models more workable in the post-processing phase.

In any event, one should be aware that scanning multiple sherds in one batch might affect the automatic alignment. Occasionally, multiple scans of such fragmented material are too homogeneous in geometry for NextEngine to find good features to align. As a result, the operator needs, after reworking and cutting, to align ten to twelve scans manually, and much of this work has to be done on the basis of the texture layer. Another possible obstacle is that when more than two scans are recorded and overlap too much, the texturing results are a bit disappointing (although in our research, textures are not necessary). This entails further reworking/cutting time per scan to reduce the overlap, although multiple files should still overlap to some extent in order to proceed with the alignment. As a consequence, the overlapping parts — for instance sharp edges — can leave traces in the mesh, possibly misleading both specialists and software while analysing surface macrotraces.

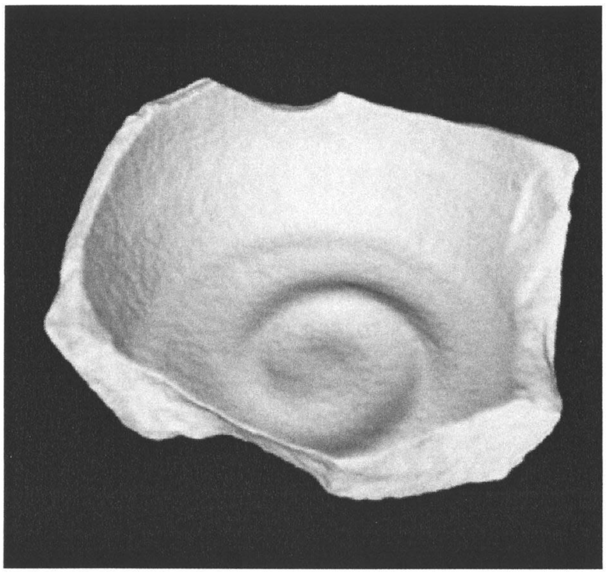


FIG. 6. EXAMPLE OF BASE FRAGMENT MODEL CREATED WITH NEXTENGINE HD ULTRA LASER SCANNER.

3.3 David SLS-1

Given the previous experience in the 4D Lab with other projects, we initially decided not to use the DAVID SLS-1 scanner for this project. This is mainly because it takes some time to master both scanner and software (aside from the fact that it crashes frequently, provoking loss of data). Moreover, it is a rather time-consuming job to create good meshes useful for analysis. Therefore, we opted to concentrate our efforts on the NextEngine, which seemed more suitable for detecting surface macrotraces of potsherds. Given the ime constraints, however, we also mastered the DAVID scanner to operate simultaneously with the NextEngine, in order to accelerate the recording process of the ceramics. The DAVID was not able to scan in batches, not even with the aid of an automated rotary table. This resulted in scanning one sherd at a time, varying in time from 10 minutes to one hour, making it an average of 30 minutes per scan (i.e. per sherd; Fig. 7).

3.4 The ideal system?

As is clear from the above, at the beginning of our work we struggled to determine the best practice for scanning ceramic fragments for detailed pottery analysis, but not in vain. Now we can say with more certainty that the NextEngine is a valuable device only if the research questions do not require a high level of detail. The DAVID SLS-1 can meet this level of detail, but is only of value when the operator is highly experienced (and it requires a tremendous amount of time).

We ran a few test scans with the new high-end HDI Advance R3x White Light Scanner, which immediately showed that this type of machine is able to record the same sherds in less time, producing smaller files but with a higher accuracy. The White Light Scanner captured the same base fragment in 15 minutes and aligned them automatically, barely generating any noise. Scans are very clean, hardly requiring any post-processing, and provide the operator with a much smaller file of approximately 200 MB (Fig. 8). It must be said, however, that it takes a long time to calibrate the HDI (an average of 30 minutes), and when there are many differently sized potsherds it needs to be recalibrated. Moreover, the HDI is not designed for mass scanning of small pottery fragments in batches, leading to the conclusion that this is not the ideal device for such a type of analysis either.

