

Hubert Mara – Robert Sablatnig

Evaluation of 3D Shapes of Ceramics for the Determination of Manufacturing Techniques

Abstract: Motivated by the requirements of today's archaeologists we are developing a system for the documentation of daily finds of excavations using 3D acquisition. The most widespread finds are fragments of ceramics called sherds. We have shown in previous work the acquisition and documentation of these sherds using 3D scanners based on the principle of structured light. The traditional documentation of sherds is based on the extraction of the profile line, which is a horizontal intersection through the orientated sherd. Our system automatically estimates the profile line by use of computerized methods inspired by traditional archaeological work. Based on the methods used for estimation of the profile line, we demonstrate a method for determination of ancient manufacturing techniques, which is important to determine the technological advancement of an ancient culture. As ceramics were generally manufactured on rotational plates, the profile line is theoretically identical for a complete (symmetric) vessel. Due to the manufacturing technique the symmetry is broken and therefore we can determine it by estimating the variances of the shape of the profile line. For the proposed method we use complete vessels, because sherds of excavations of living places have been dumped and re-used as filling material for floors and walls. Therefore sherds virtually never reassemble a complete vessel and therefore no real ground truth is known. As archaeologists are also excavating burial places where individual unbroken ceramics or complete sets of sherds are found, our method can be applied on, but is not limited to, individual vessels. Results for traditionally manufactured new vessels and ancient vessels acquired during our field trip to the excavations in the valley of Palpa, Peru are given and the applicability of the method in archaeology is shown.

Introduction

Documentation of ceramics is a main task in archaeology, because ceramics are the most common finds, used and produced in large numbers by humans for several thousands of years. Archaeologists use analysis of ceramics (LEUTE 1987) on a daily basis to reveal information about the age, trading relations, advancements in technology, art, politics, religion and many other details of ancient cultures.

Therefore we are developing an automated system for ceramics documentation to help archaeologists document their finds in an efficient and accurate way, which can be used for further (computerized) research. The basis of documentation of ceramics is a manually drawn horizontal intersection, which is called the profile line (LEUTE 1987). The profile line is the longest elongation around – or cross-section through – the wall of a ceramic defined by its rotational axis (axis of symmetry). The term rotational axis relates to the fact that rotational wheels (plates) have been used for thousands of years for manufacturing ceramics. This assumption can be made especially, but not only for daily finds on archaeo-

logical excavations. Therefore we have based our work on the rotational axis to orient a ceramic or its fragment to estimate the profile line as is done manually by drawings. This work presents processing of 3D models of ceramics beyond estimating the profile line, because experiments for estimation of multiple profile lines at random positions of unbroken ceramics have shown notable deviations (> 1 mm), leading to quality criteria for classification and determination of manufacturing techniques, which is another important question for archaeologists. This question is of even more interest for the Americas where – unlike the Mediterranean Area – no written sources about vanished civilizations exist.

As the ceramics are found in tens of thousands at virtually every excavation, these drawings require a lot of time, skill and manpower of experts. Therefore we are assisting archaeologists in interdisciplinary projects (KAMPEL / SABLATNIG 1999) by using an automated system for acquisition and documentation of ceramics using a 3D scanner based on the principle of structured light (DEPIERO / TRIVEDI 1996; LISKA 1999).

First we describe the acquisition process of ceramics, followed by the description of the symmetry analysis including results of synthetic and real ceramics. Finally a summary and an outlook is given.

Acquisition

The challenging tasks for developing a documentation system for archaeology are to build a system which is accurate, portable, inexpensive, easy-to-use and robust for all kinds of climate, which can range from desert to jungle to arctic. This means technologies like computer tomography and other laboratory equipment are often unsuitable for the daily work of archaeologists - especially not for ceramics. As photography has already proven its reliability for archaeology, we chose to use a camera and a light-source for 3D-acquisition. For recent work we use 3D scanners from the Konica-Minolta Vivid product range (MARA 2003; MARA / HECHT IN PRESS), because of their resolution (< 0.1 mm), which meets the requirements given by archaeologists for their documentation. *Fig. 1(a)* shows one of the vessels acquired and *Fig. 1(b)* shows a manual drawing of a profile line. *Fig. 1(c, d)* shows the setup of our 3D scanner from recent experiments at the excavations in the valley of Palpa, Peru (REINDEL / ISLA 2001). *Fig. 1(c)* shows the triangulation principle (MARA 2003) using a laser (bottom) and a camera (top) with a known distance and orientation. Additionally the turntable – also shown in this figure – is used to get a complete 3D model of the ceramic. The number of 3D scans depends on the complexity of the ceramic and typically ranges from two scans for sherds up to eight scans for vessels. The 3D scans are registered using the method proposed by TOSOVIC (2002) to reassemble a complete 3D model.

