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Pictorial, Three-dimensional Acquisition of Archaeological Finds as Basis for an Automatic Classification

1 Introduction

A large number of sherds of archaeological pottery is found at excavation sites. 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.

The aim of our project is to construct an acquisition system for archaeological finds that forms the basis for a subsequent automatic classification. Therefore we are constructing a system (prototype), that carries out an automated 3-D 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. Figure 1 shows the drawing of a sherd found at the excavation site Petronell near Vienna. It was first 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 described above can be carried out by computerized methods in both a faster and a more accurate way. The process of drawing and archiving a sherd can be automated by computing the cross section from 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 is proposed consisting of a combination of the *shape from stereo method* (Menard 1991b) and the *shape from structured light method* (Sablatnig 1991) 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 3-D 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 is given for a computer based automatic classification of archaeological finds. 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 Velia in the future. In order to compare the new method with the traditional archaeological method, the material is tested and documented with both methods.

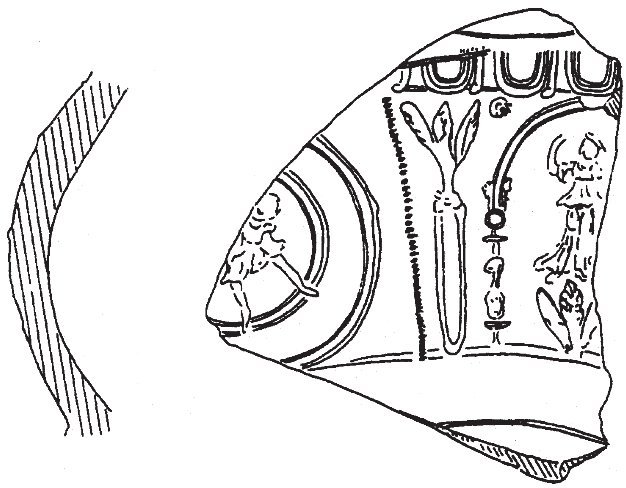

Figure 1. Sherd drawn by hand.

2 State of the art

Because conventional methods for pictorial acquisition are unsatisfactory, the search for possible automatic solutions began early. We show two systems, ARCOS and SAMOS, which are representative for many other methods of getting pictorial and 3-D 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-

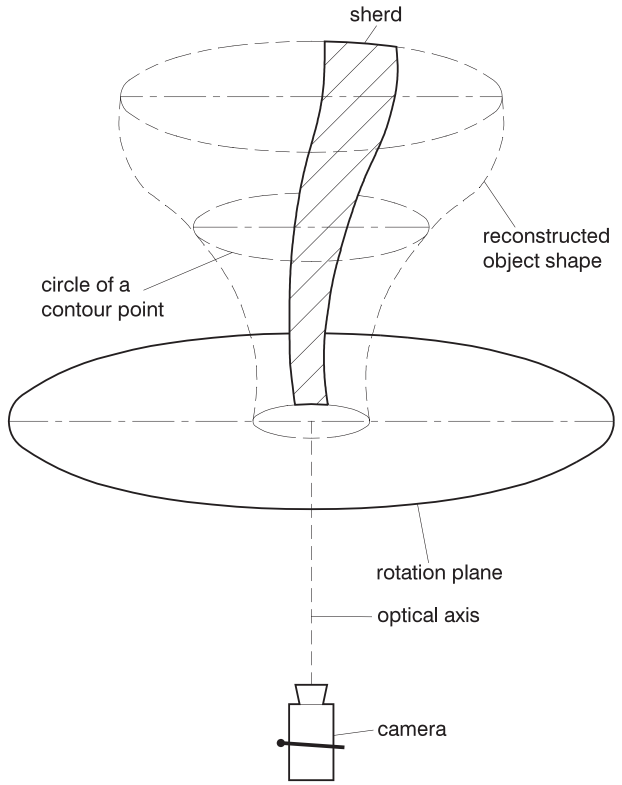

Figure 2. Acquisition system ARCOS.

