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On the Interactive 3D Reconstruction of Iberian Vessels

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Abstract

Reconstructing vessels from sherds is a complex task, specially for hand made pottery. That is the case of the Iberian vessels. The reconstruction process can be done in three steps: orientation of the sherd, computing the symmetry axis and detecting the profile. This paper presents methods to accomplish these three tasks in a semi-automatic way. This algorithm has been implemented within a reconstruction application that has been successfully used to reconstruct Iberian pottery.

Categories and Subject Descriptors (according to ACM CCS): I.3.8 [Computer Graphics]: Applications

1. Introduction

One of the more tedious tasks after an archaeological excavation is to manage the thousands of small fragments of pottery that may appear on the site, trying to select those which offer more information so as to be able to reconstruct the original shape of the vessels, to draw them and take the measurements necessary to classify the pots. Once the sherds from a vessel have been selected, the reconstruction process can take about fifteen minutes, and involves five steps:

1. *Orientation*. The sherd is placed on a table, with its rim completely in contact with the table surface. In this position, the vertical projection of the sherd is measured; the sherd is orientated by placing it in such way that the vertical projection is the same as the previously measured (Figure 1.a)
2. *Diameter estimation*. Carried out using a rim chart (Figure 1.b), i.e. is a set of concentric circles drawn on a sheet of paper. The diameter of the vessel at the rim is the diameter of the circle that best fits the external arc of the rim.
3. *Profile extraction*. The profile, which is the cross-section of the fragment in the direction of the rotational axis of symmetry [3]. To extract the profile, the expert uses a calibre, and measures the width of the sherd at different positions (Figure 1.c)
4. *Drawing*. Based on the measures taken previously (diameter, vertical projection, profile), an artist makes a pen-and-ink drawing, following a standard that establishes the appearance of the drawing: lighting and shading, stippling lines, textures, etc. as shown in figure 1.d
5. *Documentation and Classifying*. Taking measurements like the diameter at different heights, rim angle, etc., and recording them into a database, the archaeologist can classify the vessel in a typology.

Classifying ceramics allows archaeologists to distinguish between chronological and ethnic groups. Furthermore, ceramics are used in economy history to show trading routes and cultural relationships [7].

Several studies have shown that the error made via this procedure can be estimated at $\pm$15% [4].

We work with fully hand made pots, made without potter's wheel. These pieces have a lot of surface and rim irregularities (see figure 2).

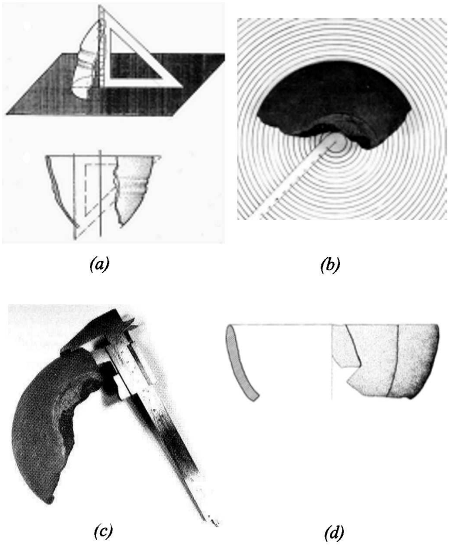

Figure 1: *Steps of traditional pottery reconstructing: a) Orientation, b) Diameter estimation, c) Profile extraction, d) Drawing. (From [4])*

(a) (b)

Figure 2: *Hand made Iberian vessel (a) and sherd (b)*

2. Proposed method

Briefly the reconstruction process aims to find out the revolution axis of the original pot and its profile. From this information it is possible to build a complete 3D model of it.

We have designed a software tool to carry out this task in a semi-automatic way. The software has been developed under the Windows platform, using C++ as programming language and OpenGL as graphic library[1].

One of the aims of this software is that the archaeologist should feel comfortable working with it. The goal was not to build "perfect" software, leaving no freedom to the expert to interact in the reconstruction process, giving the solution without taking into account the archaeologist's experience and knowledge.

