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GEOMETRICAL 3D LASER SCANNER MODEL OF A CHALCOLITHIC VESSEL (GOR, GRANADA, SPAIN)

1. Introduction

The technology of 3D laser scanning has been applied to archaeological research to construct geometric scanner models with different characteristics. Most archaeological work has been carried out to digitalize objects of an intermediate size, such as settlement structures, sphinxes, statues, etc. The most recent works have been focused on modelling structures during the excavation of archaeological sites, either of only one zone (Doneus, Neubauer 2006) or the complete ensemble (Gaisecker 2006). These studies have been carried out from the ground surface or using a mini-helicopter (Eisenbeiss 2005).

Other authors have used stratigraphic analysis (Doneus *et al*. 2003), and in one case the remains of a house built with whale bones in Thule at the end of the 12th century have been scanned, and this information then used for the computerized reconstruction and the structural analysis of this house (Levi, Dawson 2005). Other objects have been registered digitally, mainly for documentation and reproduction, such as statues (Koller *et al*. 2004), relief sculpture, fragments of walls, or of Roman ships (Boehler, Heinz, Marbs 2001).

The scanning of small archaeological artefacts has special characteristics due to the texture of the material, the concavities and convexities of the internal surface, the damage, and the necessity of fitting the inner and the outer surfaces. Once the different scans are integrated, the 3D image provides archaeological graphics such as vertical, horizontal, and oblique profiles and sections, providing other relevant information including textural data, damage, technical surface treatment, etc. Also, the model provides a metric and geometric analysis such as morphometric dimensions, the mean width, the features of the inner and outer areas, the centre of masses, the inner and outer volumes, the volume of clay used by the artisan, the regularly spaced contour levels of the interior and exterior.

In this paper a spherical Copper Age pot from the Las Angosturas settlement (Gor, Andalusia) was studied using a 3D laser scanner. This vessel was digitally modelled to view the sections at different levels, to determine their metric and geometric characteristics, to analyse some of the constructive characteristics, and to propose an ideal model for this vessel.

2. The 3D laser-scanning technique

The high-definition 3D laser scanner is an instrument that collects 3D data from a given surface or object in a systematic, automated manner, at a relatively high rate, in near real time using a laser ray to establish the surface coordinates. Traditional methods such as tapes and theodolites, and more modern technology such as total stations and GPS, provide accurate but relatively slow and cumbersome methods for gathering spatial data, and their use to scan small objects is not feasible. High-definition survey devices such as laser scanners are able to sample at rates that were previously impractical, resulting in highly detailed data and, correspondingly, very large datasets.

Three-dimensional scanning technologies are generally based on one of three methods having different technical characteristics and operational modes (Boehler, Heinz, Marbs 2001):

– Time of flight. With this technique a laser pulse is emitted from the instrument and the time of flight is measured, from which the distance to the object can be determined.
– Phase comparison. The instrument emits a beam of light with a known frequency and phase and by comparing the emitted phases to the returned phases the distance to the object can also be determined.
– Triangulation. This system uses two sensors which simultaneously record the reflected laser pulse and determines the dim.

Three-dimensional scanning can be broken down into two classes of instruments based on the optimal distance of the sensor. Long-Range LIDAR technology was initially developed as a tool for the creation of as-built drawings in complex retrofit and construction projects such as oil refineries (where the intricate infrastructure would render traditional surveying techniques inadequate). Typical distances of long-range systems vary from a minimum of one to two meters to a maximum distance of hundreds of meters. This breadth and resolution makes long-range scanning systems suitable for the recording of architectural-scale features and objects. The use of 3D scanning in cultural heritage is relatively new, but is equally applicable to the technique.

3. Materials and methods

The material consists of a small ceramic pot, with a spherical shape and handles on the sides, found at Las Angosturas (Gor, Granada, Spain), a Copper Age settlement located in the Betic mountain range at 1150 m a.s.l. The cultural features and the archaeological remains indicate that the settlement belongs to the "millariense" culture, which has its origin at Los Millares Chalcolithic settlement (Santa Fe de Mondújar, Almería, Andalusia). The pot, measuring 9.7 cm high and 11.15 cm mouth diameter, was made by hand and subjected to a faulty firing. Its colour is greyish with blackish parts due to the firing process, and the surface is polished except for the damaged parts. Although there are no studies of absolute radiocarbon dating, the settlement has a stratigraphic sequence from Later Copper Age to Middle Copper Age.

