Doerr, Martin and Apostolis Sarris (eds) 2003. The Digital Heritage of Archaeology. CAA2002. Computer Applications and Quantitative Methods in Archaeology. Proceedings of the 30th CAA Conference, Heraklion, Crete, April 2002.

Recognition and Classification of Fragments from Ceramic Artefacts

Luigi De Napoli, M. Laura Luchi, Maurizio Muzzupappa and Sergio Rizzuti

Università degli Studi della Calabria, Dipartimento di Meccanica,
Ponte Pietro Bucci 44/C, 87030 Arcavacata di Rende (Cosenza), Italia
{ldenapoli, luchi, muzzupappa, rizzuti}@unical.it

Abstract. The paper describes a procedure for the analysis of fragments from ceramic artefacts The methodology employs the well known Reverse Engineering approach to suggest the collocation of a fragment on the surface of the vessel to which it seems to belong. The paper discusses the methodology and reports its validation, conducted by means of a numerical simulation and its application, for the recognition and classification of two real fragments belonging to two Apulian artefacts. The developed procedure can be considered a valid aid for the archaeologist in order to speed up his/her activity.
Keywords. Reverse Engineering, Surface Modeling, Surface Fitting, Curvature Analysis

1 Introduction

This work reports the activities that have been carried out at the Department of Mechanical Engineering of the University of Calabria (Italy), for a PRIN project (Progetto di Ricerca di Rilevante Interesse Nazionale), in collaboration with the chair of "Methodology of Archaeological Research", Bachelor degree in Tourism Sciences at the same University.

The main task of the project consists of the development of a computer aided tool that aims to simplify and speed up the activity of an archaeologist, skilled in filing ceramic finds. The project is particularly concerned with finds (typically vessels) that are associated with mass manufacturing, when the number of fragments is high, and, in this context, one of the goals for the archaeologist consists of determining the total number of complete items that can be found in a site. The purpose of the project is to provide the archaeologist with a tool able to automate the counting of archaeological finds. This can be done only if the position of a fragment on a vessel can be recognized automatically. This basic aspect will be investigated in this paper.

Some techniques, well known in engineering science, such as surface modeling and reverse engineering, have been employed in order to create, in a virtual environment, the operating conditions to evaluate the intrinsic geometric characteristics related to each fragment, that can be characterized by Gaussian and principal curvatures. The comparison of these estimated values with those computed on a virtual vessel allows the fragment to be located unambiguously.

The paper reports the mathematical aspects related to the employed methodology and discusses the numerical simulation of the procedure. Furthermore, the recognition and classification of two real fragments is presented.

2 Brief Historical Background

The work is related to vessel artefacts coming from a site located in the province of Cosenza in Northern Calabria. The place is called Cozzo la Torre, near Torano Castello, and the site is interesting from an archaeological point of view, because in it settlements dating from the twelfth to the second century BC have been located (de La Genière, 1977).

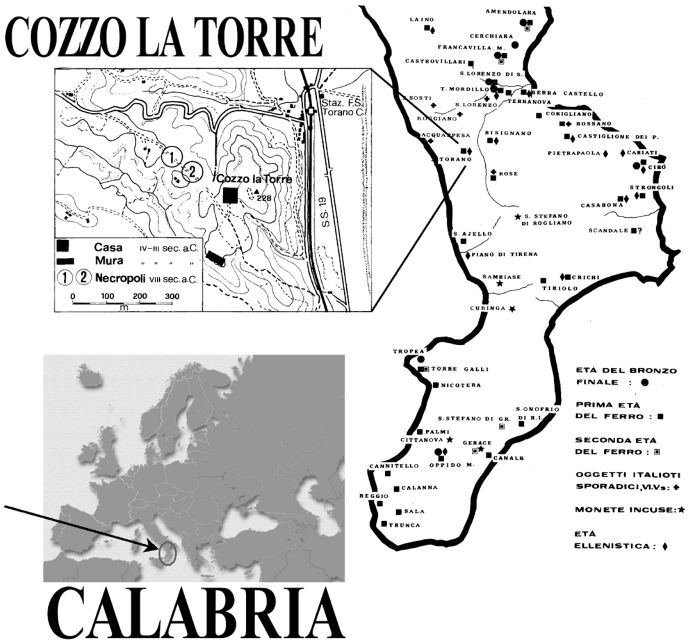

Fig. 1. Map of Cozzo la Torre, Calabria, Italy.

