REPLICATION OF MARBLE EXHIBITS USING PHOTOGRAMMETRY AND LASER SCANNING (OR HOW TO FORGE EXHIBITS).

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ABSTRACT:

The replication (exact copying) of marble museum exhibits using marble powder is being analysed in this paper. Optical and laser scanners has been used to collect dense point clouds, which form a three-dimensional computer model. This model has been used to physically reconstruct the object using rapid prototyping techniques. Model of objects from 0.15m up to 1.86m have been replicated as examples. The procedure and the problems confronted with the solutions given on each case, along with experience gained are being discussed. Problems concerning accuracy, number of points and formulation of the model are reported. Comparison of the systems in terms of accuracy, speed and functionality is the main concern of this paper.

Particular reference is being done to the optical scanner. In order to minimize the number of the photographs, maximize the data collection rate and automate as much as possible the procedure, a slide projector with a grid is being used as the second camera. The process is depended on machine vision techniques, which automates line extraction and point cloud calculation thus reducing time, but deteriorating a bit the accuracy. The physical reproduction of Kouros, a 1.86 meter statue is being examined as an example.

1. INTRODUCTION.

It is quite a common statement to say that the computer evolution has altered many aspects of our lives, but it is also true. A few years ago photogrammetry was an exotic application for precision measurements, open only to experts, and only a few experts from similar fields were aware of this scientific application.

The work described in this paper, has been done as part of the European research programme "Eco_marble". The main scope was to create marble copies from marble dust. The main steps in this procedure were:

- digital modelling of the object using laser scanning, photogrammetry, or both,
- manipulation of large point clouds, nurb modelling, processing and finishing of the model
- development of high marble percentage mixtures for use in a variety of manufacturing machines
- pre processing of the point cloud and preparation for the rapid prototyping machine
- evaluation of the copies, in terms of material quality, accuracy and authenticity by the archaeologists and museum representatives

This paper is mainly concerned with the modeling methods used, namely laser scanning and optical scanning (or photogrammetry if you prefer) and their comparison in terms of accuracy as well as ease of application, density of points and limitations.

2. SELECTION OF METHODOLOGY

2.1 Review of systems and available techniques

The main aim was to develop methodology for object modelling. Since this model was to be used for reconstruction it had to be very dense and very accurate. The accuracy for such work is being dictated by the manufacturing precision. Most of them have precision of 150 um, to 100 um, while in some of them is down to 50um.

Software such as 3D Builder, Photomodeler and Canoma can offer interesting modelling features in a reasonably priced package, but their applications are limited by the low automation level. Hence useful only in gathering a few points and simple geometry objects. The only work with complex objects is reported in Yixuan, Z. et al. (1999). It is rather discouraging in terms of time and man months spend, hence completely abandoned.

Conventional photogrammetric software with automatic point collection module was also tested with poor results.

Another interesting case is reported in Scaioni M., et al. (1996). In this particular paper InduSURF was the commercial package used. InduSURF is a close range application with the possibility to automatically collect points in the same reference system from all images, hence constructing a complete 3d point cloud, which fully describes the object. The selection of the extraction areas and the corresponding pairs is being done manually. The description of the work as well as accuracy for the final point cloud, are not discussed well enough, but the system is described with more details by Kloudas (1995). Two interesting points in the paper are the fact that a random pattern is projected over the object to provide texture for matching and the RMS of the bundle adjustment reported, 0.027,0.029 and 0.022 mm in X,Y,Z respectively.

Luhmann (2000) reports on accuracy assessment methods for 3d measurement systems, including automatic or semi automatic software.

Zhou and Fraser (2000) report on a new method for surface reconstruction, with good results, but this is not wet implemented in a commercial system.

Most of these cases are completely depended on classical photogrammetry. A promising approach is raising using moving digital cameras (Heikkinen, J., 1996 and Pollefeys M., et al., 1999). These techniques focus on a fast and automatic production of 3d models for presentations, rather than on accurate 3d models. Provided a set of control points and a more sophisticated approach to accurate measurements, it is possible that this systems will become the industry standard.

