

Laser Scanning and Digital Close Range Photogrammetry for Capturing 3-d Archaeological Objects: a Comparison of Quality and Practicality

Athanasios Velios

Royal College of Art / Victoria and Albert Museum Conservation programme
Sculpture Conservation
Victoria and Albert Museum
London, SW7 2RL, UK
Phone: +44 20 7942 2134 - Fax: +44 20 7942 2092 - E-mail: t.velios@vam.ac.uk

John P. Harrison

Department of Earth Science and Engineering
Imperial College
London, SW7 2BP, UK
Phone: +44 20 7594 7348 - Fax: +44 20 7594 7444 - E-mail: j.harrison@ic.ac.uk

Abstract: One of the commonest problems in the conservation of big and heavy fragmented objects is the estimation of the original relative position of the fragments (known as the matching problem). Help on the matching problem is obtained using specialized software for the estimation of the original position of every fragment. Prior to this the geometry of the fragments must be stored on the computer. We consider two non-contact capturing methods: laser scanning and digital close range photogrammetry. Laser scanning has been found to be rapid in use producing a dense, irregular point cloud that describes the object, stored in a digital file. Close range photogrammetry is slower, resulting in sparse measurements on a much more regular pattern. Data is stored on film first, and then converted to a digital file. We show how this intermediate step offers advantages related to the potential for future refinement of the model. We suggest the combined use of laser scanning for quick and easily usable models together with photogrammetry for future reference records.

Key words: laser scanning, photogrammetry, matching, Propylaia, recording, capturing

Introduction

Stone archaeological objects are often discovered in fragments, as breakage due to mechanical trauma is likely to have occurred at some time since their creation. The conservation of these objects involves the time-consuming process of the estimation of the original position of each fragment, in order to perform reconstruction of the overall shape of the object. This problem becomes more complex when dealing with heavy and large objects, as these are difficult to mechanically handle. Although modern computer software can help in this process by allowing virtual movement and matching of the fragments, prior to this virtual manipulation digital recording of the fragments is necessary.

In this paper, two remote methods for digitally recording objects — 3D laser scanning using hand-held scanners and digital close range photogrammetry — are compared on the bases of their suitability for making permanent high quality records of the objects and assisting in their virtual reconstruction. For this comparison, a cornice from the Propylaia of the Acropolis of Athens was used as a case study (figs 1-2).

Photogrammetric capturing process used at the Propylaia

When photogrammetrically capturing objects that possess only one scientifically important face (e.g. engraved objects), two cameras placed opposite the face of interest are usually used. There are many examples of the use of photogrammetry for this purpose, as this methodology has been used for the recording of buildings, objects and monuments (Bähr 1988, Cuny 1981, Masygan 1993, Milella 1997 and Rivett 1977). However, in the case of the cornice, a complete 3D model (comprising all sides of the object) is necessary, as the criteria for the matching of fragments prior to virtual reconstruction use a combination of characteristic features located on all sides of the object. In contrast to the previous case, the authors were unable to locate any previous references describing photogrammetric set-ups for the complete capturing of ancient objects. Indeed, there are only a few references describing similar procedures in other fields (Müller 1982). This is so because:

- a) much more complex set-ups are needed for the complete capturing of the object (an example to demonstrate this

is described later);

- b) photogrammetric tools are developed mainly for the earth-mapping market, and close range photogrammetry, being a secondary market, tends not to have the necessary funds to support the research on its own (Bähr 1988); and
- c) the rapid recent development of laser scanning has overtaken the development of close range photogrammetric techniques because of certain advantages that we will describe later.

In our work, the set-up for photogrammetrically capturing the Propylaia's cornice (fig. 4) involved photographing the object in 12 pairs of stereo-images (i.e. 24 photographs in total). These photographs were taken from 12 elevated positions around the object, without the object being moved. Elevated positions were selected in order to allow simultaneous capturing of both the sides and top of the object (the top is scientifically important, and if a lower elevation was used, it would not be visible). Twelve camera positions were selected (three on each side) so that sufficient overlap of the image data would exist to permit complete measurement of the object.

