A Comparison of Manual, Semiautomatic and Automatic Profile Generation for Archaeological Fragments *†‡

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Abstract

Thousands of fragments of ceramics (called sherds for short) are found at every archaeological excavation site and have to be documented for further archaeological research. The traditional documentation is based on the profile, which is the intersection of the sherd along the axis of symmetry in the direction of the rotational axis.

Traditionally this is done by experts using different tools like a profile comb to get this profile. This manual method is error prone and time consuming, therefore a semiautomatic method using a *profilograph* was introduced to increase accuracy. Since the measurement is still manually, the time for drawing was not decreased.

We propose an fully automatic system for the profile generation and compare the results with traditionally acquired profiles of fragments of *Tel Dor*, Israel. We joined the field trip to *Tel Dor* in July 2004 to compare in-situ the accuracy and performance of the traditional hand drawings, the *profilograph* and our system.

Furthermore, a new method for axis of rotation estimation is presented, results of the comparison of all three techniques of documentation of sherds, the improvement using our system and a methodological experiment for future work are shown in this paper.

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1 Introduction

Motivated by the requirements of modern archaeology we are developing an automated system for documentation of pottery. The fragments of pottery, called sherds, are among the most widespread archaeological finding. Archaeologists therefore find tens of thousands of sherds per month on an excavation like in *Tel Dor* [18], Israel. The documentation, classification and publication (e.g. [4]) of these tens of thousands of sherds is an important task for archaeologists [14], because these sherds represent information about cultural groups, population movements, inter-regional contacts, production contexts, and technical or functional constraints (archaeometry [10]).

The traditional method of documentation of the sherds is a drawing of the profile line (Figure 1), which is an intersection of the sherds along the axis of symmetry (also called rotational axis), which can be found for sherds manufactured on rotational plates [22]. Finding this axis of rotation and drawing the profile line by hand requires expert knowledge and a certain amount of time. The time we measured for manual drawings is from 10 minutes up to an hour. It is therefore an impossible task to draw all the profiles of the tens of thousands of sherds. Another disadvantage is that the hand drawing is dependent on the skill of the draftsperson. It is also very difficult to manually compare several hundreds of profile lines found in publications.

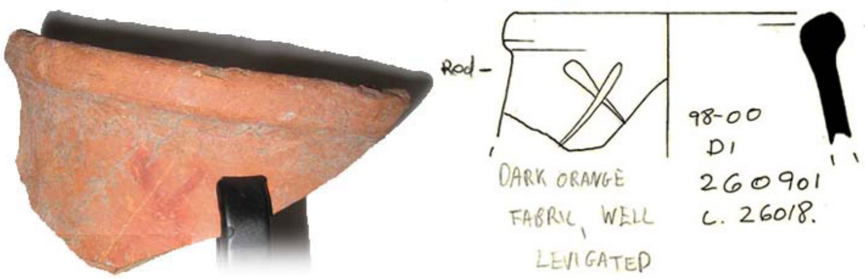


Figure 1: A sherd and its manual drawing. Registration number of the sherd: 98-00 D1 260901 found in Locus 26018 in Area D1, Season 1998-2000

The Department of Physics of the Weizmann Institute of Science (WIS) introduced new, computerized methods [5] to compare digitized hand drawings of profile lines. The next step was to introduce the *profilograph*, which is mechanical interface device, which can directly acquire and transfer a profile by pin-pointing the profile on a sherd, to a computer. The accuracy of the *profilograph* has been estimated by experiments to be $0.5\ mm$, which is sufficient for archaeological applications. The remaining disadvantage of this procedure is, that the axis of symmetry still has to be found manually and also the time for acquisition of a profile line requires approximately the same amount of time as the manual drawing.

We have already proposed a fully automated system for acquisition and documentation of profile lines using a 3D-Scanner based on structured light [7, 3, 17, 11, 12, 8]. The time for scanning and processing a sherd was estimated in laboratory experiments to be from 2 up to 10 minutes. Hence the proposed time for documentation of sherds is 5 times faster than the *profilograph* and the traditional hand drawing. We joined the *Tel Dor* Excavation in July 2004 together with the Department of Physics from the WIS to compare all three methods of documentation in respect with accuracy and performance.