Nowadays laser scanner technology becomes open to public. Systems are composed from a laser head with one or two CCD cameras and a system (usually an electromechanical arm, or a CNC machine), which moves and calculates the head's position and rotations in 3d space. The projected laser realize on the surface a line (or points) while the 2 CCD cameras calculate the position of the well defined line (point) in 3d space using simple triangulation. These points are calculated in the head's reference system and then transformed in the real world reference system through the attitude and position values from the head carriage. Density of points and automation are the strong points of such systems. The overall accuracy depends mostly on the accuracy of the system, which calculates the attitude and position of the head in 3d space. Acquisition times are usually long, but justified by the huge number of points gathered.
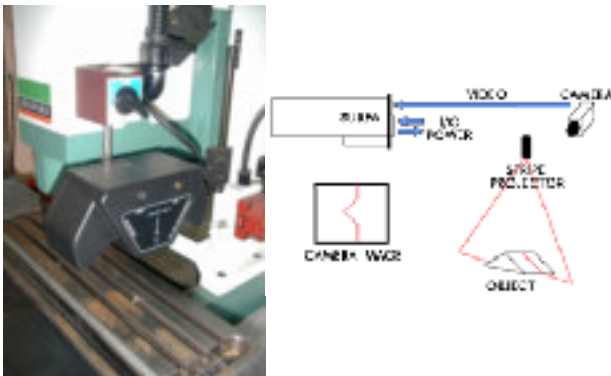

Figure 1. On left the CNC machine with the double CCD laser head used in this project. On the right the laser stripe triangulation principle.

The combination of a CNC (3 axis Denford CNC machine) machine with such a laser head (Reversa 10H Laser Head) provides very good accuracy. Laser head accuracy is 10 um, as reported by the provider, and this is equivalent to CNC movements (5 um, using step motor).

Portable laser scanners are a new trend and address mainly the problem of functionality, but they still depend heavily on surface matching and positional accuracy over the whole object. Their accuracy is somewhere between optical scanners and the aforementioned system.

In any case laser scanners provide exceptional accuracy among points in a single scan, for almost all possible applications.

2.2 Selection and description of optical scanner.

In order to accommodate modelling of variable objects, a portable scanning system was necessary. Desirable features of such system were automatic extraction of point clouds, ability to handle full 3d objects and maximum flexibility in terms of sizes and lighting conditions. A structured light system, which is much closer to author's photogrammetric background, was finally chosen from Eyetronics. This system is designed by electrical engineers and therefore uses fundamental matrices instead of the robust geometrical model of the pinhole camera. In principle, the second image of the photogrammetric pair is being replaced by a slide projector. The information necessary for point calculation in 3d space (x, y pixel coordinates), which is extracted from the second image, is now "projected" through the slide projector and recorded in a single image.

In order to make a single scan the relative positions of camera and projector must be known. Therefore after positioning favourably the camera and the projector so that the projected grid has the desired density over the object, a calibration box with circles must be photographed instead of the object (fig. 2). Due to the known geometry of the box and the circle distance, the software can calculate the relative position of camera and projector in real world coordinates.

As the dens grid from the slide project is realized over the object, it becomes distorted and photographed using a digital camera. During post processing, software automatically locates the grid intersections and calculates 3d coordinates of the points (fig. 3). Therefore, density of points in the final model is depended on the grid density during photography.

Although computation can be done on site, usually is being done back in the office, due to the excessive number of photographs being taken in site for obvious reasons.

Figure 2. Set up of camera and projector during Kouros' plaster replica photography in ARF's lanoratory.

The process described seems easy and requires almost no expertise, but in practice a number of problems arise.

The automation degree of the system is high. The detection of the projected grid over the calibration box and the object itself is very good (fig. 3). Material and colour of the object play an important role to the procedure. White objects provide better contrast for the projected grid in comparison to black. In any case a few manual corrections are needed in areas with occlusions or steep slopes with respect to angle of view.
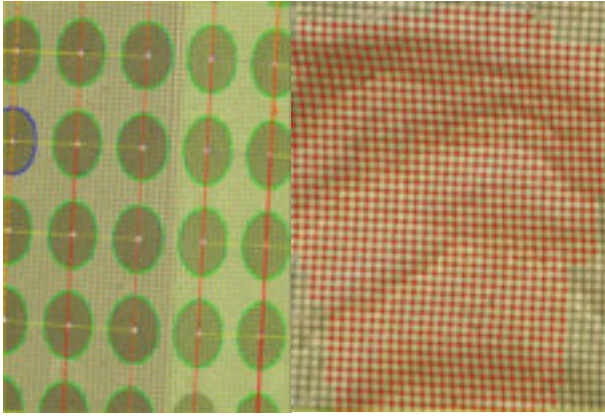
Figure 3. Details from photographs used during orientation and grid detection for surface reconstruction.