Therefore, our system follows the same steps as in the traditional procedure, but using an interactive process that works with a 3D model of the sherd (Fig. 3).

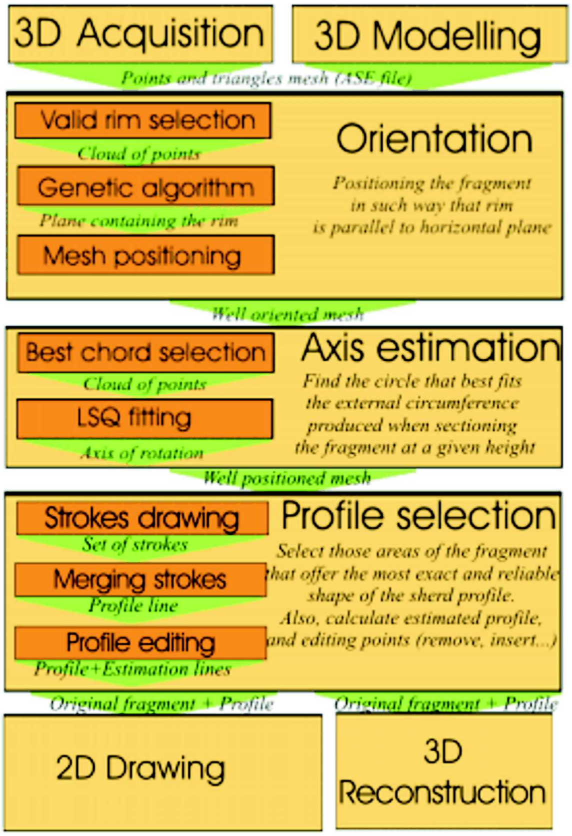

Figure 3: *Scheme of the proposed method*

The process begins capturing the sherd using a 3D scanner that generate polygonal surface of it, and then manipulate it with the software. The tool can load 3D meshes in .obj, .3ds or .ase formats.

The second step is the orientation of the sherd. Orientating a sherd merely involves finding the plane that contains its rim and rotating the sherd in such way that the plane is parallel to the XZ plane. Note that this implies using a sherd that contains part of the vessel rim. Working with hand made vessels make this process more difficult, as its rim is not uniform. We solve this problem making the manual selection of the relevant part of the rim.

Once we have oriented the sherd, we can intersect it with a plane parallel to the rim plane. This intersection must be a circle arc, whose centre is on the symmetry axis. So computing this centre we can build the symmetry axis. Once again, the non-uniformity of the pieces poses special difficulties on this process.

Finally we draw the profile of the sherd on the 3D model of the sherd. This profile is projected onto a plane containing the axis, producing the 2D profile of the vessel. Here, the non-uniformity, together with the form of the sherd makes it difficult to use as profile the intersection of the sherd with a vertical plane. We have decided to use a semi-automatic method, allowing to draw the path that generate the best and longest profile over the 3D drawing of the sherd.

This paper presents a detailed description of the algorithms used for the orientation, axis estimation and profile generation of the sherd. These algorithms have been successfully used for the construction of a software application. The practical use of this tool has been previously presented at CAA Conference 2003 [5].

3. Orientation

Orientating a sherd involves finding the α plane that contains the rim and rotating the sherd in such way that the α plane is parallel to the XZ plane.

The input to this process is a subset of rim points. To avoid distortions produced by irregular part of the sherd, the user must select the area of the rim that is useful for this step (Fig. 4), seeking to avoid noisy parts of the rim like bubbles, breaks and other irregularities. This area is used for generating the population of the GA and finding the plane.

This problem may be solved via Least Squares Fitting or other statistical or mathematical methods.

We have chosen Genetic Algorithms, as they are a more flexible approach [9],[6]. These algorithms are easy to implement and allow one to change the goodness criteria, it being possible to make the method more robust by adding constraints to these criteria (e.g., the incident axis of the surface normals).

A genetic algorithm is based on a set of individuals, each one defined by a chromosome, which is a solution for the problem at hand.