Equipment

The reference points for measuring the object were given by a rectangular metallic frame. An important factor in on-site photogrammetric measurement of objects is portability of the equipment, and because of this, the frame is designed to be readily disassembled and reassembled, and made of aluminium for lightness. The frame is also made to be adjustable, in order to encompass objects of various sizes. This is achieved through the bars of the frame being made of three, concentric square cross-sectioned adjustable elements, accurately positioned relative to each other with the aid of locating pins that pass through drilled elements in each bar (fig. 3). Hence, by changing the position of the locating pins, the size of the device can be changed from a minimum of 120cm × 120cm × 120 cm up to a maximum of 300cm × 300cm × 300cm. The bars of the frame are also equipped with rectangular targets (12 each bar, 144 in total) that are used as photogrammetric control points (fig. 3). Accurate fabrication of the frame means that the positions of the targets relative to each other are readily computed on the basis of the dimensions of the frame's components, and as a result high-quality photogrammetric control easily achieved.

A semi-metric ROLLEIflex 6006 camera (film size 6cm × 6cm) equipped with a reseau plate back and a 40mm lens was used for the photography. This equipment was selected for the following two reasons:

- a) It is much simpler to use, and is smaller lighter and cheaper, than a fully metric camera. As a result, there is much less risk involved in its use than with a fully metric camera.
- b) Because the available space around the object for setting up the equipment was limited, a wide-angle lens had to be used, and the only calibrated wide-angle lens available was for a ROLLEIflex camera.

Calibration

The frame was measured using terrestrial surveying techniques, and the relative positions of the control points estimated with a three-dimensional spatial accuracy of 1mm. However, it was recognized that the assembly – disassembly process would introduce errors that could only be quantified through re-measurement of the frame, which negates the frame's main purpose. The impracticability of constantly re-measuring the frame led us to decide that monitoring of the error would be done during the data analysis stage, using the photogrammetric software.

Photography

Figure 4 shows the positioning of the equipment around the object. Subsequently, the photogrammetric models produced from every stereo-pair were aligned and scaled according to the fixed control points of the frame, so that they shared the same co-ordinate system and could then be combined in the same 3D space to produce the complete model.

The photography took place in a single day, starting at 7 a.m. and finishing at 6 p.m. This same eleven-hour period was used for the laser scanning process, in order that a comparison could be made between the techniques in terms of the amount of data obtainable in a given time. A total of 96 photographs were taken. Photogrammetry usually uses a colour positive (i.e. slide) film, due to its superior photographic properties over colour negative film. However, these films have limited exposure latitude, which means that accurate setting of exposure time on the basis of light meter readings is required. With this work, as the object was located outdoors, there were substantial changes to the light throughout the day. This indicated that constant adjustments to the exposure times on the basis of light meter measurements would be required, and this would dramatically increase the time taken for the photography. As a result, we chose to adopt a colour negative film with wide exposure latitude, and used only a limited number of exposure times determined from a few light measurements. The film used was FUJICOLOR Superia 100, with an ISO film speed of 100 and a diffuse RMS granularity value of 4.

Data Processing – Resulting models

The films were scanned using a PhotoScan 2000 scanner (distributed in the U.K. by ZI Imaging U.K.). The scanner was used at its maximum resolution of 7¼m, in order for us to be able to take full advantage of the photogrammetric potential of the film, and the size of the resulting digital image was therefore about 8500 pixels by 8500 pixels. The software used for the processing of each pair of digital images in order to produce a digital elevation model was ImageStation 2000 (developed by ZI Imaging). Usefully, after photogrammetric orientation of the models using the co-ordinates of the control frame, the software provided us with reports on the estimation of the accuracy of the measured control points. In this way it was possible to assess the accuracy achieved while building the stereo-models,

and this is shown in table 1 for two objects of different shape.