The next section shows the types of different sherds acquired during our in-situ experiments and the improvements made for the setup of our acquisition system. Afterwards the processing of the data is shown by describing our methods for noise removal and estimation of the orientation of the sherds. Finally the latest results based on the data acquired during our field-trip and an outlook on future enhancements considering the color-decorations on sherds is shown.

2 Data Acquisition

For the comparison of accuracy between hand drawings, *profilograph* and 3D-Scanner, we measured 35 different sherds, provided by archaeologists. The criteria of the archaeologists for choosing these samples were to see, where each method has its limits. The expected rate of failure for these sherds was expected to be more than the proposed rate of 30%, because the sherds contained flat and/or small pieces and pieces with a handle.

Regarding performance measurements we used additional sherds which were brought from the excavation to the pottery registration office to gather a representative selection of routine data.

For acquisition of sherds with respect to performance, which is measured in sherds per hour, we trained a student, without archaeological, computer science or 3D-scanning expert knowledge.

We also measured the steps of work for the single sub-tasks for 3D-Scanning and the average of 4 minutes of work used for sherd consist of only 30 seconds for the 3D-measurment. The rest of 3.5 minutes were spent on reading and entering the registration number of the sherd, positioning the sherd for 3D-Scanning and idle time for moving the rotational plate, so that the 3D-Scanner can acquire the back and the front side of the sherds (see Figure 2b,c).

For the performance evaluation we set up the 3D-Scanner (see Figure 2a), such that we could scan sherds from small ($4{\times}3cm$) to large size ($27{\times}20cm$). This was necessary, because rearranging the optimal setup for each sherd requires up to 15 minutes of work, which gains an insignificant increase of accuracy in respect to analysis of sherds.

The volume for scanning was not used optimally, when we scanned sherds of small up to medium size ($15{\times}12cm$). As we could not decrease the time for the scanning of a single sherd for this preliminary in-situ experiment, we increased the number of sherds per scan. This was done by placing small and medium sized sherds into a frame (see Figure 2b,c). We could than scan up to 6 sherds per scan, which resulted in a rate of 40 sherds per hour.

(a) (b) (c)

Figure 2: (a) Setup of the 3D-Scanner, Rotational Plate and Illumination. (b) Frontview and (c) Backview of the Sherds.

We acquired one 2.5D-Image (depth-image) of the inner side of the sherds and one image of the outer side. If the sherd is part of the rim of an object or has decorations, handles, etc. a third 2.5D-Image was acquired. These images are used to describe the surface required for the extraction of the profile line [12]. The points of the 2.5D-Image are registered using the known position of each image given by the rotational plate. The Iterative Closest Point (ICP) Algorithm [1, 2] is used to register the vertices to a connected surface. If no rotational plate is used we can also use the known dimensions of the frame for registration. As the 2.5D-Image contain several sherds, the connected surfaces are labeled and processed separately after the registration.

3 Data Processing

This section describes the processing of the 3D-data beginning with the removal of noise. The following two subsections describe the proper orientation of the sherd in respect to the unbroken vessel. The processing is concluded by the profile extraction and the comparison of the traditional and computerized methods in the next section.

The 2.5D-Image also contains noise, like the background, dust and the frame, which has to be removed. The background is identified and removed by the color, because the background and the frame are either white or black. Small objects like dirt or dust, which can not be recognized by their color are removed based on their surface area. Every labeled surface smaller than processed sherds (e.g. $100\ mm^2$) is removed.

Beside the registration we also have to orientate the sherd. For orientation we determine the axis of rotation of the sherd. The axis of rotation is present in all objects and their fragments manufactured on a rotational plate, which was generally used for production of daily used ceramics.

The traditional, manual way to determine the axis of rotation is to look orthogonal at the inner side of the sherd, where you can see rills from the manufacturing process. These rills are artifacts from tools or fingers used while giving the object its shape on the rotational plate.

