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COMPUTER BASED ACQUISITION OF ARCHAEOLOGICAL FINDS: THE FIRST STEP TOWARDS AUTOMATIC CLASSIFICATION

1. Introduction

Usually a large number of sherds of archaeological pottery is found at excavations. These sherds are photographed, measured, drawn and catalogued. Up to now, all this has been done by hand, and means a lot of routine work for the archaeologist. Therefore it is necessary to construct an acquisition system for archaeological finds to form the basis for a subsequent automatic classification. We are currently constructing a system (prototype), that carries out an automated 3D-object acquisition with respect to the archaeological requirements. With the help of this system and the knowledge of an expert an automated classification of archaeological finds should be achieved.

Whereas the results of the conventional acquisition by different archaeologists may differ, this system should serve the archaeologist as a powerful tool to reduce the amount of routine work and to get an objective, reproducible acquisition of the material. Fig. 1 shows the drawing of a sherd found at the excavation site Petronell near Vienna. First it was measured with the help of a profile "comb" to get the contour line (Fig. 1a) and then a top view of the sherd was drawn (Fig. 1b). Approximately 1½ hours were necessary to complete this drawing. The processes can be carried out by computerized methods in both a faster and a more exact way. The process of drawing and archiving a sherd can be automated by computing the cross-section out of the three-dimensional model of the sherd and the topview with the help of the pictorial information of the surface of the sherd and the surface model.

In this paper an acquisition system consisting of a combination of the *shape from stereo method* (Menard 1991) and the *shape from structured light method* (Sablatnig 1991) is proposed that could help the archaeologist in his work and automate the archivation process. First we present an overview of existing methods for archaeological image acquisition methods. These systems are half-automated, so the amount of work has not really been reduced. Next we focus on the two acquisition methods to minimize failures in the output, providing a 3D-surface representation of a sherd.

The results of the two methods are compared with each other and the fusion of these methods for an archaeological application is shown. Finally, the outlook for a computer based automatic classification of archaeological finds is given. At the current stage of the project it is not possible to show final results, but we will test the new acquisition method with provincial Roman material from Austrian excavation sites and ceramic material from

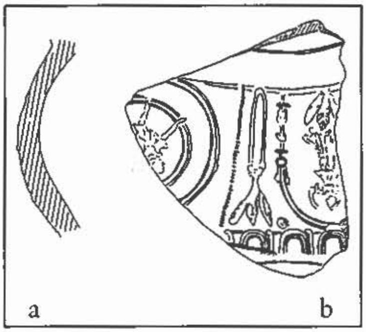

Fig. 1 – Sherd drawn by hand.

Velia in the future. In order to compare the new method to the traditional archaeological method, the material is tested and documented with both methods.

2. State of the art

Because conventional methods for pictorial acquisition are unsatisfactory, the search for some possible automatic solutions began early. We show two systems, ARCOS and SAMOS, which are representative for many other methods for getting pictorial and 3D-information from a sherd, because the stage of development of these two systems is comparable to our system. Further tests in the field of macrophotogrammetry are discussed.

2.1 *ARCOS (Kampffmayer/Karlsruhe)*

ARCOS, the *AR*chaeological *CO*mputer *S*ystem, was developed in Karlsruhe and combines video- and computer-techniques for the evaluation analysis and storage of archaeological data (Gathmann *et al.* 1984; Kampffmeyer 1985; Kampffmeyer, Teegen 1986; Kampffmeyer *et al.* 1986). Ceramic sherds are placed on a rotation plate, recorded by a video camera, then interactively processed and measured, and then drawn automatically. Ceramic sherds were oriented on a rotation plate according to their original position on the pot. Therefore, the reconstruction of the shape of a pot was based on the exact positioning of a sherd on the plate with the help of plasticine. The rotation of the sherd determined the shape of the original pot. Small inaccuracies in the positioning could therefore cause mistakes in the reconstructed pot. Textures on the sherd were not recorded and had to be added manually. The archivated drawing was printed on a matrix printer creating steps in the contour line.

