GENERATION AND USE OF DIGITAL SURFACE MODELS FOR VOLUME OBJECTS

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ABSTRACT

The paper shows the conception and the achieved results for an archaelogical project aiming at the description and reproduction of a 3D surface body by means of digital photogrammetric techniques. Therein it is of main interest, to make full use of the 3D characteristic of the object surface. That means the collection, storage, organization and extraction of all discrete surface points as individual 3D elements within a unique 3D coordinate frame. The paper shows the actual stage of development, allowing for the complete description of the body surface and the use of the data for visualization purposes.

The data collection will be done by application of an image matching process onto each stereo model, resulting in a local Z=Z(X,Y) description. Due to the known geometric relation to the object bounded coordinate frame the local surface description can be transformed into a S=S(X,Y,Z) representation, taking some qualtity measures and geometrical parameters as additional attributes. Finally all transformed data sets will be merged into a unique object description, taking into account the supression or aggregation of individual point data within the overlapping areas.

As actual use of the surface data some graphical reproductions will be shown, using a selection process collecting all individual points which have to be considered, followed by the necessary geometric and radiometric transformations to achieve the desired surface representation.

KURZFASSUNG

Im Aufsatz werden Konzeption und Resultate eines archäologischen Projektes vorgestellt, das sich die vollständige geometrische Erfassung der Oberfläche eines im Raum gegebenen Volumens mit Hilfe der digitalen Photogrammetrie und der Nutzung dieser Geometriedaten zum Ziel gesetzt hat. Der geschlossenen Charakteristik der zu bestimmenden Oberfläche ist dabei besondere Beachtung zu schenken, da zu ihrer funktionalen Beschreibung ein echt dreidimensionaler Bezug S=S(X,Y,Z) erforderlich ist. Dementsprechend ist auch die Auswahl, Bestimmung, Organisation und Nutzung der Punktdaten in diesem Bezugsrahmen vorzunehmen. Die Ausführungen geben den aktuellen Stand der Arbeiten wieder, die eine komplette Erfassung der Oberfläche und ihre Visualisierung erlauben.

Die Datenerfassung erfolgt durch Anwendung eines Bildzuordnungsverfahrens mit dessen Hilfe in den verschiedenen Stereomodellen lokale Objektmodelle erzeugt werden, die die jeweiligen Oberflächenteile als lokale Z=Z(X,Y) Funktion beschreiben. Durch den bekannten Bezug zum einheitlichen, objektgebundenen 3D Koordinatensystem lassen sich die lokalen Objektmodelle in eine S=S(X,Y,Z) Beschreibung überführen. Dabei werden die aus der Punktbestimmung gewonnenen Qualitätskriterien als Attribute mitgeführt. In einem letzten Schritt erfolgt die Zusammenfassung der Teilmodelle, bei der in den Überlappungsbereichen die Attributdaten zur Entscheidung über das Fortlassen oder die Mittelung mehrfach bestimmter Punkte herangezogen werden können.

Als aktuelle Verwendung der Oberflächendaten werden Visualisierungen vorgestellt. Zu deren Generierung sind über einen Selektionsprozeß die in Frage kommenden Punktdaten auszuwählen, geometrisch wie radiometrisch zu transformieren und in die gewünschte Objektrepräsentation zu überführen.

MOTIVATION

Among the increasing number of algorithms using digital image data, those allowing for the description of objects by means of a great number of regular or irregular distributed points have achieved an almost operational stage and open up the access to new applications. These algorithms generate points by means of image matching techniques applied onto data sets of stereo image pairs. As result, the appearent object surface is described as a function related to the XY-plane Z=Z(X,Y), assuming Z being the height calculated from the image parallaxes.

The use of a Z=Z(X,Y) function satisfies many applications, because the objects (eg topographic surfaces) have commonly their main extensions in the X and Y direction, with Z varying in a small range forced by the surface cover and morphology. However, this mathematical concept is not applicable to volume objects, they need extended descriptions.