The error values given in the table describe the mean estimated error of the control points of the frame. It is expected that the corresponding values for the measured points on the object will be smaller than this. This is because the object appears towards the centre of each image, whereas the frame appears towards the edges, and the photographic errors due to camera and lense distortions increase way from the image centre.

The digital elevation models from each pair of photographs were combined to produce a complete model of the object as a single entity. The resulting model consisted of a group of points (generally referred to as a point cloud) with X, Y, Z co-ordinates in the frame's co-ordinate system. The minimum distance between two points on the object's surface was about 5mm, which means that, although the position of each point was estimated with the accuracy shown above, the low density of the points results in surface features located between any two points not being detected. Clearly, closer point spacing is desirable, but the point spacing obtained is that which resulted from the image matching algorithms used in the process, rather than being specified *a priori*. As the performance of these algorithms is affected by the quality of the images, the low point density is thought to have occurred because of:

- a) low picture quality on the medium, exemplified by the extreme diversity in lighting conditions causing a loss of data; and
- b) the scanning of the negatives, with user-defined colour settings possibly affecting the quality of the resulting digital image and hence limiting the available data.

Production of the digital elevation model is a time consuming process. Although several software packages include algorithms for the automatic calculation of the co-ordinates of the points in such a model, it is usually the case that the automatic process needs to be monitored by a user who intervenes when necessary. The production of the models for the two objects took about 8 hours of systematic work to complete.

Laser scanning capturing process

Laser scanning is a method for capturing objects that is extensively used in engineering. There have been several applications of this technology to the recording of the cultural heritage, beginning in the 1980s (Ahmed 1983, Taylor 1987) and with very good results in more recent years (Larson 1994, Levoy 1999). However, there are few applications with specific orientation to conservation. In 1992, Baribeau et al. (Baribeau 1992) described the use of a laser scanning system for the evaluation of the damage caused to paintings by vibrations. More recently, Geary (Geary 2001) has reported on the use of laser scanners to capture the geometry of polychrome sculpture. We conclude that there is little guidance available in the published literature for the use of laser scanning in conservation.

Equipment

The scanning of the objects here was performed using a laser scanning device ("Model Maker H", available in the U.K. from

3D Scanners Ltd., and in Greece from FTS Ltd.) mounted on a precision articulated arm (the "Bronze" arm produced by FARO). The theoretical accuracy of the equipment is about 0.5mm (Faro 1999), and a simple calibration process (see below) confirmed this accuracy. Nevertheless, given the crystal structure of the pentelic marble used in the building of the Propylaea (Tanoulas 1994), it is possible that greater error could be introduced by the refraction of the laser beam in the crystals, as pentelic marble can be transparent up to 15mm from its surface (Orlandos 1994: 83). However, given the deterioration of the material and the patina, which has made the surface opaque, this error is not considered to be of significant magnitude here.

Calibration

The calibration process of the scanner involves the scanning of an object with known dimensions (usually a cube). The resulting digital model, when compared to the dimensions of the real object, provides all the information for the calibration of the instrument. This calibration is then done automatically within the control software. However, the accuracy of the system in any given application depends on both the user and the object being scanned, and therefore the actual model accuracy obtained is not known.

Scanning

A critical component of the scanning process is for the camera embedded within the scanning device to detect the laser beam reflected from the object. Direct sunlight on the marble would therefore make the process impossible, and because of this the scanning was done indoors (fig. 5).

The nature of the scanning instrument and the support to the object meant that at any one set up there was at least one surface of the object that was hidden and therefore could not be scanned. To overcome this problem, after the visible sides had been scanned, metallic registration marks were placed on the object (with water-soluble glue) and scanned separately. The object was then rotated such that the registration marks and the previously hidden surfaces were visible to the scanner, and the registration marks scanned again (fig. 6) before being removed. In this way, sufficient data were obtained to allow the results from the scans of the various surfaces to be linked through co-ordinate transformation.