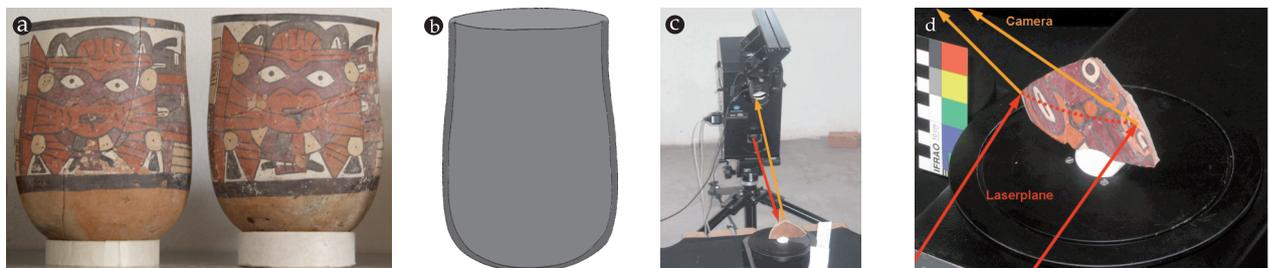


Fig. 1. (a) Photograph of vessel 2801-V3 and its twin found near Palpa, Peru and (b) a manual drawing (CARMICHAEL 1986) of a vessel having the same shape. (c) Konica-Minolta Vi-9i 3D-scanner projecting a laser plane (bottom arrow) onto a sherd, while the camera (top) acquires the projection of the laser. Having a well-known distance and orientation of the laser plane and the field of view of the camera the distance (range) can be estimated. (d) Detail of this setup showing a sherd mounted with plasticine on the turntable, which is used for controlled acquisition of all sides of an object.

After the registration, noise from dust and other objects like holding devices (e.g. clamps or plasticine) are removed from the 3D model. Then the orientation is estimated based on the assumption that ceramics are rotationally symmetric objects (MARA 2003), because they were generally manufactured on rotational plates. The principle of our orientation method is fitting of circle templates (GANDER / GOLUB / STREBEL 1994). In comparison to other computerized, but manual methods (MELERO ET AL. 2004) our orientation method can be used fully- and semi-automatically (LETTNER ET AL. 2006). Furthermore our system is capable to store the 3D model and further archaeological information (e.g. description, photographs, etc.) in a database. For solving the puzzling problems of other – typically industrially manufactured – rotational objects, other methods (POTTMANN / RANDRUP 1998; WILLIS 2004; ORRIOLS 2004) can be applied. Once an orientated 3D model is obtained, a vertical cross-section is estimated using the point of maximum height of the 3D model. This cross-section is the so-called profile line, which concludes the traditional archaeological documentation. *Fig. 4* shows a result for an automatically estimated profile line.

Symmetry Analysis

As such a rather simple two-dimensional profile line – as shown in *Fig. 4* – does not reflect any information about the manufacturing quality leading to the manufacturing technique, we decided to enhance our system by giving the archaeologists a tool to gather further information about the acquired 3D model. Even though the Nasca ceramics may not have been produced on rotational plates – as assumed by our method – the estimation of the profile line is possible. But like manual orientation, varia-

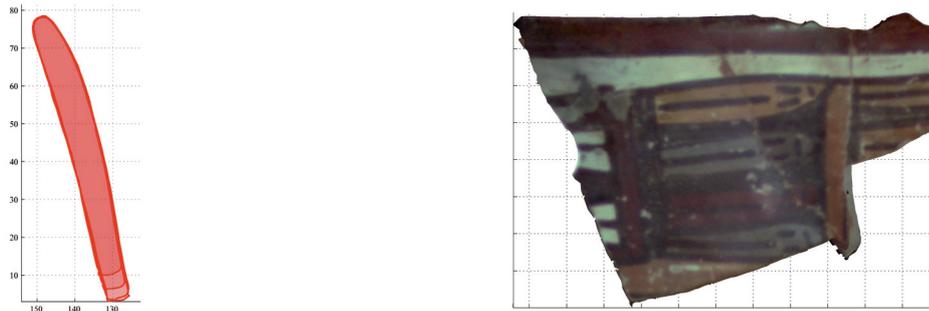


Fig. 2. Automatically estimated profile lines and frontview of the Nasca sherd 824-157.

tions of the orientation of the profile line take approximately twice the time than for ceramics manufactured using rotational plates.