Genetic algorithms are very flexible, allowing to solve a problem using difference approaches, changing either the representation of the chromosomes, the goal function, or the type of genetic algorithm used.

We have used different approaches to solve the orientation problem both for the codification of the genes and for the goal functions. We have used two codifications for genes:

- *Real genes*. The chromosome are composed of four genes (A,B,C and D), that correspond to the four coefficient of the ‘plane equation (Ax + By + Cz + D = 0). This approach was abandoned as, for the mutation and merge criteria used, we do not get convergence in real cases.
- *Discrete genes*. A chromosome composed of three genes, each one corresponding to a point of the selected rim. More precisely, the rim is divided into three zones (rightmost, central and leftmost) by a k-means algorithm, and the chromosome contains one gene for each zone. These three points define a plane, and our aim is to evaluate the goodness of this plane.

We are interested in two different goals: To maximize the number of points of the rim contained in the plane and to maximize the number left bellow the plane. That is to say, it is not sufficient to have a plane containing a lot of points, but it is also necessary for it to lean on the rim, just touching it, not crossing through the middle of the fragment.

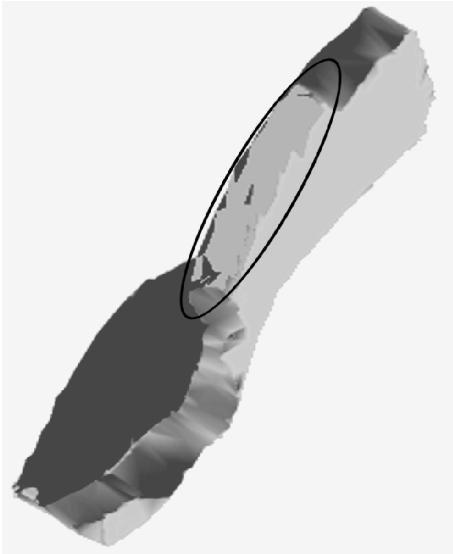

Figure 4: *Sherd with the relevant part of the rim marked (the interest area is surrounded by an ellipse in this drawing)*

Getting two different goals can be done computing each goal independently or combining both them into a single goal function. When the two functions are computed independently, a family of solutions is obtained that can be ‘plotted on a 2D diagram as a function of its goals values. Every solution, which is represented by a chromosome, is drawn as a point whose coordinate are its goodness value. So the best solutions are those whose distance to the origin is larger. From these solutions the user must choose the best one, deciding which criterion is more important.

To avoid this decision step, we have combined the two goals into a single one. The goodness G of a chromosome c can be expressed as:

$$G_c = 100 \times \frac{|R_c - L_c|}{N_b} + P_c \tag{1}$$

Where R_c and L_c means the number of points that are over or below the plane defined by c, and N_b is the number of points selected as a part of the rim. P_c is the number of points whose distance to the plane is below a threshold ε and so can be considered to be on the plane c.

$|R_c$ - $L_c|$ gives the difference between the number of selected rim points that yield at each side of the plane. Dividing this by N_b we get a number between 0 and 1, that represented the deviation of the plane from the border of the rim. The coefficient one hundred modulates the relative weight of the two criteria: the plane deviation against the number of point on the plane. This value implies that it is so important having 100 points on the plane as having no point over the plane.

As an example let us suppose we have two chromosomes C1 and C2. C1 contents 3 rim points and its deviation is 0.99, that is 99% points are bellow the plane. C2 contents 4 rim points but cross the middle of the point cloud, and so its deviation is 0.0. If we where using coefficient 1, the goodness of C1 would be 3.99 and that of C2 would be 4.0, while it is clear that C2 is not a good solution. With a coefficient of 100, these chromosomes have goodness of 102 for C1 and 4 for C2, according with the idea that C1 is much better than C2.

The parameters of the genetic algorithm can be modified by the user. The remainder of this section explains all these parameters giving reference values for them.