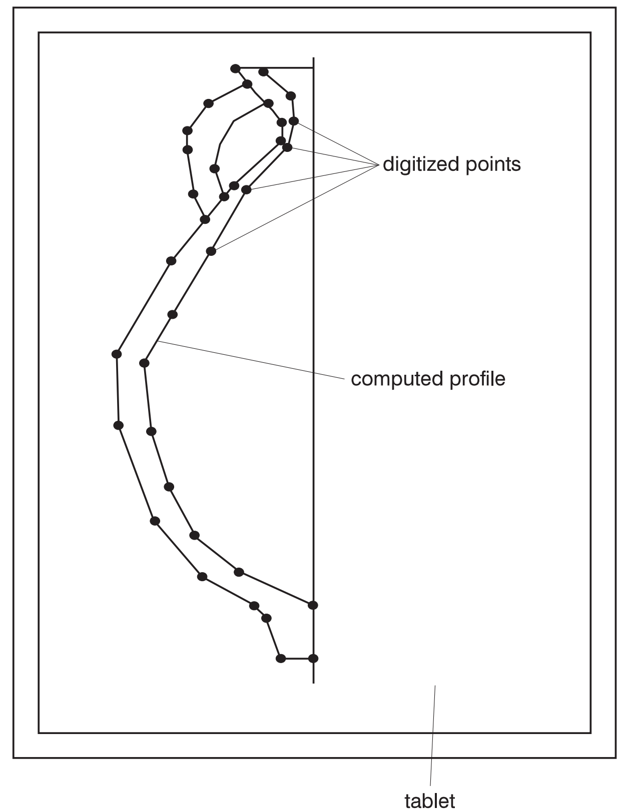

Figure 3. Tablet data acquisition: SAMOS.

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 finally drawn automatically. In figure 2 the acquisition process is shown schematically: Ceramic sherds were oriented on a rotation plate according to their original position in the pot. The intensity images were taken with the help of one CCD-camera. The program extracts the contour of the sherd from the intensity image. The archaeologist can select the best cross section from several image acquisitions. Therefore, the reconstruction of the shape of a pot is 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 enormous 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 were rather high (Kampffmeyer *et al.* 1988; Luebbert/Kampffmeyer 1989). The program is installed in the computer as a chip and cannot 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 work method 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). Textures on the sherd were not recorded and had to be added manually. The development of ARCOS was stopped, because of the bad results of the prototype and the work for archaeologists not really having been reduced.

2.2 SAMOS (Steckner/Hamburg)

The second system is called SAMOS (*S*tatistical *A*nalysis of *M*athematical *O*bject *S*tructures). It provides the automatic drawing and reconstruction of profiles from pottery (Steckner 1988, 1989; Steckner/Steckner 1987, 1988). In order to get a contour line of a sherd or pot, this contour line is digitized with the help of a tablet by determining several points on this line (fig. 3). 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 from 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 needs to be drawn separately or described.

Both systems are not able to record plastic decor or paintings on sherds, so it will be necessary to draw such details separately or to describe them.

2.3 Photogrammetry for archaeological finds

Tests concerning the recording and measuring of archaeological finds were also performed in the field of photogrammetry (Gruber/Schindler-Kaudela 1986; Kandler *et al*. 1985; Kladensky 1981; Waldhaeusl/Kraus 1985). These tests deal with the documentation of stamps in bricks and ceramics. The object is recorded photogrammetrically with the help of a camera and measured with an 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. 4). The measurement process is not automated and the archaeologist is not able to make the image acquisition without knowledge about the configuration and illumination parameters. Moreover, a special stereo evaluation system will have 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, 1991b).

It can be said that methods of digital photogrammetry for archaeological finds can only be used if a system can be constructed for the archaeologist, that reduces his work and does not require additional technical expense for archiving and evaluating the ceramic pieces. The acquisition process should be automated so that the archaeologist needs no knowledge of the measurement area, system parameters or digitizing photos. The expense of the acquisition procedure should only be the positioning of the sherd in the measurement area and the input of archaeological data. The system should be able to compute and display the object model on the monitor to see if the acquisition was successful. Direct control is very important at excavation sites, as it is not allowed to take the finds home. Analysis of the sherds (e.g., cross-section) can be done later.