3. TESTS ON OBJECTS

3.1 Initial remarks

Both scanners collect a large number of 3d points. In each case these points are correctly scaled, but positioned in the scanner's coordinate system. This means that the independent point clouds need to fit together and then stitched in order to produce a full 3d model.

Provided there are common areas between scans, the point clouds are manually placed together crudely and the system can automatically calculated the best fit. This technique is quite different in photogrammetry, where the position of the independent models is being calculated precisely during the bundle adjustment and therefore points are calculated directly to the control point system. If a linear object is to be modelled using a scanner and the independent point clouds are being connected afterwards, it is quite possible that the final model might not have the exact size nor be straight enough. Therefore misalignment between scans is dangerous and might lead to erroneous models, especially since it is being applied additive. In this aspect photogrammetry with its homogeneous accuracy is advantageous.

In any case the final points were used to create a triangulated surface. Optical scanner's software supports these kinds of operations, but it is a closed box, in the sense that it does not allow import other than the processed images. Laser scanner's software controls the machine and can only store the points. Since the number of collected points is huge, another important feature of such software is the ability to manipulate and reduce points based on their importance over the surface. Points are erased based on their local derivatives; hence flat areas become sparse while irregular areas keep necessary information.

3.2 With the laser scanner

The laser scanner procedure also seems quite straight forward, but there are a number of limitations and key factors..

Since lenses are involved, depth of field is a crucial factor. If the side to be scanned is quite planar with small relief there is no problem (fig. 5). If the object to be scanned is complicated with big relief (fig. 4) then two or more scans over the same area are necessary. The fixed focusing distance is 5 cm and the depth of field ±0.5cm.

The main disadvantages are:
- the time required to make a single scan,
- the need to spray the object for better results,
- the CNC's operational area sets size limitations,

- the fact that you need to touch the object in order to rotate it under the scanner,
- the fact that the system is not portable means that the object has to be transferred to the scanner.

It is quite obvious that many museums will not give away their exhibits and archaeologists will not be very happy seeing artefacts sprayed.

On the other hand, accuracy (10 um) of the specific system is excellent, and the density of points unsurpassed (5 um is possible but noise is discouraging).

A variety of small objects from coins to small figurines and bas-relief, were scanned using the laser scanner and most of them were reproduced using resin.
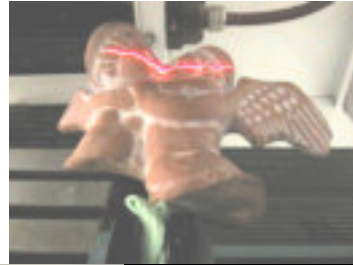

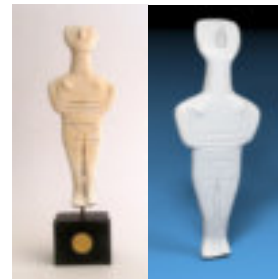Figure 4. Eros and Psyxi. Laser scanning, replica and final model, created using 15 independent point clouds.

Figure 5. Cycladic figurine. Replica used and final model, created using five independent point clouds.

3.3 With the optical scanner

The optical scanner is designed for fast, easy collection of 3d models for a wide range of sizes. It has been used to scan objects from 20 to 186 cm. If combined with a digital camera, which allows in site checking of object coverage and excessive gathering of photographs with no cost, the system becomes versatile, fast, portable and quite robust.

Following the rule that nothing is as easy as it seems, it soon became apparent that if accuracy is expected the procedure must be exercised with extreme caution. Scanning twice the same object with a digital camera and a video camera revealed that the system was designed for speed and versatility rather than accuracy (fig. 5). It must be noted thought that these models were created within 4 and 8 hours respectively including set-up, photography and processing.

