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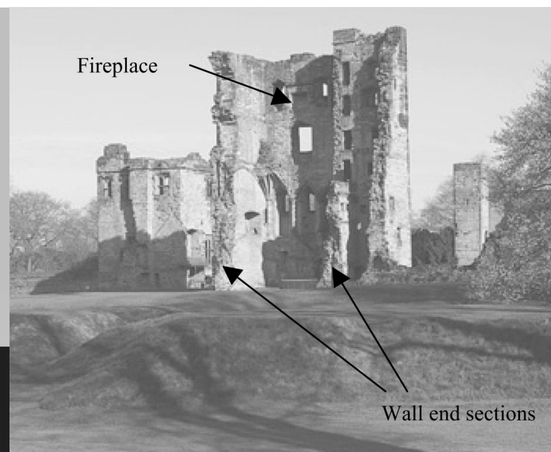
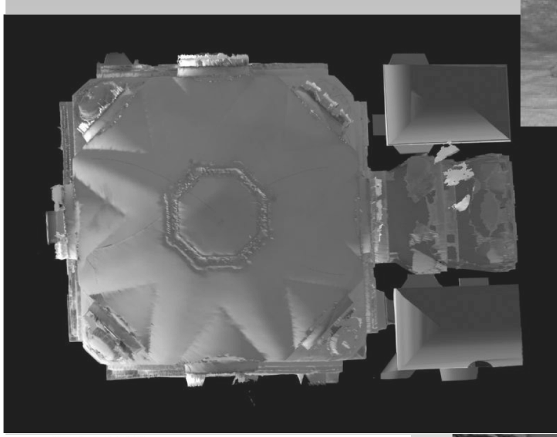
PROJECTS AND EXPERIENCES





THEALASERMETRY: A HYBRID APPROACH TO DOCUMENTATION OF SITES AND ARTEFACTS

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Key words: Laser Scanning; Theodolite Total Station; Close-Range Photogrammetry; Hybrid Approach; Cultural-Heritage; Metric Propagation Error

Abstract

The use of digital technology for measuring and recording three-dimensional shapes of high morphological complexity, as in the case of the pre-historic temples in Malta, offers a lasting and faithful virtual record that can be used by future researchers. This paper discusses an integrated system, based on the accuracy of the theodolite, and the technologies of laser scanning and photogrammetry by maximizing the data collection capacity of each instrument. This hybrid system overcomes limitations encountered when using solely photogrammetry or laser scanning. Photogrammetry used in combination with laser scanning leads to a more cost-effective and less time-consuming project. Using photogrammetry in combination with the laser scanner overcomes the metric error propagation which is generated when using laser scanning alone. This data acquisition and processing system can be applied to a wide range of applications; from the documentation of historical buildings, artefacts and monuments to site and engineering surveys.

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1. Introduction

The concept underlying this paper was developed as part of the preparatory work underlying the establishment of the 3D Imaging Department (3DID) of the Documentation Division of the Malta Centre for Restoration (MCR) in the second half of 2001. The issue arose when determining the extent of precision attainable with the digital photogrammetry and laser scanning equipment which was being evaluated by 3DID for procurement. It was noted that in their 2001 Case study on Donatello's Maddalena, Beraldin, Guidi et al.[1] had chosen digital photogrammetry over a 3D range camera as a reference measurement system because the former had promised a 0.2mm accuracy range over a 2mm accuracy range for the cloud points produced by the range camera scanning system and this in a statue which is approximately 180 cm high. The metric error propagation in the 3D range camera scanning system was induced by the requirement to "stitch"[2] together several scans of the same object in order to produce a complete 3D model. Beraldin et. al resolved the problem by using non-impeding optical targets placed around the object to obtain reference points for the digital photogrammetry to operate with.

One of the primary applications of 3D imaging for MCR is that of surveying relatively large megalithic temple complexes and other architectural edifices where the necessity of stitching several scans together was evident *ab initio*. Therefore the issue of metric error propagation was immediately taken into account when planning 3DID's systems since the procurement of hardware and software for both digital photogrammetry and laser scanning was undertaken simultaneously as part of a holistic approach to documentation solutions in the cultural heritage sector.

It was clear that MCR's intention to use the 3D surveying systems for complex temple sites as opposed to single statues posed additional problems to those inherent in the case study tackled by Beraldin et. al. In large-scale close-range photogrammetry, such as that required for a temple site, it was obvious that the photogrammetrical exercise alone would also require the "stitching" together of many images thus risking metric error propagation without even considering the probems of the 3D range camera. On the other hand, at least one of the leading contenders for the MCR's laser scanning system relied on targets whose geometry was accurately known and recognised by the restitution software which in turn used the targets (in this case spheres) to stitch scans together even in an automated manner. Would these targets afford MCR the time-saving cost-effective data collection method that it was seeking i.e. would it enable the laser scan data and the photogrammetrical data to be gathered in one single data acquisition session with, preferably, only one set of targets in place? This combined data acquisition was notionally an attractive process since it was clear that however reliable photogrammetry may be for metric accuracy, it could never match the detailed surface modelling that was possible using the cloud of points produced by a laser scanner. This was especially true for the first main application area i.e. that of Malta's megalithic temples. These offer a mix of a large number of regular and irregular shaped stones as the main constituents of the building fabric with a stone surface often richly textured due to weathering and erosion. What MCR should be looking for therefore was a system that combined together the best of both worlds, the speed and detail of the laser scanner with the metric accuracy of digital photogrammetry.

These functional specifications were also necessary since the MCR's client wished that the survey was non-task specific i.e.of

1 J.-A. Beraldin, G.Guidi, S.Ciofi & C. Atzeni, Improvement of Metric Accuracy of Digital 3D through Digital Photogrammetry. A case study: Donatello's Maddalena, http://www.vit.iit.nrc.ca/References/NRC-44911.pdf

2 "Stitching" denotes the assembly, automated or manual, of several single scans of a site or an object to produce one single 3D model of a large site or artefact.

the highest resolution and quality possible in order that it could be re-utilised and data restituted at various later stages for various purposes, including the on-going monitoring of the sites. Thus the metric accuracy had to be very high as was also the quality of the photogrammetry and the surface detailing using laser scanning.

The MCR's 3DID team was naturally aware that before digital photogrammetry came into existence, surveyors had used theodolites to provide an accurate reference measurement lattice within which conventional film-based photogrammetry could be utilised within acceptable metric error levels. A Theodolite Total station registers 3 dimensional co-ordinates and is the only tool that offers the possibility of maintaining overall precision by using a closed-network system. This data can be read up to an accuracy of 0.1mm. The Theodolite Total station is not designed for creating virtual surfaces and contours, as are photogrammetry and laser scanning. However, as the most precise instrument of the three mentioned, the co-ordinates gathered from the theodolite total station may be used to consolidate all the data generated by the other surveying tools The 3DID team therefore resolved to use a theodolite to achieve five objectives:

a) To create a closed network providing an accurate framework against which the digital photogrammetry could be tacked on and measured

b) To set-up a one-stop target regime that can be utilised by both photogrammetry and laser scanning ;

c) To laser scan the temple site using the same targets left in an identical position when previously used by the theodolite and the digital photogrammetry.

d) To take the results produced independently by the digital photogrammetry and the laser scanning at the data acquisition stage and "marry" these results into one integrated and composite image where the outlines are largely produced using photogrammetry and the detailed surface imaging is produced using laser scanning

e) To compare the results of the stitching of the laser scans by the restitution software with those obtained by photogrammetry in order to assess the levels of accuracy obtainable by the different systems independently;

Thus the concept of ***Thealasermetry***[3] was born: instead of using two devices in synch[4] as proposed by Beraldin et. al., 3DID opted for 3 classes of device used in conjunction – theodolite, laser scanner and digital photogrammetry. The MCR team also opted to run a series of tests in pilot sites in order to identify other difficulties, strengths and weaknesses of the different classes of devices being employed.