ARCOS was tested in June 1987 at an excavation site in Velia, southern Italy, where the following problems occurred: the parameters for the description of the ceramic were numerically coded, so that the possibility of making mistakes is rather high (KAMPFFMEYER *et al.* 1988; LUEBBERT, KAMPFFMEYER 1988). The program is installed in the computer as an chip and can not be adjusted to suit the requirements of individual excavation sites. The necessity to add contour lines manually (the inner profile cannot be seen by the camera) on the monitor leads to inaccuracy and depends on the method of work of the archaeologist (SABLATNIG *et al.* 1993). Moreover, the resolution of the system was too low, so that very small cracks in the profile were not detected. Another considerable problem was the computation of the thickness of a pot, because small differences in the illumination cause great differences in the results (KRINZINGER *et al.* 1990). The development of ARCOS was stopped, because of the bad results of the prototype and the work for the archaeologists was not really reduced. Textures on the sherd were not recorded and had to be added manually.

2.2 *SAMOS (Steckner/Hamburg)*

The second system is called SAMOS (*Statistical Analysis of Mathematical Object Structures*). It provides the automatic drawing and reconstruction of profiles from pottery (STECKNER, STECKNER 1987, 1988; STECKNER 1988, 1989). In order to get a contour line of a sherd or a pot, this contour line is digitized with the help of a tablet by determining several points on this line. The missing points are interpolated by the computer-system. Although the accuracy of a tablet is very high, errors occur from inaccurate positioning of the pen and from interpolation. A small number of measure points may cause edges in the contour line (MENARD, SABLATNIG 1991). After the half-automated input of the contour, several measurements – like volume, width, maximal perimeter etc. – are computed. These relevant measurements are computed automatically out of the digitized profile. Reconstructions of pots from sherds are made by comparing the actual contour line with the contour lines already existing in the system. The most similar is taken for the complete reconstruction and classification. This system is also not able to record the texture of sherds, so it is necessary to draw it separately or to describe it.

2.3 *Photogrammetry for archaeological finds*

Tests concerning the recording and measuring of archaeological finds were also performed in the field of photogrammetry (KLADENSKY 1981; KANDLER *et al.* 1985; WALDHAEUSL, KRAUS 1985; GRUBER, SCHINDLER-KAUDELKA 1986). These tests deal with the documentation of stamps in bricks and ceramic. The object is recorded photogrammetrically with the help of a camera and measured with a analytical stereo-measurement-system. With such a system the accuracy of the measurement of stamps on a brick can be increased, but the complete model of the object cannot be computed (Fig. 2). The mea-

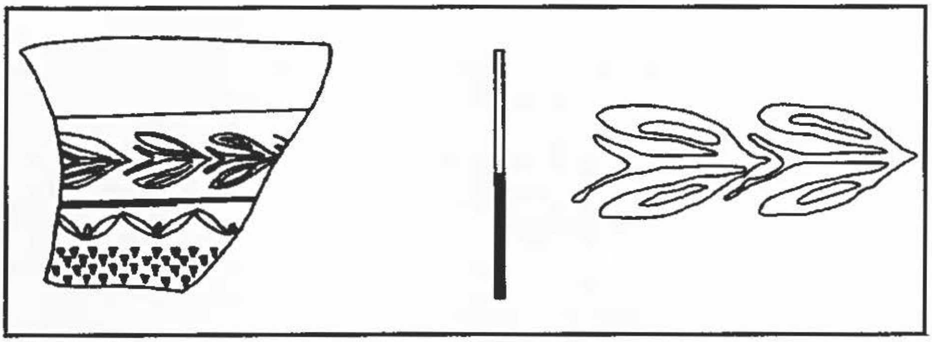

Fig. 2 – Result of a photogrammetrically measurement (GRUBER, SCHINDLER-KANDELKA 1986).

surement process is not automated and the archaeologist is not able to make the image acquisition without knowledge about the configuration parameters and illumination parameters. Moreover, a special stereo evaluation system has to be provided. The evaluation on such a stereo system can only be made by a specialist and does not reduce the amount of work. The evaluation method could be simplified by methods of digital photogrammetry (softcopy photogrammetry). For this method it is necessary to scan the photos on a scanner. The two digital stereo images can be used as input for a digital stereo evaluation system. The development of these systems are not finished, yet costs computation time and requires an operator (ALBERTZ *et al.* 1991; LEBERL 1991a,b).

2.4 *Monocular acquisition systems for archaeological finds*

In contrast to stereo methods, monocular methods work with only one camera and try to get the 3D-information using a priori knowledge, such as illumination direction and surface texture. This class of algorithms is called "Shape from X", where X stands for the type of evaluation. Two representatives are "Shape from Shading" and "Shape from Texture".