These initial problems were rather easily solved using larger overlaps, which strongly reduce sliding and provide much better positional accuracy. Better selection of photographs depending on the angle of view for each side overcomes the problems of small deformations. Similar work with stereo pairs and a stereo plotter would probably had better results in terms of accuracy, but time for triangulation, on site photography and control measurements, along with manual collection of points would exceed 70 hours (10 pairs). Hence time and cost savings are obvious.
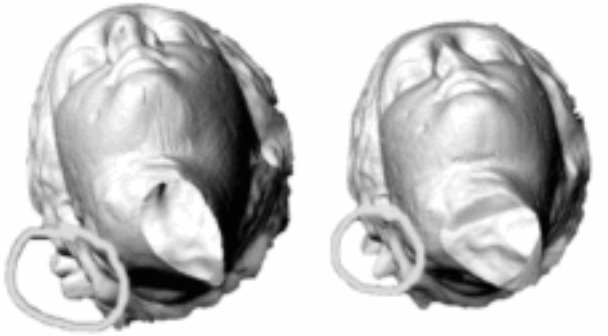

Figure 5. Ygeia's head, scanned twice. Small deformations and a significant change of size and shape are noticeable.

3.4 The special case of Kouros

Kouros was a special case considering the volume of data, the size of the object (1.86 m) and the reproduction scale of 1:1. A plaster copy was provided by ARF (Archaeological Receipt Fund). Photography took place in ARF's laboratories.

It must be noted that more complex geometries were tested (two statues from Bremen Museum, sized 1.4 and 1.6 meters respectively). Photography took place in site, but during processing undercuts and extending arms made modelling almost impossible. That's the reason Kouros was finally selected for testing.

3.4.1 Photography

The body of Kouros is of rather simple geometry (fig. 6) but it is necessary to maintain characteristics in detailed parts, such as head and feet. Hence two different densities were used. 441 digital photographs were acquired in two days. Ten different set ups of camera and projector were required in order to cover every part and aspect of the object. Setting up the projector so that the grid is dense enough and well focused, in conjunction with the well focused camera covering as mush of the area and keeping imaged grid crispy, was the most time consuming procedure. Since a replica of the original was used, it was quite easy to handle and rotate it (fig. 2).

3.4.2 Computer Processing

In the beginning of the processing a clear problem has risen. Lens distortion was not mathematically modelled within the software and therefore the digital model appeared curved (fig. 6). In order to overcome this problem, distortion correction has to be taken into consideration prior entering the images into the software.

Lens distortion forces straight lines in real world to be imaged as curves in the photograph. Therefore if a number of straight lines are photographed, then is it possible by measuring points on them over the image to calculate the lens distortion parameters (Karras et al., 2001). The straight lines of the grid,

when projected over a flat surface should remain straight. That's the case with the calibration box, which has two flat panels, and therefore the projected grid should remain straight over each panel. This information can be used for a pre calibration of the images (Sechidis et al., 1999), which could be applied in order to produce new "calibrated" images.

It must be noted that the photographs record the result of two lens distortion effects; one from the projector over the object and a second one from the camera itself. In the general case the combination of these two lens distortions cannot be combined under the single lens distortion mathematical model. Since development of new lens distortion models was not the purpose of this project, the simplified model used managed to improve the 3d model (fig. 6).

The lens distortion was being calculated by the straight lines in the calibration image and then applied in all photographs of the particular set-up.
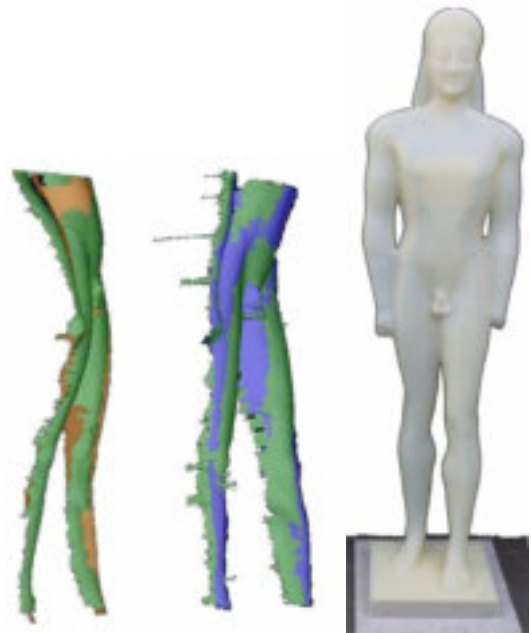

Figure 6. Kouro's digital model prior (left) and after (centre) lens distortion correction, along with the reconstructed model from resin (right).