The ***Thealasermetry*** experiment was organised in the following stages:

1. A sample survey at various grades of resolution of part of the Ggantija temples in Gozo (December 2001) was undertaken to test the data acquisition capabilities of MCR's SOISIC LG scanner and the restitution (including stitching) abilities of MENSI's 3D IPSOS Software;
2. A sample digital photogrammetrical survey(January 2002) was carried out on the same part of the Ggantija temples which had also been subject to a laser scan, thus providing the basic data which would enable a test marriage between the laser scan data and the photogrammetric data;
3. A sample laser scan at high resolution was carried out on the Tarxien Temple altar at the National Musuem of Archaeology in Malta (December 2001) in order to measure the MENSI LG SOISIC scanner's accuracy on an object which is roughly the same size as that use for the Beraldin case study;
4. A sample laser scan at various grades of resolution was carried out on a non-megalithic monument (the crypt of St. John's Co-Cathedral in Malta) in order to evaluate other system limitations that may be learned from different type of architectural/archaeological applications;
5. A sample laser scan at various grades of resolution was carried out at the San Salvatore Church in Kalkara (January 2002) in order to test operational advantages between the MENSI LG SOISIC (plane triangulation) laser scanner and the MENSI NG 100 time-of-flight laser scanner in preparation for the Temples Survey Project;
6. A small-scale integration test was undertaken (March 2002) combining photogrammetric data and laser scan data obtained from Ggantija, using the vector outlines obtained from photgrammetry and the data from laser scanning to provide the in-fill between the outlines;
7. A sample combined survey was carried out at a portion of Tarxien Temples in Malta (June 2002) using the following systems in combination:
   a. Spheres with an integrated prism capable of being used as a target by both the theodolite and the laser scanner in quick succession without their being moved in the process;
   b. Theodolite Total Station to provide framework within which to integrate data from digital photogrammetry and laser scanner;
   c. SOISIC LG Laser scanner to work in areas with range 2m-5m;
   d. SOISIC NG Laser scanner to carry out fast scans to compare results with those obtained from SOISIC LG;
   e. Nikon D1 digital camera to provide digital photogrammetry data for back-office integration and restitution process;
8. A large scale integration test of the data captured during stage 7 was carried out (June 2002) using DIAP and 3D Ipsos software in order to repeat the successful integration test carried out at stage 6 but this time on a larger scale and with a clear view to minimising metric propagation error having used the ***Thealasermetry*** process Stages 1 to 6 have been successfully completed and will be fully reported upon in this paper while parts of stages 7 & 8 were still work-in progress at the time of going to press but will be completed – and reported upon by the time the paper is due to be presented at the September 2002 Corfu workshop.

3 The reasons for coining the word Theodolite in have been lost in the mists of time vide Alasdair Downes Q & A Theodolite http://www.quinion.com/words/qa/qa-the1.htm *Thea* (Greek for sight) is here being proposed together with *lasermetry* since all 3 systems are line-of-sight systems and many modern Total Station Theodolites employ laser range-finding systems too.

4 I.e. a digital camera and a 3D range camera

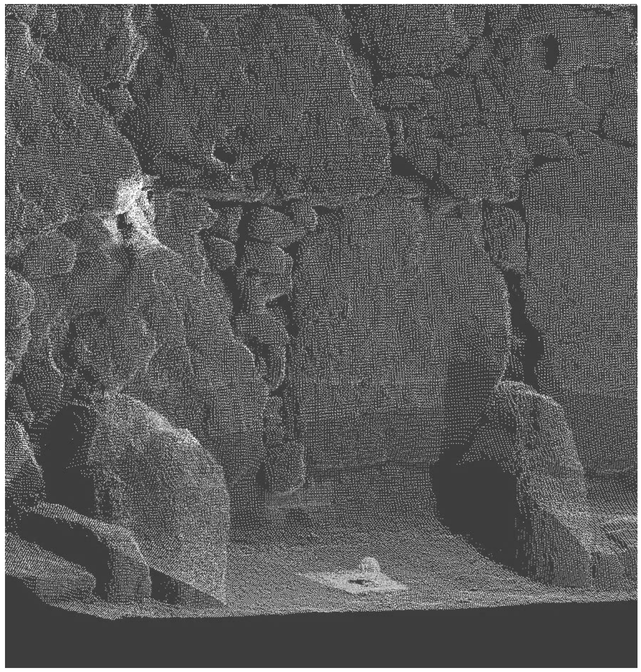

Fig. 1 Masking produces shadow effect

2. 3D Data Collection and Imaging Systems for Documentation

The various systems used in the *Thealasermetry* trials are outlined below:

Prior to embarking on the testing in pilot sites, a decision also had to be taken with regard to the type of digital camera to be employed. The MCR's 2D Imaging Department had been in existence since 1999 and was originally equipped with at least one eye firmly fixed on the option of going completely digital. It had at its disposal anything from a Nikon Coolpix 950 to a Nikon D1 to a Hasselblad 550 equipped with a Megavision S1 back. Constant experimentation with digital photography, including over 4000 images shot with a SONY Cybershot DSC-70, appeared to *prima facie* confirm the findings of Beraldin et al when they reported that the use of a low-cost Digital Camera was satisfactory[5] Thus, although MCR was due to procure at least two other digital backs ranging from 96 Mb file size with 4,000 x 4,000 resolution (medium format) to 549 MB file size with up to 12,000 x 15,990 resolution (large format), it was not deemed necessary to await the availability of such equipment for the tests on the *Thealasermetry* hypothesis. The resolution possible from any one of the smaller format digital cameras available appeared to be more than sufficient for the outline rendition required to test metric accuracy.

In close range **photogrammetry**,[6] digital cameras can offer the precision of analogue cameras, and today it is claimed that the latest generation backs for large format cameras can provide even more detail in the same shot for the same area than a conventional 5 x 4 inch film.[7] In our experiment we compensated for the fact that we used a 35mm size camera and not a medium or large format by shooting more digital stereopairs, and adding more control points. This is a satisfactory approach for the integration exercise envisaged in stages 2 and 6 outlined above but would possibly increase propagation error when completing stage 8.

In our sample photogrammetric survey we opted for a Nikon D1 digital camera. The features of this camera include:

- 2.74 mega pixel digital
- (24mm x 16mm format back)
- with a 24mm lens camera
- Manual Exposure Control

This camera offers the possibility of shooting restricted areas with little stand-off distance. In comprehensive survey projects however, it is planned to later mostly use (where distance permits) a digital back for a 5 x 4 inch camera capable of producing up to 549 megabit files of data per shot.

For the control of the orientation and integration of the extra stereo models required when carrying out data acquisition with the Nikon D1, the Theodolite Total Station surveyed photo-control becomes more important.