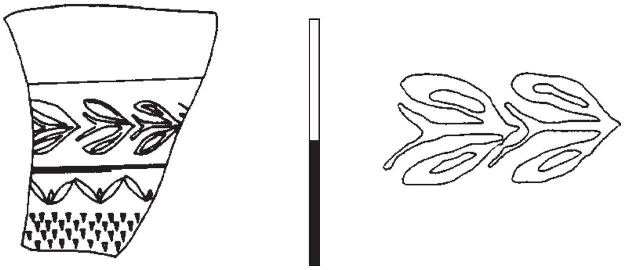

Figure 4. Result of a photogrammetrical measurement (Gruber *et al*. 1986).

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 3-D information with the help of 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 grey 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 of an object to compute the model (Ikeuchi 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. From 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 is necessary.

3 Acquisition method

With the help of image processing methods it will be possible to make an automated acquisition of archaeological sherds. In order to get the 3-D 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; Jarvis 1983; Lin *et al.* 1989; Wust/Capson 1991).

3.1 Shape from stereo

The stereo analysis method is similar to the human visual 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. Figure 5 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:

$$B=65 \text{ mm}, d=520 \text{ mm}, f=16 \text{ mm}, res=512\times 480 \text{ Pixel}$$

where B is the distance between the two cameras, d the distance between object- and image plane, f is the focus of the lenses and *res* is the resolution of the CCD cameras. From these parameters an accuracy of 1.6 mm can be determined.

Consider the case of a single point 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. The difference between one single point in the two images is called *disparity* between the two images, which is a function of depth and geometrical relationships between the imaging devices. By locating corresponding positions in two images a stereo system can recover the geometrical relationships and depth (Barnard/Thompson 1980; Eastman/Waxman 1987).

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). Our first attempt to solve the correspondence problem was to use the area-based stereo technique using image pyramids. This method finds corresponding points on the basis of the similarity of the corresponding areas in left and right images. The process consists of extracting feature points in the left image with the help of the *Horizontal Gradient Operator* (Shirai 1987) and finding the corresponding points in the other image. Given a feature point in the left image, the corresponding point is computed on the basis of the similarity of the neighbouring regions. In order to determine the similarity, we used the correlation of light intensity between the left and the right windows. The correlation $\boldsymbol{C}$ is defined as:

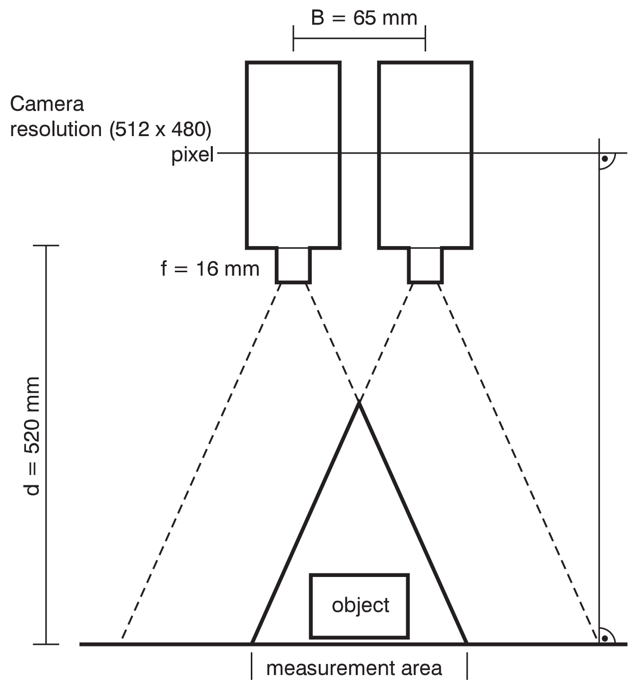

Figure 5. Configuration of the stereo system.

$$C = \frac{\sigma_{LR}^2}{\sqrt{\sigma_L^2 \sigma_R^2}}$$

where σ_L^2 and σ_R^2 represent the variance of the light intensity in the left and right windows and σ_{LR}^2 is the covariance of the light intensity.