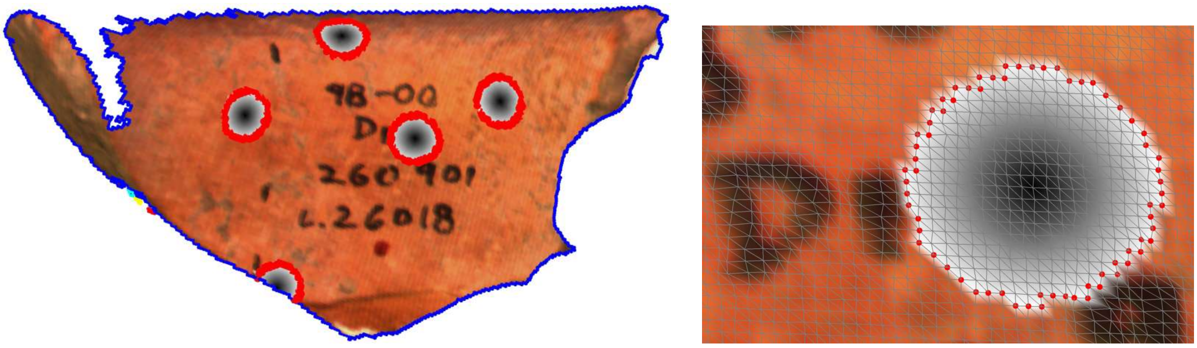
These rills describe concentric circles with their centers along the rotational axis. So the sherd has to be twisted and tilted until the rills are positioned horizontally. For estimation of the radii or when the rills are not clearly presented, archaeologists use circle-templates to estimate the axis of rotation given by the center of the circle-templates.

Due to our experiments on the field-trip we have seen that the method of finding the axis of rotation by the normal vectors fails for S-shaped objects. The Hough-inspired method [22] works best for fragments of cylindrical or conical shaped vessel. So we choose a new method for estimation of the axis of rotation inspired by the manual method used by archaeologists.

3.1 Preliminary Orientation

The first step of this method is to identify the inner side of the sherd where the rills are located. For many, but not all sherds rills can be found also on the outer side of the sherd. Due to the fact that the outer side can have applications like handles or decorations, these applications can lead to wrong axis of rotation. As we have two or three 2.5D-Images we have to find the 2.5D-Image which contains the surface of the inner side of the sherd.

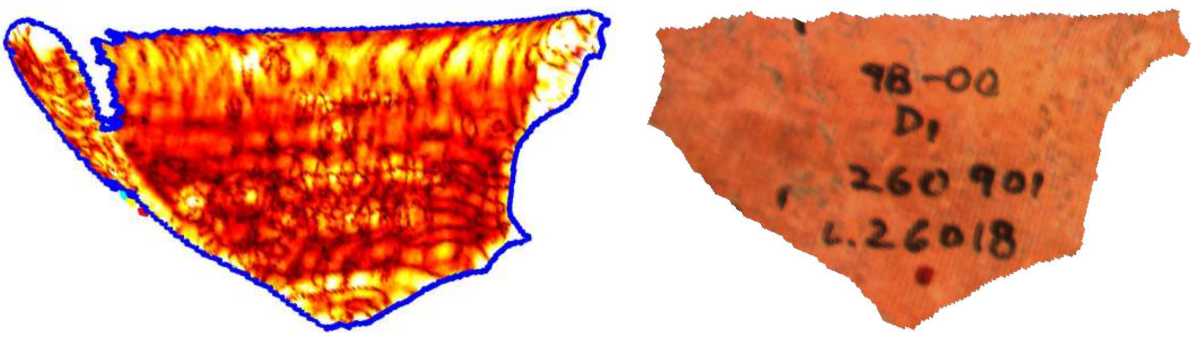
This can be done by measuring the curvature of the surface. The sign of the curvature for each vertex of the surface correspond to a concave or convex part of the surface. To estimate the curvature we determine the geodesic neighbourhood [20] for each vertex. Figure 3a shows (for example) 5 vertices with their geodesic neighbors. Figure 3b shows the geodesic neighborhood with the triangulated mesh for one of the vertices from Figure 3a. The level of gray in Figure 3a corresponds to the geodesic distance.