MCR's strategy for 3D laser imaging finally settled on procuring a minimum of 4 different systems:

5 BERALDIN, GUIDI op.cit at pages 1 and 2

6 Photogrammetry allows the user to produce very accurate outlines in 3 dimensional polygons. Lines and points can also be 'traced' with a cursor across the surface of the model derived from the stereopairs. As the line drawing is made by the operator, tracing complex surfaces, such as eroded stone, can be a long process

7 www.digital-photography.org

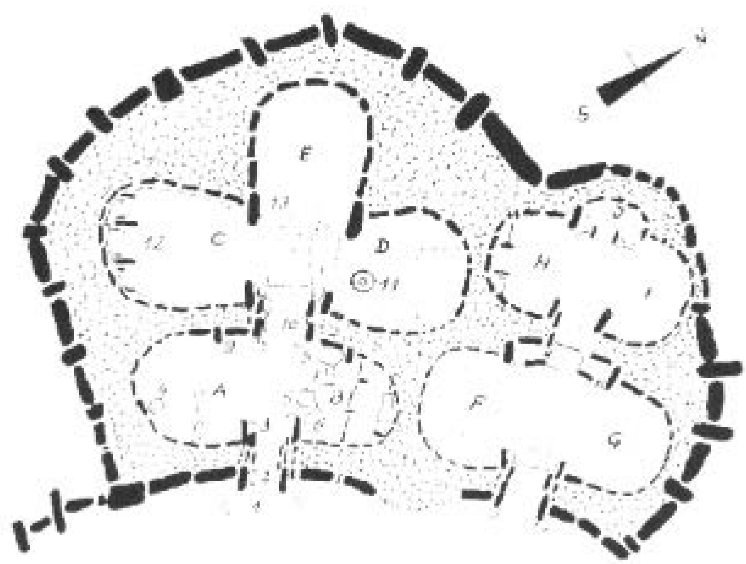

Fig. 2 Plan of Ggantija Temples, Gozo (Malta)

i. a long-range scanner for architectural applications where an accuracy range of 2-4 mm is admissible;
ii. a medium-range scanner for close-range architectural applications and scanning of artefacts such as statues and vases with an accuracy range of better than 1mm (in practice an accuracy of up to 300 microns appears to have been achieved);
iii. a short-range scanner with an accuracy rating of better than 100 microns for scanning of surface detail of items like archaeological small artefacts such as coins;
iv. a very short-range scanner with an accuracy capable of measuring the smallest possible variations - typically on a paint surface;

The procurement process resulted in MENSI of France being selected for provision of both the long-range and the medium range scanners. The choice of the other two systems is still under consideration.

In our initial survey (Stage 1) 3DID used the **Soisic LG scanner**[8] from Mensi which operates on a plane triangulation principle. This is a medium range scanner and operates at a range of 2m up to 20m. This instrument has a quoted standard deviation of 0.6mm at 5 meters range, but this value decreases to 9.6mm at 20 meters. To ensure maximum accuracy, scans were taken at a distance of 2m to 5m. The scanner was set at vertical and horizontal positions in order for the camera and laser beam to record the stone surface, and to avoid parts of the temple itself 'masking' the surface being scanned.

The margin of error of up to 0.6mm of the instrument can result in an error propagation, and as a result there is the risk that the points gathered from different viewpoints do not consolidate into a complete virtual structure.

At a human level one disadvantage of the Soisic LG is that, despite its very high accuracy when compared to most other laser scanners, it only scans in low-light conditions, therefore in this case the scanning of the temple could only take place at night. Scanning with a tight grid is also time-consuming.

The option of using this scanner was taken in order to record as much surface detail of the eroded stone as possible. However, should the amount of information needed about surface texture not have been a priority for the aim of the survey, we would have opted to use MCR's long range scanner The NG range scanner from Mensi is a time-of-flight technology machine which is many times faster and more accurate at a distance than the SOISIC LG. 3DID was fortunate to have an NG prototype available for testing purposes even before it took delivery of the production version of the NG system.[9]

These data acquisition systems systems in the field are backed by seven workstations for back-office restitution and other post-processing within 3DID. Five 1.6GHz Compaq workstations equipped with 1Gb RAM, Wildcat video cards and a Sony 24

8 The **laser scanning** system records 3 dimensional co-ordinates that are presented as thousands and millions of points. Multiple scans are taken from different viewpoints creating a 3 dimensional mosaic of the object.
From the cloud of points, a mesh can be created through triangulation. This process gives a solid surface to the points. The mesh can be given a photo-real surface through texture mapping. Segmentation and gathering detailed measurements from the mesh permit the creation of sectional elevations and plans. From all three systems mentioned here, laser scanning gives the most surface detail, however, it does not give the necessary data to realise object outlines. Furthermore, although it is possible to take digital photographs with the integrated camera, the resolution is lower than may be desired for texture mapping

9 The long-range scanner presents different problems to the medium range machine especially when it comes to aiming at targets which can afterwards be used for stitching purposes at the post-processing restitution phase. It is not easy to aim at small targets from a distance. As stated above, the dual-purpose target issue was settled by using spheres which integrate prisms which permit the target to be used by a theodolite as well as by a laser scanner;

Fig. 3 Megalith scan assembled from three view points

inch 100Hz scan monitor run MENSI's proprietary 3DIPSOS software which is used primarily for laser scanning restitution. Two other Compaq workstations, also with 1.6Ghz processor and 1 Gb RAM but equipped with MATROX graphics cards driving two Sony 24 inch monitors apiece run the Microstation and DIAP family of Products from ISM which permits all the digital photogrammetry post-processing required by 3DID.

3 The Development of the hybrid system: marrying laser scanning and photogrammetry to overcome the defects of either system

The hybrid system has come about through our experiences with the 3D imaging systems described above: Table 1 summarizes the strengths and weaknesses of these 2 systems which we gathered from 3DID's experiences with the three systems. This section will further expand on this table with the aid of illustrations from projects carried out by3DID. We have taken as our primary case study, a sample survey of 3 apses and part of the façade from *Ggantija*, a megalithic temple structure in Gozo. Ggantija in fact provided the data both for laser scanning and digital photogrammetry that was successfully integrated in March 2002. (Stage 6 above) .

Ggantija is a large temple complex at the ridge of one of the largest plateaus on the island of Gozo. As we can see in **figure a**, it consists of 10 apses. It is made up of great slabs of Coraline stone which span several feet in length and height. For a sample survey using by laser scanning, our concern was to establish a suitable grid to achieve a good representation of the surface of the stone, thus establishing the level of data the scanner could provide for monitoring the erosion of the stone. Secondly, we needed to establish whether the data provided by the scanner would be sufficiently precise to monitor the movement of the stone, thus acting as a reference if any stones were to collapse.

3.1 Speed & detail obtained by laser scan

Scans of Ggantija were taken from different viewpoints. The temple proved to be relatively difficult to scan as it has many cavities that are not easily accessible to a laser scanner. Entry to many parts was only possible through additional scans and some openings. On the other hand, the level of detail provided by the SOISIC LG proved to be highly impressive. **Figure 3** is a megalith from the temple that was scanned. The different colours represent the three different viewpoints from which it was scanned and highlight how a surface is mosaiced together so as to create the whole visible form.. It is planned that the entire temple structure would later be scanned from different viewpoints and consolidated later using 3D Ipsos and/or Diap software.

Total number of points collected in this first stage were: 2,496,832 over two nights, with an average grid of 2mm at an average distance of 3.0 metres.[10]

In terms of 3D data collection, the laser scanner is impressive in the amount of surface data which is collected in such a short period of time. This means that the human hours involved are a fraction of what it would take any other system in processing collected data in order to display a 3D surface at such accuracy. Figure 4 below demonstrates the level of detail obtained.