To find the corresponding point in the right image for a given feature point in the left image, the correlation for all candidate points must be computed. The maximum of the computed correlation function is supposed to be the corresponding point. Figure 6 shows the principle of this algorithm. The image at the top shows the feature image of the sherd containing vertical edges, because the disparity can only be computed from these edges. The two images at the bottom are the stereo intensity images of the sherd. The horizontal dotted line is the epipolar line on which the

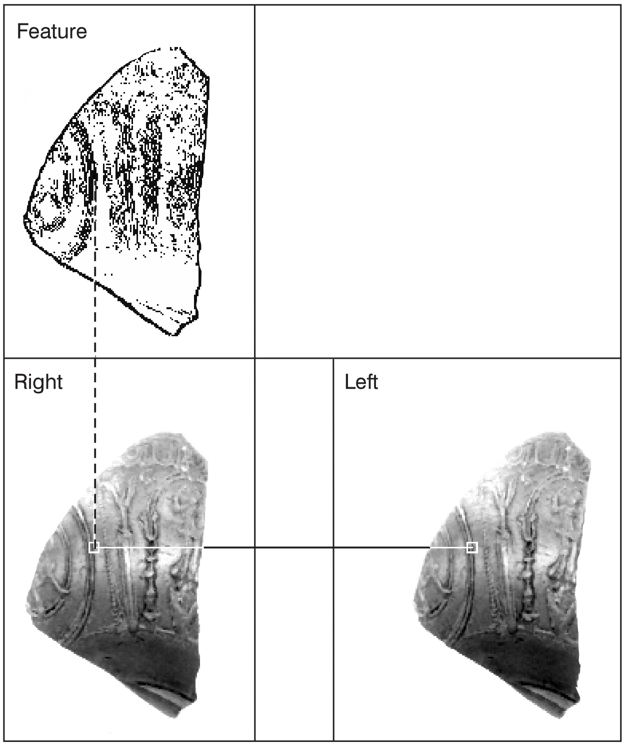

Figure 6. Principle of area-based stereo algorithm.

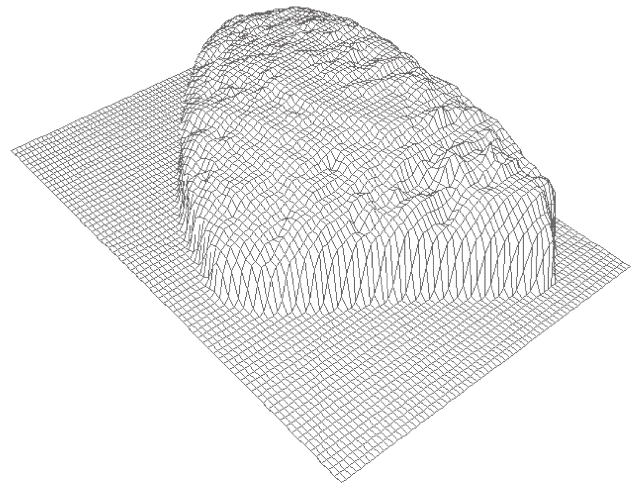

Figure 7. Surface representation of the disparity map.