(a) (b)

Figure 3: (a) Inner side with 5 random points and their geodesic neighborhood. The level of gray corresponds to the geodesic distance - darker means closer. (b) Detail of one of the 5 random points.

The curvature is estimated by fitting a second degree polynomial function and estimation of the curvature of the polynomial function [21]. The 2.5D-Image generally contains in parts of the surface of the breakage, which is not part of the inner side of the sherd. In case of bottom fragments there can also be a plane included, where no concentric rills are present. Therefore we have to remove the breakage and parts of the bottom plane. This is done by the segmenting the surface into parts with high, medium and low curvature and removing the parts with high and low curvature. Additionally we remove vertices along the border of the surface, because they often contain incorrect vertices, because of the sliding intersection of the laser-beam from the 3D-Scanner with the surface of the sherd. Figure 4b show the surface from Figure 4a after removal of the parts with high and low curvature.



(a) (b)

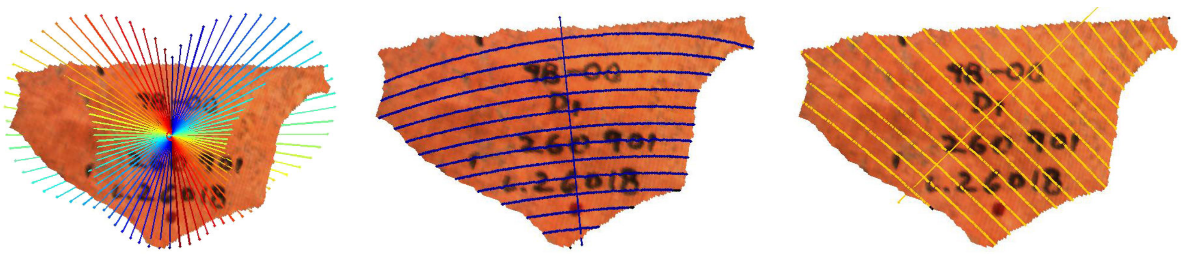
Figure 4: 2.5D-Image of the inner side of the sherd (a) colored by the curvature (lighter means high curvature, dark means low curvature. (b) 2.5D-Image from (a) after removal of the parts with high curvature and the parts close to the surface of the borde.

3.2 Final Orientation

The next step is to find a preliminary estimation of the rotational axis. The following algorithm is based on the manual approach, where the sherd is tilted and rotated, so that the concentric rills can be seen as parallel lines, which are orientated horizontally.

Therefore we estimate the mass point and the balancing plane of the remaining vertices of the reduced inner surface. The balancing plane is described by the two longest eigen-vectors of the mean-normalized vertices, which are estimated by using the singular value decomposition (SVD) [19]. The preliminary estimation uses an iterative search for concentric circles along n hypothetical axes (Figure 5a). These hypothetical axes are defined by the mass point and the longest eigen-vector which is rotated about the mass point in the balancing plane (Figure 5b,c). The value of $n = 18$ corresponds to an axis every $10°$ and has shown the best trade-off between accuracy and performance in empiric experiments.

Along the hypothetic axes we fit circles and estimate their center. In general these centers are not concentric, but when a hypothetic axis is coplanar to the rotational axis, the centers are also coplanar. For each hypothetic axis the variance of distances between the circle centers and a plane defined by the hypothetic axis is estimated. The variance can have zero, one or two global minima. In general there is one minimum. There are two minima for U-shaped sherds, where the second smallest minima describe an orthogonal rotational axis. If the sherd is part of a sphere there is no minimum, because in this case no single axis of rotation exists.



(a) (b) (c)

Figure 5: (a) Axes used for the first estimation of the rotational axis. These axes are defined by the masspoint and the balancing plane. (b) First Axis from (a) defined by the first eigen-vector of the balancing plane. (c) Axis from (a) defined by the about $130°$rotated first eigen-vector of the balancing plane.