Therefore we had to investigate the question of manufacturing technique and quality of the symmetry of Nasca vessels to determine these variations. Furthermore there is an ongoing discussion between archaeologists about the existence of rotational plates for the manufacture of ceramics in South America. The general opinion is that in this region the wheel was not invented, therefore ceramics were produced without a rotational plate (CARMICHAEL 1986); on the other hand there is evidence that rotational plates were used (WIECZOREK / TELLENBACH 2002).

In general technological advancement is determined by archaeologists from ceramics which have been produced either on slow or fast turning rotational plates. As we use structured light as 3D acquisition method, we cannot make assumptions about the internal structure of a ceramic as others have (WIECZOREK / TELLENBACH 2002), but we can estimate the surface with a high resolution (0.1 mm). Therefore we can analyze the symmetry and estimate features like deviation of real surfaces in respect to a perfectly symmetrical surface. Such features can help archaeologists to decide about the technological advancements of ancient cultures.

As archaeologists also excavate burial places, where unbroken ceramics or complete sets of sherds are found, we are presenting a method to determine the manufacturing process of ceramics, which reveals information about the technological advancement of an ancient culture. Furthermore, this method can be applied, but is not limited to, unbroken or reconstructed vessels.

To begin our investigation and answer questions about the manufacturing process of ceramics, we chose to use two modern pots which were manufactured in a traditional way. Therefore this data can be interpreted as mixture between synthetic and real data, because we used real objects. However, unlike real archaeological fragments, we know how they were produced.

In addition, we decided to use the method for finding the orientation of a sherd (MARA / KAMPEL 2003). We began with the profile line, which can be estimated in a similar way to the process used with sherds. The difference is that for complete vessels the bottom plane can be used for orientation, because it is the counterpart to the rotational plate, which defines the (orthogonal) axis of rotation.

We estimated multiple profile lines, which can be overlaid by transforming them into the same coordinate system, where the y-axis equals the rotational axis. Therefore the distance between profile lines can

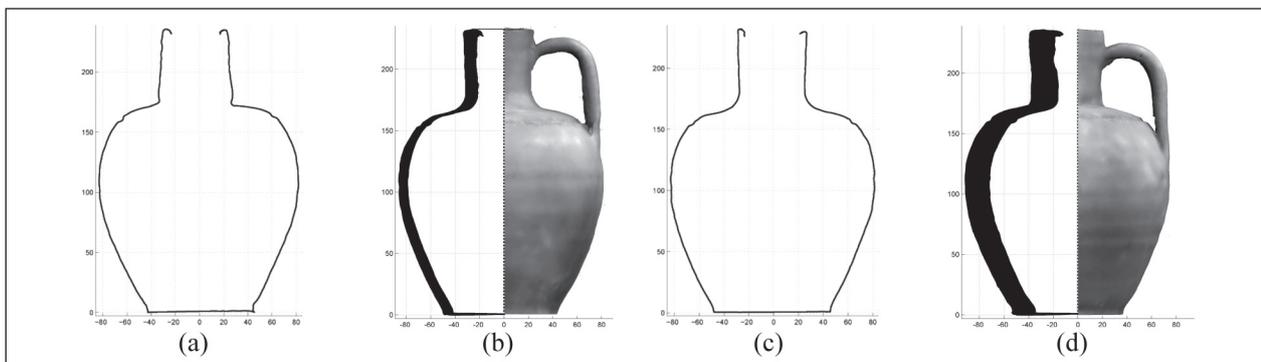


Fig. 3. (a, c) Longest profile lines and (b, d) multiple profile lines of modern ceramics, manufactured in a traditional way, which are supposed to be identical.

be estimated. *Fig. 3* shows the longest profile line and multiple profile lines combined with the side-view, as archaeologists show such vessels in their documentation. In the case of the multiple profile lines, we have estimated that the distance between the profile lines differs and therefore these pots and their profile lines are unique. The maximum distance between two profile lines of the first pot was 9.8 mm, whereas for the second pot it was 21.2 mm.