The site is on a hill, on the west slope of the Crati valley (Fig. 1). It was a fortified settlement, populated in the fourth and third centuries BC by the *Brettioi (*or *Brettii* or *Bruttii*), an indigenous Calabrian people, who for many centuries had been influenced by Hellenic culture. The work has been carried out on fragments of two types of Apulian made artefacts (Lippolis, 1996), found in surveys (Genovese, 1990), (Genovese, 1999) (Fig. 2):

- *kraters*, open shapes, typically with a diameter of 350 mm at the rim and 350 mm high;
- *skyphoi*, open shapes, typically with a diameter of 130 mm at the rim and 130 mm high.

The manufacture of all these types of pottery is very elaborate. In fact, most of these were decorative objects to show status.

Fig. 2. *Two examples of Apulian vessels, similar to those from Cozzo la Torre.*

In particular *kraters* and *skyphoi* were exhibited in important meetings such as banquets or symposia connected with wine drinking, and for this reason indicate high social position; these artefacts were so precious that they were enclosed in the funerary kit to display wealth.

The *kraters* under consideration are red-figured, often decorated with various scenes, mostly of a mythological type, on the two opposite sides and separated by ornamental subjects such as palms, gyrals and acanthus leaves.

The *skyphoi* are also red-figured but they have a dark white-washing.

3 The RE Methodology for the Reconstruction

In order to achieve the identification of a fragment as a piece of a vessel, a three-step procedure has been implemented following the Reverse Engineering (RE) approach (Fig. 3).

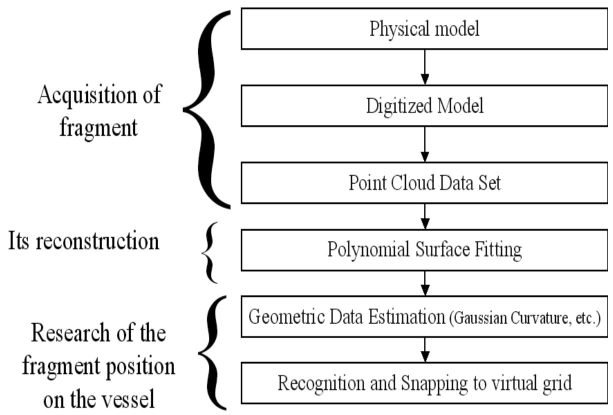

Fig. 3. *Summary of the employed methodology.*

The RE technique can be so summarized: given partial shape information of an unknown surface, construct, as far as possible, a complete representation of the surface of an object (Varady et al., 1997), (Elsasser and Hoschek, 1996).

The main purpose is to convert a discrete data set into a piecewise smooth, continuous model that can be employed on a wide range of applications.

The first step of the procedure consists of the acquisition of the fragment, a discrete data set, typically consisting of (x,y,z) coordinate values of measured data points, scattered or regular (depending on the specific set-up).

The second step provides the mathematical formulation of the surface by means of the best fitting technique.

The third step consists of the evaluation of the position of the fragment on the virtual vessel by the estimation of some intrinsic geometric parameters.

3.1 Acquisition of a Fragment

Many different methods for acquiring shape data (point cloud data, in general) exist (Fig. 4).

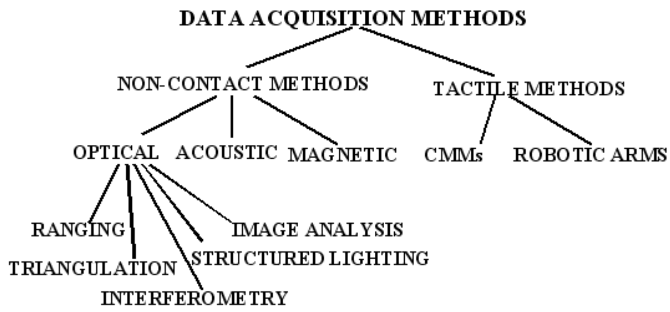

Fig. 4. *Classification of 3D data acquisition methods.*

They can be classified as contact and non-contact methods. In the first type, the surface is touched using mechanical probes at the end of an arm or of a coordinate measuring machine (CMM).