A line is fitted by minimizing the least-square error to the centers of the concentric circles with the minimum variance. The fitted line is used as estimated rotational axis. It is tilted orthogonal towards the balance plane to find the best line fit. After each tilt the centers of the concentric circles are estimated. For these centers a line fitting is applied. The line with the best fit is chosen as rotational axis.

4 Results

As proposed in Section 2 we used 35 selected sherds for testing the robustness of our system. These 35 sherds were selected among the daily finds with the criteria that their size is small and their curvature is low, so that the axis of rotation is also difficult to find by manual orientation. It is important to mention that the ground truth is not present for all findings. So we can divide the results of experiments, where the three methods do not agree, into two different groups. The first group shows alternative profile lines estimated by our objective and repeatable method based on the geometry of an object, which might be camouflaged for the human eye by decorations or applications. The second group consists of sherds that have to be tagged as not processable and therefore analysed by archaeologists to classify them not by the profile line. Instead of the profile line, properties like material or context to other findings, can help to classify a sherd, when no profile line can be found.

4.1 Proper Orientation

We already proposed a rate of successfully processed sherds for daily findings in general [12]. With our new approach, we could increase this ratio for fragments that could not be processed based on the Hough-inspired method. The ratio for our 35 sherds is approx. 50% of the sherds have the same result for all three methods. For 30% of these sherds the radii varies less than $20\ mm$ and the orientation differ for a maximum of $20°$. The remaining 20% were not properly processable.

Table 1 shows the numerical result of the comparison. The first column is the unique id of the sherd describing the area, locus number and a serial number. The second column shows the maximum and the minimum difference Δr between the radii at the top-point of the rim. The third column shows the angle between the rim-part of the different profile lines reduced to uniform height of $20\ mm$. The last column shows the pairs, with minimum and maximum correlation of the three profile lines. The results for the radii Δr have been grouped into $5\ mm$ steps, so for example a value of 10 means that Δr is between $5\ mm$ and $10\ mm$. A similar grouping has been applied to $\Delta\alpha$, which is grouped by steps of $5°$.

The sherds in Table 1 with only one result for Δr and $\Delta\alpha$ have only been documented by two out of three methods due to logistical problems during the field-trip. For one sherd (19743-306051-2 shown in Table 1 - Row 4) the difference between the profile line of the *profilograph* and the 3D-Scanner is less than $1\ mm$ ($\Delta r = 0$) similar to sherds of medium and large size like shown in Figure 2.

4.2 Performance

The performance measured for the acquisition by the 3D-Scanner had an actual average of 90 seconds per sherd using the frame. This time can be decreased by improving the handling of the 3D-Scanner down to approximately 35 seconds per sherd. The 3D-Scanner used for the experiments was a *Minolta VIVID-900* together with a $3.0\ GHz$ *Pentium IV* with $1.0\ GB$ memory for acquisition. The extraction of the profile line was done on a separate computer to

Sherd Locus No. from Area D2	Δr (mm) min/max	$\Delta\alpha$ min/max	min (Correlation)	max (Correlation)
19732-305940-6	10/20	5°/15°	Man.-*Prof.*	*Prof.-3DS.*
19742-305996-2	10/15	15°/45°	Man.-*Prof.*	Man.-*3DS.*
19743-306028-4	5	20°	*Prof.*n.a.	
19743-306051-2	0/15	5°/15°	*Prof.-3DS.*	Man.-...
19732-305940-1	25	5°	Man.n.a.	
19732-305940-1	5	10°	Man.n.a.	
19742-305996-4	60	5°	Man.n.a.	
19742-305996-1	15/15	5°/5°	Man.-*3DS.*	*Prof.-3DS.*
19743-306028-6	10/10	5°/5°	Man.-*3DS.*	*Prof.-3DS.*
19743-306028-4	10/40	10°/30°	Man.-*3DS.*	Man.-*Prof.*
19742-305996-3	20	5°	*Prof.*n.a.	
19743-306028-2	20/50	5°/50°	Man.-*Prof.*	Man.-*3DS.*
19732-305940-7	5/50	10°/80°	n.a.	all
19732-305940-11	15	20°	*Prof.*n.a.	
19739-306012-5	5/10	5°/5°	*Prof.-3DS.*	Man.-*3DS.*
19732-305940-5	5/15	10°/10°	Man.-*3DS.*	Man.-*Prof.*
19743-306028-3	5/10	5°/5°	Man.-*Prof.*	*Prof.-3DS.*
19739-305994-2	20/25	5°/15°	Man.-*Prof.*	*Prof.-3DS.*