For the final model 98 images were used for an equal number of independent surfaces. Processing the full model with one million points was not an easy task for the software, and therefore the final manipulation of small gap filling, refinement and stitching has been made externally. Since sliding along the independent parts was a clear danger, the digital model was measured in height, to ensure that there will be not essential difference. The four millimetre difference measured from the original (measured with tape) is negligible and cannot be observed even by experts.

One million points correspond in an average density of 1.3 mm. Density in the head and toes was 0.7 mm, while on the body was up to 1.5 mm. The final file in stl format has been send for reconstruction. Since a number of problems have been confronted during this project, it is impossible to have exact time data. A crude estimation for a complete re-built of the model is about 50 workdays.

3.4.3 Physical reconstruction

Physical reconstruction needed extra post processing in order to translate data for the rapid prototyping machine (approximately

20 work hours). The huge rapid prototyping machine used was designed for this particular project. It incorporates three laser beams working simultaneously and a large basin full of resin (fig. 7). Although the model was made hollow, the machine was working continuously for five days.

The first test over the head only, showed that the precision of the rapid prototyping was better than the digital model and therefore edges from the triangles were visible in the surface of the reconstructed model. Modifications over the existing software overcame this problem and the final model created was continuous.
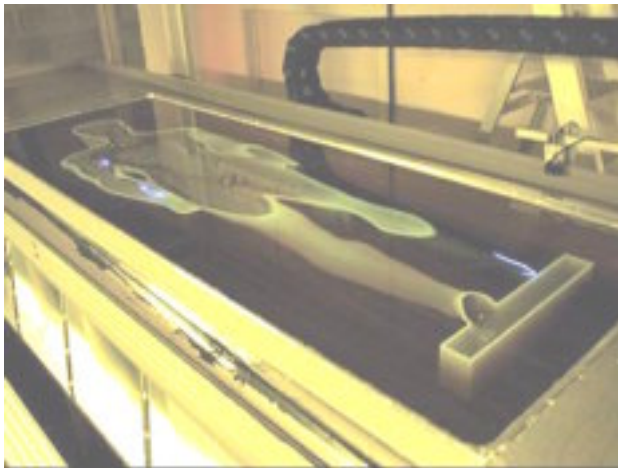

Figure 7. Kouros during reproduction in the basin. The three blue laser beams are clearly visible.

4. COMPARISON OF SYSTEMS

Although the two systems are complimentary rather than competitive, a comparison has been made using the only object, which could be scanned by both. The test object was Athina's bas-relief, sized 31.1 x 53.7 cm.

The objective of this test was the evaluation of optical scanner's accuracy. Accuracy does not necessarily include occlusion problems and missing information. In this particular case optical scanner performed better in this aspect.

Since the acclaimed accuracy of the laser scanner is much better than the expected from the optical scanner, it is quite safe to use laser's 3d model as reference. The comparison has been done using the corresponding METRIS module and purpose built software (fig. 8). The connection between independent scans is apparent in some areas, but it should be noted that in this case the lens distortion has not been taken in consideration, hence deteriorating results.

	Optical	Laser
Independent scans/photos	15	30
Post processing [days]	2	30
Density [mm]	1	0.1 to 0.05
Number of points in final model	162000	115000
RMS/accuracy [mm]	0.22	0.01 (acclaimed)
Mean [mm]	0.04	-
Max. residual [mm]	0.6	-

Table 1. Comparison of methods over Athina's 3d model.

Table 1 reveals that the procedure with the laser scanner is much slower. The number of points used in final models is

misleading. It seems that the density of points of the optical scanner is better, but this is only due to the fact that the vast number of points accumulated with the laser scanner were reduced for obvious reasons. A denser grid with optical scanner would have been possible, provided the projector have been positioned closer to the object. 0.5 mm of even denser is feasible, but in such case the post processing time rises rapidly.

Mean difference of 0.04 mm, shows that practically there is no systematic error. RMS error of 0.22 mm, which is the criterion for the goodness of the model, reveals that there is certain smoothing of the surface due to the inability of the relative sparse points to model the object. In any case though, the difference is not noticeable just by observing the model.