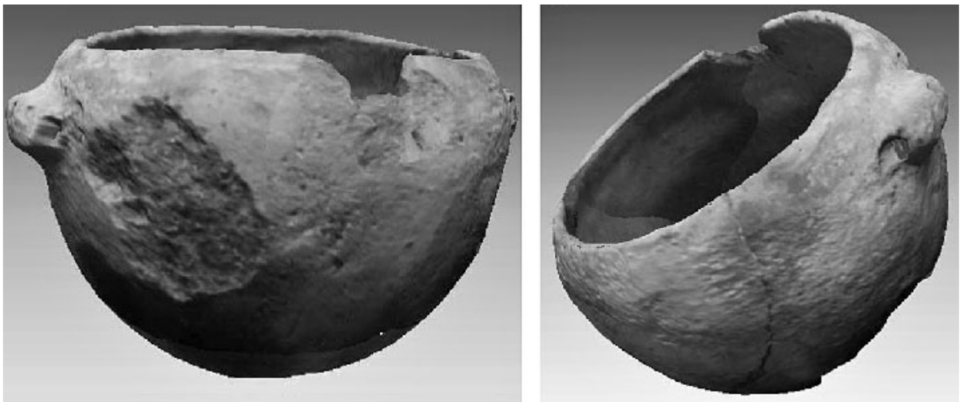


Fig. 1a-b – Vessel showing the cracks due to the surface damage and the breach on the rim.

Distance to object	0.6m-1.2m
X-Direction Input Range	111 to 463mm (lens f=25mm) 198 to 823mm (lens f=14mm) 59 to 1196mm (lens f=8mm)
Y-Direction Input Range	83 to 347mm (lens f=25mm) 148 to 618mm (lens f=14mm) 269 to 897mm (lens f=8mm)
Z-Direction Input Range	40 to 500mm (lens f=25mm) 70 to 800mm (lens f=14mm) 110 to 750mm (lens f=8mm)
Input time	0.3 sec (FAST mode) 2.5 sec (FINE mode) 0.5 sec (COLOR)
Coordinate precision	+/-0.008mm (Condition: FINE mode, Minolta's standard)

Tab. 1 – Laser scanner Minolta VI-910: technical specifications.

The small vessel was found in a good state of conservation, although it presents some damage on the external surface and shows substantial losses of material along the rim, presumably due to use constantly in contact with fire (Fig. 1a-b).

This vessel was scanned using a high-resolution laser scanner Minolta VI-910 (Tab. 1) designed for use on small objects. This scanner uses an automatic device that allows the object to be rotated and computes the coordinates of the scanned images. In each rotation the coordinates of each image are computed and, when concluding, a mathematical process can be applied to establish a georeferenced model with respect to a common coordinates system. The scanner dataset was processed using the Rapidform 2004 PP2 software by Inus Technology which easily transforms the raw data into a polygon and offers many analytical functions.

For the visualization of the 3D model, we made six images of the lateral surface of the vessel with a 60° rotation angle covering the entire lateral surface. The scan ended with eight additional images: two views of the bottom exterior and six views of the bottom interior from the top, providing a complete set of images to cover the entire vessel. The cloud of points was recorded and processed to construct the shells that complete the image of the entire vessel, including the information of external and internal sides as well as the information of the width. Furthermore, these shells previously recorded were linked and then merged in a single shell by means of geometric triangulation that constitutes the 3D georeferenced model of the vessel. This 3D model enabled us to carry out a different analysis of the metric and geometric patterns of the vessel, achieving high-resolution images (1024 pixels) with high coordinate accuracy and offering detailed images and a process to fill the damaged zones with non-preserved material.

4. IMAGE TRANSFORMATIONS

The first process was focused on creating a suitable image without the holes (computational artefacts) produced by scanning and 3D triangulation. The entire image was processed to a polygonal optimisation and modelling using geometric triangulation to produce continuous polygonal meshes composed by triangles with a resolution of 2048 pixels. Furthermore, the application of the tools to detect the surfaces bearing irregularities and the abnormal points, by scanning, deletes topological objects that could cause severe errors in calculations such as 1) non-manifold with three or more edges faces; 2) crossing faces resulting from edges sharing vertex intersecting; 3) faces with auto-intersections; 4) faces with normal vector reversed with respect to the faces in the neighbourhood; 5) redundant faces; 6) unstable faces having one side and one loop like a Moebius Strip; and 7) scanning peaks.