Shape from shading tries to compute depth out of the gray level variations of an intensity image if the position of the light source is known (BICHSEL, PENTLAND 1992; HORN 1990; OLIENSIS 1991; PENTLAND 1990; WOODHAM 1972). Shape from texture uses the surface texture from an object to compute the model (IKENCHI 1984; KENDER 1979; OHTA *et al.* 1981). The orientation and the distance surface elements can be computed with the help of the texture gradient. This texture gradient describes the modification of the density and the size of texture elements and so the surface orientation can be determined. Out of the distortion of the texture the angle to the image plane can be computed. If the texture is not distorted the image and object plane are parallel. None of these methods was used for the pictorial acquisition of archaeological sherds. Monocular acquisition methods have the disadvantage that a priori knowledge about surface and illumination are necessary.

3. Acquisition method

With the help of image processing methods it is possible to make an automated acquisition of archaeological sherds. In order to get the 3D-information of a sherd, we tested two different representative methods, in particular shape from stereo (Cochran, Medioni 1992; Grimson 1981; Hoff, Ahuja 1989) and shape from structured light (Ishii, Nagata 1976; Jervis 1983; Lin *et al.* 1989; Wust, Capson 1991).

3.1 *Shape from stereo*

The stereo analysis method is similar to the human vision system. Because of the way our eyes are positioned and controlled, our brains usually receive similar images of a scene taken from nearby points of the same horizontal level. Therefore the relative position of the images of an object will differ in the two eyes. Our brains are capable of measuring this disparity and thus estimating the depth (Marr, Poggio 1979). Stereo analysis tries to imitate this principle. Fig. 3 shows the experimental configuration of the stereo system. The sherd to be recorded is placed in the measurement area. Two fixed CCD cameras are used to get intensity images from two different positions. The orientation parameters of the stereo configuration are given as follows:

B = 65 mm	distance between two cameras
d = 520 mm,	distance between object – and image plane
f = 16 mm,	focus of the lenses
res = 512x480 Pixel	resolution of the CCD cameras

Out of these parameters the accuracy can be determined with 1.6 mm. The search for the correct match of a point is called *correspondence problem* (Jenkin *et al.* 1991), the central and most difficult part of the stereo problem. Several algorithms were published to compute the disparity between images, such as the correlation method (Luo, Maitre 1990; Subrahmonia *et al.* 1990) the correspondence method (Grimson 1985) or the phase difference method (Jenkin *et al.* 1991). Consider the case of a single point $P(x,y,z)$ in the scene. If this point can be located in both images its three dimensional world coordinates may be computed, if the relative orientation between the cameras is known. For a given pair of stereo images and the known orientation parameters of the cameras, the corresponding points are supposed to be on the epipolar lines (Weng 1992). Since a parallel camera alignment is used in this paper the epipolar lines are the scanlines in both images. If for a given point $I_L(x,y)$ in the left image a corresponding point $I_R(x,y)$ in the right image can be found the three dimensional position of $P(x,y,z)$ can be computed with the additional information about the camera parameters. The larger the distance between corresponding points $I_L(x,y)$ and $I_R(x,y)$ the nearer is the point $P(x,y,z)$

to the camera. The difference between the two image positions is called disparity. A disparity map is an intensity image where the disparity is represented by the gray level. A correspondence partner for a point $I_L(x,y)$ in the left image is searched by considering a rectangular window of intensity values around $I_L(x,y)$ and computing similarity measures between this window and windows around potential correspondence points in the right image, shown in Fig. 4. The correlation $C(x_L,y_L,w)$ between two regions of size w can be written in a continuous way in the one-dimensional case as:

$$C(x_L,x_R,w) = \frac{\int_{\xi=-w/2}^{w/2} [I_L(x_L+\xi)-\mu_L][I_R(x_R+\xi)-\mu_R]d\xi}{\int_{\xi=-w/2}^{w/2} [I_L(x_L+\xi)-\mu_L]^2 d\xi \int_{\xi=-w/2}^{w/2} [I_R(x_R+\xi)-\mu_R]^2 d\xi} \quad (1)$$

The correlation $C(x_L,y_L,x_R,y_R,w)$ for two-dimensional regions can be extended from (1). The two-dimensional function C is used fo r matching. In order to fulfill the archaeological requirements it is essential to compute a dense disparity map, where disparity is defined for every pixel in the entire image. In order to get a dense disparity map and to increase efficiency of the algorithm, 5x5/4 gaussian image pyramides are used to solve the correspondence problem in a hierarchical manner (KROPATSCH 1991; ROSENFELD, KAK 1982). The disparity maps $D(x_L,y_L,n)$ for each pyramid level n are computed as follows:

$$D(x_L,y_L,n-1)=\begin{cases} |x_L-x_R| & \max\{C(x_L,y_L,x_R,y_R,w,n-1)\} > t \\ 2*D(x_L,y_L,n) & else \end{cases}, \quad (2)$$

where t is the treshhold accepting a corresponding point.