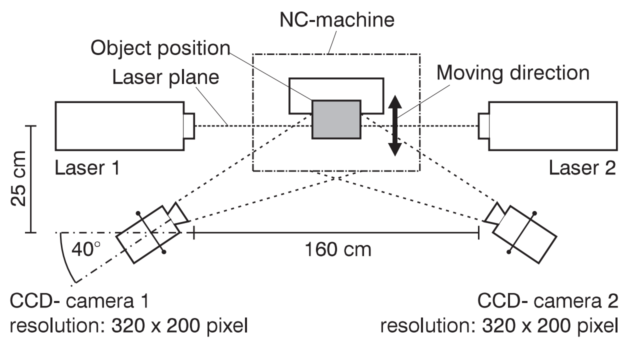

Figure 8. Structured-light acquisition principle.

correlation function is computed. The maximum of this function defines the corresponding point. The depth information of the surface points of the sherd is only computed for the extracted feature points, thus the disparity map has large regions without information, especially in homogeneous regions of the intensity image. Image pyramids are used to fill these gaps in the disparity map. First the 5×5/4 Gaussian image pyramids (Haralick/Shapiro 1991; Kropatsch 1991) for the left and right intensity images are generated. Then the feature extraction is applied to each level of the left pyramid. These three pyramids are the new input for the stereo algorithm. It starts at the top level of the pyramids and uses the gained information as input for the pyramid level below. With this principle an average disparity can be determined for homogeneous regions in the stereo intensity images. Figure 7 shows the surface representation of the computed disparity map.

3.2 Shape from structured light

The second acquisition method for estimating the 3-D shape of a sherd is shape from structured light. A predefined light pattern is projected onto the surface of the object and then observed with a camera. The range information is computed from the distortions of the light pattern seen from the camera. Instead of a light pattern in our configuration, we used one laser light strip, projected onto the object. This light strip is recorded by a CCD camera. The image from the camera consists of a profile line that has the information about the position of the surface points observed, if the illumination and scene geometry is known (Kramer *et al*. 1990). With the help of the distance between the line observed and the calibrated line one can determine the position of the surface points in the 3-D space.

Two lasers and two CCD cameras were used in our test configuration. Figure 8 shows the configuration of the acquisition system with the orientation parameters. From these parameters a theoretical accuracy of 0.6 mm can be determined. This theoretical accuracy was confirmed with a calibration object. The two lasers are positioned in order to produce one lightplane. This lightplane intersects the sherd and the resulting light strip is observed by the two CCD cameras. In order to get the complete 3-D surface of the object, a NC machine is used to transport the object through

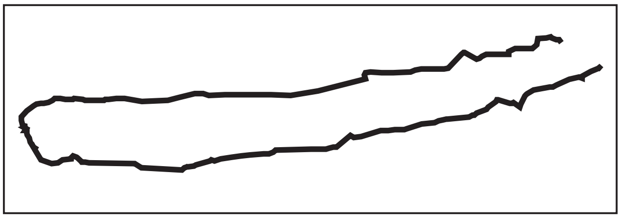

Figure 9. Cross section through the sherd.

the measurement region. The results are serial cross sections through the sherd. Figure 9 shows one of these profile sections. With the help of these serial cross sections, a 3-D model of the sherd can be generated. One way to construct this model is to stack up this serial cross section and to colour each cross section with different lightness. To get a real 3-D model of the sherd we used triangular surface patches (Lin *et al*. 1989; Shirai 1987). Figure 10a shows serial stacked up cross sections and figure 10b the model interpolated with triangular surface patches.

4 Combination of the two acquisition methods

The results of the two acquisition methods were not sufficient for archaeological requirements, because each of the methods presented has 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 but the pictorial acquisition is available in high quality. The structured light method fulfils the accuracy requirement but there is no way to get the pictorial information (Sablatnig/Menard 1992). Furthermore reflections on the surface of the sherd caused by the laser can change the results of depth.

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 from two data points for one object point. Furthermore the pictorial acquisition of the visual surface of the sherd is possible in true colour. The accuracy of the individual results of the two acquisition methods is improved through interdependencies of the two computation 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, thereby increasing the accuracy and reliability of the computed data.