It was found possible to undertake both the calibration process and the scanning in a single day: Work commenced at 8 a.m. and was concluded at 6 p.m.

Data Processing – Resulting models

As with photogrammetry, the output of the scanner is a point cloud, with each point defined by a triplet of values corresponding to X, Y, Z co-ordinates in 3D space. Because of the scanner's potential for collecting 3600 points per second (300 points per frame, 12 frames per second) the output files can contain vast numbers of co-ordinate values and are usually extremely large. As a result, post processing of these files involves the filtering of the points, such that coincident points are removed. The software which accompanies the scanner (or

other commercial software packages) is capable of such basic filtering of point clouds.

Comparison of the techniques

Accuracy – Quality of the models

From inspection of the figures of the models (fig 7-10)¹ and table 2, it is readily apparent that the number of points in the photogrammetric model (8,907) is much smaller than that in the scanned model (479,374). It is therefore obvious that a lot more information is exported (not captured — see the later section on Ethics) by the scanner than by the photogrammetric software. The effect of this is clearly seen in the photogrammetric model where, because of the sparse points, small-scale details cannot be seen on the final model.

However, an issue of possibly greater importance than the quantity of data is their quality (i.e. accuracy). The software used in the photogrammetric method can provide us with information, for each stereo-pair of photographs, that includes the estimation of the error both for every control point and for the overall accuracy of the model. On the contrary, similar information is not available when exporting data from the scanning software. The only indication of the accuracy of the scanned data is the performance data provided by the manufacturer of the instrument. As described earlier, prior to scanning the instrument is calibrated, but this only shows whether or not the equipment at least reaches the accuracy stated by the manufacturer. We can assume that the accuracy of the scanned data equals this, but as the quality of the scanning process depends on both the experience of the user and environmental conditions, it is possible that the stated accuracy is not always the accuracy of the model.

Hence, judging from the resulting models of the two methods, laser scanning gives the greater number of measurements (more points and improved surface definition) and probably (but not necessarily) better accuracy than the photogrammetric system. However, it is not possible for the accuracy of the scanning system to be determined as robustly as that of the photogrammetric system.

Time

The work reported on here was a preliminary investigation, rather than a highly optimized production process. As a result, we can see with hindsight how simple improvements to our methods and equipment would reduce the capturing time. For example, with the photogrammetric work, had the object been placed closer to the ground, then the use of a stepladder for the photography would have been avoided and as a consequence the amount of time needed for this greatly reduced.

However, the time needed for photogrammetrically capturing extremely large objects is almost the same as the time needed for capturing small objects, as the number of images required is the same. In contrast, the scanning of extremely large objects would dramatically increase the time of the recording process, since the area that needs to be scanned will be substantially

greater. For such large objects it is likely that scanning will be an impractical solution.

As far as post-processing is concerned, in the case of the cornice it is obvious that laser scanning software performed its tasks much more quickly (~2 hours) than the photogrammetric software (~8 hours). Again, here, one has to consider the case when it is extremely large objects being captured. The post-processing of the data for scanning could be extremely slow and demanding of computational resources. On the other hand, photogrammetric software runs equally fast no matter what the object size is, as its speed depends on the size of the digital image that holds the information, and not the object itself. There is, of course, the related issue of accuracy of the measurements and their spatial distribution, in that small images of large objects will be processed quickly, but at the expense of quality of the final digital elevation model.

Practicality

It appears that most issues regarding practicality of the equipment are down to personal prejudice. For example, both sets of equipment are portable and can be easily carried on site, and both methods depend on the ambient lighting conditions. It is likely though that some users would feel happier with one set of equipment than the other for purely personal reasons.