Fig. 5 depicts the principle of this approach. Fast stereo evaluation is carried out in the top pyramid level n (due to the low resolution) resulting in a disparity map which is the course information considered in the evaluation process of level $n-1$. This process is iterated until the disparity map for the lowest level is computed. If no corresponding point can be found for a candidate in the left image, the information of the pyramid level above is used to get an average disparity information for that point (MENARD, BRÄNDLE 1995). The result is a dense disparity map, which can be seen in Fig. 6, and in Fig. 7 an object model with the mapped intensity image is shown, which is constructed out of the disparity map.

3.2 *Shape from structured light*

The second acquisition method for estimating the 3D-shape of a sherd is shape from structured light, which is based on active triangulation. A very

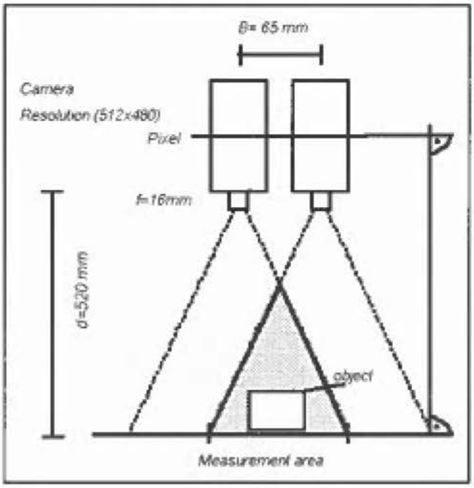

Fig. 3 – Configuration of the stereo system.

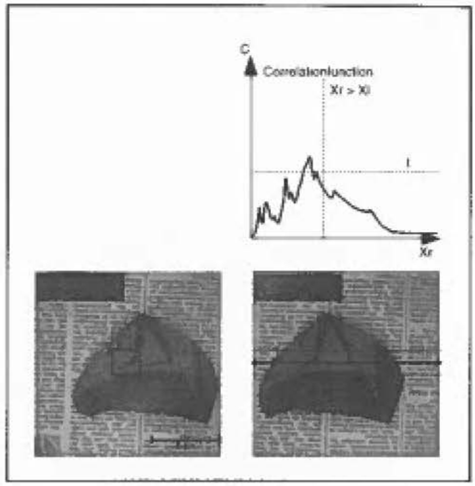

Fig. 4 – Stereo pair of a test sherd.

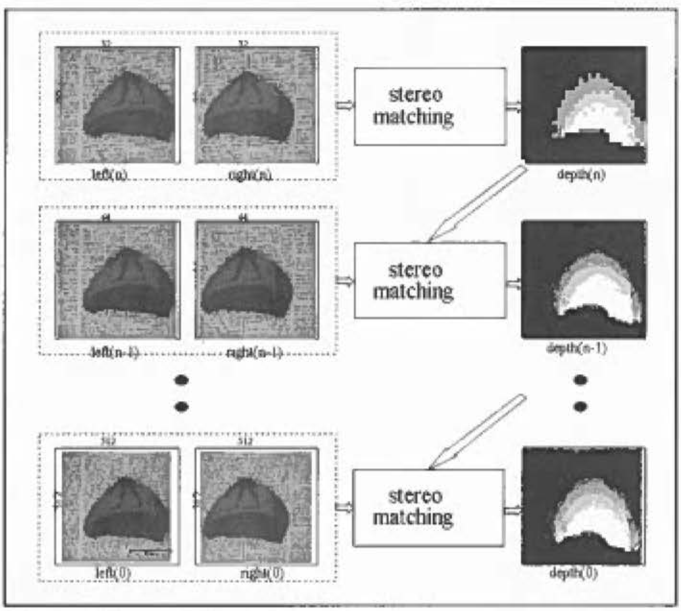

Fig. 5 – Hierarchical matching algorithm.

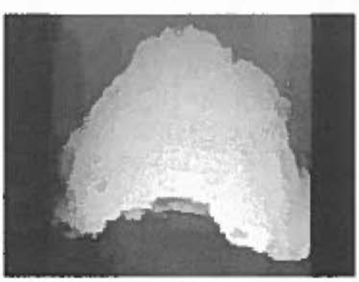

Fig. 6 – Dense disparity map of the test sherd.