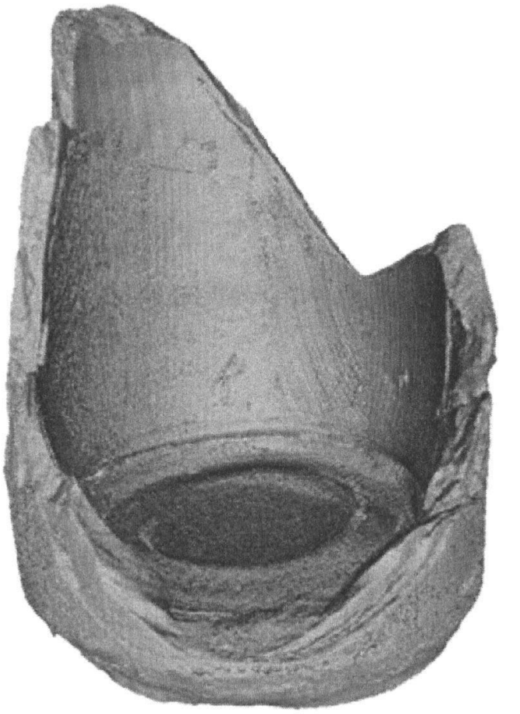


FIG. 7. EXAMPLE OF BASE FRAGMENT MODEL CREATED WITH DAVID SLS-1 STRUCTURED LIGHT SCANNER.

To conclude, the NextEngine is a fairly accurate tool for purposes such as the (low-res) digitization of museum objects. As for the structured light scanning, the DAVID SLS-1 is in more or less the same price range, but may produce slightly greater accuracy, although if suffers from a greater time issue than the NextEngine (batches of sherds VS single sherd) and is far from user-friendly. The HDI R3x has the highest LOD and scans faster, but the calibration issue slows this down. Combined with the fact that it can only scan one sherd at a time (at least at this point in our research), this expensive device is not the best candidate either.

Therefore, in terms of (time-)efficiency and the type of research (i.e. LOD), the NextEngine UltraHD is the most suitable device to do the job.

4 Post-processing and digital analysis

4.1 Exploring algorithms for analysis with high-level software

Having developed the scanning strategy, we had to choose what software best suits the testing of scans in order to answer our research questions.

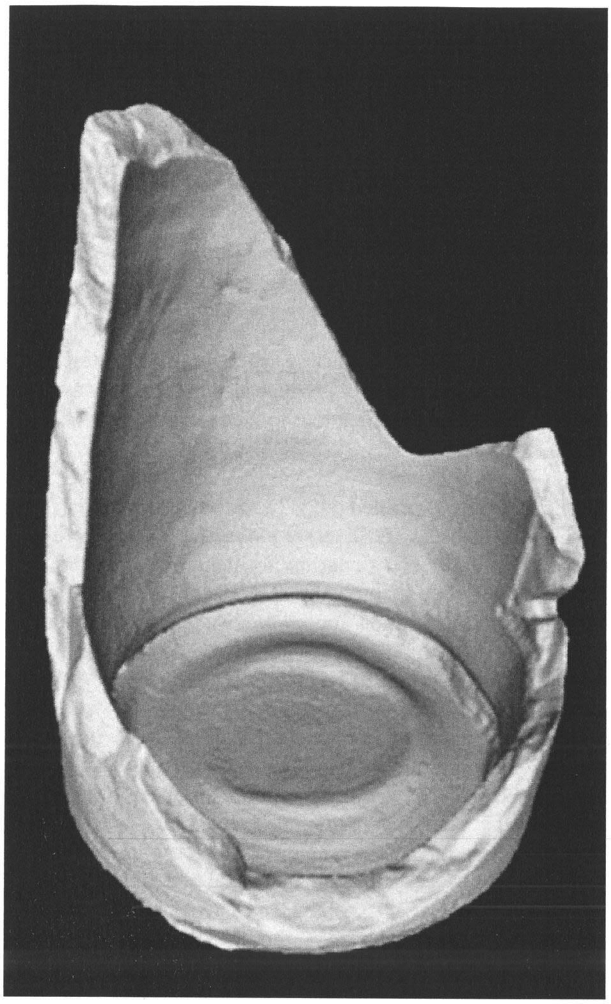


FIG. 8. EXAMPLE OF BASE FRAGMENT MODEL CREATED WITH HDI ADVANCE R3X WHITE LIGHT SCANNER.

To explore which algorithms might prove useful for working out manufacturing techniques, we have been testing some algorithms integrated in existing software: the ever-popular Meshlab and some medical packages (3D Slicer: www.slicer.org/, Paraview: www.paraview.org/). We have also used programs such as Netfabb and Meshmixer to manipulate the meshes so that they are in workable condition for some of the software.

It worked to an extent: the ridges separating coils could be detected (Fig. 9). We could also isolate some of the voids caused by coiling (Fig. 10 but hardly visible) by searching for contours after computing the vectors perpendicular to the surface.

We also tried the various curvature algorithms native to Meshlab, to find patterns matching broken-off coils and coil ridges in pot walls. The NextEngine scanner produced some dirty meshes, but after a little light smoothing, the curvature algorithms (APSS in this case; see Guennebaud and Gross 2007 and Guennebaud *et al.* 2008) clearly show the coil ridges on the ceramic surface and also produce characteristic patterns where there are broken coils on the breaks of the sherd (Fig. 11).