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The discrete surface description (digital elevation/object models (DEM,DOM)) serves as data base for different purposes. Common are graphical/visual reproductions (orthophotos, maps, perspective views) or numerical analysis. This might be achieved by putting the data into specific terrain modelling programs or into geographical information systems (GIS).
However, the use of DOM data within GIS is restricted to Z=Z(X,Y) surfaces, because of the planar geometry, supported by the today GIS software. As consequence, there arise some restrictions in the use of height informations:

⇒ no z-oriented query within the data possible
⇒ no height ambiguities allowed (eg as existing at buildings)
⇒ the object has to be a surface above the xy-plane

To overcome these problems new data models have to be develloped. But the change from the todays 2D+1D GIS to real 3D GIS is a very demanding way, leading to complete new data structures, query and analysis tools. One step into the direction of real 3D GIS is to find a way for the determination and uniform description of surfaces from volume objects as they are found in disciplines like architecture, archaeology or industry.
A contribution to this step will be presented here, resulting in the complete description and visualization of the surface of a roman bust.

CONCEPTION

Several aspects have been considered in order to generate the DOM of the volume surface and their visualization (cf fig. 6):

⇒ use of common algorithmic tools as far as possible
⇒ use of digital photogrammetric techniques
⇒ provide a homogeneous geometry
⇒ minimize the error propagation
⇒ provide quality measures for the surface data
⇒ make flexible use of the data
⇒ allow different forms of presentation

The first two and the last aspect are realized using the following software packages:

photo triangulation	:	BLUH (Jacobsen, 1980)
image matching	:	ARCOS (Boochs, 1989)
visualization	:	IDL (Creaso, 1995)
		ARC/INFO (ESRI,1994)

The other criterions are met by the following strategy

⇒ definition of a unique object bounded coordinate system for the description of the whole surface
⇒ definition of a circular image configuration
⇒ simultaneous triangulation of all images
⇒ generation of the DOM by combination of all local compiled surface models
⇒ comparision and aggregation of multiply determined surface parts
⇒ development of a data structure allowing the use of the available quality measures

In detail, the workflow for the project looks as shown in fig.1.

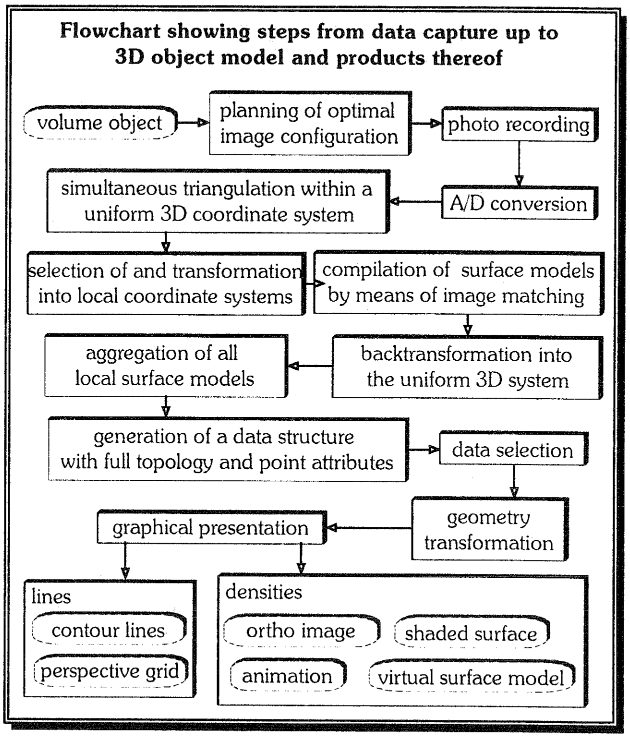


Figure 1: Flowchart of the processing steps

REALIZATION

The object. As object for this investigation the marble head of a statue of the empress Ariadne (AD 474 - 515) has been chosen. The original found in 1888 is kept in Rome. For carrying out the work, a copy was put to our disposal by the Römisch-Germanisches Zentralmuseum (Mainz).
The sculpture shows a surface with low contrast and noncontinuous areas, with only few discrete points immedeatly appearing useful for the photo triangulation. Furthermore, problems in lightning have to be considered due to the smooth shape of the surface. In opposition to other close range applications, the surface was not lightned by a texture projector, because the image data should be used for visualizations based on the natural shape of the sculpture.
As a close-range-equipment was used, special care has to be given to the generation of the photos, because of size and geometry of the sculpture, possibly resulting in a lack of sharpness within the depth range.
The facts mentioned have made the work quite difficult, what has been accepted in order to demonstrate the capability of the method used.