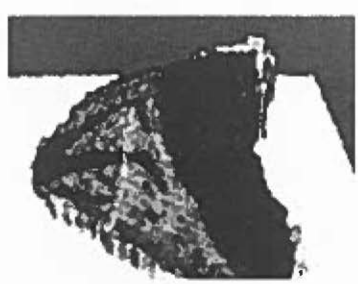

Fig. 7 – Constructed object model with mapped intensity image.

simple technique to achieve depth information with the help of structured light is to scan a scene with a laser plane and to detect the location of the reflected stripe. Out of the distortion along the detected profile the depth information can be computed (SABLATNIG 1991). In order to get dense range information the laser plane has to be moved in the scene. Another technique projects multiple stripes at a time onto the scene. In order to distinguish between stripes they are coded (Coded Light Approach) either with different brightness or different colors (BOYER, KAK 1987). A robust encoding method is the time-space encoding of projection directions. In one method a projection of time encoded laser dots was used (ALTSCHULER *et al.* 1979), which was improved by (WAHL 1984; INOKUCHI *et al.* 1984) by using time space encoding of stripes by projecting a sequence of *n* stripe pattern onto the scene.

In our acquisition system the stripe patterns are generated by a computer controlled transparent Liquid Crystal Display (LCD 640) projector. The light patterns allow the distinction of 2^n projection directions. Each direction can be described uniquely by a n-bit code, which can be seen in Fig. 9 schematically. In Fig. 8 the intensity image of the test sherd is shown. This image and one image without illumination is taken prior to the range image computation to determine the maximum and the minimum intensity for each pixel of the sherd. The camera with the optical center O_c is placed in a certain angle to the projector having the optical center at O_p. The camera grabs gray level images $I(x,y,t)$ of the distorted light patterns at different times *t*, which can be seen in Fig. 10 (a-f).

For each pixel in the image a n-bit code is stored. With the help of this code and the known orientation parameters of the acquisition system the 3D-information of the observed scene point can be computed. The orientation parameters are given by a calibration procedure performed prior to any depth computation by an algorithm developed by FAUGERAS (1993). In order to minimize the errors of incorrect coding a Gray-code is used for the direction of illuminations. The robustness of the technique depends on the correct detection of the edge between illuminated and non-illuminated area, the so-called edge, described in (TROBINA 1995). In our setup the projector stripes are approximately parallel to the image columns. The result of the test sherd shown in Fig. 8 computed by determining the depth points along the edges shown in Fig. 10 can be found in Fig. 11 as a range image comparable to a dense disparity map of the stereo algorithm. This range image can be taken to construct an object model of the sherd, where the intensity image can be mapped onto the surface in order to produce a realistic model of the sherd (Fig. 12).

4. COMBINATION OF THE TWO ACQUISITION METHODS

The results of the two acquisition methods were not sufficient enough for archaeological requirements, because each of the methods presented has

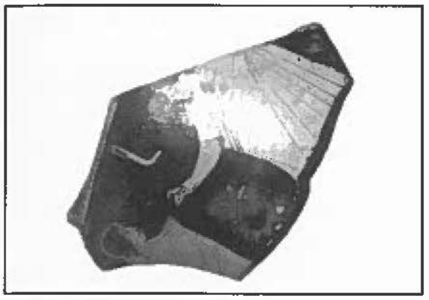

Fig. 8 – Gray level image of a test sherd.

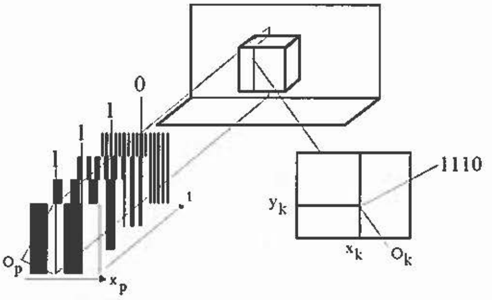

Fig. 9 – Principle of Code-Light-Approach.