In the multiple profile lines shown in *Fig. 3(b, d)*, the distance between profile lines, measured parallel to the x-axis, is not equal. If the profile lines were

(fragments). The estimation of the axis is shown in *Fig. 4(b, d)*. The numeric results for the axis are that they have a minimum distance of 4 mm towards each other and to the axis defined by the bottom plane. Furthermore the angles between the axes differ between 5° and 7° .

Using the rotational axis of the lower and upper fragment, we repeated the estimation of the profile lines, which are shown in *Fig. 5*. The maximum distance between the profile line are 7 mm for the upper and 2 mm for the lower part. Therefore the first conclusion is that the upper and lower parts

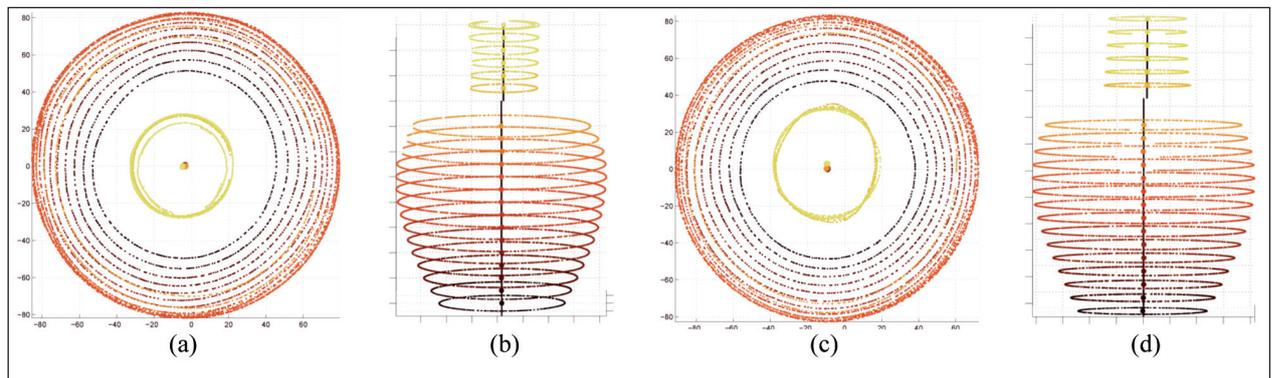


Fig. 4. (a, c) Top-view and (b, d) side-view of the horizontal cross-sections – the level of darkness corresponds to the height. The axis of rotation for the lower and upper part is shown as a black line, defined by the centres of the concentric circles (shown as dots).

parallel, this would mean that the pots have an elliptic (horizontal) cross-section. As it appears, the asymmetry is more complex. Therefore, we chose to analyze the pots slice-by-slice along the rotational axis, presumed as orthogonal to the bottom plane.

Fig. 4 (a, c) shows horizontal intersections, which have been applied with a distance of 10 mm along the rotational axis. The distance of 10 mm corresponds to the manufacturing process, which has left traces in the form of rills as seen along the right hand sides of *Fig. 3(b, d)*. These rills are spaced 10 mm apart, which corresponds to the width of the finger or tool used to "grow" the pot along the axis of the rotational plate. The intersections at 160 mm and 170 mm in height have been discarded, as they intersect the "shoulder" of the pot with a very low angle ($< 5^\circ$), resulting in an intersection having a non-representative, random curvature.

Dividing ceramics into sections by characteristic points (like the "shoulder") is carried out by archaeologists for classification. Therefore we chose to analyze the object segmented into a lower and an upper part. This means we have two fragments where axis estimation can be applied as for sherds

do have a different axis of rotation, which means that these parts have been produced separately and combined without the use of the rotational plate.

We can conclude that, based on the different deviation of the multiple profile lines shown in *Fig. 5*, the upper part is of lesser quality than the lower part. This leads to the conclusion that these parts have been made by potters with different experience and/or on a slower rotational plate. Conversely, the deviation in the upper part of up to 7 mm compared to less than 2 mm of the lower part shows that a faster turning rotational plate has been used and that more experience was required for manufacturing the upper part.

From the differing angle between the axis of rotation based on the bottom plane compared to the axis of rotation of the upper and lower fragment, we can conclude that either the bottom has been post-worked or the pot was contorted before being fired in the oven.