One issue of practicality that is important is that of the sensitivity and the robustness of the equipment in terms of tolerance to physical abuse. Both laser scanning cameras and ordinary cameras are precision instruments that require careful handling, and although the laser scanning camera felt much the more delicate, the authors are not aware of any research undertaken to compare the physical tolerance of the equipment. Although such work would probably be pleasurable to undertake, it would without doubt be expensive!

Finally, we must consider practicality in terms of the personnel requirements. Laser scanning is the more orientated to an automatic approach for the production of a digital model by non-specialist personnel, in that the training needed for successfully using the scanner does not presuppose any technical knowledge apart from that of the use of a computer generally. On the other hand, in order to be able to produce a model using photogrammetry, specialized knowledge of the subject is needed, along with sufficient experience of modern equipment and processes.

Ethics

According to the international charter of Venice (Vrieze 1964: Article 16), keeping accurate records of objects is an essential part of the conservation process. In laser scanning the collection of the data ends as soon as scanning has been completed, and no additional information can be extracted from the object unless a new scan takes place at a higher resolution. On the other hand, with photogrammetry an uninterpreted and essentially complete representation of the object is recorded on a medium (i.e. film), and the information is extracted after the recording using an appropriate technique. Hence, the inevitable improvements in these techniques will make additional infor-

mation available for extraction in the future. Permanent records of the object are kept on the film, and this is why careful photography is important.

Matching of fragments

In terms of using these digital elevation data, or point clouds, for extracting useful information for the matching of the fragments, we can make two points. Firstly, in the context of architectural elements, we believe that the point density achieved by photogrammetry is sufficient to capture identity patterns of the objects. This can be useful when large models (as result from laser scanning) would rather be avoided for speed of computer processing. Secondly, Papaioannou et al. (Papaioannou 2001) state that the better the definition of the fractured surface, the more reliable the results of the matching, in which case laser scanning may be preferable. Our investigations are continuing to determine whether photogrammetric data may be appropriate for measuring the roughness of the fractured surfaces, and whether this can assist in the matching of fragments.

Discussion

The comparison of these techniques was based on very specific equipment and software that, according to the authors' experience, combine good quality with accessibility. Although better equipment (and probably software) will undoubtedly exist, it was not accessible to use. As a result, although a more extensive comparison of the methodologies would have been useful, it would have had a rather theoretical character.

One of the major problems we encountered during the recording of the objects was the capturing of the hidden side. We consider that further research is necessary on at least two aspects of this problem. Firstly, a simple process for accurately registering the point clouds that arise from different sides of the same object during laser scanning, without having to attach any registration marks to the object, is urgently required. Although such registration is currently feasible through software, the authors are not aware of any reference to its reliability or accuracy. Secondly, and similarly, simple techniques are required that will allow alteration of the photogrammetric set-up such that all surfaces of an object can be captured, without the object having to be moved.

Lack of standardisation during post-processing of the data is also a significant problem. Several parameters exist that have to be optimally selected for the best results in terms of accuracy, and used consistently. We depended on the skills and expertise of specialist personnel employed by the various equipment suppliers for this; such a solution is impractical at large.

Finally, the issue of introducing high quality photogrammetric control in a simple fashion is one that requires urgent attention. We chose to use a precision-built frame, but due to its cubic shape, distortions can easily occur during disassembly and reassembly. If a control frame is to be used, development of a simple and robust system that is both dependably accurate and able to surround large objects is required.

Conclusions

Laser scanning gives high definition digital models of objects, quickly. However, no improvement to these data can occur later on, and no permanent uninterpreted record of the object exists. Current photogrammetric platforms in combination with medium format photography are unable to produce such dense models, although if new software packages and film scanners are introduced in the future, more information can potentially be extracted. The use of photography does, however, mean that a permanent uninterpreted record of the object exists.