Image configuration. The whole surface has to be covered by stereo images which should be arranged as image pairs with parallel camera axis in order to simplify manual measurements with an analytical plotter. From the viewpoint of the photo triangulation a more dense coverage of the object would be useful, what together with the choice of an optimal geometry for the intersection of corresponding image rays leads to a symmetric configuration.

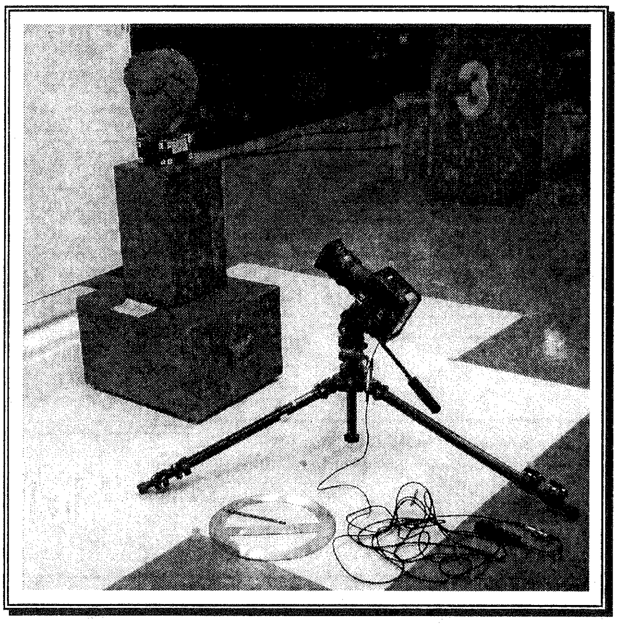


Figure 2: Photo capture

This configuration brings several advantages:

⇒ the calculation of approximate values for bundle ajustment and the check of blunders therein is easily achieved

⇒ the process of taking photos is simplified

⇒ the definition of local coordinate systems for the generation of the DOM can be done systematically

For this reasons the configuration looks as shown in fig.3. Horizontal stereo models from eight directions have been taken followed by corresponding photos with zenith angles of 45° and 135°. To increase stability of the ajustment two models with a zenith angle of 10° complete the work.

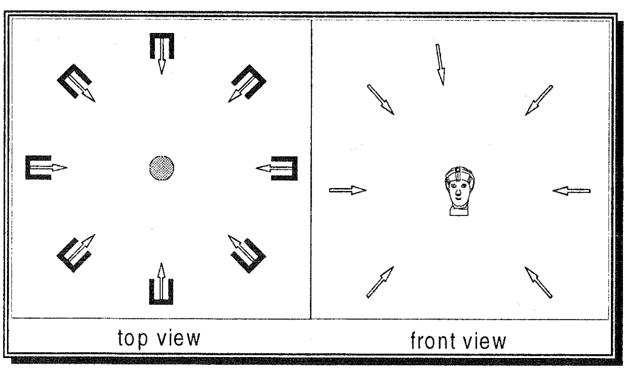


Figure 3: photo configuration

Image capture. The images were recorded with a Rollei 6006 metric camera with a 120 mm macro-lens and 11 x 11 réseau meshes (cf fig. 2). The mean exposure distance of 86 cm results in an image scale of about 1 : 8. The base length was chosen to 10 cm giving an overlap for adjacent images of 80 %.

The images were recorded on a colour reversal film (AGFA RS 120 Plus Professional) with a sensitivity of 50 ASA. In order to achieve a maximum sharpness a small aperture (32) was used. The object was illuminated simply by the ordinary room lights, because additional spotlights would have produced specular reflections.

The model scale was introduced by a metallic ruler positioned just in front of the busts plinth and as information for the orientation of the model axis served the edges of the plinth itself.

A/D conversion. Due to practical reasons, the anlog images were digitized using two different equipments.

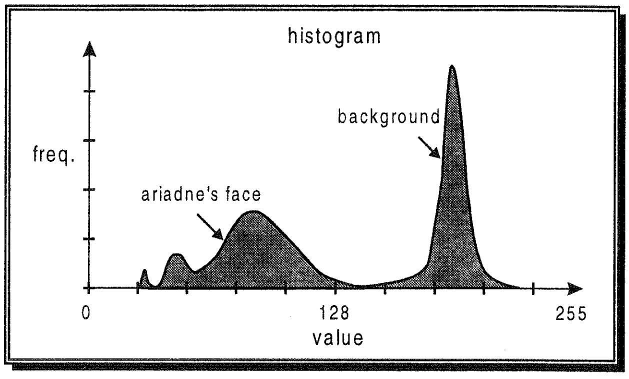


Figure 4: Gray value distribution

Using a Wehrli scanner the images were produced with a resolution of 12.5 µm, wheras the data from the Rollei scanner came up with 15 µm. All scan processes were optimized, in order to get a uniform distribution of the gray values. Fig. 4 presents a typical distribution for a picture, showing two parts corresponding to the objects surface and the light background.