Non-Contact methods can be magnetic, acoustic or optical. The latter are based on triangulation, interferometry or structured lighting. The Non-Contact methods are probably the most widely used and the most popular since they allow relatively fast acquisition rates.

3.2 Reconstruction of the Fragment

Specialized software, capable of generating a digital mock-up, starting from point clouds exist. The most famous are: Surfacer® (SDRC), Geomagic® (Raindrop), ICEM Surf® (PTC), Paraform® (Paraform), which share the common characteristic of their high cost. In the proposed procedure the reconstruction has been done by home-made routines written in Mathematica® 4.0, based on the classical best fitting approach.

3.3 Research of the Fragment position on a vessel

The reconstructed surface of the fragment must be investigated in order to extract some geometric characteristics that can be

employed as useful parameters to correctly position the fragment on the vessel. The surface patch has to be processed and the Gaussian curvature computed. A first evaluation of a possible position can be obtained immediately comparing the computed value with those of the Gaussian curvature calculated on the surface of a digital model of the vessel.

Frequently similar values of Gaussian curvatures relate to different points on the vessel. In order to differentiate these cases, the principal curvatures have also been computed, and the correct position of the fragment is determined by matching these three parameters.

4 Numerical Validation of the Methodology

In order to validate and to calibrate the procedure described above, a numerical simulation has been carried out. Firstly a surface model of each type of the considered vessels was made.

Then a virtual fragment was reconstructed starting from points clouds extracted from a virtual vessel.

Furthermore some basic elements such as the density of point clouds and the degree of polynomial fitting, that greatly influence the effectiveness of the procedure, have been tested.

4.1 Modeling of the Vessels

Starting from drawings of the vessels, employing free-form surface modelling techniques, a set of virtual models have been reproduced (Schurmans et al., 2001), (Razdan et al., 2001), (Rowe, 2001).

Fig. 5. Geometric models of the vessels. The porcupine of the curvature of each profile is also shown.

The surface modellers Rhinoceros® and Pro/Engineer® have been used. The axial symmetry of the vessels allowed them to be modelled, revolving their profile around the axis. The models have been made with great care because the effectiveness of the procedure also depends on this first phase (Fig. 5).

4.2 Description of the vessel by geometric parameters

In order to investigate the nature of a surface the Gaussian curvature is the most significant parameter (McIvor and Valkenburg, 1997). Its general expression (1), in terms of classical differential geometry, is :

$$K = K_1 K_2 = \frac{LN - M^2}{EG - F^2} \qquad \textbf{(1)}$$

with *E*, *F*, *G* being the terms present in the first fundamental form and *L*, *M*, *N* those present in the second fundamental form.

Also the principal curvatures K_1 and K_2, in this particular case, are significant: they represent the curvature of the surface curves contained in the osculating (K_o) and binormal (K_n) planes (Fig. 6).

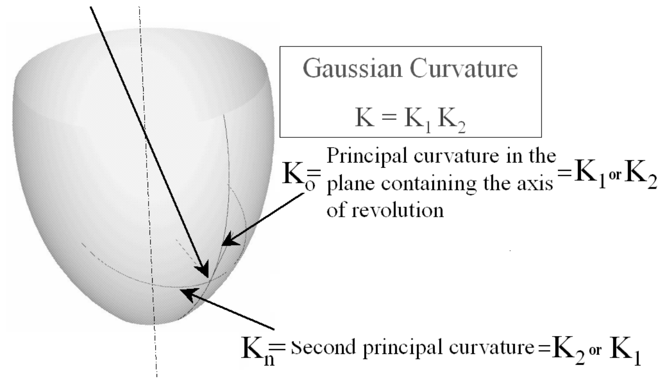

Fig. 6. Gaussian curvature is calculated at a point, in the same way as the principal curvatures.