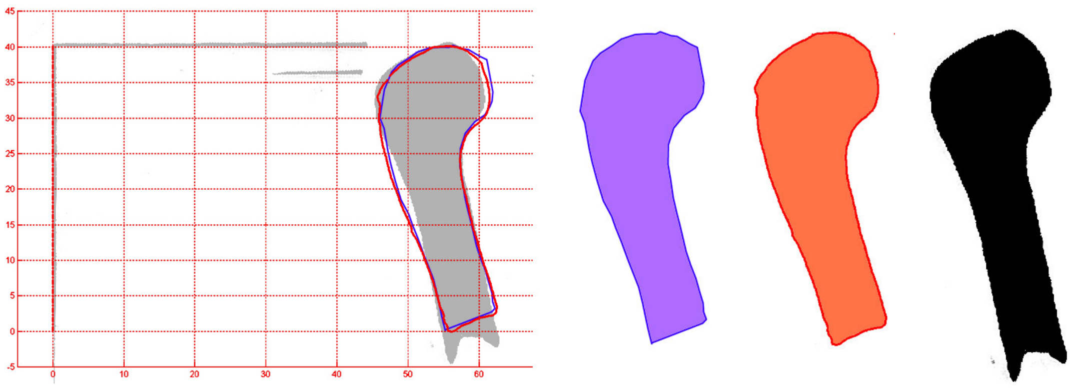
Sherd Locus No. from Area D2	Δr (mm) min/max	$\Delta\alpha$ min/max	min (Correlation)	max (Correlation)
19743-306028-5	15/40	15°/70°	Man.-*Prof.*	Man.-*3DS.*
19743-306028-12	10/25	5°/15°	*Prof.-3DS.*	Man.-*Prof.*
19742-305996-7	5/10	5°/10°	*Prof.-3DS.*	Man.-*Prof.*
19732-305940-8	5/10	10°/30°	Man.-*3DS.*	Man.-*Prof.*
19739-305994-4	5/10	5°/25°	Man.-*Prof.*	Man.-*3DS.*
19714-306020-30	10	5°	Man.n.a.	
19766-306231-7	40	35°	*3DS.*n.a.	
19751-306083-2	5/20	5°/15°	Man.-*3DS.*	Man.-*Prof.*
19736-306146-8	15	5°	*Prof.*n.a.	
19736-306027-1	5/20	5°/25°	Man.-*Prof.*	*Prof.-3DS.*
19720-305925-12	10/20	5°/15°	Man.-*3DS.*	*Prof.-3DS.*
19766-306231-4	5/15	5°/5°	*Prof.-3DS.*	Man.-...
19736-306146-2	5	25°	*Prof.*n.a.	
19736-306146-2	10	30°	Man.n.a.	
19720-305925-1	50	5°	*3DS.*n.a.	
19766-306231-3	5/15	5°/5°	Man.-*3DS.*	*Prof.-3DS.*
19766-306231-12	5/10	5°/5°	Man.-*3DS.*	*Prof.-3DS.*
see Figure 1	0/0	0°/0°	all	none

Table 1: Comparison of Profile-Lines. Man. means manual drawing. *Prof.* means *profilograph*. *3DS.* means 3D-Scanner.

free processor time for data acquisition. The average time for processing the data and extracting the profile line was 90 seconds per sherd on a $2.0\ GHz$ *Pentium IV* with $0.5\ GB$ memory. The execution time is linear dependent on the number of vertices, which depend on the 3D-Scanner resolution and the area of the surface of a sherd.

