# Chapter 12

## Applications of 3D technology as a research tool in archaeological ceramic analysis

This paper describes the stages of integrating 3D technology in archaeological pottery analysis, from general visualization instruments, more than a decade ago, to high-resolution systems used today for accurate data acquisition. As an example of the great potential of this technology, two new quantitative measurements are defined: the uniformity of a vessel and the degree of its deformation. The uniformity is defined based on correlations between many profiles of the same vessel, and the deformation value is defined from the roundness of its horizontal sections. Both quantities, which could not be traced using traditional methods, are highly relevant in finding solutions to real archaeological problems.

Avshalom Karasik
Weizmann Institute of Science, and Archaeological Institute, Hebrew University, Israel

## *Introduction*

The potential of 3D scanning for pottery analysis was recognized more than a decade ago. 3D modelling is increasingly used in archaeology in general and for pottery in particular. Most of the 3D applications in the past have concentrated on visualization—either for teaching or for publication—and on fast and accurate data acquisition. The advantages of 3D technology in these topics over the traditional methods are self-evident. However, there have been few efforts to harness this new technology for the development of new research tools. In the last four years, a joint Israeli research group at the Institutes of Archaeology at Hebrew University and Haifa University, in collaboration with the Weizmann Institute of Science, has developed new methodological tools for pottery analysis in archaeology (Gilboa *et al.* 2004; Saragusti *et al.* 2005). We started our project by developing computerized tools for classification and typological analysis of 2D profile drawings, of the type found in every archaeological report. Experience with these drawings convinced us that the future is in 3D technology. The biggest obstacles to pottery analysis are the huge amount of data and the expense, as well as the lack of accuracy of manual drawings. Experimentation has shown that 3D scanning is not only more accurate than manual drawing of profiles, and provides much more information on the potsherd, but is actually much faster. An added bonus is that 2D scanners generate raster images, but 3D scanners typically produce output in vector format, which is more amenable to mathematical manipulation. As will be demonstrated in the text, the tools which we have developed for 2D analysis are the basis of 3D investigation as well. This paper describes the main contributions and applications of 3D scanners used so far in pottery analysis. It also provides a short description of the tools developed by our group and

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some results (Karasik *et al*. in press; 2007; Mara *et al*. 2004). These tools offer new quantitative measures for attribute analysis, dependent on 3D techniques. Finally, I discuss possible future directions for research.

## *The history of pottery visualization and data acquisition using 3D scanners*

Manual drawings remain the standard means of presenting and publishing pottery. Most post-excavation research is based on such drawings. The justification for using a 2D abstraction of 3D pots and potsherds is that most ceramic vessels are axially symmetric, especially wheel-thrown ones. Where a vessel is axially symmetric around its centre (henceforth 'axis of rotation'), a single profile is thought to reveal all morphological information. However, this is only true in a perfect world. Deformation can occur throughout the production process, e.g. when a vessel is removed from the wheel to dry elsewhere, when several (wheel-thrown or handmade) parts are assembled to make a composite pot, during the finishing and/or decoration process (necessitating remounting on the wheel or not), or during firing. Therefore, 3D modelling can improve our understanding of pottery production and add a new dimension in the representation and publication of pottery.

Researchers wishing to improve the process of pottery data acquisition for applications such as visualization, VR presentations, computerized restoration, and so forth were first drawn to 3D scanning because of its speed and accuracy, as well as the ease and accuracy of manipulating vector models in operations such as rotation, zooming, etc. Several groups around the world are researching pottery using 3D technology. They use different devices and software but their goal is the same: to acquire accurate reconstructions of artefacts. Here, a distinction ought to be made between two orientations or interests. One is the technological development of ever more sophisticated and precise 3D devices and accompanying software. The leaders in this field are large companies developing products for industrial purposes. A quick search on the internet reveals several websites that sell 3D technology.[1] Despite the fact that some refer to archaeological finds, the companies in question are sometimes unfamiliar with the specific needs of archaeologists. The second (and for our purposes, more important) direction is dependent upon technology developed by the latter group, but aims at 3D applications designed specifically for archaeological research. Groups engaged in the latter kind of research are few (even fewer focus on ceramics) and are to be found, for obvious reasons, in the academic and non-profit sector.

One of the earliest research centres to have published on the subject is the PRIP group[2] at the Technical University of Vienna. Menard and Sablatnig (1992) described two methods for 3D data acquisition of pottery. Later on, they suggested that the 3D technology used for automatic pottery data acquisition may serve in the future for classification and deeper analysis (Menard & Sablatnig 1996). However, since archaeologists were accustomed to work with 2D profiles, they concentrated on extracting the same kind of profiles more accurately from the 3D models. Nevertheless, in the last few years, the Vienna group offered new tools that utilize data which can only be given by 3D reconstructions. For instance, they studied the colours of the ceramic surface in order to detect lines of decorations (Kammerer *et al*. 2005). They also tried to reconstruct sherds into a complete vessel based on its geometry (Kampel & Sablatnig 2004).

Another group that invested considerable effort in harnessing 3D technology for pottery analysis is located at Brown University.[3] Their publications on the subject go back to late 1980s. They, too, started with the analysis

1. E.g. Arctron (http://www.arctron.com/Archaeology/), Cyberware (http://www.cyberware.com/ index.html), Fastscan (http://www.fastscan3d.com/), Scantech (http://scantech.dk/) and Polygon Technology (http://www.polygon-technology.com/). Of these, only Arctron is a company dedicated specifically to archaeological applications.

2. http://www.prip.tuwien.ac.at/Research/ArcheologicalSherds/index.html.

3. http://www.lems.brown.edu/~leymarie/.

of 2D contour profiles (Leymarie & Levine 1988), but they have recently used 3D technology for pottery analysis as a part of larger project for computerized archaeology, SHAPE (Leymarie *et al.* 2001). They focus on visualization but also deal with tasks like pottery classification and reconstruction from sherds using 3D representations (Willis & Cooper 2004). A third project, PRISM-3D Knowledge, is based at Arizona State University. This project concentrated on acquisition, representation and analysis of all kinds of archaeological finds, including pottery.[4] In their publications one can find general papers that describe the project (Razdan *et al.* 2001) and specific papers dealing with the details of the research. With regard to pottery analysis, their efforts were towards fast and accurate data acquisition and the utilization of such data for 2D-profiling, height, maximum diameter measurement, as well as the calculation of attributes that are harder to measure by traditional means, e.g. volume, surface area, volume of vessel wall and symmetry (Henderson *et al.* 1993).

Most researchers in the field of computers and archaeology have presented and published their work in the annual CAA conferences. In the 1990s, the occasional paper dealing with 3D applications could be found. Only as late as 2002 was there a full session (*Visualization Techniques and Photogrammetry*) on such applications. Even then, the only paper on ceramic vessels dealt with 3D modelling merely as a means to extract accurate profiles, analyzed using statistics—and was therefore presented in the statistics session (Kampel *et al.* 2002). In the 2005 conference, on the other hand, four sessions were dedicated to these applications. Such a dramatic growth reflects not only the excitement of the archaeological community with these innovative 'toys', but also the maturation of 3D technology in recent years. Considerable technological improvements now make high-resolution reconstruction potentially available to any archaeologist. Granted, 3D models which can be zoomed and rotated on the screen are cool, but the $64,000 question is what do we do with them? We chose to concentrate on the extra information available in the 3D model in order to investigate issues that were rarely studied before.