Topologically correct triangulation enabled us to detect the holes produced in the scanning process and to fill them using the texture of neighbouring zones (Figs. 2-3).

The resulting shell was processed using standard methods from 3D image analysis. First of all, the coloured image was transformed into an image of the vessel with the original colour modified using metallic colouration. This process provides a homogeneous texture to study any major archaeological features such as the technological manufacturing process (surface polishing mainly), the zones with flaws, the holes in the surface, the zones with faulty or irregular application of fire, etc. (Figs. 4-6).

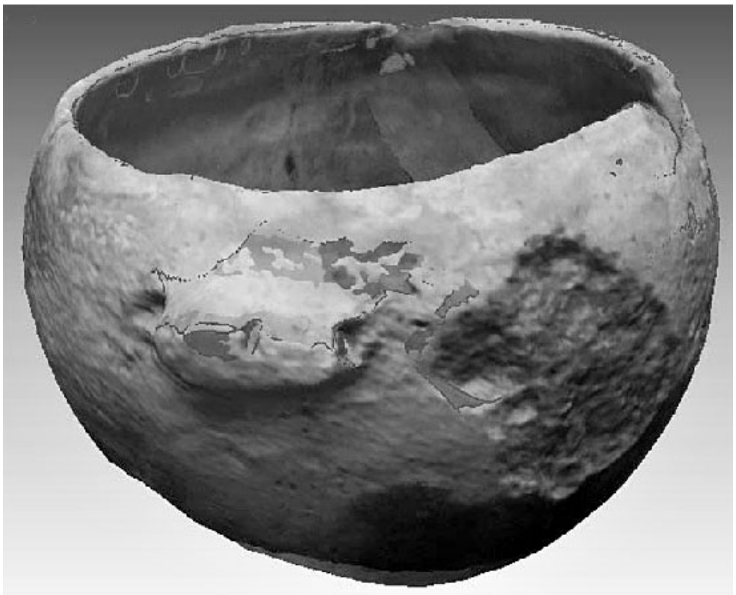


Fig. 2– Detection of holes produced by the triangulation process.

Fig. 3 – Vessel after the hole-filling application.

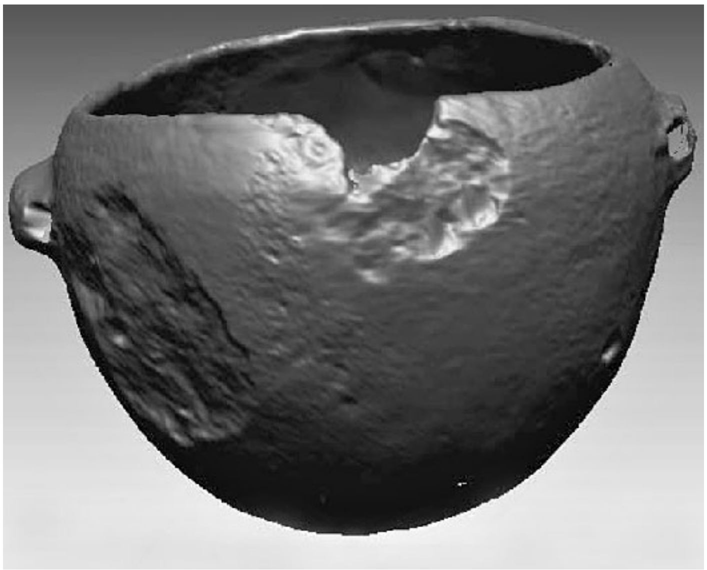


Fig. 4 – The faults due to manufacture and use, showing the border holes without clay.