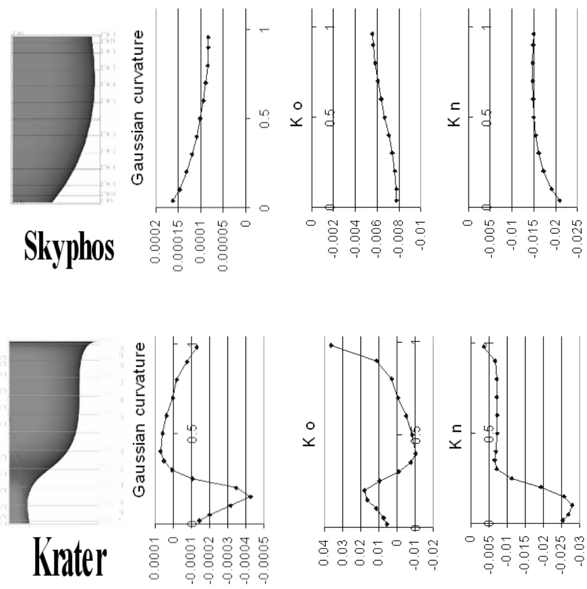

Fig. 7. Graphs of K, K_o and K_n of both the vessels vs h/H.

These three parameters have been computed along the profile at several heights (h), and in order to compare the two different vessels, the values have been normalized to the total height (H) of the vessel, using the h/H ratio.

In figure 7 the two vessels are represented in terms of these intrinsic parameters.

4.3 Creation of a Virtual Fragment as Surface Patch and Generation of Point Clouds

In order to simulate a real fragment, a surface patch must be defined starting from a point data set extracted from the virtual vessel. The most suitable surface patch seems to be the Monge patch. It is defined on a rectangular domain in the *xyz* space as an explicit bivariate function, expressed in parametric form (2):

in the *(u, v)* domain, that coincides with the *(x, y)* domain, defined as ($x \in \{x_{min}, x_{max}\}$, $y \in \{y_{min}, y_{max}\}$).

In order to simulate the acquisition phase, conducted by scanning systems, the following step consists of the creation of cloud points on the surface patch. A square domain is positioned on a tangent plane of the surface of the vessel model, where the z axis coincides with the normal to the surface and the origin with the barycentre of the domain corresponding to the tangent point.

This reference system allows us to reproduce the Monge condition and guarantees the consistence of the methodology employed (Fig. 8).

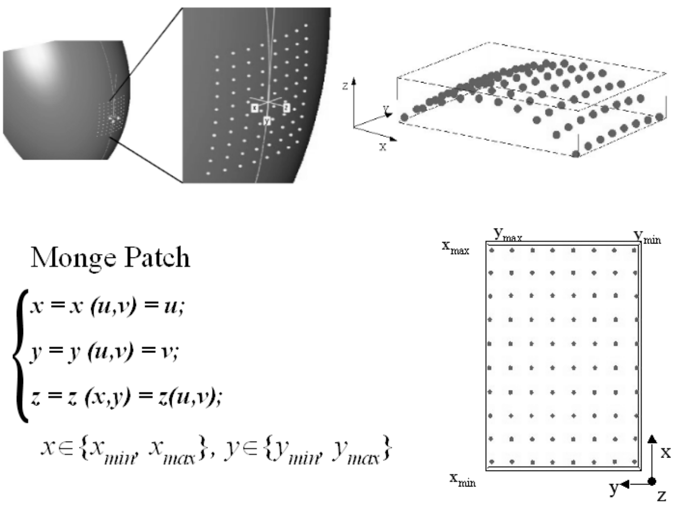

Fig. 8. Data acquisition of the virtual fragment. The reference system is oriented to permit the fitting with a Monge patch.

The square domain is subdivided into a certain number of equally spaced points. The normal to the square domain, conducted from these points, intersects the vessel surface in points, characterized by a triplet of co-ordinates, which constitute the virtual cloud of points to be fitted.

4.4 Surface Fitting by Polynomial Approximation

In order to obtain the bivariate function that characterises the surface of the virtual fragment, a series of functions have been tested. The most suitable form, for this application, has been a polynomial function (Muzzupappa and Rizzuti, 1994). A procedure has been written in Mathematica® for fitting the virtual point clouds, and polynomial functions of third degree gave the best trade off, in terms of accuracy of the results and computational time.

$$\begin{cases} x = x(u,v) = u; \\ y = y(u,v) = v; \\ z = z(x,y) = z(u,v); \end{cases} \qquad (2)$$

From the mathematical formulation of the virtual fragment the parameters (Gaussian and principal curvatures) have been computed corresponding to the barycentric point of the patch.