4. http://3dk.asu.edu/home.html.

## *Uniformity and deformations: new quantitative definitions for pottery analysis*

As mentioned above, potsherds should have axial symmetry. But no vessel is perfectly symmetric, hence a single section as supplied in a conventional drawing is not an accurate representation of the entire vessel. Hand-drawn profiles provide, at best, an average section of a pot. This would be good enough for most archaeologists. But, one wonders, what is the effect of real-world variability on profile-based typologies? Or, can deviations from uniformity be archaeologically interesting as well? The study of such deviations and deformations can supply invaluable information regarding the *chaînes opératoires* that characterize specific production processes, workshops, or even craftsmen/-women. What is aimed at here is the extraction and comparison of many vertical and horizontal sections of a single vessel. Summarizing these comparisons enables the evaluation of a pot's *uniformity* as well as its *variability*, construed as the correlations between these sections. To my knowledge, this has not been attempted to date.

### Uniformity

The comparison and correlation of different profiles of the same sherd is utilizing the same method adopted for the comparison of profiles of different vessels (Gilboa *et al.* 2004). It is based on the idea that one can represent the profiles by *planar curve* functions (Saragusti *et al.* 2005). The curvature function ***k(s)*** is used as the curve representation. In the past we have shown that the curvature function is very sensitive and useful in the analysis of ceramic profiles (Gilboa *et al.* 2004; Saragusti *et al.* 2005). Its main advantage is that it is a function of one parameter that completely characterizes the 2D profile. Moreover, it emphasizes naturally curved sections usually more important in archaeological studies, such as rims, carination points

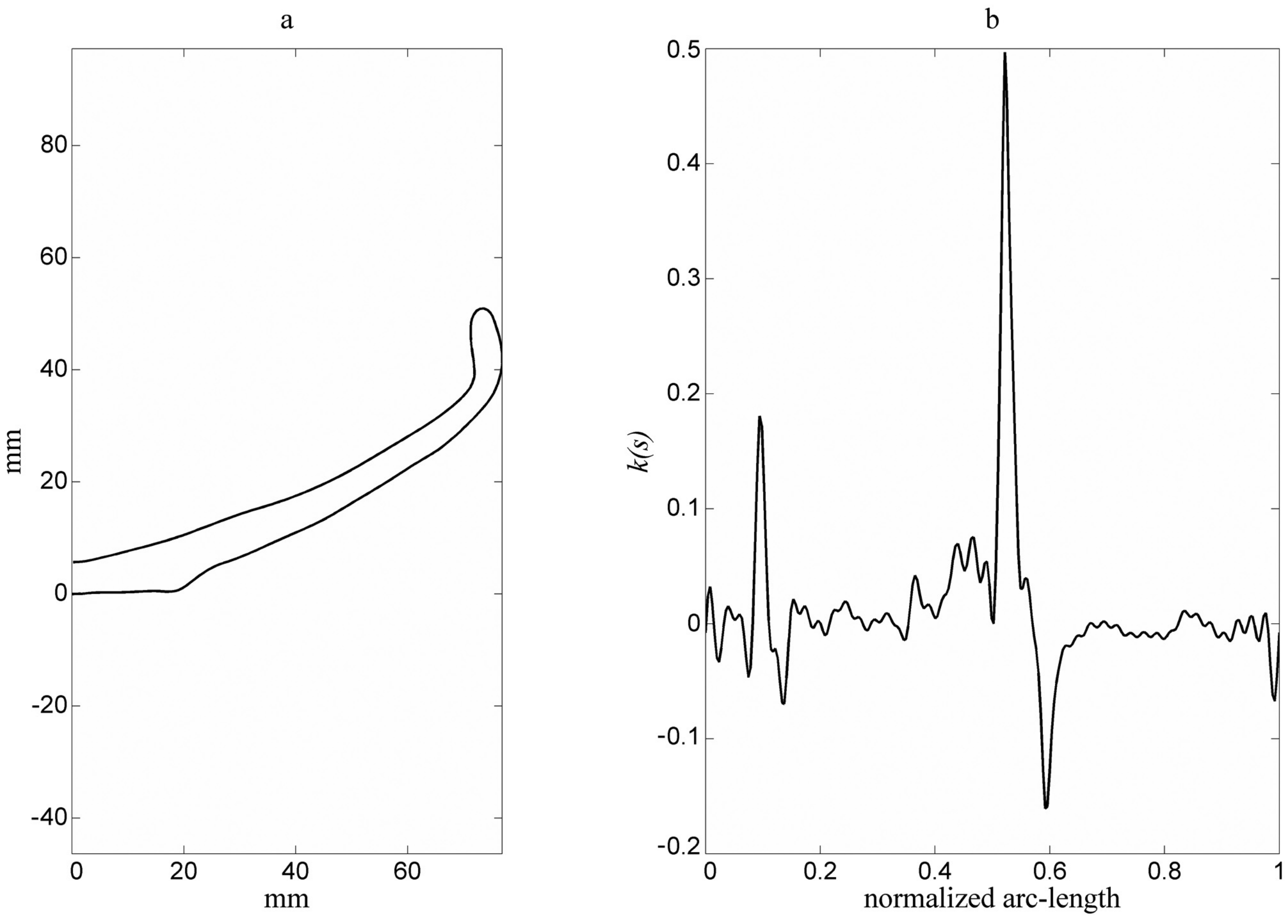



***Fig. 1.*** *A. A profile of a bowl; B. its corresponding curvature as a function of the normalized arc-length.*

etc. **Fig. 1A** shows a bowl profile while **Fig. 1B** shows its corresponding curvature function. The correlation between two profiles is defined in terms of the scalar product of their corresponding curvature functions $\boldsymbol{k_1(s), k_2(s)}$ (after the profiles are scaled to a constant length). The correlation is given as:

$$C(k_1, k_2) = \frac{\int k_1(s) \cdot k_2(s) ds}{\sqrt{\int k_1(s) ds} \sqrt{\int k_2(s) ds}} \cdot$$

***Equation 1***

Notice that $\boldsymbol{-1 \leq C(k_1, k_2) \leq 1}$ and that it assumes the highest value if and only if $k_1=k_2$. The smaller the correlation, the less similar are the compared profiles. A correlation value smaller then 0.5 usually indicates a significant difference between the compared profiles. Let $k_n(s)$ with $1 \leq n \leq N$ be the curvature functions of $N$ profiles of *different* sections of the same vessel. Using **Equation 1** we compute the correlations matrix $\boldsymbol{C_{i,j} = C(k_i, k_j) = C_{j,i}}$ for the profiles under study. The *uniformity* of the vessel is defined as:

$$uniformity = \frac{\sum_{i,j}^{N} \left(C_{i,j}\right)^2}{N^2}$$

***Equation 2***

Notice that $\mathbf{1}/N \leq uniformity \leq \mathbf{1}$. The uniformity reaches its maximum value when all the entries in the correlation matrix have the value 1. That is to say, when all the profiles are identical. The minimum value is