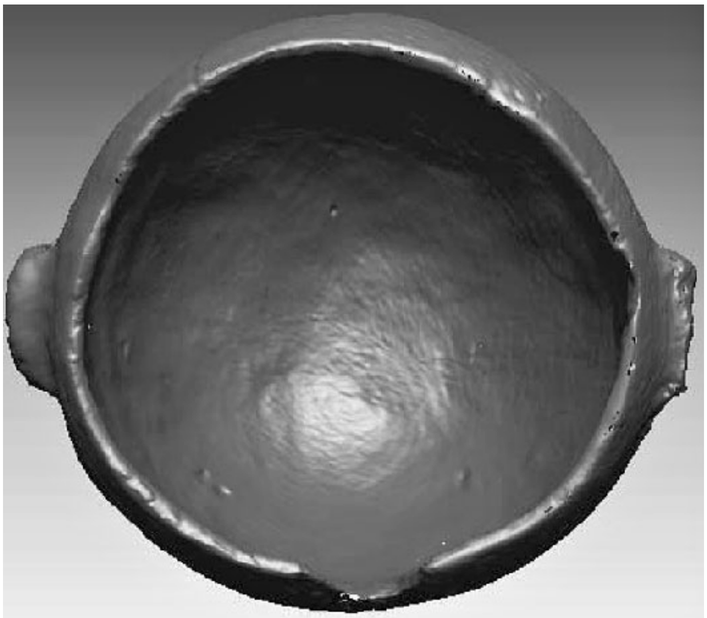


Fig. 5 – The vessel was polished to great perfection.

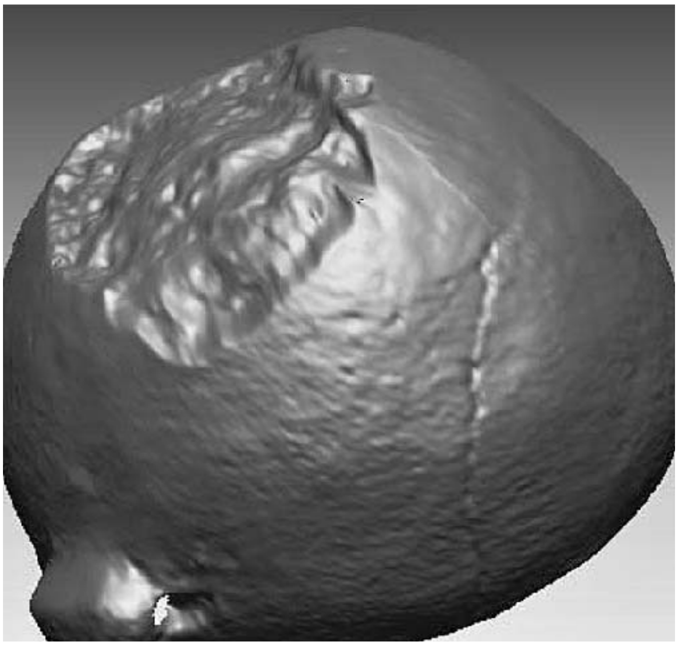


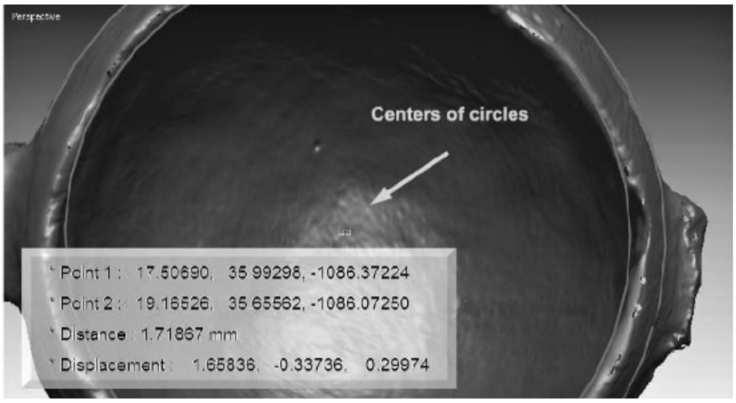
Fig. 6 – Vessel bottom showing many flaws such as cracks and the absence of clay.

5. METRIC AND GEOMETRIC FEATURES

Pottery vessels during the Chalcolithic period were handmade. However, this did not prevent the artisans from using an accurate technique in the design as well as the technological aspects and the treatment of surfaces, mainly polishing. Once the polygon model is built, it is possible to use the tools provided by the 3D software to establish some parameters of great archaeological importance in connection with typological patterns, functionality, and the production of this vessel.

The basic geometry of this vessel was found to be based on the circle, both in the rim as well as in the widest part, and this figure provides the guideline for the entire vessel. For the analysis of this geometric pattern, an ideal circle was superimposed on the rim, providing an almost perfect fit between the ideal circle and the real vessel. Another ideal circle was drawn and adjusted to the maximum width, discounting the two handles, and the fit to the real vessel was again almost perfect (Fig. 7). Also, both circumferences were almost perfectly concentric, their being centres located at two points very close

Fig. 7 – Ideal circles drawn on edge and on the maximum width.