The values obtained have been compared with those computed on the virtual vessels. This computation and comparison have been carried out to set out the best density of cloud points useful for the experimental testing.

This point is strictly connected to some features that have been established for the whole procedure. It must in fact:

- be used even with low computational resources;
- attain an error of less than 1% in the estimation of K, K_o, K_n;
- be employed in conjunction with low cost scanning systems.

4.5 Calibration of the Procedure

The calibration of the procedure, after several tests, has indicated a value ranging from 0,1 ÷ 0,15 for the ratio p/L (pitch between points/length of the patch). The point density can be rather coarse, and a limited number of points (90÷100) on the patch can be considered.

5 Experimental Procedure

Two fragments of the vessels taken into consideration have been subjected to the procedure. For the reconstruction of the physical fragment a Non-Contact Acquisition System has been employed: the LDI PS-1100 laser scanner.

The acquisition has been done laying the fragment on a plane and scanning it along an oblique direction with respect to the plane, with the scanner installed on a tripod, within the reference system **x,y,z**.

5.1 Point Clouds Acquisition and Processing

As can be seen in fig. 9, the scanned region spans a wide area, so the extraction of the significant data has required a manual operation. Using the Spider® software the region close to the fragment has been restricted and some points (typically those corresponding to the boundaries) have been removed. Inside the region corresponding to the more representative zone, a domain of maximum area has been inscribed. The selection of the domain is particularly delicate because it must be chosen taking into account that, in the scanned region, zones with different reflectance can be present, and also because the scanning points cannot be spanned regularly. The next step consisted of a selection of points in order to reproduce the density employed in the numerical calibration, employing a p/L ratio, ranging from 0,1 to 0,15, and no more than 100 points (Fig.9).

5.2 Extraction and Elaboration of Surface Patches

In order to reproduce the Monge patch, the cloud points must be subjected to a change of the reference system associated to the physical fragment. The new reference **X,Y,Z** is formed by a plane (that can be considered quasi tangent to the cloud) which passes through three points of the cloud, sufficiently far from each other, and another two planes perpendicular to the first and passing through the barycentric point of the cloud.

Then the procedure described in the previous section has been employed, and curvature parameters have been computed on the reconstructed fragment.