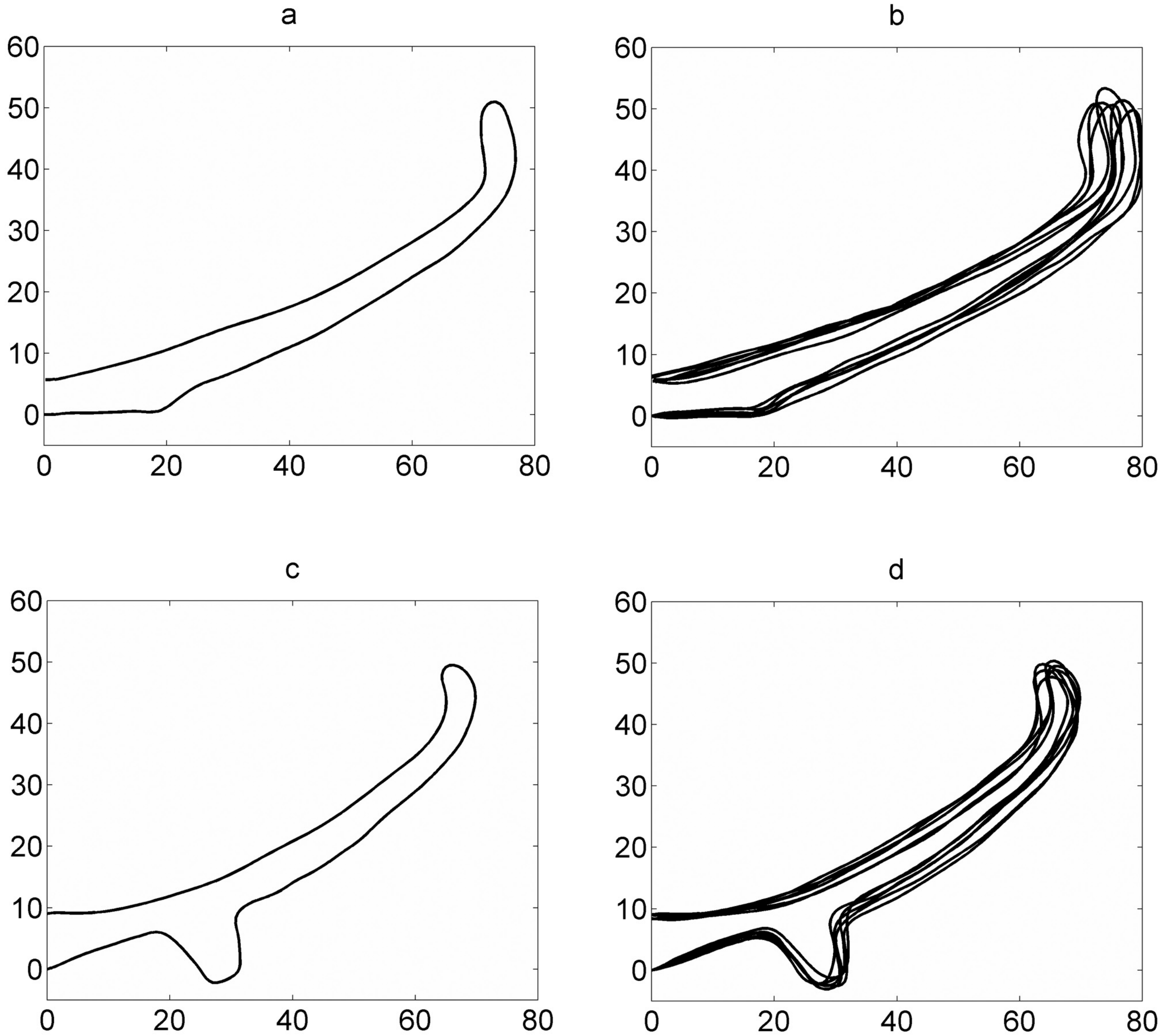



***Fig. 2.*** *A, C. Single profiles of two different bowls from Tell Dor, Israel; B, D. the overlap of six profiles of the same bowls, respectively.*

obtained when the only non-vanishing entries are on the diagonal, i.e. every profile is similar only to itself and is very different from all the others. Obviously this definition of uniformity makes better sense when a larger number of sections are measured, and $1/N$ asymptotically approaches 0. In the same way, we can also measure the correlation as prescribed by **Equation 1** between profiles of different vessels, as we have done elsewhere (Gilboa *et al.* 2004). Thus, the variability of an entire assemblage of vessels (e.g. a 'type') can be quantified in terms of the *uniformity* defined in **Equation 2**. We can thus compare two measures of uniformity, the *intra-vessel* and the *inter-vessel* uniformities, the former representing the quality of the production of single vessel, and the latter measuring the reproducibility of the manufacturing process.

To test this measure, two different assemblages of complete vessels were analyzed. The first is a collection of 16 bowls, which were picked randomly from the Tell Dor collection. Their dates span the period between the Early Iron Age and the Hellenistic period and therefore do not represent a homogeneous assemblage or a single morphological type. The second assemblage