10 There were areas where the grid was reduced to 0.3 mm thanks to the overlap between one scan and th eother

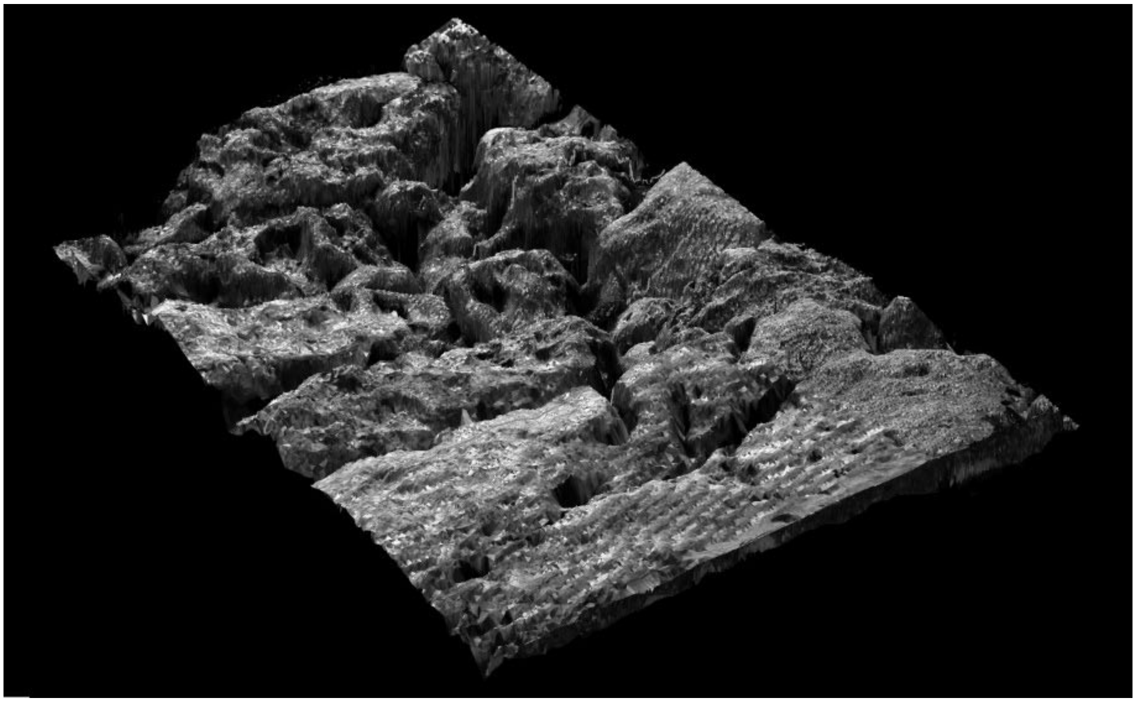

Fig. 4 Isometric view of stone surface (obtained solely from laser scan data)

Fig. 5 Negligible propagation error on smaller objects – Tarxien Temple altar

Having said this, we need to recognise the laser scanner's limitations in data collection. The SOISIC LG scanner utilised is unable to register points within a space of less than 2m. In order to collect 3D information from tight spaces it is necessary to use a different system, such as a short-range laser scanner [11]or by taking stereopairs.

3.2 Metric error propagation for large vs. small objects

In post-processing the data the following observations could be made. An important problem that was incurred, and which was partly due to largeness of the structure/site, was that the metric error (0.6mm) was multiplied when consolidating the large number of viewpoints. As a consequence, the viewpoints taken at this stage do not consolidate properly into one structure[12]. It must be noted, however, that the error can be avoided if a primary viewpoint can be taken which contains most of the target spheres that will then form part of individual viewpoints. This can easily be done with relatively small objects. For example, in the case of the Tarxien Temple altar (H167cm x W128cm x D180cm) at the Malta Museum of Archaeology (Stage 3 - **see Figure 5**), the metric error propagation was negligible when tape and known measurements were compared with the scanned data. In the case of Ggantija temple, a primary viewpoint containing a sufficient number of spheres could be attained within one or at best between two opposite apses, however, this would not be possible for the temple as a whole.

3.3 Lack of clarity in outline forms obtained through laser scans

Although the laser scanner gives very rich surface detail, it does not provide sufficient data to construct the clearest outline possible of the object scanned. This becomes more evident where lines in reality are clearly defined, such as in the following example from a laser scan of St John's Cathedral's crypt, Malta (Stage 4).

It is immediately noticeable that the collection of surface data from the laser is relatively easy. Obtaining such a number of points at a grid of 2mm is no mean feat. All this data was collected in a period of two nights. Considering the amount of data collected, there were relatively very few human hours involved. This statement is made in relative terms when comparing the results of the laser scan to the post-processing work required by photogrammetry, in which it is very tedious to collect all data on the surface in order to produce the mesh/3d model. Photogrammetrical restitution is also very time consuming and its accuracy is very much dependent on the capability of the operator.

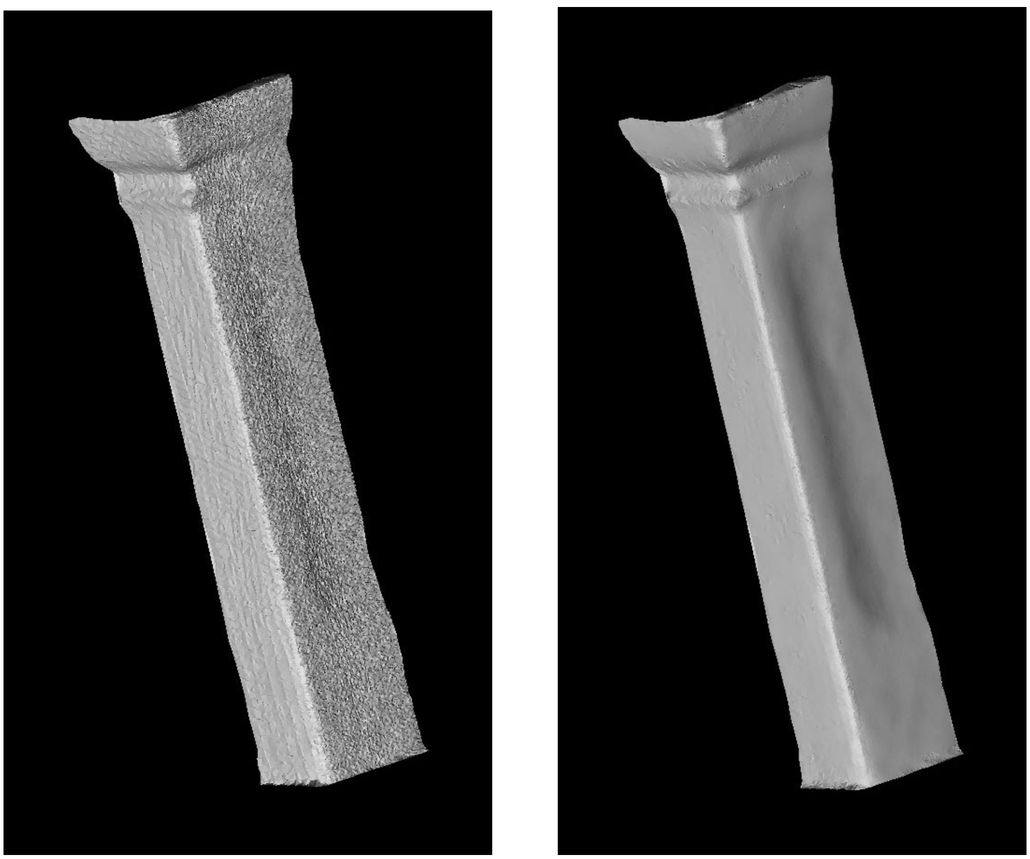

Fig. 6 Outlines in laser scanned data are not clearly defined even when smoothening (right) technique is applied