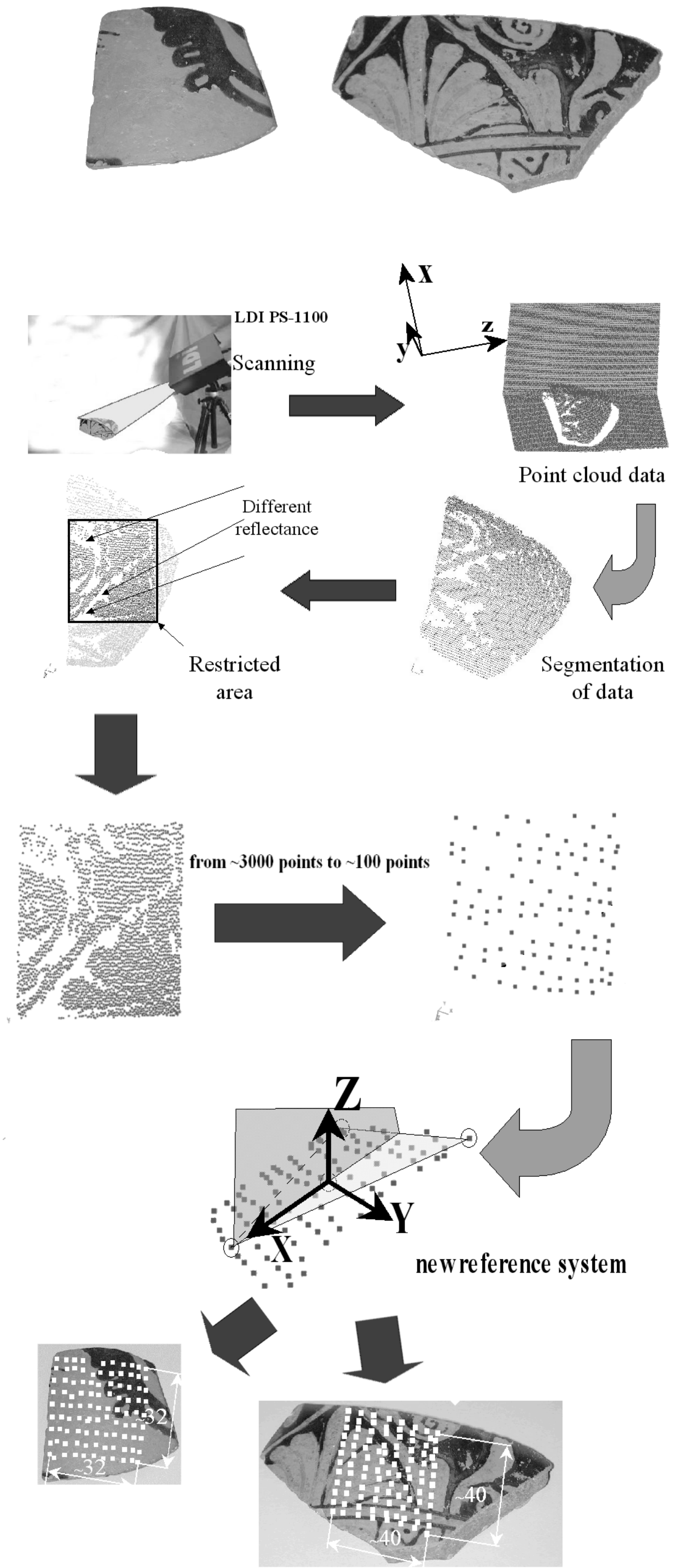

Fig. 9. Acquisition and processing of the point clouds of two real fragments.

5.3 Comparison between Experimental and Numerical Data

The skyphos fragment has been analysed with a domain of 32x32 *mm*, with a ratio p/L= 0.15 and 101 points; the krater fragment with a domain 40x40 *mm*, a ratio p/L=0,1 and 97 points.

In order to establish the height where each fragment can be positioned the diagram of the Gaussian curvature is examined. In correspondence to the K value a straight line is traced and its intersection with the diagram allows to determine the location of the height (or the heights) where that value is achieved.

The other two diagrams for K_o and K_n can be used as an aid to distinguish between different possible solutions.

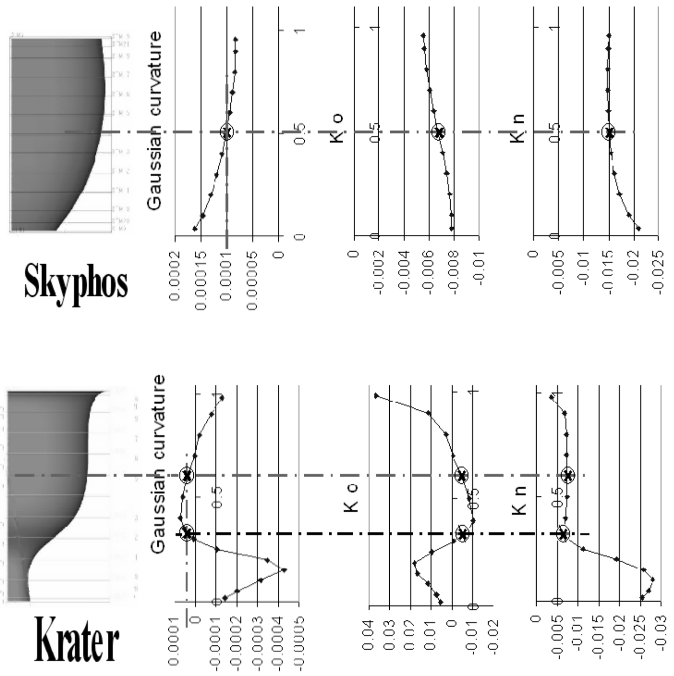

Fig. 10. Identification of the position of the fragments, matching the estimated K value with those stored.