Even when correcting the axis for the parts of the object, the horizontal intersections are not perfectly circular. The horizontal intersections

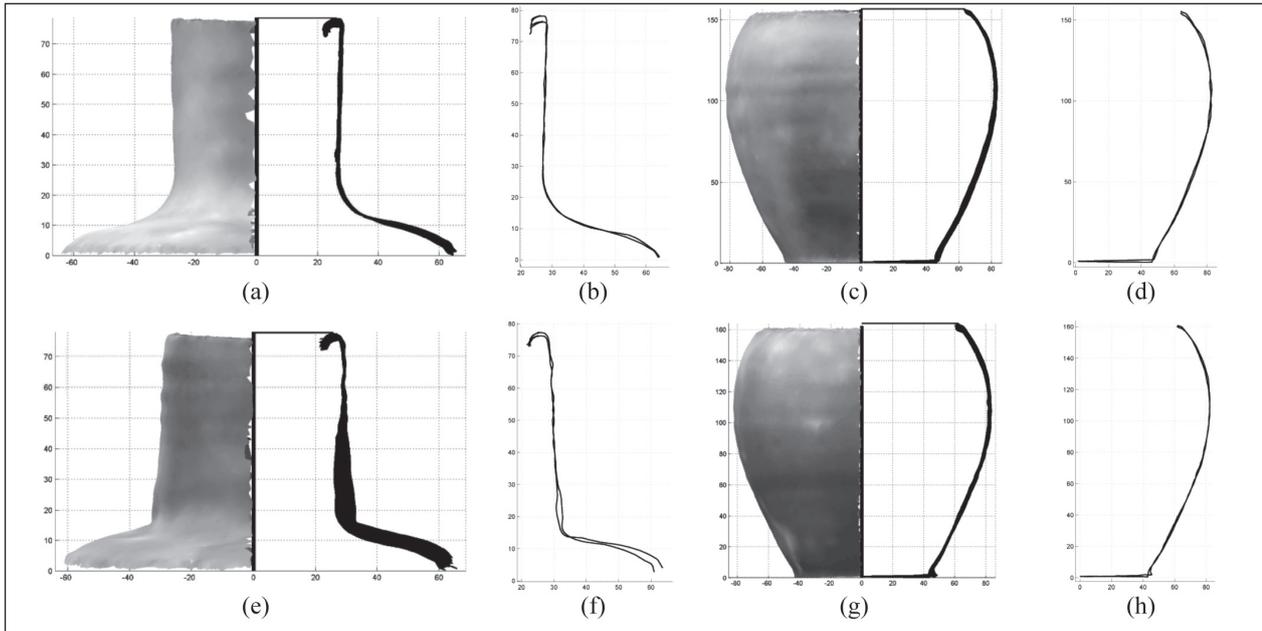


Fig. 5. Axis of rotation and multiple profile lines of the upper part (a, e), lower part (c, g) and (b, d, f, h) the longest profile lines of the parts of the objects.

are elliptic. Therefore we estimated the direction of the major and minor axis of the ellipses. We estimated that the minor axis has the same direction as the orientation of the handle. This means that the symmetry of the pots was broken, when the handle was attached and the pots were still wet. Fig. 6 show the pots intersected by a plane defined by the centre of gravity of the pot and the direction of the major axis of the ellipses. The angle between the minor axis and the handle of the pot was 7° and 14° for the second pot. Furthermore Fig. 6 shows an example from the excavations in the valley of Palpa, Peru.

We additionally conclude that the ellipses fitted (GANDER ET AL. 1994) to the horizontal cross-sections can be used as an additional feature. Therefore the distance between the foci of the ellipse is estimated. Ceramics with a distance con-

verging towards zero (circular cross-sections) are of higher quality.

The proposed method has also been tested on 17 real vessels (MARA 2006) dated to the Nasca period (CARMICHAEL 1986), which were found in the valley of Palpa, Peru (REINDEL 2001). Therefore we could separate these vessels into three classes determined by the symmetry. The vessels (60%) of two of these three classes were not produced on rotational plates. Beside this information – answer to the question of the manufacturing technique – about the use of rotational plates in South America, this classification is used by archaeologists of the German Archaeological Institute (DAI/ KAAK, Bonn) for refinement of their classification schemes.