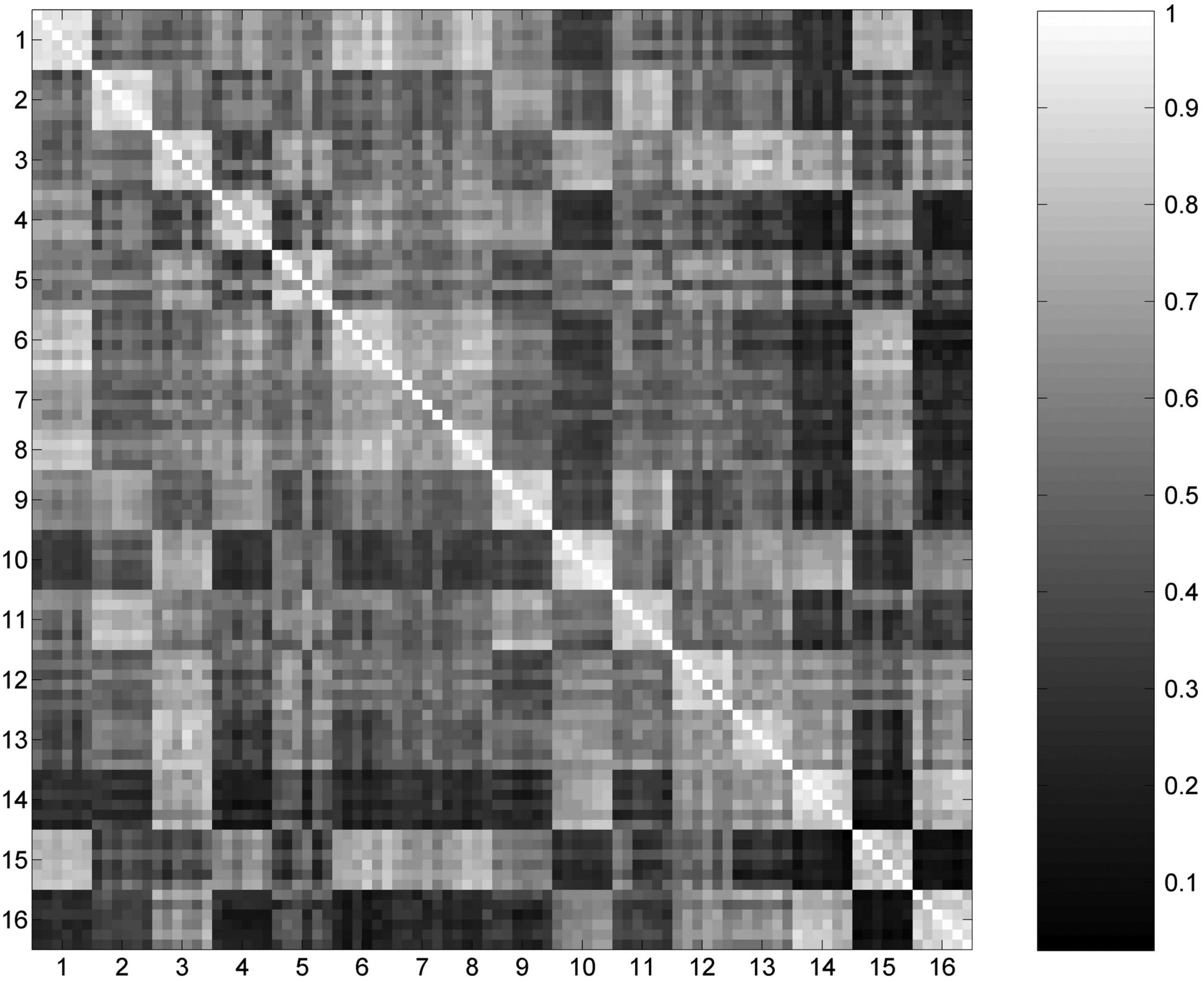



***Fig. 3***. *The correlations matrix of Tell Dor bowls. The index of the bowls is given along the axes.*

is composed of 11 flower pots, which were produced by a contemporary potter who uses the traditional kick wheel. This was used as a control group to represent an assemblage which is as homogeneous as wheel-made pottery can be. For each vessel, six section profiles were measured with an accuracy margin of  0.2 mm using a profilograph. Typical sections which illustrate the deviations from perfect cylindrical symmetry are shown in **Fig. 2**. These deviations were observed to be as large as several mm. While the profilograph is not a 3D scanner, it enables the extraction of several profiles from the same vessel. These profiles were judged to be good enough to test the method and the mathematical definitions which we have developed here. When a 3D scanner is used instead of the profilograph, more sections can be drawn and the accuracy of the method will be higher.

The correlations matrix of the bowls from Tell Dor is shown in **Fig. 3**. The columns and rows are arranged such that sections of each bowl appear consecutively (six per vessel, except Bowl 8 which is represented by only four sections). The value of the correlation of any two profiles is given by the gray level of the pixel at the intersection of the corresponding column and row. The numerical equivalents of the gray levels are provided by the bar at the right of the figure. The intra-vessel correlations are represented by the 16, 6 x 6 square matrices on the diagonal. The values of these correlations are usually higher than the inter-vessel

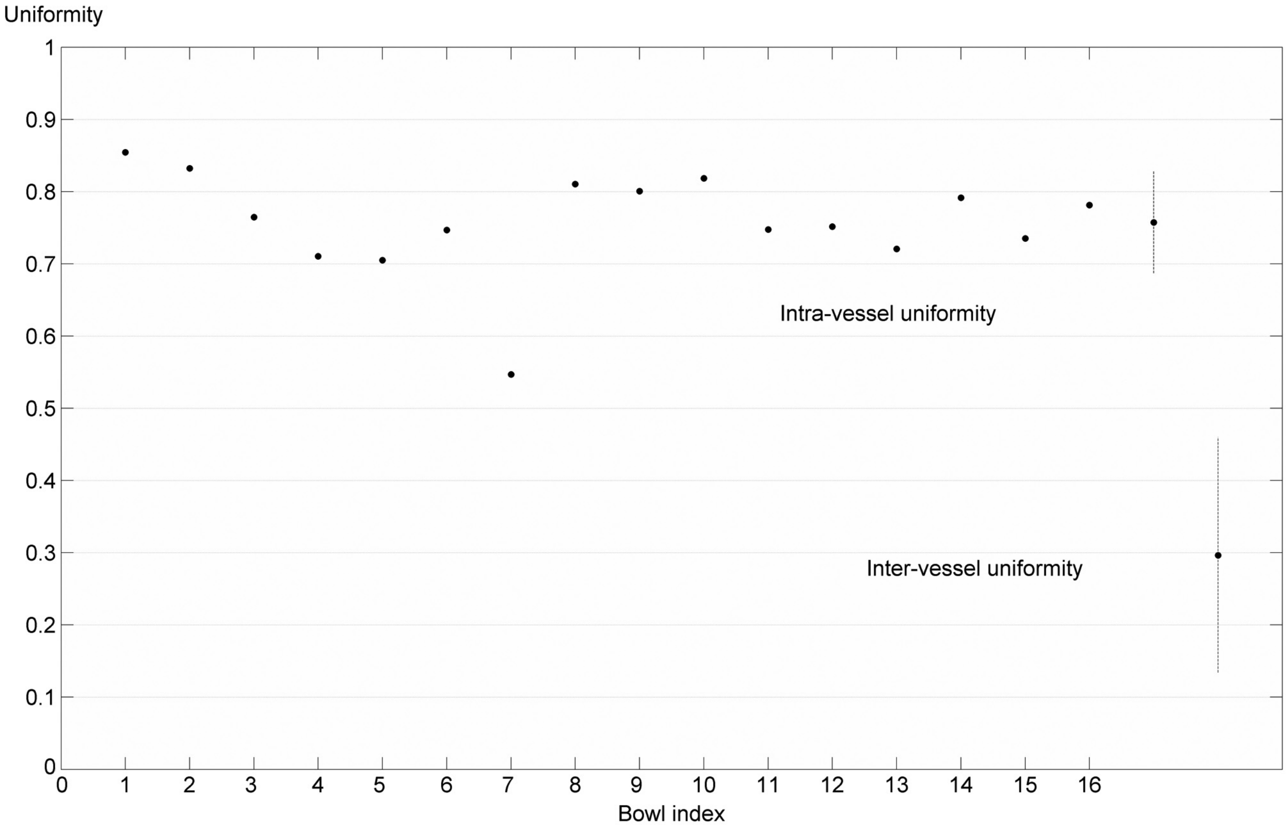



***Fig. 4.*** *Summary of the inter/intra-vessel uniformity values for the Tell Dor bowls.*

correlations, as can be seen by the lighter gray squares along the diagonal. Some high inter-vessel correlations do exist, for instance between the profiles of Bowls 1 and 15. On the other hand, the intra-vessel correlations are not uniform and darker pixels can be seen, for example in the intra-vessel matrix of Bowl 7.

We used the formulae of the previous section to compute the inter- and intra-vessel uniformity for the Tell Dor assemblage. The results are summarized in **Fig. 4**. The mean intra-vessel uniformity is about .75, with Bowl 7 being exceptionally non-uniform. The mean of the inter-vessel uniformity is approximately 0.3, i.e. much lower than the typical individual uniformities. This difference is consistent with the fact that the bowls were chosen randomly and do not represent a typologically homogeneous assemblage. Different results are expected in the analysis of a uniform assemblage, such as the flower pots. A preliminary inspection of those immediately reveals that most are deformed: their base and rim planes are not parallel and opposite profiles have different lengths, which might have been caused by the removal of the wet pots from the wheel using string. Nevertheless, the pots look very similar by eye. To give a quantitative description of the above observation we compared the pot sections, which were truncated at five levels shown in **Fig. 5**. The first level corresponds to the upper part of the pot, and the fifth level is the entire profile including the base. The truncated sections can be considered as representing rim sherds, and their correlations can be obtained by using the formulae of the previous section with minor modifications. The results of the inter/intra-vessel uniformity as a function of the truncation level are shown in **Fig. 6**. The most prominent trend in this illustration is that the inter/intra-vessel uniformities are rather high so long as the base is not included in the analysis. The numerical values of the inter-vessel uniformity are almost as high as the intra-vessel uniformity. The difference becomes larger when the complete profiles are considered. Thus quantitative analysis confirms the intuitive expectations