In order to fully cover the comparison, it should be mentioned that the laser scanner is six times more expensive than the optical one.
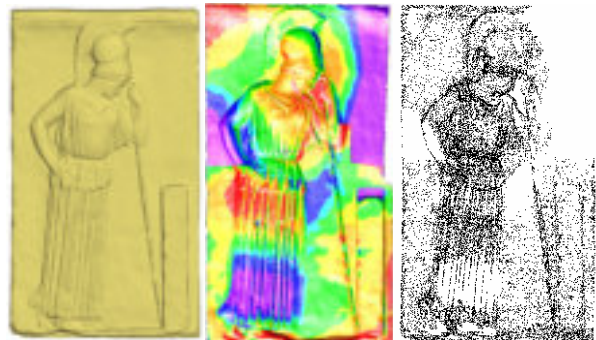

Figure 8. Athina's bas-relief. 3D model (left) and accuracy tests with raster (centre) and vector (right) visualization.

5. RESULTS AND DISCUSSION

	Laser scanner on CNC	Optical scanner
Black surfaces	-	Difficult
White surfaces	Excellent	Excellent
Open space	-	-
Max. Object size [cm]	50x50x20	Unknown
Min. Object size [cm]	Limited only by accuracy	10x10x10
Objects that shouldn't be touched	-	Feasible
Portability	-	Portable
Complicated geometry	Very good	Difficult
Accuracy [mm]	0.01	>0.22 (tested)
Density [mm]	>0.02	>0.7 (0.4 expected)
Processing time	10 x optical approx.	
Investment cost	6 x optical	

Table 2. Comparison of methods. Optical scanner's accuracy and density depend on camera and projector's distance respectively.

The two systems are complementary since each one covers different spectrum of objects, at least in terms of size. Laser scanner is excellent for small objects that require high accuracy and density, while the optical scanner can accommodate larger objects, where accuracy and density are not as important, or relatively to the object's size still very small.

Density and accuracy have a very big range in the optical scanner; therefore it is a flexible system. It is quite obvious that improvements in accuracy and density are exponentially expensive in processing time, approaching laser scanner's figures if decided to compete. Still there is a certain limit for the optical scanner in terms of density and accuracy, not to mention that in laser's figures of density and accuracy the optical scanner cannot compete. From the very beginning though, this was not the task for the optical scanner.

Laser scanner's processing time is dig mainly because the total time for a single scan with the optical is much smaller, although additional processing is necessary. The CNC is moving slowly in order to achieve the requested density and therefore a single scan can take from 30 min up to 4 hours. On the other hand points gathered are many and there is no problem in discontinuous surfaces. If there are many discontinuities it will be necessary to rescan the same area with different focusing settings, hence exploding time. On the opposite side, the optical scanner cannot accommodate discontinuities due to conceptual design, no matter how much time will be dedicated in processing or photography.

Undercuts are the basic problem of both systems, but the optical scanner is more sensitive because it is based on the assumption of surface continuity. Therefore only one uninterrupted surface can be modelled by using a single photograph. This fact poses limitations on surface complexity.

Therefore, unless it is a very simple geometry, both methods need filling of small gaps. Therefore it is necessary in most cases to post process data by a specialist on 3d modelling (industrial designer in our case). The optical scanner is more sensitive in occlusions and steep slopes, hence limiting its use. CNC and laser scanner is out of the question due to limitations of the scanning area. Laser scanner on a mechanical arm might be the best solution for such objects, although double scanning of areas, which is unenviable, can cause serious problems. Portable laser scanners (in principle the laser head itself enlarged and modified for such purpose) are in author's knowledge the best solution.

In both cases the points gathered form a huge data set, difficult to handle by any system. NURD modelling (mathematical representation of the surface) although time consuming and mostly manual, produces much better results, provided one is determined to invest in time for correction and conversion in addition to the inevitable lose of accuracy. Result, though are far better for continuity of the surface on the reconstructed model.

It must be noted that certain recent improvements in the optical scanner have raised its cost, but increased its functionality, hence increasing functionality, portability and decreasing a bit processing times and sensitivity to discontinuities.

Further research includes expansion of the technique on smaller objects such as coins.

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