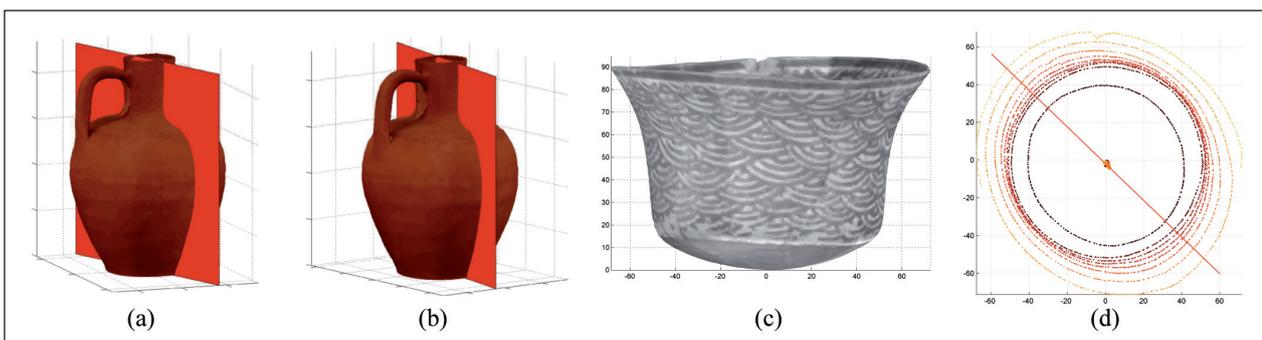


Fig. 6. Planes of symmetry of the (a) first and (b) second object. (c) frontview and topview of the horizontal intersection with plane of symmetry of vessel 2827-V1 found in the valley of Palpa, Peru.

Summary and Outlook

Summarizing the presented work, we can conclude that symmetry analysis can and will be used to estimate quality features of Nasca ceramics and related ceramics for classification and archaeometry (LEUTE 1987). Furthermore it can be used to approximate a ground truth and therefore estimate possible variations of the orientation of the profile line for manual drawings and automatically estimated profile lines. Meanwhile for the automated profiles we can estimate the expected error of ceramics which might not have been manufactured on rotational plates. Finally, we can conclude that symmetry analysis can reveal detailed information of the manufacturing process, such as quality requirements and production steps of ancient ceramics.

Beside the improvement of existing methods for 3D vision, another important work has recently begun to ensure the intellectual integrity, reliability, transparency, documentation, standards, sustainability and accessibility of the information gathered by the increasing use of 3D scanners. Therefore we are adopting The London Charter (BEACHAM/ DENARD / NICCOLUCCI 2006), which will be a future standard for the use of 3D vision within Cultural Heritage. For future work we will combine the methodologies for coins and ceramics to achieve a more generic system to retrieve stolen ceramics and to document and manage coins within digital libraries. Furthermore the methods used to retrieve stolen finds will also be used to reveal new knowledge hidden within the tremendous amounts of finds using features of their surfaces.

Acknowledgements

The authors would like to thank the Commission for Archaeology of Non-European Cultures (Kommission für Archäologie Außereuropäischer Kulturen, or KAAK) of the German Archaeological Institute (DAI) in Bonn for making available *in situ* acquisition and experiments with Nasca ceramics within the NTG project (New Technologies within the Humanities). Finally we would like to thank the European Commission for the support of the presented work through the CHIRON fellowship (MEST-CT-2004-514539) at the VAST-Lab, PIN – University of Florence.