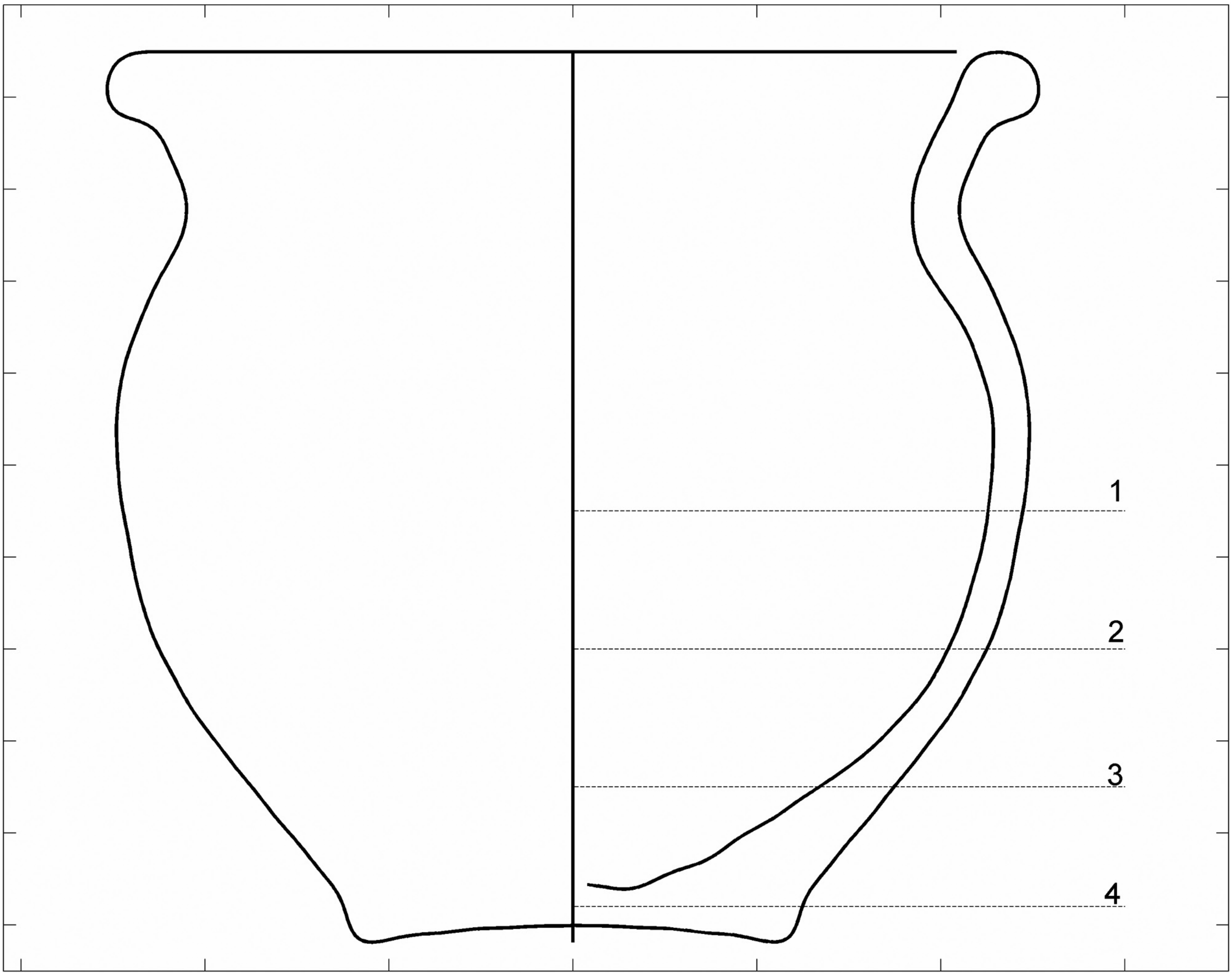


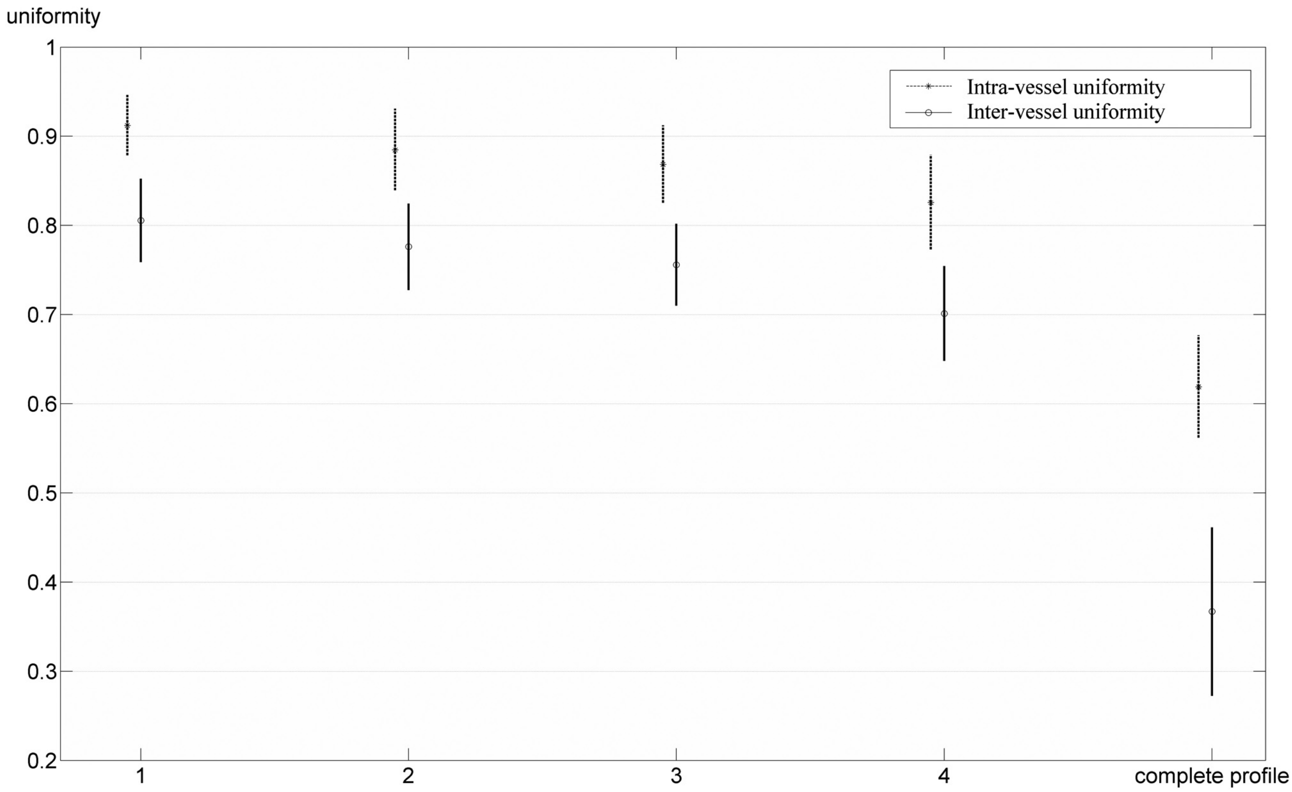

***Fig. 5.*** *Four truncation levels of a profile. The corresponding 'fragments' were analyzed separately.*

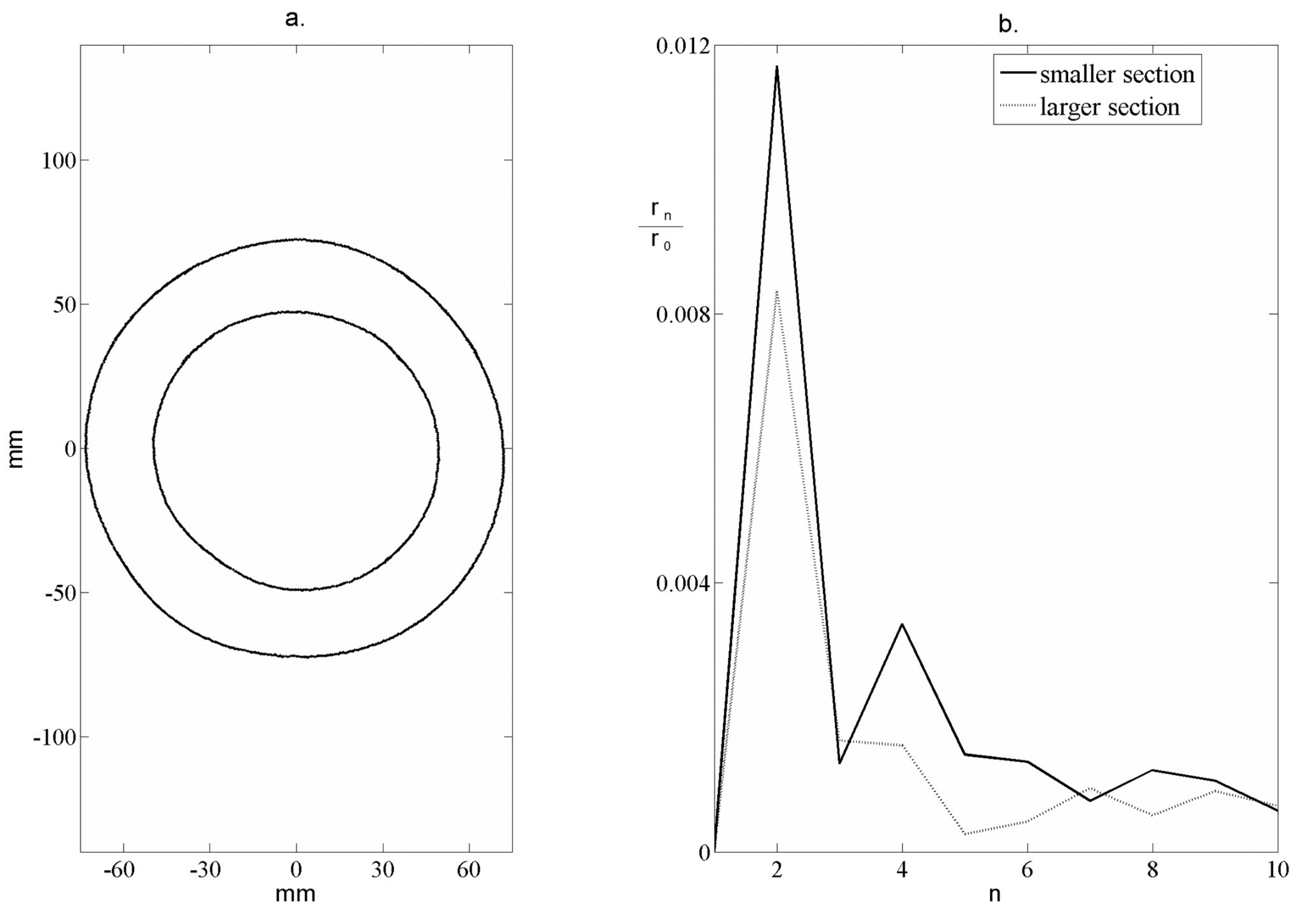
***Fig. 6 (right, top).*** *The mean and the standard deviation of the inter/intra-vessel uniformities for each section size of the flower pots assemblage. The smaller the section the higher the correlations.*

***Fig. 7 (right, bottom).*** *A. Two horizontal sections of the jug shown on the left in Fig. 8; B. the leading ten Fourier coefficients (scaled by* $r_0$*) of the sections shown in 7A.*

concerning this assemblage. In contrast with the previous assemblage, the similar values of the inter/intra vessel uniformities show that we are dealing with a typologically homogeneous assemblage.

Uniformity analysis can be very useful for the analysis of ceramic assemblages. For instance, two rim sherds found at a small distance from each other, but whose fracture lines do not match, may or may not belong to the same vessel. If two such sherds covering approximately the same fraction as 'section 1' of **Fig. 5** have a correlation of approximately 0.9, they might belong to the same vessel; whereas a correlation around 0.7 or less may suggest that the two sherds belong to different pots.


uniformity
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
1
2
3
4
complete profile
Intra-vessel uniformity
Inter-vessel uniformity


a.
100
50
0
-50
-100
mm
-60
-30
0
30
60
mm
b.
0.012
0.008
0.004
0
smaller section
larger section
$\frac{r_n}{r_0}$
2
4
6
8
10
n

### Deformation

A horizontal section through a pot with perfect axial symmetry should look like two concentric circles, representing the inner and outer surface of the vessel. Any deviation from this is a deformation. A quantitative measure of the deformations can be obtained by using the polar representation of the curves of the horizontal sections. **Fig. 7A** shows the curves obtained by measuring two horizontal sections of a jug using a 3D camera. The jug in question is a closed and complete vessel and therefore the 3D camera provided only