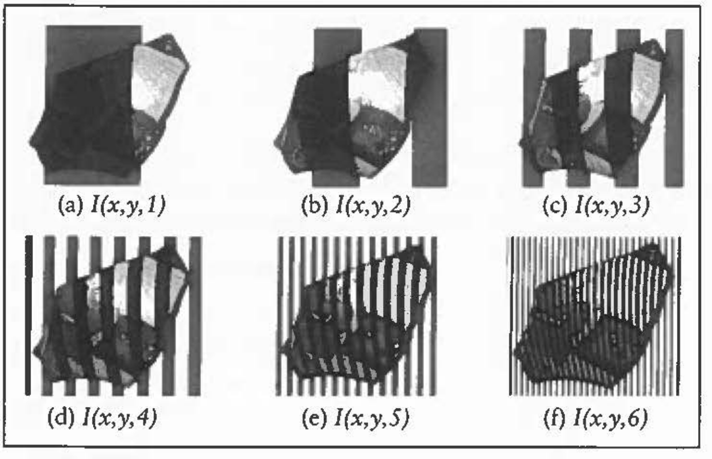

Fig. 10 – Gray level images of the first 6 out of 9 stripe patterns.

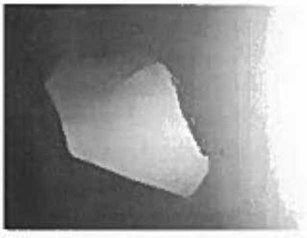

Fig. 11 – Dense range image of the test sherd.

Fig. 12 – Constructed object model.

disadvantages (MENARD, SABLATNIG 1992). On the one hand it is necessary to get an accuracy of 0.5 mm especially in regions with textures and ornaments, on the other hand the pictorial acquisition is extremely important for archiving (Fig. 1). The results of the stereo method are not accurate enough, because regions without texture are only approximated, the results of the structured light technique have the drawback of fixed line distance and therefore the accuracy between lines is not high enough.

In order to reduce the disadvantages a combination (fusion) of the two presented acquisition methods is used. A fusion of two different data sources reduces the error probability dramatically (Wei 1989) because the result is computed out of two data points for one object point. Furthermore the pictorial acquisition of the visual surface of the sherd is possible in true color. The accuracy of the individual results of the two acquisition methods is improved by interdependencies of the two algorithms, the stereo method influences the structured light computation and vice versa. Pictorial information changes for instance the grid density because only areas of archaeological interest on the surface of the sherd, such as reliefs are computed with high resolution in depth, whereas areas with low interest, like uniform areas with no texture, are computed with lower resolution. Textured areas are also computed by the stereo algorithm, therefore increasing the accuracy and reliability of the computed data.

In order to construct a robust and accurate acquisition system for the archaeologist that provides pictorial and 3D-acquisition, the system has to be portable to be useable in the field and should therefore be small and not too heavy.

4.1 *Data acquisition*

The system for the fusion of the stereo- and the structured light method is shown in Fig. 13. The two CCD cameras are used by both acquisition methods. In order to get light stripes onto the surface of the sherd, a LCD 640 light projector is used which is able to project 640 horizontal and vertical lines onto an 30cm x 30cm measurement area. Therefore the resolution of the lightstripe method is 0.5 mm in x- and y- direction. With the help of these lightstripes no transportation through the measurement area is needed. First, the light projector illuminates the measurement area without lightstripes in order to get two intensity images. These two images are used to locate the object in the measurement area and to determine where areas of archaeological interests (reliefs, paintings, lines) are on the surface of the sherd. This information is used to drive the light projector so that those parts of the surface, which are of archaeological interest are computed with higher accuracy than other parts, as shown in Fig. 14. Therefore the intensity image defines the density of the lightstripes. The two cameras are used to take 4 different lightstripe images. The use of two cameras reduces the amount of occluded areas not seen by one of the cameras and increases the accuracy, because two different images of the same structure can be used to compute the depth information. Furthermore, vertical and horizontal lines are not projected at the same time to reduce errors in finding corresponding lines and to reduce fringe computation on line crossings.

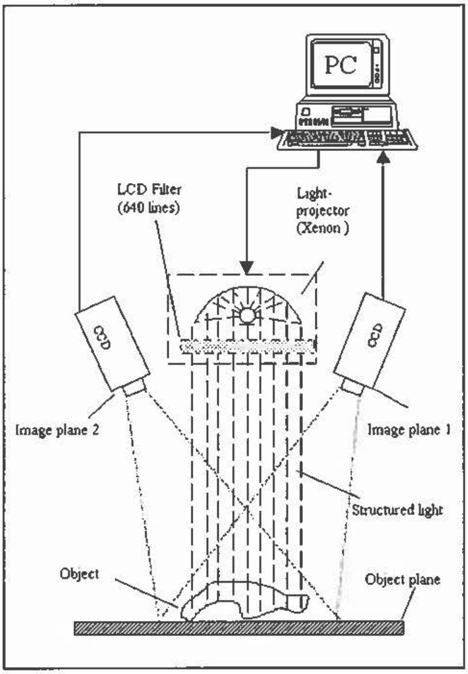

Fig. 13 – Fusion of stereo and structured light.