11 MCR was considering options from MINOLTA and OPTRONICS for such purposes

12 It will be noted that at this early experimental stage no theodolite total station was used but instead the 3DID team relied totally on the sphere targets provided by MENSI

3.4 Consolidation of cloud points

Consolidation of the cloud of points obtained by the laser scan from different viewpoints is also relatively immediate (provided the sphere targets are used). A cloud of points model rendered the temple immediately identifiable. Once consolidated however, an interesting issue arose at the meshing stage. The additional points produced at the juncture where scans overlap need to be removed through the spatial filtering command[13] otherwise homogeneity will not be obtained. Indeed, if a 2mm grid resolution is required, then such a grid has to be chosen at the outset.

*3.5 (At least) Two ways of meshing laser scan data***.**

The 3D Ipsos software has two methods of meshing available to the user: automatic or by projection. The use of a mesh to surface the scan data may result in small holes where data has not been captured, for example where reflectance is low or where practical issues prohibit satisfactory coverage. This occurs when 'Automatic Computation of a mesh' is used to triangulate a complete cloud of points. However, this method is only really effective when the cloud of points is sufficiently dense and homogenous (See Fig. 8). In the meshing triangulation by projection method, no holes are created because all the available points are computed in the mesh. This seems to result in an advantage However if a hole exists in reality, it will be filled up also. It often occurs that it is very difficult to decipher the filled holes from those holes which exist in reality.

3.6 Problems with texture mapping

When it came to texture mapping, certain problems were evident. The integrated camera of the Mensi Soisic LG scanner has a relatively low resolution since its primary function at design stage was evidently merely that of an aiming device as opposed to a recording mechanism. The SOISIC LG scanner has to be used in low light, almost darkness, while the camera requires

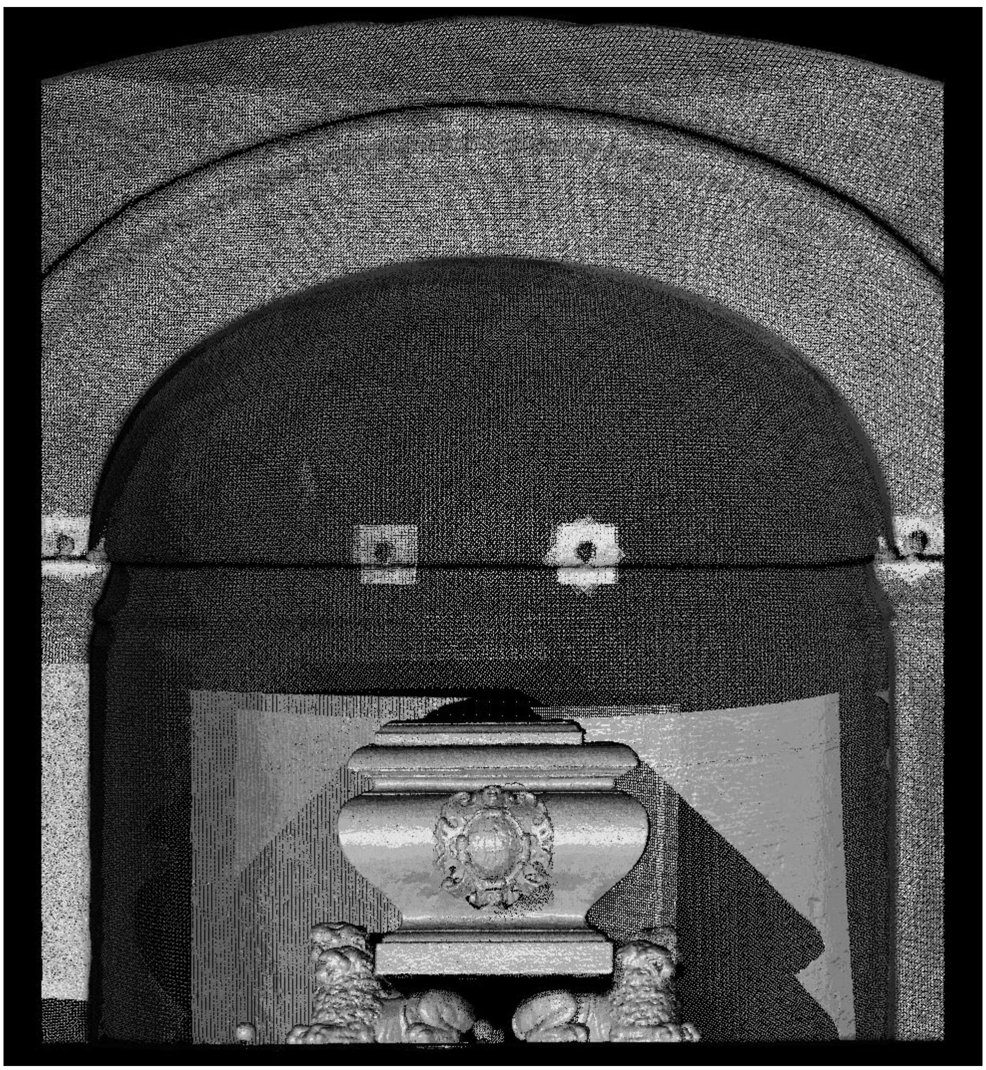

Fig. 7 Overlapping of points from different scans produces relief to right of tomb

13 available in both the 3DIPSOS and DIAP TIN software

light, which, in practice, proves to be quite a contradiction on an external site. For texture mapping to be possible at post-processing stage, the digital photos must be taken from exactly the same position as the laser scan. Thus, if one wishes to use the integrated camera for texture mapping the laser scanner cannot be shifted till daytime otherwise the texture mapping cannot be automatic.

Unless *Thealasermetry* is used, the alternative would be to add 3-dimensional targets with an identifiable point (eg. pyramids). This would add even more targets to the other targets (cross hairs & spheres) but would enable the laser scanning and the digital photography to take place at different times provided the targets are left in place.