the horizontal section of its exterior surface. As can be seen in **Fig. 7B**, the curves are certainly not the ideally expected concentric circles, to be explained below. The points on this curve can be specified by their polar coordinates ***(r(s), φ(s))*** relative to an arbitrary origin in the interior. For convex curves ***φ(s)*** is a monotonic function of the arc length ***s***, and one can describe the curve by the function ***r(φ)*** (Gero & Mazzullo 1984; Liming *et al.* 1989). If the point of origin is taken as the best estimate of the centre of revolution then for each angle ***φ*** (relative to some arbitrary line) ***r(φ)*** gives the radius of the section of the vessel at that angle. For an axially symmetric vessel ***r(φ)*** would be constant. A deformed vessel would represent some sort of a wave function as ***φ*** revolves around the section. Thus we can use the Fourier coefficients of ***r(φ)***

$$\hat{x}_n = \frac{1}{2\pi}\int_0^{2\pi} d\varphi \cos n\varphi \; r(\varphi) \quad ;$$

$$\hat{y}_n = \frac{1}{2\pi}\int_0^{2\pi} d\varphi \sin n\varphi \; r(\varphi)$$

to define the $n^{th}$ deformation parameter and associated phase by:

$$r_n = \sqrt{\hat{x}_n^2 + \hat{y}_n^2} \quad ; \quad \alpha_n = \arcsin\left(\frac{\hat{x}_n}{r_n}\right).$$

The deformation parameters are determined in an unambiguous way when the origin is chosen such that the coefficients $\hat{x}_1$ and $\hat{y}_1$ are zero. For simple shapes, this choice is equivalent to setting the origin at the centre of gravity of the curve. For an axially symmetric vessel, the centre of gravity is the axis of revolution and all the coefficients would be zero. The parameter $r_0$ is the mean radius, and it serves to set the scale (size) of the section. The first non trivial coefficients $(\hat{x}_2, \hat{y}_2)$ or equivalently $(r_2, \alpha_2)$ determine the parameters of the ellipse which fits the curve best: $\frac{r_2}{r_0}$ is proportional to the eccentricity and $\alpha_2$ is the tilt angle of the main axes of the ellipsoid relative to the coordinate axes. The higher order parameters provide information on deformations on smaller scales.