- The *population* is the number of solutions that are computed simultaneously. It must be large enough to explore the solutions space. The default value we use is 101.
  The initial population is the initial set of solutions (chromosomes) used. It can be build heuristically, or using a greedy algorithm, trying to get good initial solution. We build it randomly, just choosing groups of three rim vertexes.

- The *crossover* probability defines the probability a chromosome has to be merged with another one. Our default value is 0,8.

- The *mutation* probability is the probability a gene of the chromosome has to be mutated after a merge. The mutation allows the system to go out local minimum, but it must no be too high, in order to allow it to converge Our default value is 0,1.

- The algorithm stops either when the solution converge to an acceptable value or when a maximum number of *generations* is reached. When the system stop at this point, the best solution available is chosen. The default number of generations is 250.

- The *distance threshold* used into the goodness function can be also adjusted. It value depend on the scale used for the model and on the precision we need.

This method has been proved to be efficient and feasible, generating a solution with less than 1% error in less than one second.

4. Estimating rotational axis

Estimating the diameter of the original vessel is analogous to finding the rotational axis of the pot. As we work mainly with prehistoric ceramics, made without a potter's wheel, its surfaces are very irregular, and it is not easy to find the axis by calculating the incident axis of the surface normals like in the multi-step approach of R. Halir[2] or using concepts from line geometry as in Pottman et al.[8].

We use a procedure similar to the traditional one:

- By moving a horizontal plane, the expert selects a section of the sherd. (Figure 5). This section is an arc, and so the expert should have selected the longest arc or that one with fewest irregularities. This process is interactive, the user move a scrollbar on the sherd image and see the resulting cut on the right of the screen.
- Having this arc the problem is now that of computing the centre of the circle that best fits the external arc.

In fact, it is a double arc: the external and the internal one, we must select the points on the external arc, as this produce less error. Note that we do not need to represent the cut as a geometric entity as we need simply the set of points contained on it.

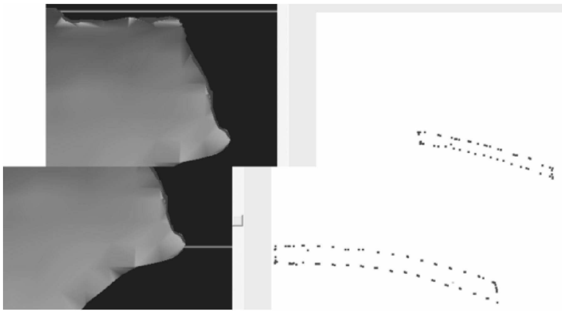

Figure 5: *Two arcs obtained at different heights of the sherd by cutting it with a horizontal plane*

To fit the circle to the arcs, we follow a LSQ fitting algorithm. First, we fit a circle using both arcs, so it will pass between them. Then, we remove the internal points and repeat the procedure with the external ones, so the new circle minimize the geometric distance with the sequence of points that define the external arc.

More precisely the algorithm used to compute the circle centre can be decomposed into two steps, computing the arcs and computing the centre.

4.1. Arc computation

Input

- A sorted list of oriented edges e_k=<p_1^k,p_2^k>, where p_1^k=x_1^k,y_1^k,z_1^k, p_2^k=x_2^k,y_2^k,z_2^k, having $y_2^k > y_1^k$ and sorted such as $y_1^i < y_1^{i+1}$.
- The cutting plane H.

Output

- A list C of 2D points from the sherd that are on the plane H that form the cutting (the external arc).

Pseudoalgorithm

h= Y coordinate for plane H.
f = first edge such that $y_2^f > h$.
While $p_1^f < h$.
    if ($p_1^f < p_2^f$)
        T=Intersection between f and H
        $C[i]=(T_x, T_y)$
        i++
    endif
    f++
endWhile

Once the user decide the cutting is good, that is, it is a long one that has no irregularities, it applies the fitting algorithm to it, using the following algorithm

4.2. Centre computation

Input

- A list C of 2D points
- The amount of arc considered as part of the breakage edge, ε