Photo triangulation. The triangulation was based on manual coordinate meaurements performed at an analytical plotter. Difficulties arised due to the lack of texture combined with the considerable variations of the perspectice for adjacent stereo models resulting in special effort needed to identify individual object points. A solution was found in the use of a digital CCD camera, mounted in front of an eyepiece and storing the image of the selected point together with the floating mark. For all subsequent measurements at the same object point the image was loaded onto a graphics screen allowing to compare the visual impression in the actual image with that one already given. This concept speeded up the whole measurement procedure and reduced the amount of misidentifications.

Over all 53 images 1090 point measurements were registered. The triangulation was performed with the program package BLUH coming up with an internal precision of σ_0 = 4.3 µm for the image measurements and an accuracy of $\sigma_{X,Y,Z}$ = 0.15 mm for the coordinates of the object points. The results show a good geometric quality of the image configuration and are the pre-requisite to establish a homogeneous DOM out of the the locally evaluated surface parts.

GENERATION OF LOCAL OBJECT MODELS

Coordinate transformation. Although the object surface will be expressed in a unique 3D-system (X,Y,Z), the use of a standard image matching procedure makes it necessary to define local coordinate systems (X_{mi}, Y_{mi}, Z_{mi}; i=1,nmodel) for the individual stereo models (cf fig. 5). This is due to two reasons:

⇒ standard matching processes describe surfaces with Z(X,Y) functions, thus driving the point selection process from the XY-coordinates

⇒ the mean camera axis of adjacent stereo models have a longitudinal tilt resulting in a corresponding inclination of the XY-planes of these models. This inclination avoids the transfer of the distribution of object points chosen for the image matching from one model into the adjacent one.

The Z axis of the local model coordinate systems are chosen parallel to the mean camera axis, what means, that the local XY-plane approximates the tangential plane of the object surface.

The use of such a model coordinate systems makes it necessary to perform a transformation step of orientation and point data from the unique X,Y,Z system into each individual model system.

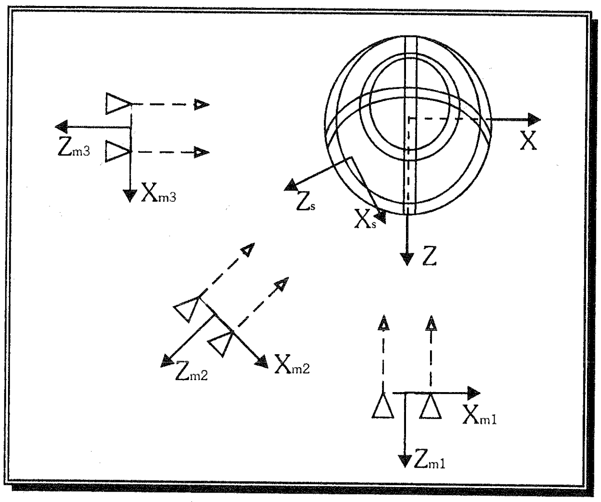


Figure 5: Global, surface $()_S$ and model $()_m$ coordinate systems

Image matching. As matching tool the program ARCOS has been used. The program is founded on an area based matching strategy keyed to the determination of more or less steady object surfaces, which will be described by a dense grid of regular distributed points. Practical tests have shown (Bennat, 1990; Gülch, 1994), that the program produces very accurate results even in cases of low image contrast. Just the latter aspect is of importance here due to the shape of the given object.

As already mentioned, the image scale is about 1:8 with a base to height ratio of approximately 1:8. According to these values a parallaxe of 1 pixel equals to a height difference of about 0.8 mm in the object space.