As can be seen in fig 10, the fragment belonging to skyphos (K=0,000099) has been identified unambiguously at h/H= 0,5; otherwise the krater (K=0,000032) has two possible solutions at h/H=0,33 and h/H=0.62 respectively.

The skyphos has been identified with an error of about 10%: K_o computed = -0,00737, K_o simulated =-0,00675; K_n computed = -0,0135, K_n simulated = -0,0150.

The krater has been identified with a mean error of less then 4%: K_o computed = -0,00485, K_o simulated =-0,00470; K_n computed = -0,00662, K_n simulated = -0,00700 at the normalized height of 0.62. The other solution, at h/H=0,33, gave a greater error for K_o and K_n. In such a case of ambiguity the correct choice is referred to the archaeologist who can consider other aspects, such as surface texture. In this case the correct solution is at h/H=0.62.

6 Conclusions

The procedure described in the paper has been proved to be sufficiently precise. Further improvements can be made by employing a scanner laser on a device that allows the acquisition of the cloud of points along a direction perpendicular to the plane where the fragments will be placed. The procedure will be made quicker and automated by assembling and integrating all the software employed.

Acknowledgement

The authors would like to thank Dr. G. Genovese, assistant professor of Methodology of Archaeology Research, Bachelor degree in Tourism Sciences at the University of Calabria for his valuable contribution.

The research has been carried out with the financial support of the MIUR (Ministero dell'Istruzione, Università e Ricerca) within the ambit of the PRIN Project "Archiviazione e restauro di reperti archeologici mediante tecniche CAD-RP".

References

de LA GENIERE, J., 1977, Torano Castello: scavi nella necropoli (1965) e saggi in Contrada Cozzo della Torre nel 1967, in *Notizie e Scavi delle Antichità*, Roma, 1977, Accademia dei Lincei, pp. 389- 422.

LIPPOLIS E., 1996, Lo stile proto-apulo e apulo antico e medio, in Arte e artigianato in Magna Grecia. In *Catalogo Mostra Taranto 1996*, Napoli, 1996, Electa, pp.377-ss.

GENOVESE G., 1990, Gli insediamenti bruttio-italici nella Calabria attuale, in *Studi e materiali di Geografia Storica della Calabria antica, 2. Sui Bretti*, Cosenza, 1990, Due Emme, scheda 63, pp.103-105.

GENOVESE G., 1999, I santuari rurali nella Calabria greca, Roma, 1999, "L'Erma" di Bretschneider, pp. 163.

VARADY T., MARTIN R. R., COX, J., 1997, Reverse engineering of geometric models – an introduction. In *Computer-Aided Design*, Vol. 29, No. 4, pp. 255-268.

MUZZUPAPPA M., RIZZUTI S., 1994, Approssimazione mediante polinomi ortogonali e rappresentazione in 3D di dati sperimentali. In *Pixel*, Anno 15 Vol. 11/12, pp. 27-36.

McIVOR A. M., VALKENBURG R. J., 1997, A comparison of local surface geometry estimation methods. In *Machine Vision and Applications*, Vol. 10, No. 1, pp. 17-26.

ELSASSER B., HOSCHEK J., 1996, Approximation of digitized points by surfaces of revolution. In *Comput. & Graphics*, Vol. 20, No. 1, pp. 85-94.

SCHURMANS U., RAZDAN A., SIMON A., Mc CARTNEY P., MARZKE M., VAN ALFEN D., JONES G., ROWE J., FARIN G., COLLINS D., ZHU M., LIU D., BAE M., 2001, Advances in geometric modeling and feature extraction on pots, rocks and bones for representation and query via the internet. In *Proc. Computer Applications in Archaeology (CAA 2001)*, Visby, Sweden, April 25-29, 2001.

RAZDAN A., LIU D., BAE M., SIMON A., FARIN G., HENDERSON M., 2001, Using geometric modeling for archiving and searching 3D archaeological vessels. In *CISST 2001*, Las Vegas, USA, June 25-28, 2001.

ROWE J., 2001, A model digital library for 3D pottery data. In *Proc. of Coalition for Networked Information (CNI),* Washington, D.C., USA, April 8-10, 2001.