Output

- The circle , $O2$

Pseudoalgorithm

Adjust a circle $O1$ to C using LSQ
Compute the radio r_1 of the circle
Compute the centre a_1,b_1 of the circle
Transform the points C to polar coordinates (r,θ) with respect to a_1,b_1.
Compute the maximum an minimum angles θ_{min} and θ_{max}
Create a list of points, $C2$, of points from C satisfying $r_i < r$ and $\theta_{min} + \varepsilon < i < \theta_{max} - \varepsilon$
Adjust a circle $O2$ using LSQ
Compute the centre a_2,b_2 of the calculated circle $O2$

The rotational axis is the vertical line that passes through the centre of the calculated circle $O2$. So, the axis of the vessel is the line $x = a_2$, $z = b_2$, assuming that it is oriented being Y the vertical axis. Figure 9 shows this process. The initial set is shown as green marks, the C2 set is marked as blue squares and the circle is shown as red marks.

5. Profile extraction

From the tridimensional model of the sherd, the expert selects those areas considered to best define the shape of the profile. This step is done by drawing lines over the sherd, using the mouse, as if it were a pen over the real sherd (Figure 6), thus obtaining a set of 3D lines that are projected over the planes containing the previously calculated rotational axis. This can be done because we have previously translated the point coordinates into polar coordinates; when selecting a point, we take the module and the azimuth of its polar coordinate, and so it is easily translated into 2D coordinates.

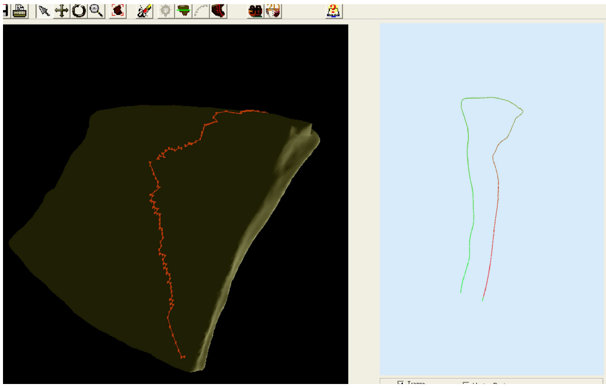

Figure 6: *Profile extraction: the strokes on the right image indicate the profile obtained, and at left the strokes that generates it.*

Given the sequence of 2D lines, the system fixes them in a unique stroke, detecting overlapping and irregularities, by the following algorithm:

Input

- A list I of 2D strokes, being each stroke a sequence of connected vertexes
- The maximum distance to consider a stroke "close" to another, ε

Output

- One stroke P defining the profile.

Pseudoalgorithm

For each stroke k.
Reverse k if firstpoint(k).y < lastpoint(k).y
Detect the stroke S_m that holds the point p_m with maximum Y coordinate
If p_m is in the extreme of the stroke S_m
    Find the stroke S_n with the nearest point p_n to p_m
    Depending on its orientation, mark S_n and S_m as $begin-of-internal$ and $begin-of-external$ strokes
else
    Divide the stroke by p_m, having two strokes $begin-of-internal$ and $begin-of-external$

endif
insert into *internal* stroke $begin-of-internal$
insert into *external* stroke $begin-of-external$
while there are strokes not used before and with a point p closer than ε from lastvertex($internal$)
  append to *internal* the closest stroke to lastvertex($internal$)
while there are strokes not used before with a point p closer than ε from lastvertex($external$)
  append to *external* the closest stroke to lastvertex($external$)
P=concatenate *internal* and *external*

This profile is fully editable, being possible to add, eliminate or move points, so, if the software does not remove all irregularities, the expert can do it in a few seconds (figure 7).

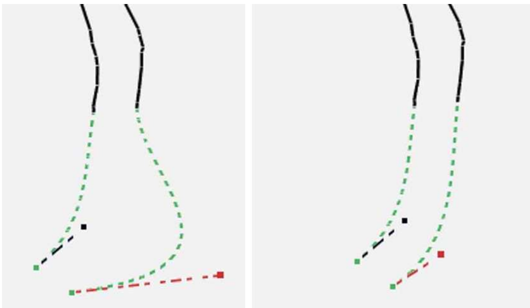

Figure 7: *Editing the estimated profile. Note the tangent has been moved and, due to this, the stroke has changed.*

The traditional drawing of vessels includes an estimated profile, that indicates how the profile should have continued if the whole vessel had been available. The length of this estimation differs from one sherd to another, because it depends on the typology and the experience of the expert, but standard practice is to extend it by about two centimetres.