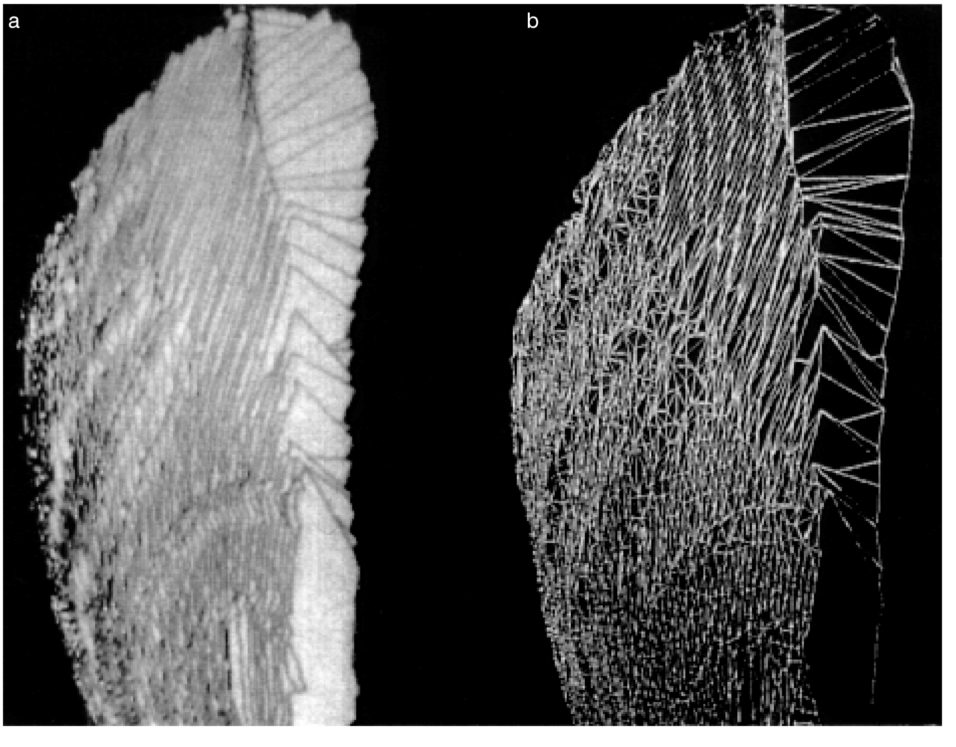

Figure 10. a. Cross sections.
b.Triangular surface patches.

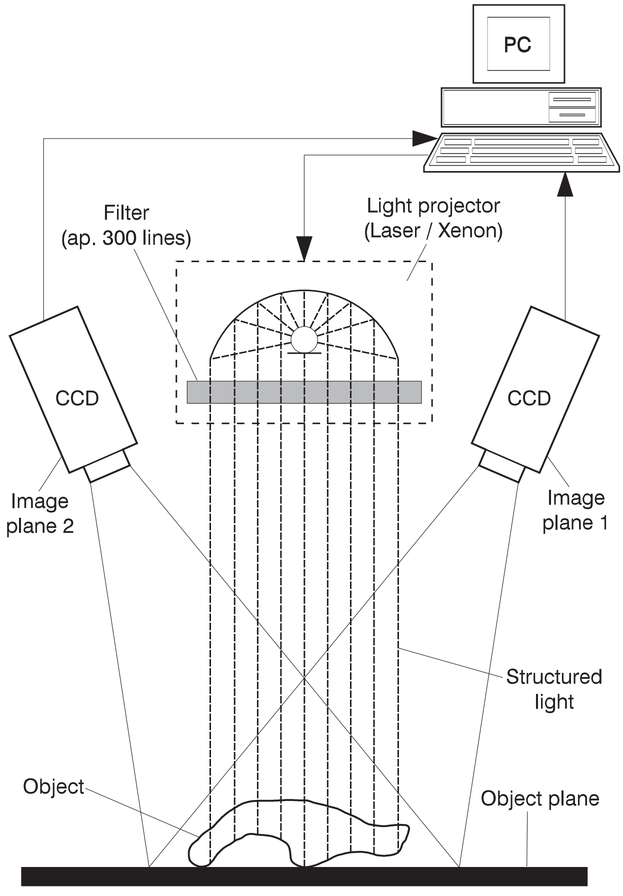

Figure 11. Fusion of stereo and structured light.