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* Point 1 :   17.50690,   35.99298, -1086.37224
* Point 2 :   19.16526,   35.65562, -1086.07250
* Distance : 1.71867 mm
* Displacement :   1.65836,   -0.33736,   0.29974
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Fig. 8 – Centres of the two circles that determine the basic geometry of the vessel.

together: the coordinates were equal and the distance between them was only 1.7 mm, demonstrating the precision of the potters that lived in this settlement (Fig. 8). The knowledge of metric and geometric concepts in the Chalcolithic period was indicated with respect to the entire Chalcolithic society, mainly

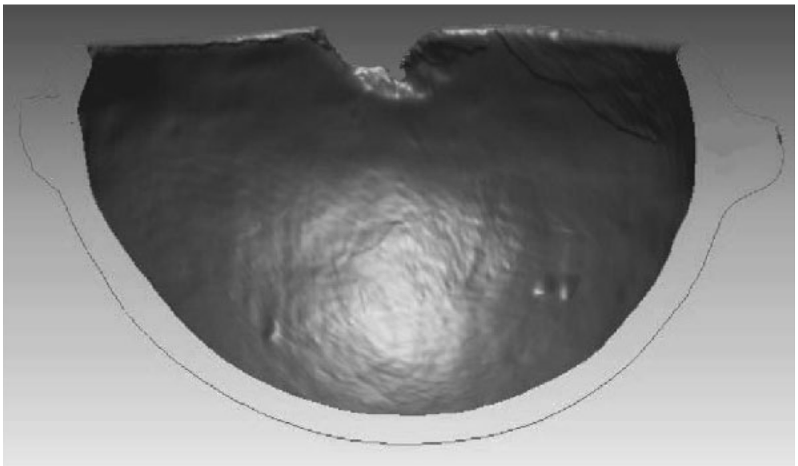

Fig. 9 – The profile of vessel is drawn from the polygon model.

the architecture of dwellings, the monuments, and the fortified towns having great constructive complexity (Esquivel, Navas 2005, 2007).

The construction of a high-resolution polygon model (1024×1024 pixels) provides results of great archaeological importance, revealing the design with detailed metric and geometric parameters. Based on this geometric model, the profile of the vessel has been traced and, besides the obvious archaeological interest, reveals that the pot has a notable width with respect the height (Fig. 9), as the index between the maximum height and the mean width i=8.14 is quite a low value.

Using the profile provided by the polygon model, we made a detailed statistical analysis of the width taken from a random sample of size n=14 along the profile of the vessel (except the handles), finding a mean width $\bar{x}=6.54$ mm and standard deviation $\sigma=0.493$. The t-Student test, applied to fit a random sample to a dataset, revealed no statistical significant differences between the width of the vessel at any point with respect to the mean width (t=0.00012, a=0.997) (Sokal, Rolf 1982; Venables, Ripley 2002).

The coefficient of variation ($CV=\frac{\sigma}{\bar{x}}$) was 7.5% according to a standardized production method to determine a homogenous width. The application of the mathematical expression to compute the confidence interval of the mean of a population from a random simple with size n (Sokal, Rolf 1982; Venables, Ripley 2002) gave:

$$\mu \in \left(\bar{x} - Z_\alpha \frac{\sigma}{\sqrt{n}}, \bar{x} + Z_\alpha \frac{\sigma}{\sqrt{n}} \right)$$

Width of B. Box:	152.33830 mm
Heigth of B. Box:	177.27035 mm
Depth of B. Box:	127.15040 mm
Center of Model:	0.29179, 34.07790, -1047.46542
Center of Mass:	3.84235, 16.81212, -1050.88178
Area of Model:	77908.45287 mm^2
Volume of Model:	243355.17128 mm^3

Tab. 2 – Metric parameters provided by the polygon model.

with Z_α being the value of a normal distribution with mean=0 and variance=1 N(0,1) for the significance level α. In this case, it was found that the mean width for the entire vessel was within the confidence interval (6.28, 6.80) with significance level α=0.05, giving a 0.6 mm width variability. In practice this value is zero and constitutes evidence of the level of perfection and skill of the potters in producing clay vessels during the Chalcolithic period.