The software generates a first approach to this prolongation by a cubic spline that follows the shape indicated by the lowest 15% part of the profile. This spline is calculated by taking 4 points separated by 5% of the height of the profile obtained.

As typologies in prehistoric ceramics are very hard to establish, and very restricted to small areas, we consider that the experience of the expert is very important at this point, so we also allow him/her to edit the estimated prolongation, by moving the points or the tangents at the end of the prolongation (fig 7).

In figure 10 can be seen how important human interaction on profile selection is. At left image we can see two strokes over the rim of the sherd. Although they might seem similar, when looking at left image, we can see two very different strokes of the rim. So at this point, which is the correct one? It depends on expert decision.

6. Drawing and 3D Reconstruction

Once the profile and the rotational axis have been obtained, it is an easy matter to obtain the traditional drawing of the ceramic (Figure 11).

This step of the reconstruction process is also interactive, because the system allows the expert to:

- Decide the position of the sherd in the drawing, depending on the details he wants to show. As in manual drawing, a false perspective is used, to avoid hiding part of the surface when placing the sherd at left or rightmost position.
- Modify the lighting, to improve the visualization of several details of the sherd.
- Take measurements over the drawing, such as the diameter at several points, height of the sherd, etc... These measurements can be translated, modified, etc...

The image can be saved as a GIF, JPEG or BMP image, and so it can be edited by any image editing software.

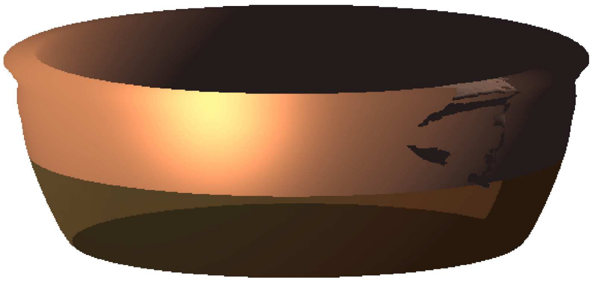

Figure 8: *Virtual 3D Reconstruction of a vessel. Note the original sherd and the lighting*

The three-dimensional reconstruction of the pot is generated by rotating the profile (both the real one and the estimated prolongation) around the rotational axis. The surface corresponding to the estimated part of the pot is shown with a semi-transparent texture, in order to identify clearly both parts of the reconstruction. The original sherd is shown in the vessel, as in real reconstruction, so the goodness of the reconstruction and the exact place where the sherd was located can be appreciated (Figure 8).

The reconstruction can be rotated and zoomed to obtain different views of the vessel, each of which can be saved also as an image.

7. Results

We present at table 1 showing measurements taken of external radius over different 2D drawings of synthetic and real pieces.

Sherd	Max. Radius	Min. Deviation	Max. Deviation
Real01	25,74	-3,33%	+4,16%
Synt01	516,05	-3,08%	+4,34%
Synt02	490,18	-2,28%	+0,82%

Table 1: *Results of radius measurement over synthetic and real reconstructed sherds.*

Sherd	Polygons	Loading	Orientation	Diameter
Real01	19428	19,90	2,77	0,65
Synt01	2468	0,49	1,69	0,04
Synt02	2774	0,46	1,40	0,39

Table 2: *Computing Time (in seconds) at each step*

At table 2 we show timing of several automatic processes of the software. Files used for loading are in .ASE format, and in this results does not appear estimation about user interaction time, just computing time.

8. Conclusions and Future Works

We have proposed a software method that reduces the time required to draw and measure a sherd by 80%. The system is completely operative. Figures 12 and 13 show two screenshots of the application.