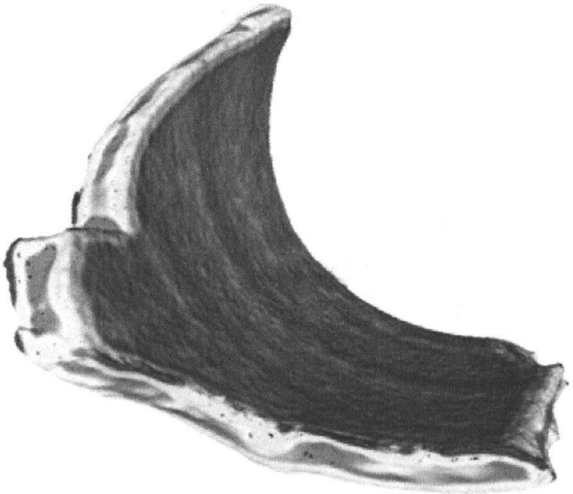


FIG. 9. COIL RIDGES HIGHLIGHTED AFTER FILTERING APSS CURVATURE IN PARAVIEW.

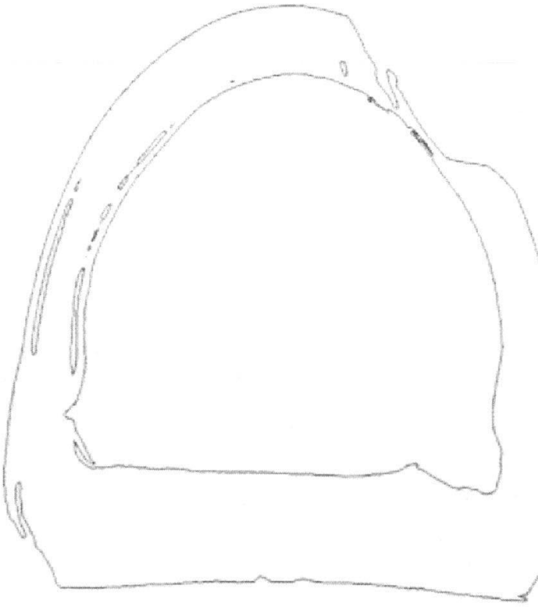


FIG. 10. VOIDS HIGHLIGHTED AFTER EDGE DETECTION IN PARAVIEW.

Surface normals also seemed a promising way to find characteristic cracks and ridges, tapered edges and dislocated coils computationally, but the problem is that sherd meshes do not have a standard orientation, so the X, Y, and Z normals cannot provide a consistent enough direction to be used to identify the phenomenon in question. This is still a problem as we have not yet found a way to detect in a consistent way the 'up' side of undiagnostic sherds (e.g. wall fragments not featuring diagnostic elements such as rim, neck, shoulder, base,