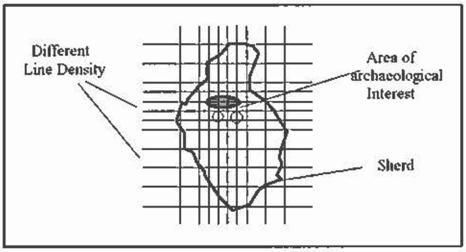

Fig. 14 – Influence of stereo.

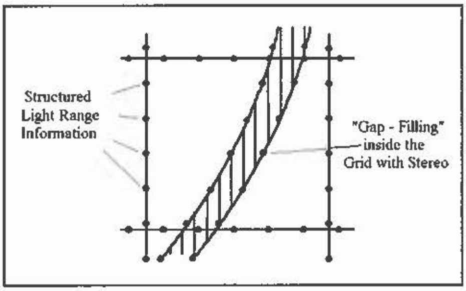

Fig. 15 – Higher accuracy due to stereo.

4.2 *Depth computation*

Following image acquisition, four different structured light computations take place and lead to four range images produced by the structured light algorithm. These four range images are then combined into one range image, which is the first range approximation for the following stereo matching algorithm. Fig. 15 shows one grid produced by the structured light method, where the dots indicate points with depth information. Depth computation with the help of the stereo matching can be obtained for all texture points on the surface of the sherd inside the grid. So the stereo algorithm fills the "gaps" inside the grid. Because of the depth information along the grid lines an approximation of the height inside the grid is possible. This reduces the search space for the corresponding point in the two stereo images considerably. Fusion of the data obtained by structured light with the information obtained by stereo will give more exact depth information.

The range data computing process is shown in Fig. 16. The result of this working process the object model of the sherd – is one element of the archaeological system which is able to provide the cross section and the top view of the sherd as shown in Fig. 1. Together with the color image archive and the color classification based on the color image this archaeological system provides multi data information about the archived sherd. The object model can be visualized on a computer monitor as well as on a laser printer in any desired viewing angle by interactively rotating and scaling based on geometric transformations. One possible way of visualization is a representation of the 3D-object model by a wire frame model and can be rotated in any direction interactively. In addition to the wire frame model the corresponding intensity image can also be displayed. As a third feature, the cross-section of the sherd is permanently displayed. So the archaeologist can orientate the sherd very precisely, in order to get the correct profile section for plotting. After defining the correct profile section it is plotted together with the additional parameters of the sherd such as excavation site, excavation layer, material and others.

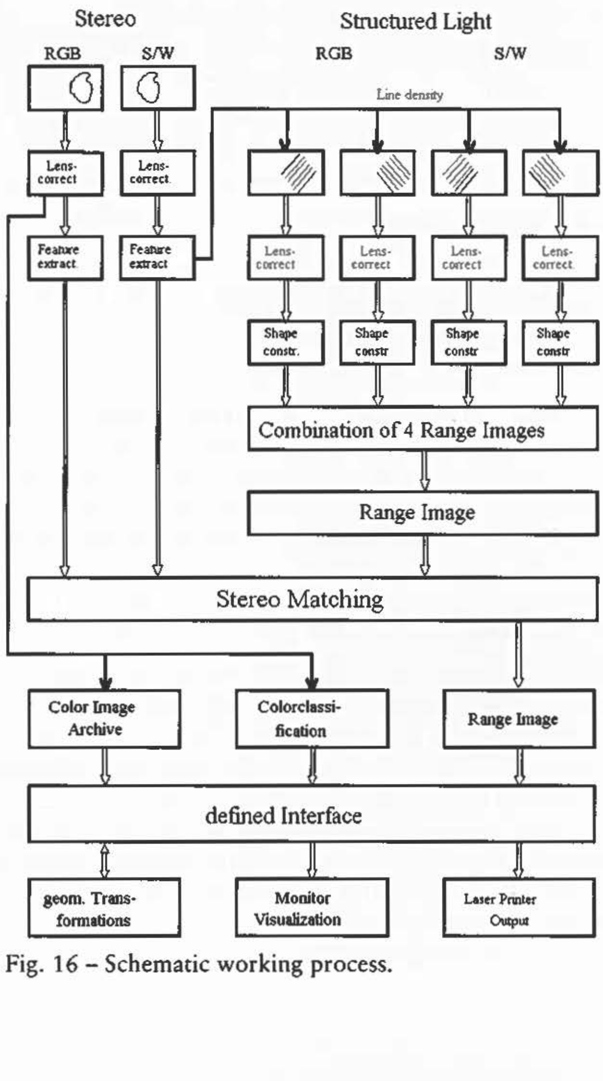

Fig. 16 – Schematic working process.