We have tested it with several synthetic models, and the error margin is reduced by a 60% with respect to the traditional method, so we believe this system can be very useful for archaeologist. The most serious problems were encountered in scanning the sherd, and so the software will not be fully operative until the scanning procedure is capable of providing sufficient accuracy and speed.

Our intention is to add other capabilities to the software such as:

- Morphological measurements, such as the angle of the rim, volume, etc.
- Realistic textures for the three-dimensional reconstruction
- Pen-and-ink textures for traditional drawing
- The addition of a database to register all measurements for later statistical studies

More information about the software can be found at *http://lsi.ugr.es/∼fjmelero/sidrac*

9. Acknowledgements

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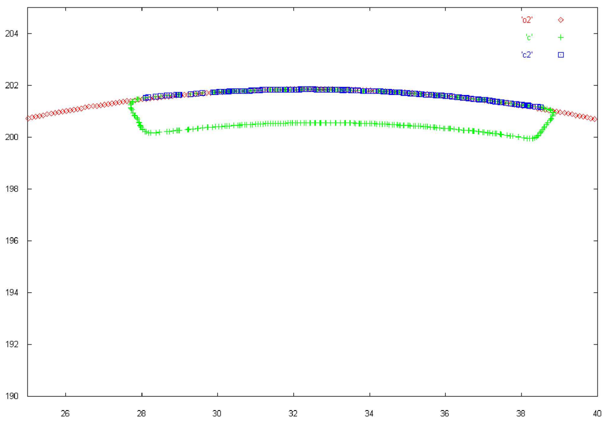

Figure 9: *Computing the centre of the circle.*

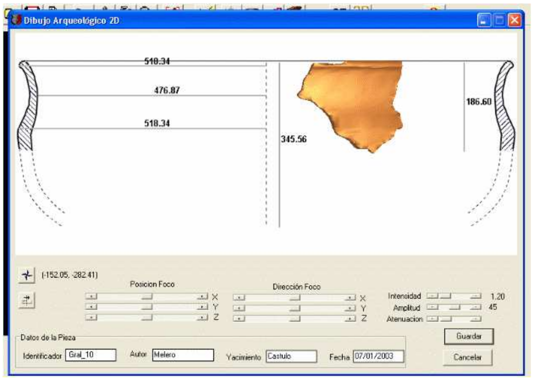

Figure 12: *Screenshot at 2D Drawing step*

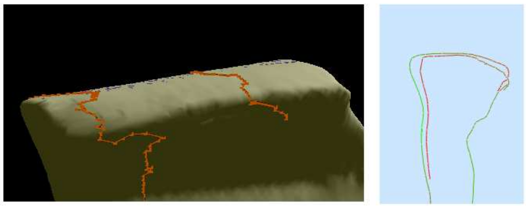

Figure 10: *Selecting two areas of the rim is possible to obtain two different profiles*

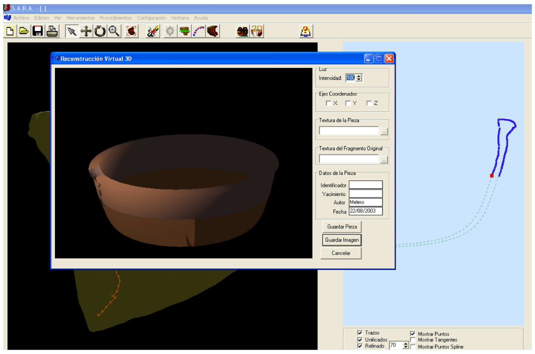

Figure 13: *Screenshot at 3D Reconstruction Drawing*

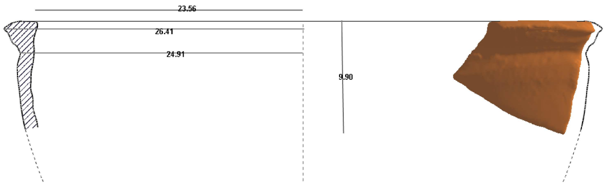

Figure 11: *2D drawing of the computed profile following the archaeological standards*