Considering the height extensions of the evaluated surface parts, ranging from 40 up to 70 mm, maximum parallaxe differences of about 100 pixels have to be expected in a single stereo model. Although the maximum value won't arise between adjacent object points, considerable differences have to be managed even on short distances. Therefore the algorithm has to provide a large pull-in range, otherwise severe convergence problems would occur. In addition, the magnitude of the parallaxe differences expresses geometric distortions forced by the surface slope, leading to matching failures if they are not modelled correctly.

The calculations are based on a hierarchical strategy, starting with a coarse point grid, which is densified in two steps (point spacings: 4, 2, 1 mm). The extensions of the point grids ranged from 15.000 to 19.000 [mm^2] or 15.000 to 19.000 points per model.

In order to obtain optimal results some tuning investigations concerning target size and matching threshold have been made. They showed, that

⇒ small targets gave a high success rate with accuracy problems in regions of strong parallax differences

⇒ great targets used together with a standard threshold produced problems with the success rate leading to a loss of accuracy in regions of strong parallax differences

⇒ great targets used together with a lowered threshold, dynamically adapted to the image contrast gave the expected success rate (98 %) and accuracy

The behaviour can be explained by the interrelation of the low image contrast and the influence of geometric distortions.

⇒ Small targets have low information content and in case of low contrast does this lead to statistical similarities although the geometry might be modelled incorrectly. Consequently the surface can not be traced succesfully, what is especially disadvantageous for steep surface slopes.

⇒ Great targets are more influenced by geometric distortions. If this is not modelled completely, the similarity is lowered beneath the threshold, resulting in failures. In regions of steep slopes two or three successive failures then lead two inaccurate start values for the following matchings, what can not be overcome due to the low contrast information.

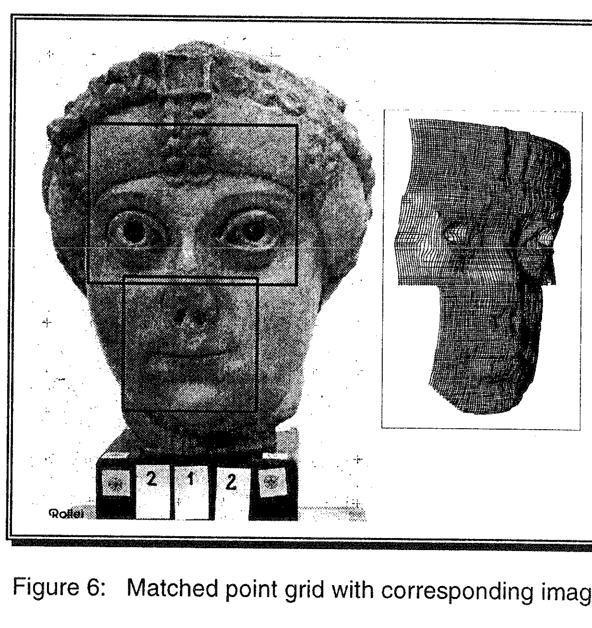


Figure 6: Matched point grid with corresponding image

Fig.6 shows an example for a point grid calculated. It is a perspective visualization of the grid, showing the front part of the face. Obviously, the low image contrast did not affect the quality of the object model, clearly reproducing the shape of the busts face. It simply remained the problem of blunders. A small number of blunders could be identified but not supressed. There are two reasons for blunders:

⇒ the crosses of the réseau grid

⇒ dirt within the images

Although the crosses have been removed by an image processing step, their influence could not be supressed completely, resulting in a misinterpretation of the image content for object points in the vicinity of crosses. In average 0.9 % blunders were in the data.

GENERATION OF AN ENTIRE OBJECT MODEL

Data accumulation. Each matching process generates an individual point grid representing an individual part of the volume surface. All these local point grids have to be transformed into the global coordinate system, in order to allow an accumulation. The transformation is performed by three rotation and shift parameters, chosen with the inverse values as used for the transformation of the orientation parameters into the local model system.

Due to the chosen image configuration, the evaluation of the whole surface needs at least 20 stereo models and can be extended to 25 models if desired.

A look at the image configuration makes obvious, that adjacent models have a considerable overlap. Consequently some surface parts are determined at least twice. These parts need a special investigation, because of

⇒ the necessity to average close positioned points

⇒ the possibility to reject failures.

As opposed to standard applications with Z(X,Y) surfaces the data is irregular distributed in the X,Y,Z space, what requires a special data structure allowing for a sorting and comparision of similar points.