The experiments with respect to the accuracy of the profile lines for the sherds as they are brought for documentation showed that the profile line from the *profilograph* and the 3D-Scanner result in the same profile line with a maximum difference of $0.1\ mm$. The profile line from the 3D-Scanner is smoother for curved sherds due to the higher density of the measured points. Along the same profile line of the sherd, we marked the spot of the extracted profile line on the real sherd, so that is extracted at the same point of the sherd for all three methods. We get 120 points from the *profilograph* and 500 points from the 3D-Scanner. This relates to an average between two points defining the profile of $1.75\ mm$ for the *profilograph* and $0.35\ mm$ for the 3D-Scanner. To compare these two profile lines to the profile line drawn by hand, we digitized the hand drawing and converted it also to a list of 2D-points. As the sampling of the points depends on the resolution of the 2D-Scanner, which is not representative for our comparison, we had to compare the radii at the top and bottom point of the profile and its orientation. The profile lines of a sherd for all three methods are shown in Figure 6.

The differences between the computerized profile lines (3D-Scanner & *profilograph*) and the hand drawings are more significant. The radii at the top and bottom point differ also only by $0.1\ mm$, but for radii measured along the profile line the maximum difference is $\pm 0.2\ mm$ including even a change of the sign of the curvature, which can have an influence on further processing such as classification [16, 13].



(a) (b) (c) (d)

Figure 6: (a) Profile Lines extracted at the same point of the sherd in respect to the rotational axis (equals y-axis), acquired by the *profilograph* (b), the 3D-Scanner (c) and the manual drawing (d).

5 Conclusion

The experiments regarding the performance of the hand drawing showed that a skilled draftsperson can draw up to 5 profile lines per hour. The performance of the acquisition of the profile line using a *profilograph* is similar and rates up to 6 sherds per hour. Using the 3D-Scanner a single person can acquire 10 to 12 3D-Models of sherds per hour during the learning phase, which increases after an experience of 5 working days to 14 and maximum of 18 sherds per hour.

We can therefore propose that using a faster turntable and an easier-to-use registration (numbering) system (e.g. barcodes) on the sherds will give a rate of 60 up to 100 sherds per hour.

All experiments have shown that the use of a 3D-Scanner has the potential to acquire data 20 times faster, with twice the accuracy than drawing the sherd by hand or acquisition with a *profilograph*.

Concluding all improvementes made with the experiments of the Field Trip to *Tel Dor*, we could show that using 3D-Scanning is the first method that fulfills the requirement of accuracy and performance for documentation and as basis for publications in archaeology.

6 Outlook

As the time for acquisition and processing is already suitable for archaeological documentation, there are other new methods based on [15] for finding the axis of rotation, which have to be tested for performance and robustness for processing of large 3D-Models of sherds. This has to be done, because these 3D-Models usually contain noise in form of surface roughness and geometrical distortion, which are rather unique compared to industrial applications or experiments with other synthetically generated objects.

We will also implement our experience from the practical experiments field-trip to reduce the time for acquisition. This major part for these improvements include a simpler, but faster turntable and sorting the sherds by size before they are scanned. Ths sorting has to be done, because the distance between the acquired objects and the 3D-Scanner depends on the size (small, medium or large) of the objects.

Other experiments concern new possibilities for archaeolgical analysis based on paintings applied on the sherd. These paintings are represented as texture map within the 3D-Models acquired by the 3D-Scanner. Some ceramics of the daily life contain line patterns and ceramics from rich people can be decorated with paintings. For both cases we have done related work in our art historian project *Cassandra* [9, 6], where we are developing methods for detecting and analysing paint strokes (lines) in paintings applied to rough surfaces like wood.