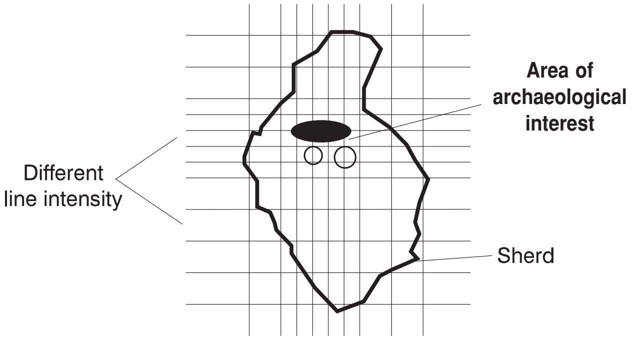

Figure 12. Influence of stereo.

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

4.1 Data acquisition

A possible system for the fusion of the stereo and structured light methods is shown in figure 11. The two CCD cameras are used by both acquisition methods. In order to get parallel light strips onto the surface of the sherd, a special light projector is used which is able to project 600 horizontal and vertical lines onto a 30 cm × 30 cm measurement area. Therefore the resolution of the lightstrip method is 0.5 mm in x- and y-direction. With the help of these lightstrips no transportation through the measurement area is needed. First, the light projector illuminates the measurement area without lightstrips 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 interest (reliefs, paintings, lines) are on the surface of the sherd. This information is used to drive the light projector, so that only those parts of the measurement area containing the object are illuminated and those parts of the surface which are of archaeological interest are computed with higher accuracy than other parts, as shown in figure 12. The intensity image therefore defines the density of the light-strips. The two cameras are used to take 4 different lightstrip 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.

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. Figure 13 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 considerably the search space for the corresponding point in the two stereo images. Fusion of the data obtained by structured light with the information obtained by stereo will give more exact depth information.

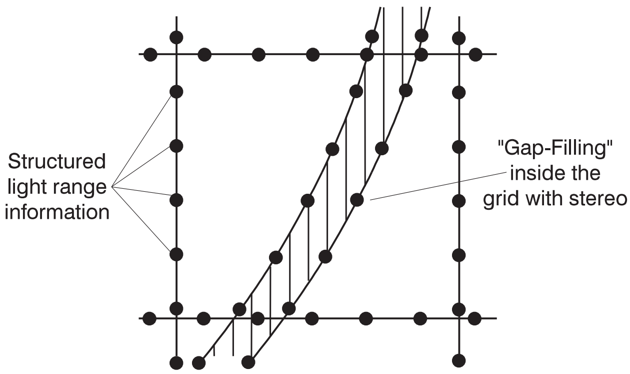

Figure 13. Higher accuracy due to stereo.

The range data computing process is shown in figure 14. 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 figure 1. Together with the colour image archive and the colour classification based on the colour 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 3-D object model by a wire frame model which 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 sherds, such as excavation site, excavation layer, material, and others.

5 Outlook

The 3-D 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 manually by the archaeologist, 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 profiles 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-Gunti/ Thommen 1977; Schneider *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, colour, archive number etc., are stored. It should be possible to search for text index keys (like excavation site or archive number), as well as for patterns in this database.
– *Proposals for pairwise sherd mosaicing:*
  Pairs of preselected, matching sherds are searched in the existing database and proposed for reassembling whether 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 accurate.
– *Reconstruction of pots with the help of existing part-assemblies:*
  The model of the complete pot is reconstructed from the existing part assemblies. This model can be transformed into a grey 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 the like can be computed.