Consequently, permanent accurate records that adhere to the principles of the international charters of conservation, can only be kept using photogrammetry. However, because today's laser scanning technology is much more efficient in the immediate production of models that are useful to practical conservation, we suggest that the combined recording of objects with both photogrammetry and laser scanning be implemented.

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End notes

¹ In the figures of the scanned model, only one quarter of the total data are displayed, as images of the point cloud in full resolution are totally black due to the point cloud's density.

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Tables

| | Fragment No 1 (highly elongate) | Fragment No 2 (approximately cubic) |
|----------|------------------------------------|--|
| Extent X | 1m | 0.4m |
| Extent Y | 0.25m | 0.25m |
| Extent Z | 0.5m | 0.45m |
| Error | ±0.003m | ±0.0021m |

Table 1. Estimated error in photogrammetric measurements compared to the size of the object.

| | Photogrammetry | Laser scanning |
|-----------------------|----------------|----------------|
| Extent X | 1,050mm | 1,040mm |
| Extent Y | 245mm | 261mm |
| Extent Z | 481mm | 472mm |
| Number of Data Points | 8,907 | 479,374 |

Table 2. Size of the models (mm) and number of points.

Figures

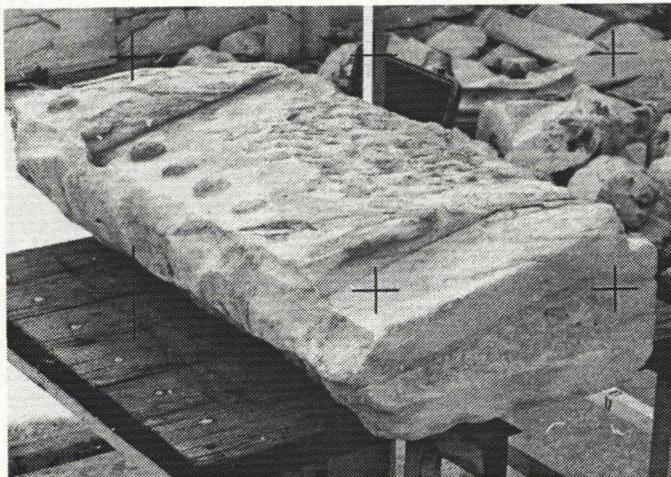


Figure 1. Elongate fragment of the cornice.

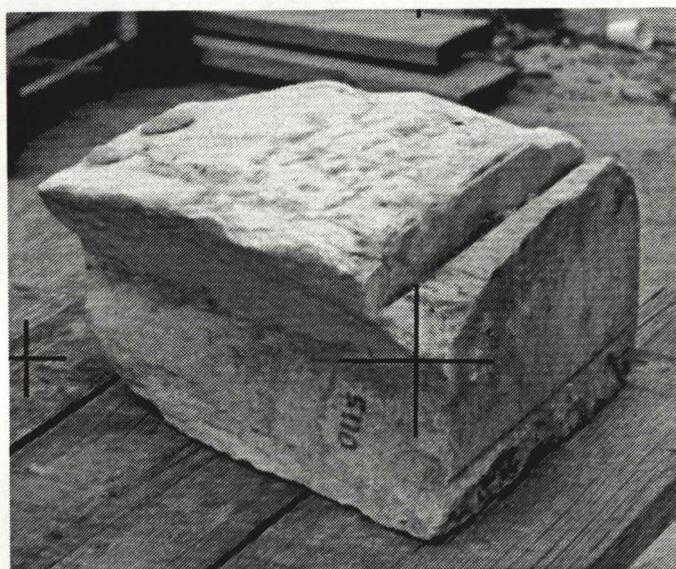


Figure 2. Cubic fragment of the cornice.