Data structure. The first step evaluates the maximum extensions of the data and constructs a data cube which is divided into individual cubic voxels of a given side length. The side length defines the snap distance for the

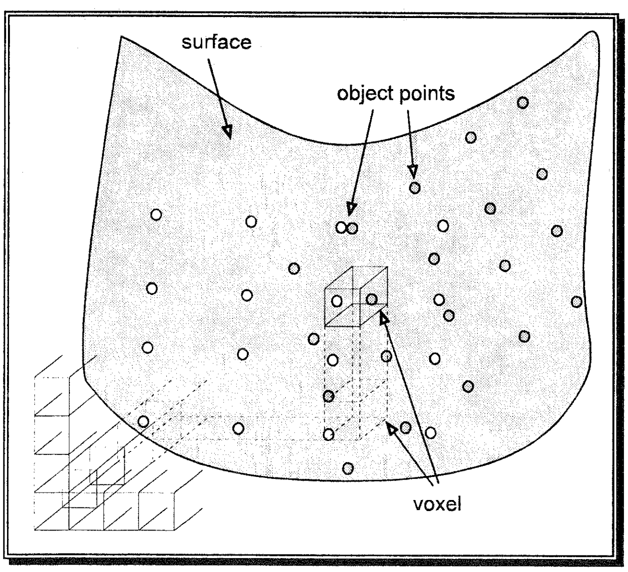


Figure 7: Subdivision of object space into voxels

decision whether points are belonging to the same object point. In addition, the side length is responsible for the morphologic precision and the amount of data used to represent the object surface (cf fig.7).

All points found to be within a single voxel will then be compared, in order to find a decision, which data has to be kept or rejected. The rejection of points will occur, if a point is identified as failure, which is based on the quality measures provided by the matching process. Furthermore this quality measure may serve as weigthing information within the averaging step.

As second step, the determination of attribute values will be done. These attribute values serve as additional informations to be used in further application steps taking the data for evaluation or visulization purposes. Typical attribute values are

⇒ the standard deviations in X,Y and Z for the averaged point location

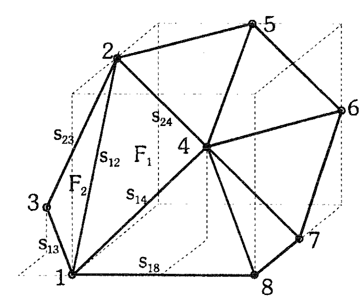
⇒ the average angle for the intersection of the image rays

⇒ the number of participated points

⇒ the identifiers for the images used

The first three values express geometric qualities, the last one establishes a relation between each object point and the images involved, what is useful for visulizations.

face	edges
F_1	s_{12} s_{14} s_{24}
F_2	s_{12} s_{13} s_{23}



edge	nodes
s_{12}	1 2
s_{13}	1 3
s_{18}	1 8

node	coordinate
1	X_1,Y_1,Z_1
2	X_2,Y_2,Z_2
3	X_3,Y_3,Z_3

node	attribute values
1	$\sigma_{X1},\sigma_{Y1},\sigma_{Z1},...,image_{11}$
2	$\sigma_{X2},\sigma_{Y2},\sigma_{Z2},...,image_{11}$
3	$\sigma_{X3},\sigma_{Y3},\sigma_{Z3},...,image_{11}$

Figure 8: Triangulation of point space and generation of topology and attribute data

In the third step the compressed data is used to build up the topologic relations between the object points (cf fig. 8). These relations are established by a Delauney triangulation realized in the 3D space. As result of such a triangulation, all object points which have to be considered as neighbours will be selected. To all of them an edge can be introduced, follwed by triangles which are constructed out of adjacent edges completed by the edge connecting their end points. Such a triangle surrounds a small face approximating the object surface. Taking all faces, the description of the volume surface is complete. Using index tables the relations between points with their attribute values and the other primitives are stored and may be used in further steps.

Results. As example of an accumulation process the combination of three adjacent point grids is presented. The grids are evaluated from the stereo models just in front of the busts face. Alltogether these grids consist of about 49.000 matched points.