All of the above mentioned goals can only be reached if the first and most important step, data acquisition 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 were proposed for archaeological finds that could help the archaeologist in his work and automate the archivation process. 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

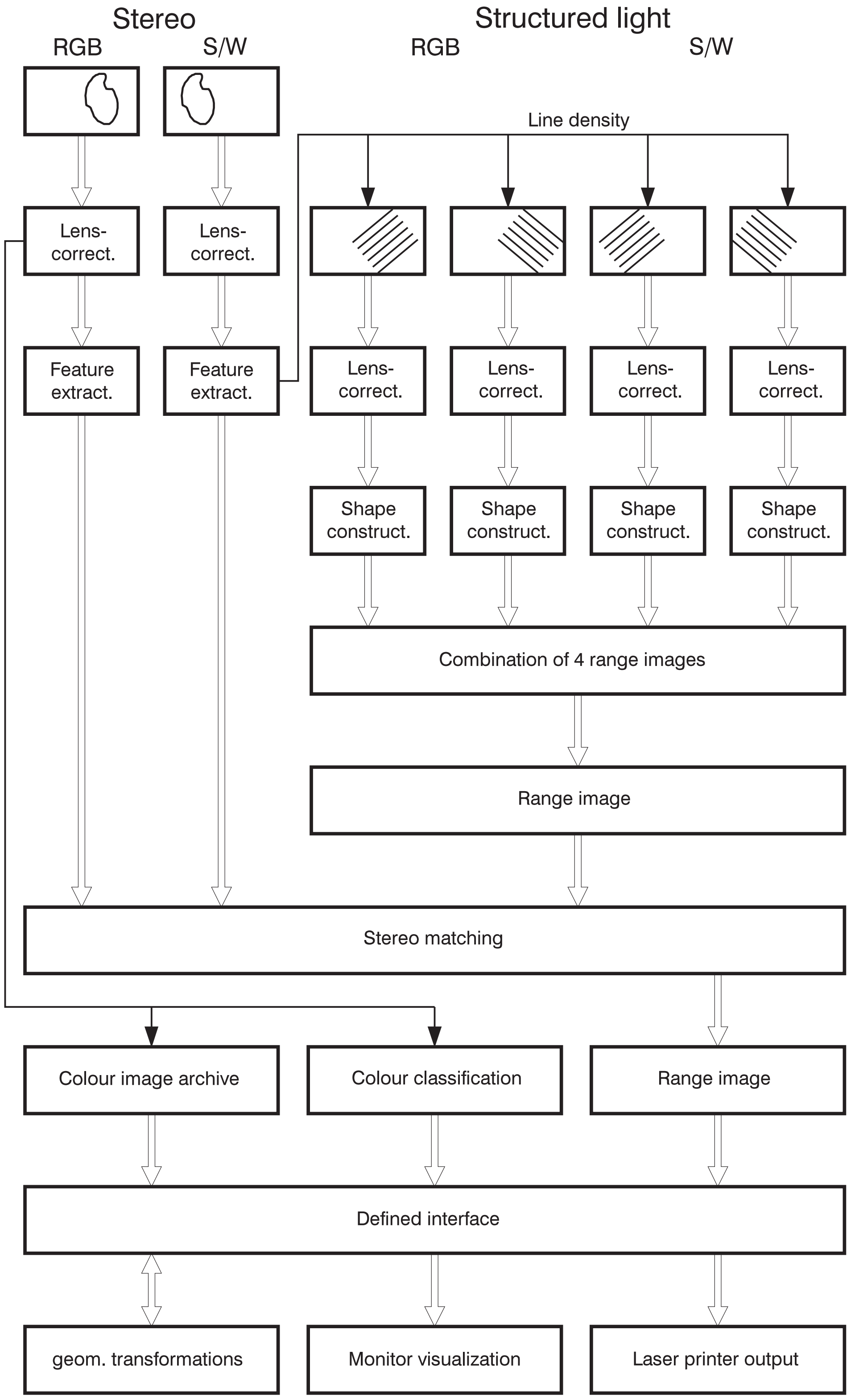

Figure 14. Schematic working process.

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 3-D information of a sherd we tested two different and representative methods, in particular, *shape from stereo* and *shape from structured light* for providing a 3-D 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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