**Fig. 7B** shows the values of ten scaled Fourier $\frac{r_n}{r_0}$ coefficients for the sections shown in **Fig. 7A**. To demonstrate the potential value of the study of deformations in the archaeological context, a case study is discussed below, in which the deformation of the horizontal sections can yield information about manufacturing processes. Two contemporary but traditionally produced wheel-thrown jugs were scanned by a 3D scanner [**Fig. 8**, left]. This scanner provides a complete 3D digital representation of the studied object, from which the horizontal sections at various heights were computed (Sablatnig & Menard 1996; Adler *et al.* 2001). This detailed information was used to determine various quantities that are relevant to the shape of the objects and their deviations from cylindrical symmetry (Mara *et al.* 2004). Here I will only discuss the information provided by the ten leading Fourier coefficients computed for 45 different horizontal sections for each of the jugs.

Even though the two jugs look rather similar, their averaged scaled Fourier coefficients $\frac{r_n}{r_0}$ are quite different, as can be seen in **Fig. 9**; the right-hand jug is more deformed than the one on the left. A detailed investigation (below) reveals that the deformation is not uniform along the jar, which indicates that different parts underwent different types of stress and pressure before the final shape was set. To reach this conclusion, deformations were analyzed by dividing the 45 horizontal sections into four groups [**Fig. 8**, right]:

- The neck (upper eight horizontal sections).

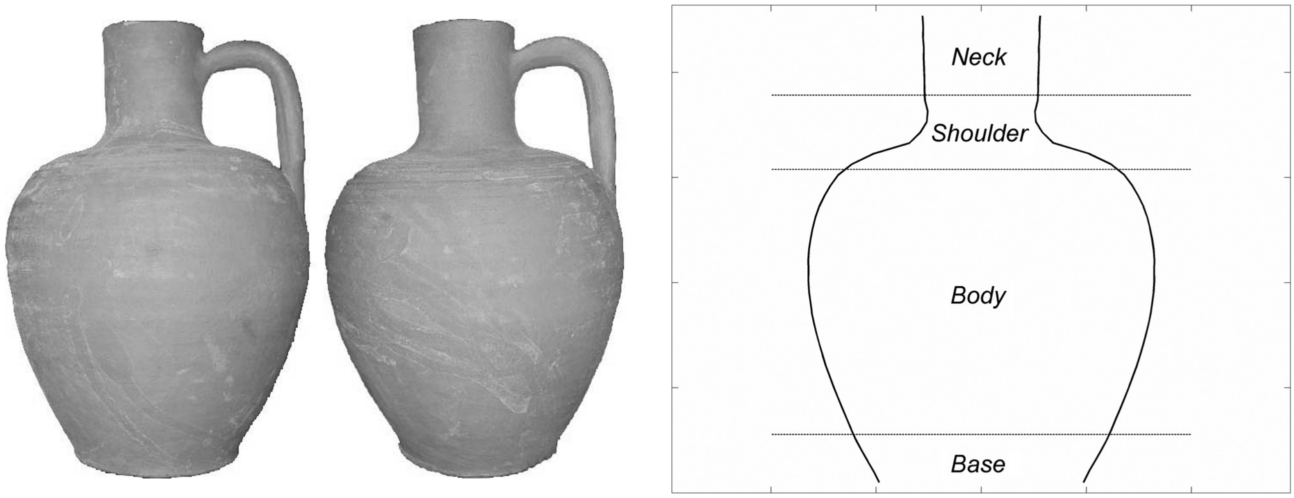



***Fig. 8.*** *Two similar wheel-made jugs from the market of Vienna, left; a plan view of a jar where the four regions used in the current study are indicated, right.*

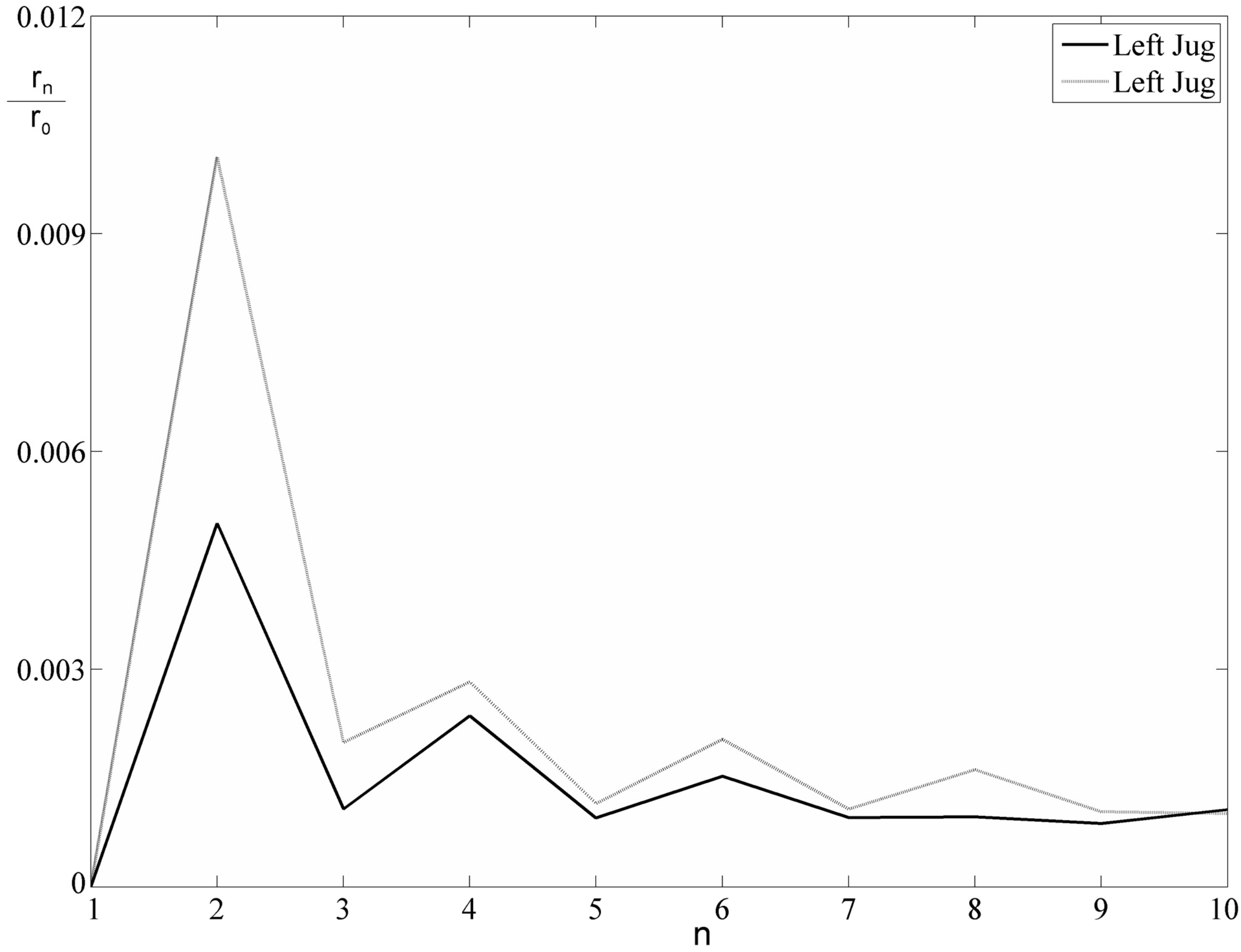



***Fig. 9.*** *The mean scaled Fourier coefficients averaged over the entire height.*

- The shoulder (the next seven sections).
- The body (the next 25 sections).
- The base (the lowest five sections).