Using the 3D software, the computation of transversal sections allows us to reproduce the shape of the entire vessel. The contour lines represent zones of equally high values and are derived from the transversal sections. These contour lines are concentric both on the internal as well as external surface, but on the exterior defects appear while the damaged areas lack material (Tavv. VIa-b). These results provide new evidence that confirm the skill of the artisans of Chalcolithic period in manufacturing pottery vessels, fitting the real vessel to a geometric model.

Furthermore, the software provides valuable parameters to study the technological features and the geometric values as the measure of the area of model, the volume of model, the centre of masses, and the dimensions of an adjusted box. The complete model is used to compute the volume of the clay (Tab. 2), and the inner volume 439905.75101 mm^3 is determined using the interior surface only.

6. Conclusions

The use of the 3D laser scanner provides valuable results in archaeological research, both to make computerized drawings as well as to analyse the technological characteristics and the design of the archaeological artefacts. Features such as the easy acquisition of the 3D data, the construction of a 3D model providing the complete visualization of the objects, the drawing of the external and internal profile, etc. constitute a major advance in the study of archaeological objects, because the fit between the computerized model and the real object is very good, but depends on the characteristics of the hardware. In this paper, a Minolta VI-910 laser scanner was used, this offering great precision for the acquisition of the coordinates (0.008 mm) and rendering very reliable results.

In the present study, this technology was applied to a small pot from the prehistoric Chalcolithic period. The result was a raw cloud of points, and a computerized polygon model based on triangles was designed and developed. From this polygon model, several key technological characteristics such as the texture of the surface, the design of the handles, etc. were analysed. Also, we studied the areas with deficiencies in the material that have produced the break in the walls and the appearance of cracks due to use of the pot to cook in continuous contact with the fire.

During the scanning process, the coordinates are stored with great accuracy and this feature allows us to study some important metric and morphometric characteristics. The profile was computed by selecting a random sample of points (size n=14) on the surface and measuring the width. The t-Student test revealed no statistical differences between the points of the vessel, indicating great skill in controlling the thickness of the pot. The confidence interval shows almost zero variation (0.6 mm) as a consequence of metric precision in the design and the handmade production. This is significant in relation to the skill of the artisan in producing a vessel with the same width over the entire surface, thus eliminating irregularities that could cause damage. Furthermore, the symmetry in the design is essential to increase the resistance of the object, showing that in the Chalcolithic period these principles were already known and applied at least in pottery making.

The ratio between the maximum height and the width was quite high, indicating that, although the quality of the clay was not good (as reflected by the areas separated from the vessel), the artisan sought a final result with greater resistance based on increasing the width of the walls. The use of the pot as a cooking vessel, either hung by the handles with ropes or placed directly on the fire, required a considerable width to resist the wear caused by the heat.

Metric and geometric concepts during the Chalcolithic period were not just applied to pottery but also to a large part of the designs of this period, as in the construction of dwellings, of fortified towns, of monuments, etc. People living in this period, at least in south-eastern Spain, had a basic knowledge of geometry and metric patterns, possibly in an empirical way, thus providing basic but important mathematical thought (Esquivel, Navas 2005, 2007).

3D laser scanner technology is also useful for the study of other archaeological objects such as skulls, stone tools, and bone tools. A possible future line of research might be the identification of pottery fragments by means of the contrast and comparison with typological patterns previously computerized. This model can automate the typological classification and quantification, both of the vessels without damaging them, as well as fragments, by constructing the specific databases for each category of archaeological artefacts and each chronological cultural period.

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ABSTRACT

The most recent computer technologies of 3D geometrical modelling provide a great quantity of tools for archaeological investigation. This paper presents an application of the 3D laser scanner to study the metric and morphometric parameters of a Chalcolithic pottery vessel based on a 3D meshed triangular model. This model is referenced geometrically by high-precision fitting to the real object, enabling the study of some of the most important archaeological characteristics with great accuracy (texture, damage, profiles, etc.) as well as a reconstruction of those damaged parts. The computerized model has been used to study the metric and geometric parameters of the vessel, applying different statistical tests to analyse the width of vessel and the variability of some constructive parameters. These analyses allow us to compute any measurement, such as the surface area of vessel, the center of masses, the volume, and the regularly spaced contour levels of the interior and exterior. The results indicate the skill of the potters of the Copper Age and their knowledge of some elementary mathematical concepts of geometry and metric.