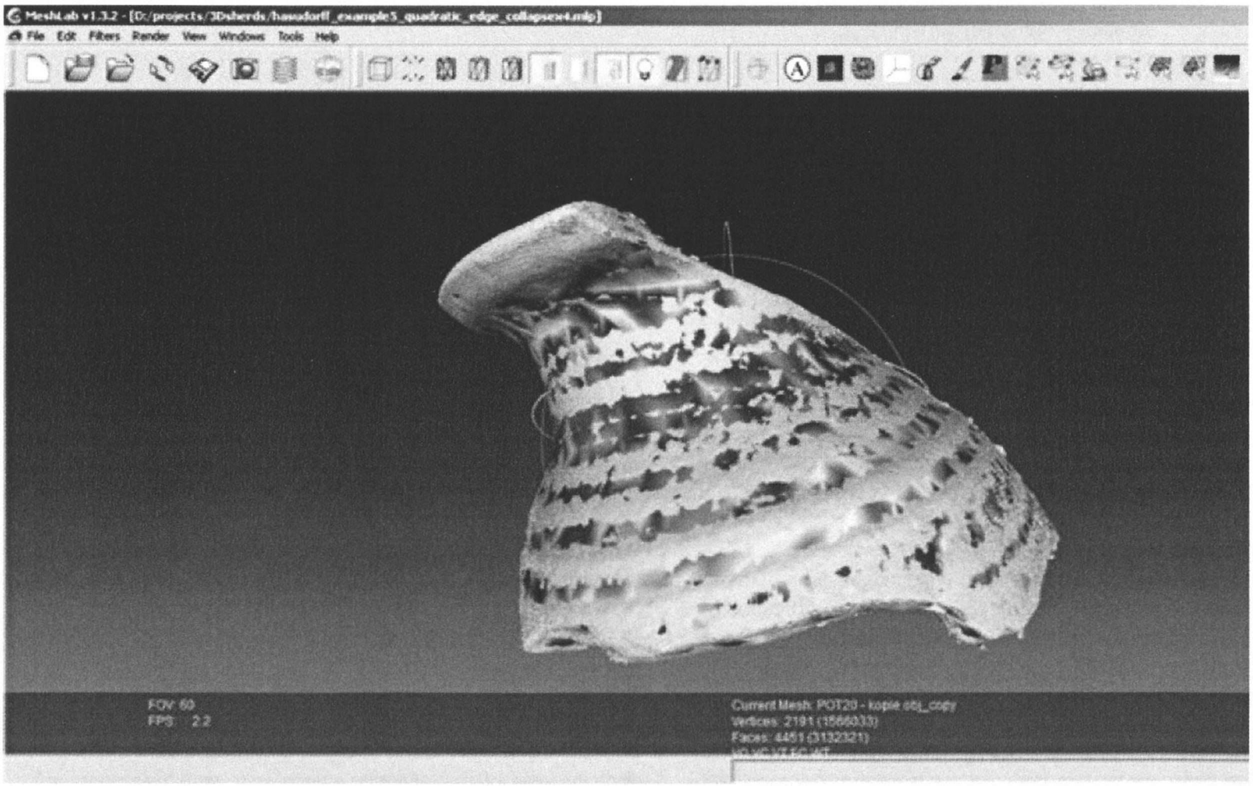
FIG. 11. Z COMPONENT OF THE SURFACE NORMALS HIGHLIGHTED IN PARAVIEW.

etc.) without manual marking. As some of the characteristics depend on fragment orientation, this is quite problematic; nonetheless, the normals should provide enough information (especially taking the local context into account) to extract valuable data (Fig. 12).

Another way to define relevant ridges and cuts was to simply smooth the mesh and calculate the distance of the smoothed mesh to the original (per closest vertex; Fig. 13).

Some of the algorithms available in these software packages (e.g. fibre bundle detection, skin separation, skeleton detection) seemed encouraging for detecting specific manufacturing markers, but in practice did not produce results for our dataset. We suspect that minor modifications to those algorithms would make them useful to us.

In the end this software turned out to be too uncustomizable (in the case of Meshlab and 3D Slicer) or too cumbersome to script (in the case of Paraview) to set up a pipeline of algorithms that can really isolate manufacturing markers. We therefore switched to the Visualization Toolkit (www.vtk.org), an open-source library with an API in Tcl/Tk, Java, and Python. We chose the Python interface to be able to also make use of the NumPy (http://www.numpy.org) and SciPy (http://www.scipy.org) scientific computing libraries and to have access to the Image Segmentation and Registration Toolkit (www.itk.org). Before proceeding, one word of caution for those thinking about venturing this way: while most programs provide a Python console that has access to a VTK library, the Python API of VTK is not very well documented and does not describe all of the methods that VTK offers in C. Moreover, some of the methods that the C interface offers are limited in Python



FOV: 60
FPS: 2.2

Current Mesh: POT20 - kopie obj_copy
Vertices: 2191 (1566033)
Faces: 4451 (3132321)

FIG. 12. SMOOTHING/DECIMATING AND COMPARING (MESHLAB).

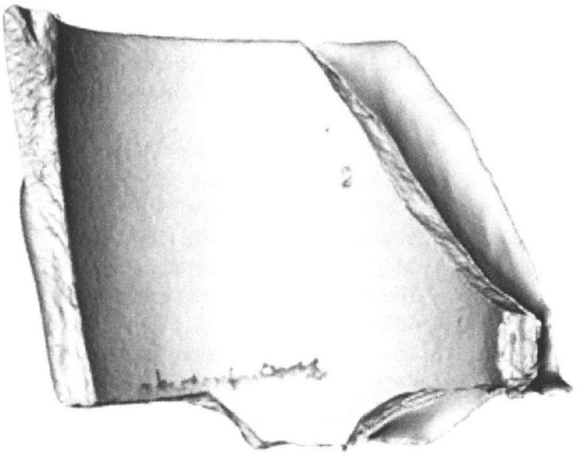


FIG. 13. SMOOTHING MESHES TO HIGHLIGHT RIDGES AND CUTS (MESHLAB).

in the argument set you can pass to it, limiting functionality. Thus, it is better to just use C++ in order to have both good documentation and a full interface. This is the path we have chosen.