Since some horizontal sections include the handle, the points on the 180° arc opposite the handle were used. The mean scaled Fourier coefficients for each group were computed, and they are shown in **Fig. 10**. The lowest coefficients for both jugs are to be found on the body section. Therefore, the bodies of the two jugs are the closest to perfect circles. This implies that the deviations from perfect symmetry were not caused by external pressure caused, for instance, by placing too many vessels in the kiln. Moreover, if the potter could produce such symmetric vessels with maximum deviation of about 0.5% of the radius, he/she was probably well-trained and the wheel used was well-balanced. The right-hand jug is more deformed as far as the neck and shoulders are concerned, although its base is less deformed than the base of the other jug. On the other hand, the base of the left-hand jug is more deformed than the one on the right jug (although on a smaller scale). Previous analysis showed that the most significant deformation of the neck is probably due to the attachment of the handle, which was pressed onto the still soft neck. The difference between the two neck deformations can be explained by the application of stronger force when the potter attached the handle to the right-hand jug. Such action affected the circular symmetry of the vessel, but preserved the mirror symmetry about the line that crosses through the handle. Indeed, when the phase of the best-fitted ellipse to the neck of the deformed jug was computed, it was found out that the axis of mirror symmetry crosses exactly through the handle area, which corresponds to our assumption (Mara *et al.* 2004, for further details). The deformation on the base is probably the result of the removal of the vessel from the potter's wheel. Even if the potter produced similar vessels, as suggested by the low deformation values of

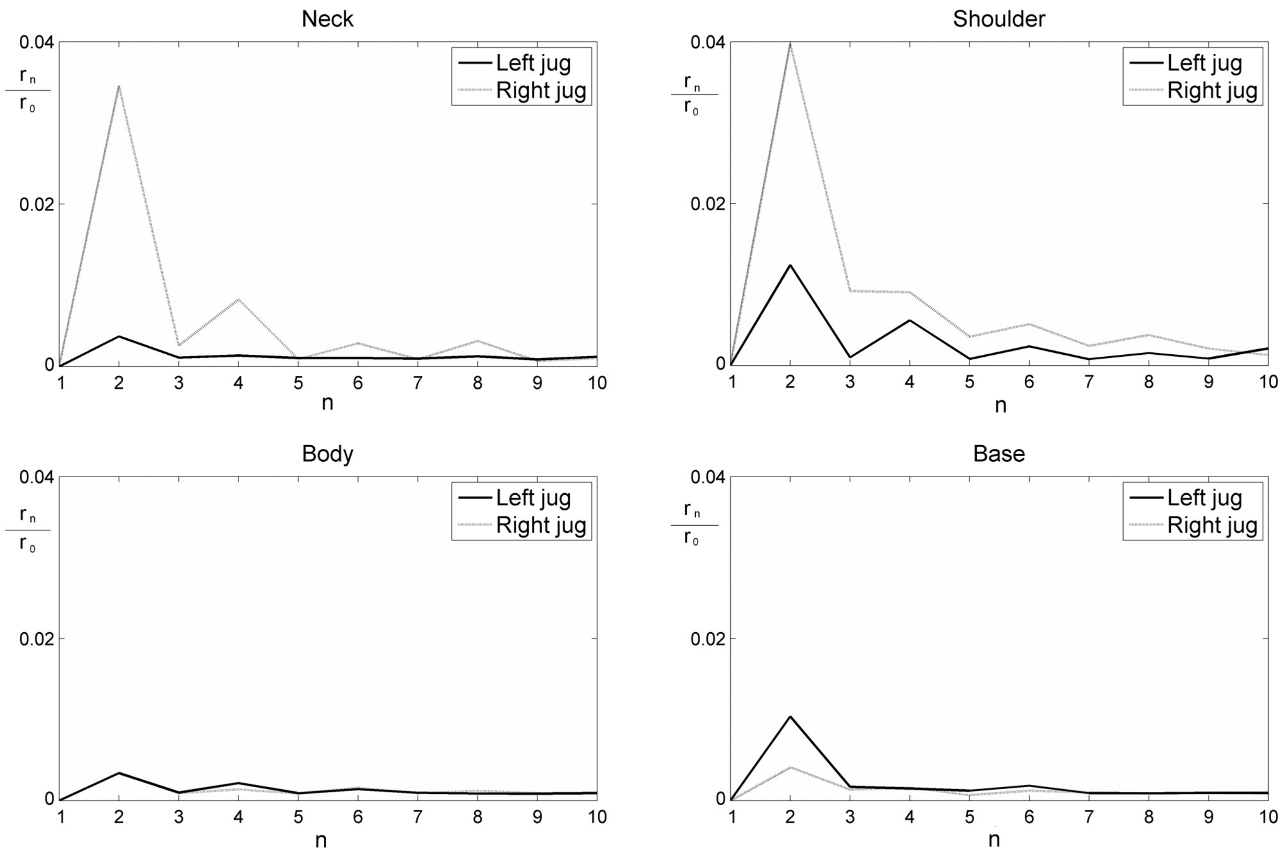



***Fig. 10.*** *The normalized Fourier coefficients for the separated parts of the two jugs.*

the body, he/she deformed them in different ways while adding decoration, handles, or string-cutting the base to remove the pot from the wheel.

## *Summary and conclusion*

In this paper I have traced the development of 3D analysis of pottery to date, and described two new quantitative tools. One evaluates the uniformity of a single vessel versus that of a vessel type. The other measures minute deformations—differences among vessels hardly detectable by eye. The value of such tools will only be apparent once they are applied to larger assemblages and real archaeological problems, but certain questions already spring to mind: can one assess the motor skills of individual potters using uniformity? Does uniformity improve with practice? Can a professional potter create an assemblage where inter-vessel uniformity equals intra-vessel uniformity? Can uniformity be used to differentiate between mass production and home-based industries? Can it be used to differentiate between a 'type' or 'tradition' in general and the production of a single workshop or even a single potter within a workshop? Can we use uniformity and deformation to differentiate between handmade and wheel-thrown vessels? Or distinguish between a fast wheel and a tournette? Further, can we identify preformed sections of composite pots?

The analyses proposed here are but the tip of the iceberg. Since this is an emergent technology, and the amount of information in an accurate 3D model vastly supersedes that encoded in a 2D section drawing, it is only a matter of time until new methods to mine such additional information will emerge, to highlight more general issues such as technological and cognitive capabilities, motor skills, production centres, and perhaps even identify individual potters in the archaeological record. In the next decade the number of excavations using 3D scanning devices for pottery drawings will increase dramatically—if only because the production of 3D models is so much faster and more accurate than that of a hand-drawn profile. Right now 3D scanners are still prohibitively expensive, but this will surely change, and soon archaeological institutions and even individual archaeologists will find such a tool to be indispensable. The challenge is to be able to use the full potential of this modern technology in order to improve our understanding of the past.

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