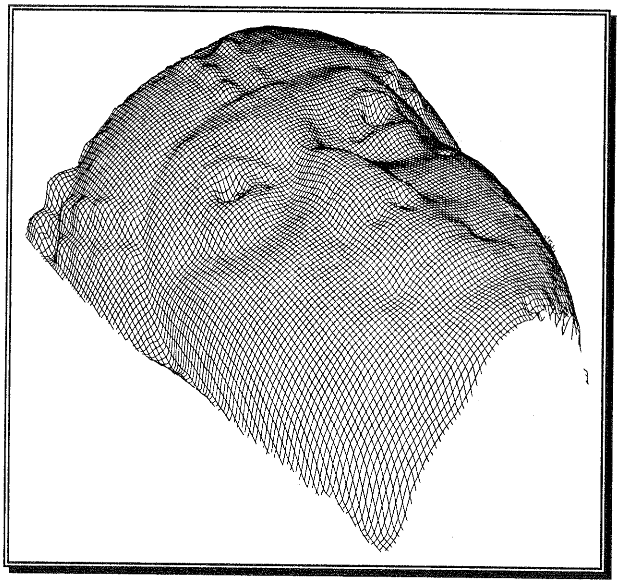


Figure 9: Perspective view of the front part of the object

The accumulation was then done with a voxel side length of 1 mm reducing the data set to 41.000 remaining points. Fig.9 shows a perspective view of the compiled face constructed from the accumulated point set.
In order to get an impression of the accuracy for the matched process the mean Z-differences within identical areas have been calculated: $\sigma_Z = 0.4$ [mm]. The value of σ_Z is influenced by the accuracy of the orientation parameters and the matching process and documents here, that

⇒ the simultaneous photo triangulation has given reliable orientation values
⇒ the low contrast has not reduced the matching quality, giving good correspondance within the overlapping areas of adjacent model areas.

Use of object data. The investigation does not aim at a complete and universal GIS solution but tries to give a procedure allowing for the establishment of a consistent data set for a DOM providing a unique description of the surface of a volume object. The unique description of the surface is first of all useful for visual application. A typical visualization in this context is volume rendering, giving a pseudo realistic view of the surface (cf fig.10). The contents of fig. 10 presents a views from an artificial space position, what might be extended to an animation of the object, turning the view point all around the volume. Another type of visualization is the presentation of surface parts with respect to a selected reference frame. As shown in fig. 5 any individual coordiante system (eg X_S,Z_S) may be taken as reference. The data of the DOM then has to be transformed into this frame followed by a selection of all those points with have to be considered for the graphical presentation.

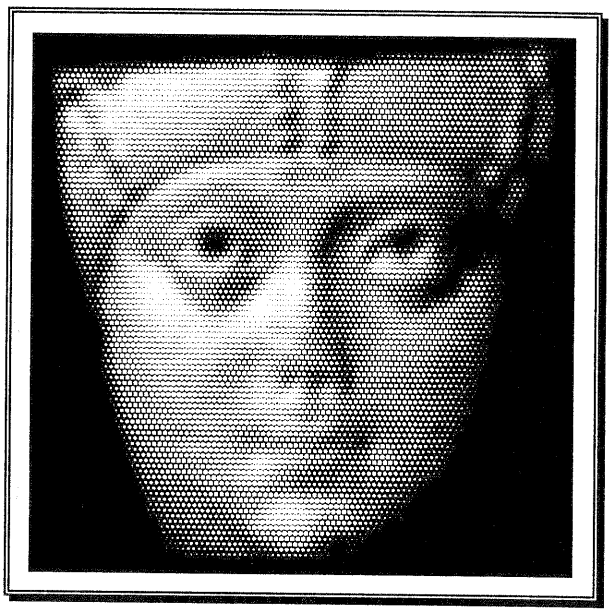
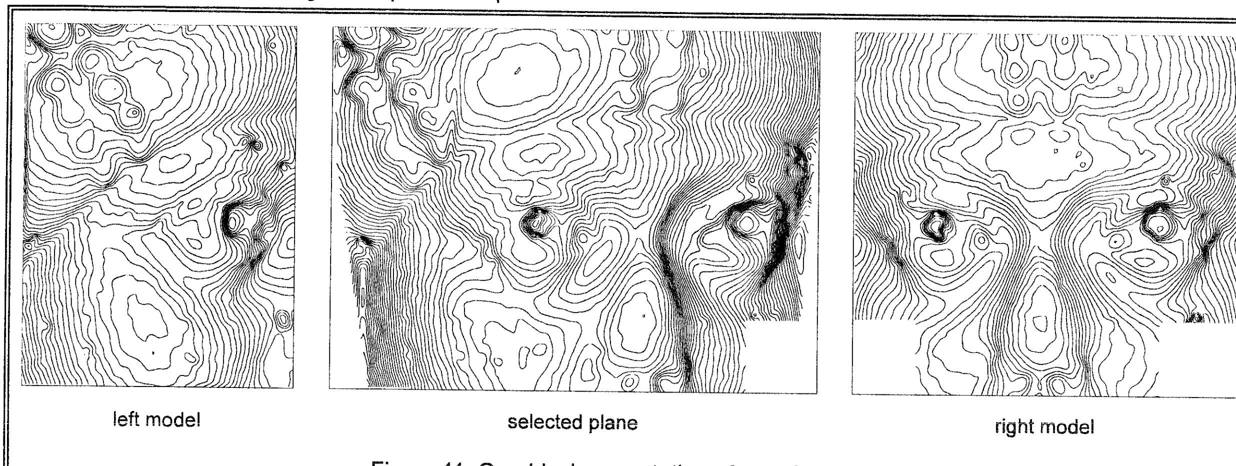