3.7 Using Laser Scan data to complement digital photgrammetry techniques

The MCR's field and lab trials thus confirmed a number of problems that the two technologies posed and suggested some methods of using one technology to complement the other. In summary:

i. Digital photogrammetry is more accurate in outline rendition and, subject to reference measurement control using a theodolite on a large site, is capable of providing a framework where metric error popagation is reduced to a minimum;

Fig. 8 Detail (Fig.7): denser cloud of points produces smoother surface when meshed

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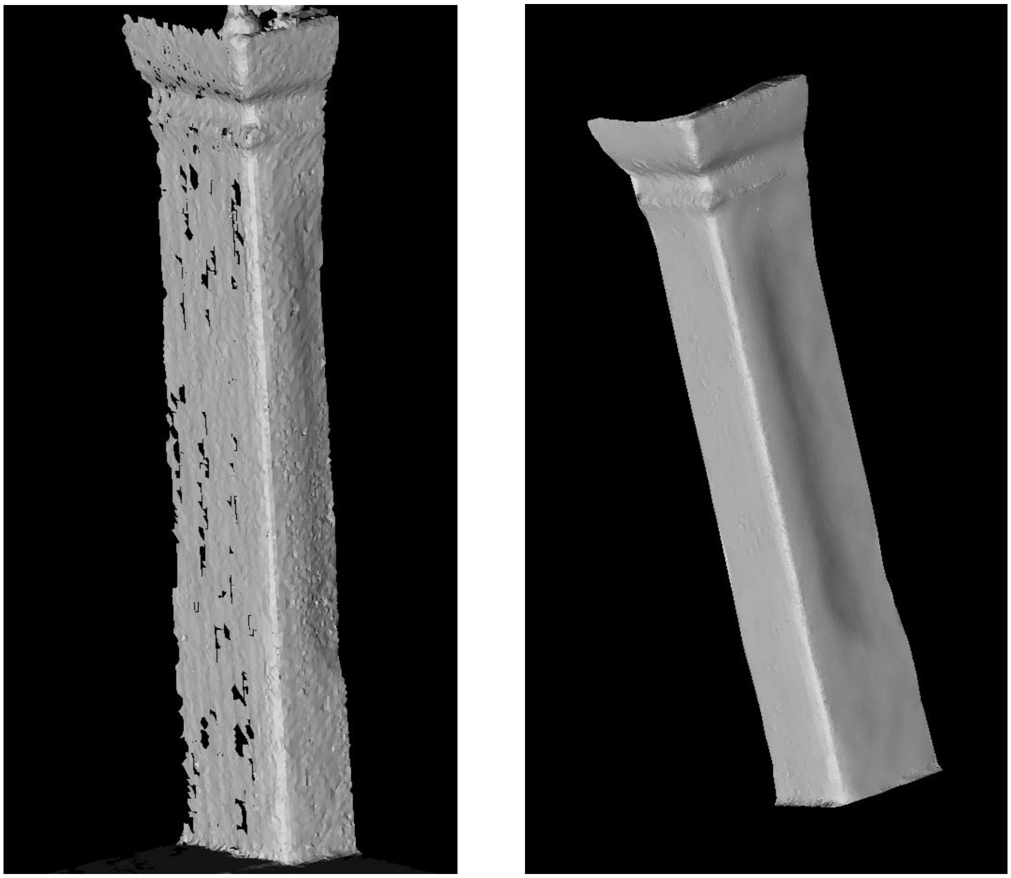

Fig. 9 Problems encountered in automatic meshing (left) and by projection right

Fig. 10 View of the apses scanned at Ggantija Temples (Stage 1)

ii. Laser scanning is far more accurate and many times faster than digital photogrammetry in providing surface detail of stones in archaeological and architectural applications than digital photogrammetry. Both the data acquisition and the restitution phases in laser scanning are much faster and more accurate than the comparable process in digital photogrammetry (or conventional photogrammetry for that matter).

These findings suggested to 3DID that the best way forward would be to develop a hybrid approach wherein the outlines are produced using digital photogrammetry and then these could be filled in with much richer data obtained through laser scanning.

4. Thealasermetry methodology

4.1 Identifying client needs and functional specifications

The hybrid approach combining theodolite, laser scanning and digital photogrammetry was developed to try and get the best of all worlds into one integrated approach. From the above observations in the field and the post-processing laboratory it is important to note that, as ever, the surveyor must be careful to identify exactly what the client requires i.e. what the ultimate functional specifications of the survey are to be. As has been seen, some surveys would require maximum detail about surface texture of the stone, thus mandating the use of a certain type of laser scanner. Other surveys would not give such priority to surface texture and, especially in the case of large architectural sites, would mandate the use of another type of laser scanner.

4.2 Two key elements of Thealasermetry: common reference points & data transfer capability

Early on in the process 3DID identified two key elements required to successfully marry laser scanning and digital photogrammetry in a way which would enable the one to best complement the other:

i. The approach must be able to use as many common reference points as possible which can be recognized by all of the three technologies employed: theodolite, photgrammetry and laser scanner.
ii. The team must be able to transfer data produced by one technology to the other

4.3 A step-by-step process for the hybrid approach

1) The first and most crucial step is the establishment and use of the same reference points for the laser scanner and the theodolite total station, so that common co-ordinates will tie different scans together. The theodolite total station co-ordinates are used as the binding factor for the consolidation of all the data gathered from the three systems. Therefore, these co-ordinates are used as the reference points for the control markers used for the photogrammetry and laser scanning during the data acquisition phase.

2) Data acquisition by all three systems, (theodolite, laser scanner and photogrammetry), is followed by the second step which is that of consolidating data sets from two different sources. The 3DID documentation specialist currently has a choice: either to combine the photogrammetry co-ordinates system into the laser restitution software (3D Ipsos) or inserti the laser co-ordinates system into the photogrammetry software (DIAP).

3) The third step is that of creating a triangulated surface out of the point cloud data obtained as a result of the laser scan. This process, known as meshing, is a representation of a surface, where points are linked together to form a solid surface. Both 3DIPSOS and DIAP have meshing functions with different levels of automation available.

4) The fourth step is that of using the photogrammetry software (DIAP) to create outlines of different stones using the stereo paired digital photographs.

5) The fifth step is to import lines drawn with photogrammetry software to 3D IPSOS (the laser scanner restitution software) – outlines are easily identifiable by using the stereo pairs. The outlines imported/exported from the photogrammetry software enable the user to recognise the objects true line. With the outline, errant triangles created at the meshing stage can be deleted.

6) The sixth step is texture mapping (if required at specification stage). The computer model is rendered to give it a realistic and solid look. At this stage, the documentation specialist can also choose digital pictures taken by the laser scanner's built-in digital camera or digital pictures taken at a higher resolution during the photogrammetry data acquisition process in order to use these to paste on to his computer model in order to enhance the realistic appearance of the final result.

5. Experimental Results and Conclusions: From a hybrid approach to hybrid machines

In summary therefore, the theodolite total station's co-ordinates are taken as the first 'viewpoint'. Using this system, the laser scan viewpoints can be consolidated within the total station's closed-network. Using the common set of co-ordinates to restitute the photogrammetric stereopairs, very accurate outline drawings can be obtained. The results obtained from the different processes are merged into one system. This allows the triangulation of the laser scanning points to be modelled within the vector outlines estimated using the photogrammetric stereopairs.The same photographs used for the photogrammetry can be directly utilized for texture mapping of the integrated data. Having the photographs directly linked to the total station, ensures that this process is completed with the maximum accuracy and ease possible. Overall, the expected object precision can achieve +/-1mm. Such a system offers an important archive which can enable closer monitoring of these sites

The above process has meant that 3DID can now save more than 50% of the time normally spent on back-office post-processing tasks on digital photogrammetry since this aspect can now be restricted to main outline drawing whereas the internal detail is filled up much faster and to a degree of detail hitherto undreamt of by using the data obtained from the laser scanner. Using a laser scanner as part of a hybrid approach has therefore truly complemented photogrammetry but the level of development of the technology to date does not enable laser scanning to replace photogrammetry completely due to the inaccuracies indicated in various sections above.