4.2 Setting up lower-level algorithm pipelines

We wrote a set of Python scripts, one for each typical manufacturing marker, using Gaussian curvature computation, surface normals, various smoothing and decimation algorithms, thresholding, connected component detection, and Boolean mesh operations. For each type of coiling feature we set up a pipeline of algorithms in a specific order using a combination of the above algorithms and special parameters relevant to the properties of the feature we were looking for (e.g. the metric size of the feature).

The most effective pipeline so far for detecting larger macro-traces of coils turned out to be first to simplify the mesh by either smoothing or decimating using quadratic edge collapse and then calculating the distance between the original and the resulting meshes, followed by either a threshold or a binary subtraction. This gave us a representation of the sherds' surface features. The choice of simplification technique is very important — how the model is simplified determines how the surface features are warped, which of course has a great effect on what is detected. The various smoothing algorithms currently native to VTK turned out not to be ideal for surface feature detection, but by adjusting the arguments to the functions we could make them work for these macro-traces.

Curvature and surface normal filters are best suited to find coil features on breaks. A small modification to the VTK curvature and surface normals algorithms (increasing the Kernel radius) would make things easier, as our earlier experiments in Meshlab had shown us, but with the right parameters we were able to detect the coil markers anyway.

Automatic orientation of the sherds in space is a problem for detecting horizontal breakage. After a few experiments, we believe that the best way to find the orientation of a sherd in space is to use the principal axes (Sylvester 1852). That makes an orientation at least reproducible. Even if it is impossible to find which way is 'up' for a sherd just by calculating the principal axes, it is always possible to calculate the 'flat lying' position of a fragment, making it possible to highlight important features such as wall thickness discontinuities.

After identifying the markers on the test set of sherds, we described the geometry of the detected areas as a set of very simple shape descriptors (i.e. numbers that describe the shape of the feature), in order to compare them to the expected shapes of the manufacturing indicators. Such statistical morphological descriptors seemed a promising way to find, for example, the variability of wall thickness of a sherd, aside from the mentioned problem of sherd position, but the imaging and mathematical libraries we found currently lack the support for three-dimensional shape descriptors. We have therefore implemented a few of our own. We limited ourselves to a small set of very simple descriptors, most of which turned out not to be (directly) useful in filtering pottery production technique markers from false positives.

The shape descriptor that proved most useful — from the few we tried — was the standard deviation of the set of distances of the cell centroids of the geometry to the centre of mass of the geometry as a whole. A kernel density estimation (see for instance Parzen 1962) of the surface areas of the detected parts seems to show a bit of clustering, even in our small test dataset. This is not surprising as this descriptor readily distinguishes elongated from roundish geometries, helpful for finding (oblong) cracks, coils, and voids from (roundish) fingerprints, lumps, and sherd surface hollows.

5 Concluding remarks

However preliminary our foray into the graphics analysis of pottery manufacturing techniques has been, we can conclude that it is a promising road to pursue. The few simple methods we have applied show enough potential to continue in this direction. The next stage of our research is to focus on the application of the recording and post-processing methods

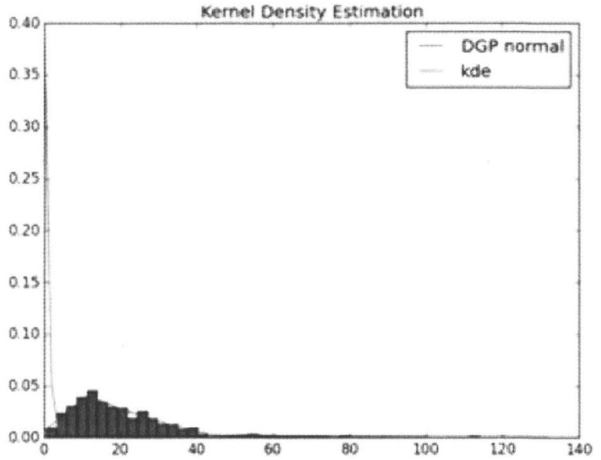


FIG. 14. SHAPE DESCRIPTORS AND KERNEL DENSITY ESTIMATION OF THE SURFACE AREAS OF DETECTED PARTS.

illustrated in this work to consistent bodies of archaeological ceramics. We are convinced that further elaboration and specification of the algorithms to suit our needs will result in a solid expert system that should be able to discern even mixed manufacturing techniques, providing a powerful analytical tool to both pottery specialists and non-specialists. The scanning of the fragments has already proved its value for several analysts who could access the material without physical contact. This adds a whole new dimension to the study of ancient manufacturing techniques.

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