Figure 10: Shading of the volume from an artificial perspective

This process allows a very flexible graphical investigation of any desired part of the surface (cf fig. 11).
Figure 11 shows two graphics of surface parts as they were calculated in the local model coordinate system. This gives an unusual impression due to the orientation of the coordinate systems, what is changed if the data is transformed into a local system better matching the surface.



left model | selected plane | right model

Figure 11: Graphical presentation of a surface part.

Finally, an orthoprojection as third presentation of common use will be shown here. Compared to the already shown visualizations, it is simply a somewhat different geometry behind this projection, allowing to perform exact geometrical investigations in the graphical plot. The structure of the object data therein allows to take the attribute values in order to give the connection to the digital images, necessary to calculate the gray values belonging to the surface parts (cf fig. 12).

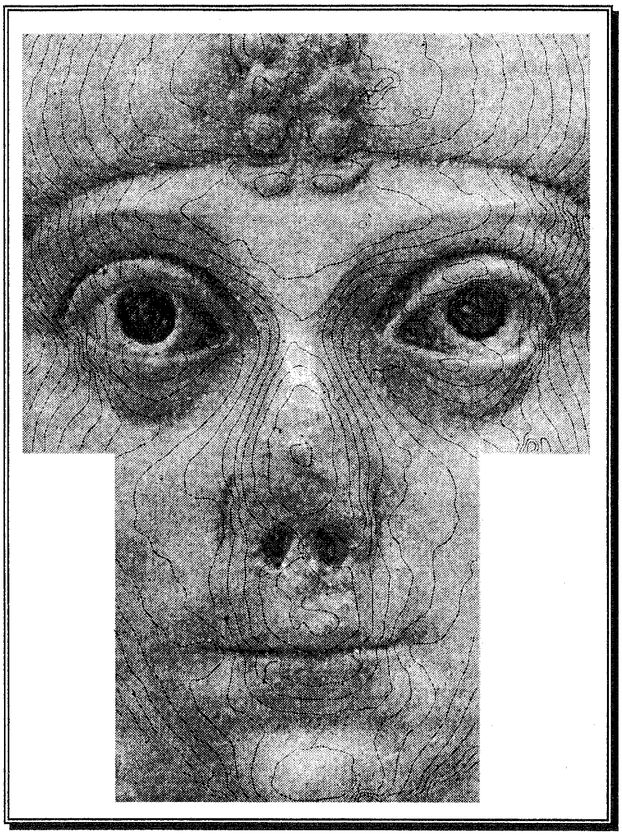


Figure 12: Orthoprojection for a surface part.

CONCLUSION

The example shown here presents a procedure giving the opportunity to evaluate the surface of a volume object by digital photogrammetric means, to establish a data structure giving a unique description of the 3D data characteristic of the object and to attach several useful attribute values to the metric data. These attributes are pre-requesite for some applications as the visualizations have shown, but might be helpful anyway.

Basically, the presented solution allows any user or scientist from disciplines having volume objects, to intensively analyze or geometrically investigate these objects, in order to support their specific applications (cf Boehler W, Heinz G., 1996). Of special value is the fact, that this is achieved without any preparation of the surface, what might be important in some cases (eg historical paintures).

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