It is not impossible however to foresee a level of development where a hybrid approach such as *Thealasermetry* is made almost redundant by improvements in the laser scanner package. It should be technically possible to achieve the following improvements:

A) Upgrade the laser scanner's level of precision at both data collection and restitution stages in order to produce accurate lines and outlines;

B) Up grade the laser scanner's built-in digital camera to a high-resolution capability minimum 5 megapixels but ideally 12,000 x 16,000 pixels;

C) Build-in a theodolite total station function into the same box as the laser scanner rendering it a hybrid machine – and thus integrating the hybrid approach into the very design of the system;

D) Developing targets which can be used by all three systems;

E) Develop the post-acquisition restitution software with a more refined algorithm capable of handling large objects/sites consisting of over 100 million points while at the same time having an advanced pattern/form-recognition function (possibly using an extensive library) which would permit automatic identification of fprms at the consolidation stage.

These developments should be technically (and economically) within reach over the next 5-10 years and would result in a single portable package which would enable the laser scanner cum high-reolution camera cum theodolite to supplant photogrammetry in most but not necessarily all cases of on-site documentation in the cultural heritage sector.

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LASER SCANNING AND TRADITIONAL SURVEY INTEGRATION TO BUILD A COMPLETE 3D DIGITAL MODEL OF "SAGRESTIA DELL'ARCHIVIO DI STATO A MANTOVA"

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KEY WORDS: Laser scanning, digital model, cultural heritage recording

ABSTRACT:

The main tasks of this work consisted of the look for an integration between methods of traditional survey and laser scanning technique in the 3D architectures survey.
The intentions to build a model that is able to satisfy the demands of precision, for example, to planning an intervention of recovery and therefore to editing architectural plates, but also those of aesthetical quality and representative effectiveness, they have conditioned the choices that have driven this work. In other words has been estimated the effectiveness and the potentialities of this new survey method , which in this case was supported and assisted with traditional methods that have also allowed to test the model obtained from laser scanner.
During this work we have realized how this new method of survey, that allows a quick acquisition of million points, that allows the description of even very complex geometries, imposes many evaluations beginning from the fitter tool until the choice of target points and about the method of textures mapping, which are very important for the quality of final digital model.

1. INTRODUCTION

The Sacristy of State archives in Mantova, is an architecture that allows to appraise the effectiveness of this integration: inside the Sacristy there are many decorations and plasters that would require a long and hard-working traditional survey. The Sacristy has an octagonal plant, 15 meters high and about 12 meters wide.
There are many ways of creating 3D model of a building and many technologies can be employed to record the spatial and visual complexity of real word environments. The work described in this paper, wants to underline the necessity to integrate these different techonolgies to optimize the costs, accuracy and visual quality of the final 3D model. Another important thing is the approach to create a complete 3D not limited to an internal or anyway partial reconstruction but a full 3D composed from an internal end external surface to create the as completed as possible representation. In this way is also possible to give a more realistic perception about the building volumes.
The 3D model obteined is not only a photo-realistic representation of the reality building but is also dimensionally rigorous so it has also an important metric value which makes it a powerful tool of investigation and study of the architecture.
Is important to underline how from such product is possible to obtain a series of graphic useful results for the planning and design of interventions to the building safeguard.

2. LASER SCANNING SURVEY

The laser scanning survey was made with *Cyrax 2500* laser sensor, that has single point accuracy equal to ± 6mm. The scanning procedure took up 1 working day, using 15 different viewpoints. In some of these the scanner was mounted on a tri-pod while for the other it was just leaned on the floor. The scanning survey has been articulated in the follow steps.

- Planning the distribution of laser viewpoints.
- Laser data acquisition.
- Images acquisition by digital camera.
- Scans merging and orientation in an absolute reference system.
- Meshing to produce a triangulated 3D.
- Editing operations on the 3D model.
- Texturing the photograph images on the geometric model.

In the most cases it is not possible to have complete 3D representation from data acquired at a single viewpoint. Indeed, to resolve occlusions in the scene or to reconstruct large scenes, it is required to have 3D data acquired from multiple viewpoints. So it was necessary to locate the sensor at several positions inside the sacristy, since all surfaces may no be visible from a single point or will data be acquired at sufficient resolution.
The problem of determining the next capture point depends on how much a priori information about the scene is available. The selection of the next capture point should consider both the resolving occlusions in the already extracted model and the acquiring additional views of the non-modelled environment. The latter are required to have a sufficient overlapping region between two scans so to aim their integration. Is easy to see that the quality of the final model depends highly from the planning strategy and in particular from the distribution of the viewpoints inside the architecture. Another important thing to consider is that the number of these points, from where the data is acquired, should be minimised to reduce the time needed for a complete scene reconstrucion. These considerations are important also for the points where photograph images are taked. The problem to chose the viewpoints position represent an important phase of the survey, in particular for a complex architecture like this one. Recently have been proposed some algorithms that allows to determine the best viewpoints position considering many

scanning parameters (occlusion detection, accuracy, time optimisation...)
All these reasons underline how is important to use digital instruments during the survey that allow to verify on the field, in real time, the data transferred on a portable PC and evaluating the best position of the point of view for the next scan or intensity image acquisition.

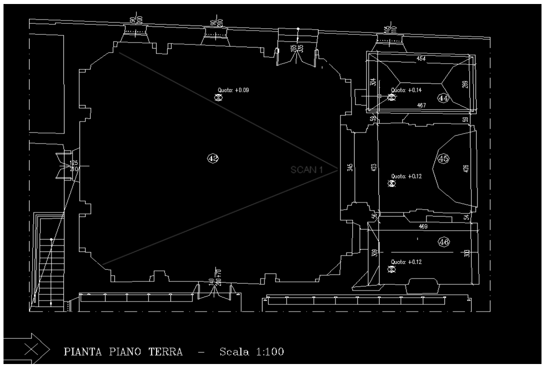


Figure 1. Scan field of view on sacresty plan.

The distance, between the center of the sensor and the points on the surfaces, has remains between 10 and 15 meters, so considering that the laser mesh was composed from 1000x1000 points with an aperture of 40°x40°, the distance between the points, in the cloud that describes the 3D model, result included between 1cm and 1,5cm. The whole process of evaluation to create a 3D model took about 7 days, fairly divided between geometrical mesh construction and textures application.
A reconstruction algorithm based on polygonal meshes was used to produce a triangulated model.

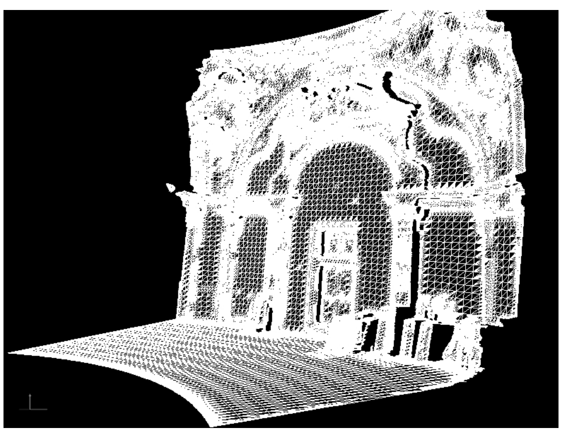


Figure 2. Triangulated model of a scan.