References

- BEACHAM / DENARD / NICCOLUCCI 2006
R. BEACHAM / H. DENARD / F. NICCOLUCCI, An introduction to the London charter. In: M. IOANNIDES / D. ARNOLD / F. NICCOLUCCI / K. MANIA (EDS.), *The e-volution of Information Communication Technology in Cultural Heritage: where Hi-Tech Touches the Past: Risks and Challenges for the 21st Century* (Budapest 2006) 263–269.
- CARMICHAEL 1986
P. H. CARMICHAEL, *Nasca Pottery Construction*. Ñawpa Pacha 24 (Berkeley 1986).
- COSMAS ET AL. 2001
J. COSMAS / T. ITAGAKI / D. GREEN / E. GRABCZEWSKI / L. VAN GOOL / A. ZALESNY / D. VANRINTEL / F. LEBERL / M. GRABNER / K. SCHINDLER / K. KARNER / M. GERVAUTZ / S. HYNST / M. WÄLKENS / M. POLLEFEYS / R. DEGEEST / R. SABLATNIG / M. KAMPFEL, 3D MURALE: A Multimedia System for Archaeology. In: *Proceedings of the International Conference on Virtual Reality, Archaeology and Cultural Heritage* (Athens 2001) 297–305.
- DEPIERO / TRIVEDI 1996
F. W. DEPIERO / M. M. TRIVEDI, 3-D Computer Vision Using Structured Light: Design, Calibration, and Implementation Issues. *Advances in Computers* 43, 1996, 243–278.
- GANDER / GOLUB / STREBEL 1994
W. GANDER / G. GOLUB / R. STREBEL, Least-squares Fitting of Circles and Ellipses. *BIT* 34 1994, 558–578.
- KAMPFEL / SABLATNIG 1999
R. KAMPFEL / R. SABLATNIG, On 3D Modelling of Archaeological Sherds. In: *Proceedings of the International Workshop on Synthetic-Natural Hybrid Coding and Three Dimensional Imaging* (Santorini 1999) 95–98.
- LETTNER ET AL. 2006
M. LETTNER / H. MARA / A. MÜLLER / R. SABLATNIG / M. SINGER / M. KRENN, PAT: Profile Analysis Tool for the Documentation of Archaeological Finds. In: *Proceedings of Electronic Imaging & the Visual Art (EVA'06 Vienna) – Digital Cultural Heritage – Essential for Tourism* (Vienna 2006) 83–90.
- LEUTE 1987
U. LEUTE, *Archaeometry: An Introduction to Physical Methods in Archaeology and the History of Art*. (New York 1987).
- LISKA 1999
C. LISKA, *Das Adaptive Lichtschnittverfahren zur Oberflächenkonstruktion mittels Laserlicht* (Vienna 1999).

MARA 2003

H. MARA, Documentation of Rotationally Symmetrical Archaeological Finds by 3D Shape Estimation. Technical Report PRIP-TR-103, Vienna University of Technology (Vienna 2003).

MARA / KAMPEL 2003

H. MARA / M. KAMPEL, Automated Extraction of Profiles from 3D Models of Archaeological Fragments. In: O. ALTAN (ED.), XIX CIPA International Symposium: New Perspectives to Save Cultural Heritage (Antalya 2003) 87–93.

MARA / HECHT IN PRESS

H. MARA / N. HECHT, 3D Acquisition and Analysis of Freehand Manufactured NASCA Ceramics. In: Computer Applications and Quantitative Methods in Archaeology 2006.

MELERO ET AL. 2003

F. J. MELERO / A. J. LEON / F. CONTRERAS / J. C. TORRES, A New System for Interactive Vessel Reconstruction and Drawing. In: K. F. AUSSERER / W. BÖRNER / M. GORIANI / L. KARLHUBER-VÖCKL (EDS.), Enter the Past: The E-Way into the Four Dimensions of Cultural Heritage. Computer Applications and Quantitative Methods in Archaeology 2003. BAR International Series 1227 (Oxford 2004) 78–81.

ORRIOLS 2004

X. ORRIOLS, Generative Models for Video Analysis and 3D Range Data Applications (Barcelona 2004).

POTTMANN / RANDRUP 1998

H. POTTMANN / T. RANDRUP, Rotational and Helical Surface Approximation for Reverse Engineering. Computing 60, 1998, 307–322.

REINDEL / ISLA 2001

M. REINDEL / J. ISLA, Los Molinos und La Muna. Zwei Siedlungszentren der Nasca-Kultur in Palpa, Südperu. Beiträge zur Allgemeinen und Vergleichenden Archäologie. 21, 2001, 241–289.

TOSOVIC 2002

S. TOSOVIC, Adaptive 3D Modelling of Objects by Combining Shape from Silhouette and Shape from Structured Light (Vienna 2002).

WIECZOREK / TELLENBACH 2002

A. WIECZOREK / M. TELLENBACH, Exkurs zur Frage der Drehscheibenkeramik. In: A. WIECZOREK / M. TELLENBACH (EDS.), An die Mächte der Natur – Mythen der altperuanischen Nasca-Indianer. Katalog zur Ausstellung im Reiss-Engelhorn-Museum (Mainz 2002) 54–63.

WILLIS 2004

R. WILLIS, Stochastic 3D Geometric Models for Classification, Deformation, and Estimation (Providence 2004).

Hubert Mara
Robert Sablatnig

*Institute for Computer Aided Automation
Pattern Recognition and Image Processing Group
Vienna University of Technology
Favoritenstrasse 9/183-2
1040 Vienna, Austria
mara@prip.tuwien.ac.at
hubert.mara@pin.unifi.it
sab@prip.tuwien.ac.at*