5. Outlook

The 3D-information of the surface of a sherd is the basis for any further classification and therefore also the basis for an archaeological database. The exact orientation of the sherd is done by the archeologist manually, correcting the orientation proposed by the system. The proposed orientation is based on the rotational symmetry which in the case of sherds is the curvature of the inner surface, since this curvature must be a circle in the direction of the rotation during manufacturing. Following the orientation, the profile section is stored together with the pictorial information and sherd relevant data for further classification. This classification is based on matching different profiles and classifying them due to the similarity of the profiles. Since the profile are very accurate and independent of human measurement errors, the result is a classification based on objective, computable and reproducible criteria, which would be very helpful in the work of archaeologists (Caselitz 1988; Furger-Giunti, Thommen 1977; Scheider *et al.* 1989).

Furthermore, the optimal configuration of the system can be guaranteed by permanent collaboration between archaeologists and technologists. Further goals to be obtained can be summarized as follows:

- **Construction of a picture database:**
  The intensity images of the sherds are stored in a picture database. Together with each intensity image, the appropriate parameters such as excavation site, excavation layer, material, color, archive number etc., are stored. On the one hand, it should be possible to search for text index keys (like excavation site or archive number), and on the other hand, it should be possible to search for patterns in this database.
- **Automatic orientation of a sherd:**
  With the help of the object model the position of the sherd on the pot should be available by detecting circles on the surface. If it is possible to detect these circles the rotational axe can be determined. Furthermore the profile of the sherd can be compared with profiles in a database and so an exact position of a sherd on a pot can be computed.
- **Proposals for pairwise sherd mosaicing:**
  Pairs of preselected, matching sherds are searched for in the existing database and proposed for reassembling if the surfaces of fracture correspond.
- **Assembling parts of pots from sherds:**
  The object model of the selected, matched sherds are assembled to parts of pots, in order to make the reconstruction easier and more exact.
- **Reconstruction of pots with the help of existing part-assemblies:**
  The model of the complete pot is reconstructed out of the existing part assemblies. This model can be transformed into a gray level image with the help of ray tracing methods.

- **Automatic computation of the dimension of a reconstructed pot:**
  The dimensions of the reconstructed pot such as diameter, height, thickness and thelike can be computed.

All of the above mentioned goals can only be reached if the first and most important step, data acquisition is works well. Therefore, we currently focus on the fusion of the two acquisition methods in order to have an optimal basis for all further goals. In the future this system could be used for various tasks like information exchange via computer networks, support in teaching, presentations, publications and many others.

6. Conclusion

In this paper two acquisition methods for archaeological finds that could help the archaeologist in his work and automate the archivation process were proposed. First we presented an overview of existing methods for archaeological image acquisition methods. These systems are half-automated, so the amount of work has not really been reduced. Next we focused on the acquisition methods to minimize errors in the output and to automate this process completely. In order to get the 3D-information of a sherd we tested two different and representative methods, in particular, *shape from stereo* and *shape from structured light* for providing a 3D-surface representation of a sherd. The results of these two acquisition methods were compared with each other and the fusion of these two methods for an archaeological application was shown. Finally, outlooks for a computer based automatic classification of archaeological finds were given.

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ABSTRACT

During excavations a large number of sherds of archaeological pottery is found. These sherds are photographed, measured, drawn and catalogued. Up to now, all this has been done by hand, and means a lot of routine work for the archaeologist.

In this paper two acquisition methods for archaeological finds are proposed forming the first step towards automatic classification, that could help the archaeologist in his

work and automate the archivation process. First we present an overview of existing methods for archaeological image acquisition methods. These systems are half-automated, so the amount of work has not really been reduced. Next we focus on the acquisition methods to minimize failures in the output and to automate this process completely. In order to get the 3D-information of a sherd we are using two different and representative methods, in particular, shape from stereo and shape from structured light for providing a 3D-surface representation of a sherd.

Further we discuss a fusion of these two methods for an archaeological application and finally, outlooks for a computer based automatic classification of archaeological finds are given.