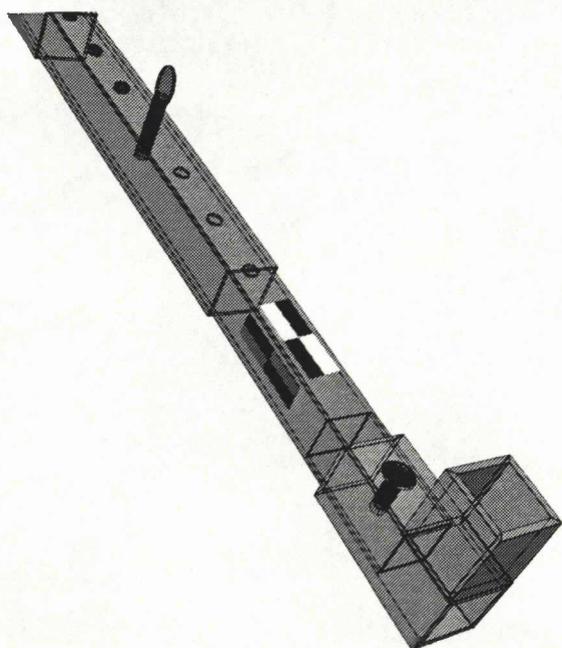


Figure 3. Extension pins and targets.

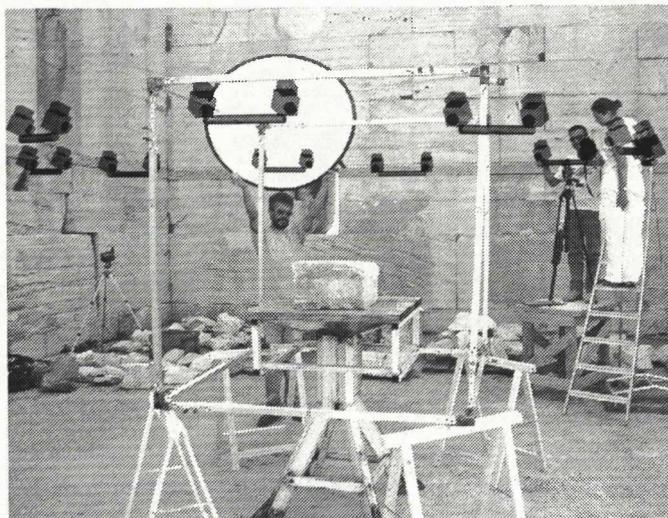


Figure 4. Photogrammetric set-up.

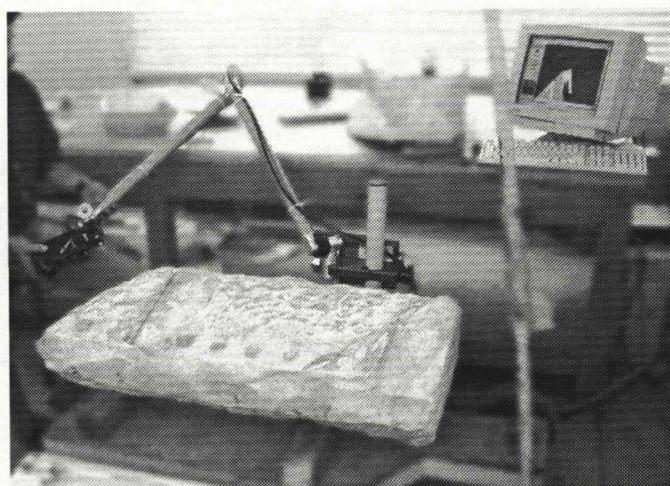


Figure 5. Scanning of the cornice.

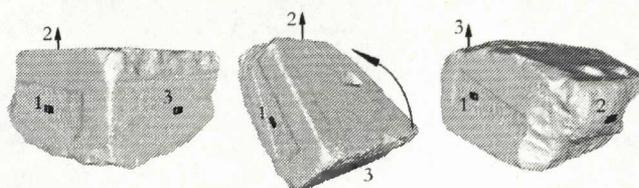


Figure 6. Registration marks.