References

[1] P. Besl and N. McKay. A method for registration of 3-dshapes. *IEEE Trans. Pattern Analysis and Machine Intelligence*, 14:239–256, 1992. 4

[2] Y. Chen and G. Medioni. Object modelling by registration of multiple range images. *Image and Vision Computing*, 10:145–155, 1992. 4

[3] J. Cosmas et.al. 3D MURALE: A multimedia system for archaeology. In *Proc. of Intl. EuroConference on Virtual Reality, Archaeology and Cultural Heritage*, page in press, Athens, Greece, Nov. 28–30 2001. 2

[4] A. Gilboa. *Southern Phoenicia during Iron Age IIa in the light of the Tel Dor excavations. Ph.D. thesis*. The Hebrew University, Jerusalem, 2001. 2

[5] A. Gilboa, A. Karasik, I. Sharon, and U. Smilansky. Towards computerized typology and classification of ceramics. *Journal of Archaeological Science*, 31:681–694, 2004. 2

[6] P. Kammerer, E. Zolda, and R. Sablatnig. Computer aided analysis of underdrawings in infrared reflectograms. In *In Proceedings of the 4 th International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage, VAST2003*, 2003. 10

[7] M. Kampel and R. Sablatnig. On 3d Modelling of Archaeological Sherds. In *Proceedings of International Workshop on Synthetic-Natural Hybrid Coding and Three Dimensional Imaging, Santorini, Greece*, pages 95–98, 1999. 2

[8] M. Kampel and R. Sablatnig. On using 3d multimedia tools to measure, reconstruct and visualize an archaeological site. *Forum Archaeologiae, Zeitschrift fuer klassische Archaeologie*, 19(IV), 2001. 2

[9] M. Lettner, P. Kammerer, and R. Sablatnig. Texture analysis of painted strokes. In *Procedings of the 28th Workshop of the Austrian Association for Pattern Recognition (OAGM/AAPR)*, pages 269–276, 2004. 10

[10] U. Leute. *Archaeometry: An Introduction to Physical Methods in Archaeology and the History of Art*. John Wiley & Sons, December 1987. 2

[11] H. Mara, M. Kampel, and R. Sablatnig. Preprocessing of 3D-Data for Classification of Archaelogical Fragments in an Automated System. In F. Leberl and F. Frauendorfer, editors, *26th Workshop of the Austrian Association for Pattern Recognition (OeAGM/AAPR)*, pages 257–264, Graz, Austria, September 2002. 2

[12] Hubert Mara. Automated profile extraction of archaeological fragments. Technical Report PRIP-TR-083, Vienna University of Technology, Inst. of Computer Aided Automation, Pattern Recognition and Image Processing Group, 2003. 2, 4, 7

[13] J. Matas, Z. Shao, and J.V. Kittler. Estimation of Curvature and Tangent Direction by Median Filtered Differencing. In *8th International Conference on Image Analysis and Processing*, pages 83–88, 1995. 9

[14] C. Orton, P. Tyers, and A. Vince. *Pottery in Archaeology*, 1993. 2

[15] Helmut Pottmann and Johannes Wallner. *Computational Line Geometry*. Springer Verlag, Heidelberg, Berlin, u.a., 2001. 9

[16] A. Rosenfeld and A. Nakamura. Local Deformations of Digital Curves. *Pattern Recognition Letters*, 18(7):613–620, July 1997. 9

[17] R. Sablatnig and M. Kampel. Model-based registration of front- and backviews. *Computer Vision and Image Understanding*, 87(1–3):90–103, July 2002. 2

[18] E. Stern. *Dor - Ruler of the Seas*. Israel Exploration Society, 1994, extended 2000. 2

[19] Gilbert Strang. *Linear Algebra and its Applications*. Harcourt Brace Jovanovich College Publishers, Orlando, FL, 3rd edition, 1988. 6

[20] Y. Sun and M.A. Abidi. Surface matching by 3d point's fingerprint. In *Proceedings. Eighth IEEE International Conference on Computer Vision, 2001. ICCV 2001*, volume 2, pages 263–269, 2001. 5

[21] Tamás Várady and Thomas Hermann. Best fit surface curvature at vertices of topologically irregular curve networks. In *Proceedings of the 6th IMA Conference on the Mathematics of Surfaces*, pages 411–427. Clarendon Press, 1996. 5

[22] S. Ben Yacoub and C. Menard. Robust Axis Determination for Rotational Symmetric Objects out of Range data. In W. Burger and M. Burge, editors, *21 th Workshop of the Oeagm*, pages 197–202, Hallstatt, Austria, May 1997. 2, 4