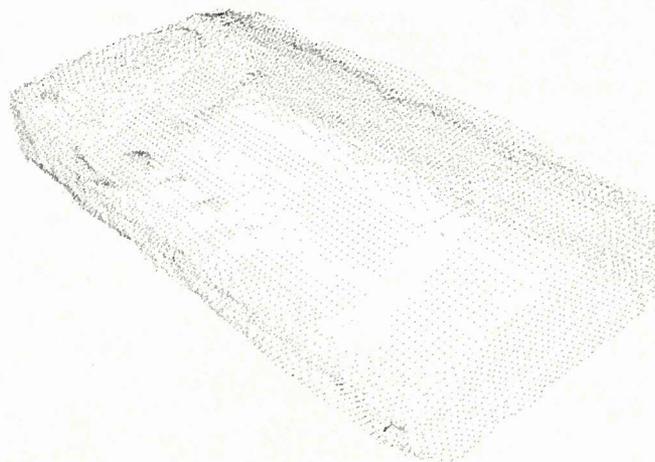


Figure 7. Photogrammetric point cloud.

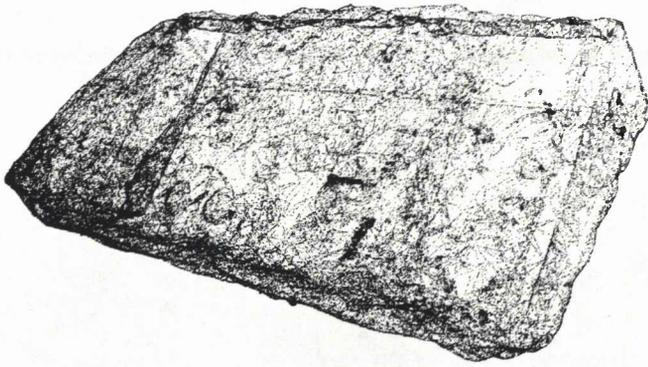


Figure 8. Scanning point cloud.

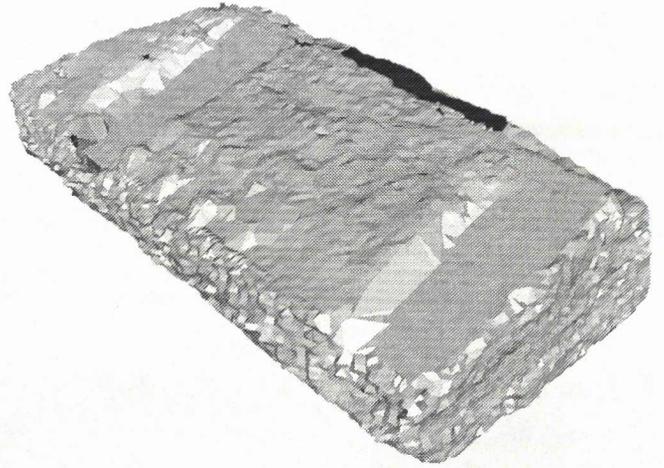


Figure 9. Photogrammetric shadowed surface.

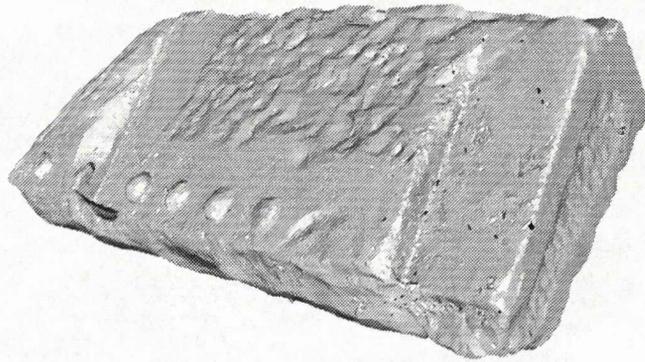


Figure 10. Scanning shadowed surface.