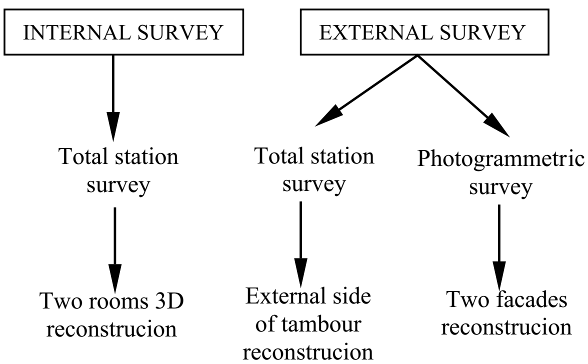
To map the texture upon the surface covered from a single scan, has been necessary two photographic images taked from a position close to the laser scanner viewpoint. The digital camera adopted is *CANON Powershot PRO 90 IS* with CCD 3,34 Mpixel sensor.
One possible solution for determining the relationship between range and color images is through calibration using the calibration board and fixtures. However, this method requires that the range and color sensors be fixed on the fixture once the relationship is calibrated. But usually a color camera is much handier than a range sensor so is better to take color images freely without having to transport a heavy and fragile range sensor.
As side product of range images, range sensor often provide reflectance images that represent a collection of the strenght of returned laser energy at each pixel. This image is aligned with the range image because both images are obtained through the

Figure 3. Reflectance image of a scan.

same receiving optical device, in other words reflectance and range data are fully registered, considering they both originate with the same echoed laser. The returned timing provides a depth measurement, while the returned strength provides a reflectance measurement. A reflectance image is itself an image of the scene and can be matched to any other image such as photographic images.
Our range sensor *Cyrax* provide reflectance image, so we decided to employ this image as a vehicle for the alignment of range images with intensity images.
Reflectance images are similar to intensity images in that both images are somehow related by surface roughness. Since the reflectance image is aligned with the range image, so to align the reflectance image with the intensity image is much easer task than that aligning the range image with the intensity image.
Corrispondences between the reflectance and the digital images are computed using a semi-automatic system, that align extracted features (edges or points) from reflectance images with those in intensity images. It is possible to guide the system by adding extra points and find further corrispondences. These edges are easy to find in the intensity images, since they are generates from a boundary between two different colors or materials that generates a discontinuity of reflectance. Thus, this method allows to align 3D points on range surfaces with 2D points in the intensity images. This is very flexible in that it allows the model to be texture-mapped using an image taken with any camera, at any time (even historic images can be uesed), from any location. The software used to process the laser scanner data is *RECONSTRUCTOR* realized by 3Dveritas.

Figure 4. 3D edges extraxted from reflectance image.

3. TRADITIONAL SURVEY



3.1 Photogrammetric Survey

For large planar and regular surfaces, like the external two façades of the sacristy, photogrammetric single image techniques has been considered the best solution. It combines true scale geometric measurements with full image information under quite inexpensive instrumentation costs. To make this survey 22 images and 40 control points were needed. The software used during streightening and merging operations is Rollei MSR.The result obteined at the and of this elaboration has required a small intervention of photograph retouch to eliminate sudden changes of contrast or illumination between the images.

3.2 Geometric Survey

Leica total station TPS 1103 was used during the geometry inquiry and the control points measuring for photogrammetric survey.
This instrument has permitted to survey two little rooms enclosed to the sacristy. By this technic the coordinates of many edge points has been measured and referred to the absolute system. After this, they were imported in the Autocad software, where, using the spline command, has been possible to build a three-dimensional wireframe model of the whole locals. This operation was conduced verifying the exact reconstrucion of the geometries as soon as comparing them with the drafts traced during the survey. The following step, always thtough Autocad software, was the construcion of the surfaces that have allowed to complete the reconstrucion from a vectorial point of view of the geometric model. The same procedure was followed for the external tambour side survey.
The choice to use this method instead laser scanner survey is because the geometry of these architectures was very simple and easy to register by a classical topographic instrumentation. It would be useless to describe a planar surface with a cloud of milion points. Moreover traditional survey methods have also allowed to test the 3D model obtained from laser scanner. The inner profile of a decoration along the tambour has been surveyed by both methods. The profiles extracted from two survey technics (traditional with total station TPS 1103 and laser scanning) present a maximum gap equal to 2 cm.

4. LASER SCANNING AND TRADITIONAL SURVEY INTEGRATION

For each position the scanner yelds a point cloud in the sensor coordinate system. The data sets of all the positions have to be orientated relatively to each other so that homologous points have the same coordinates. An absolute orientation can be performed if the coordinates of some object points are known. In this case on the scanned surface was present 10 signalised and measured target points. Their identification on reflecatnce images was very easy because the echos of the retro-reflective targets have much higher intensities than the surrounding area. In a second step other points were mesured to increase the data for scans orientation. These points were generally characteristic parts of the ornamentation.

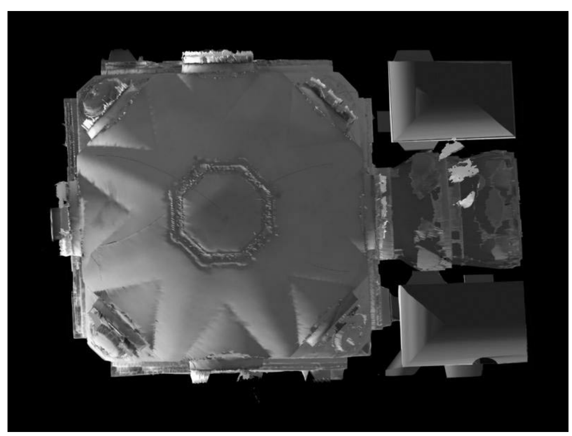


Figure 5. View of two surveys in 3D STUDIO

The 3D model of the sacristy was made from merging the 15 scans in an indipendent coordinate system and then transformed using a 3D coordinate of target points into the absolute coordinate system.

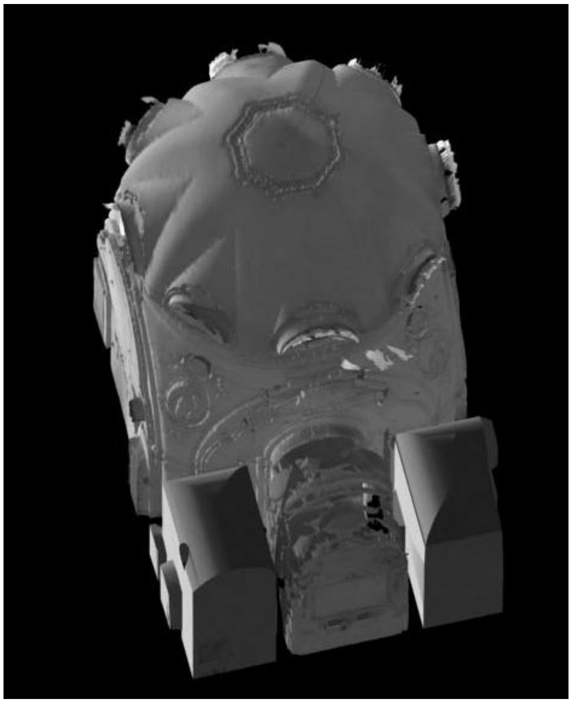


Figure 6. Perspective view of sacresty with two little rooms.

All the survey has arranged in an only one reference system rappresented from a topographical net that develops itself inside and outside the archives. Three vertexes of this net are inside the sacristy and other five around it. This has allowed:

- First of all, has been possible to refer the 3D model, that derived from the laser scanning survey, to the global reference system. That has been possible thanks to the coordinates measure of many target points with classical topographic methods.
- Then, has been possible the integration of the survey realized with laser scanner, with the reconstruction of the side small rooms. This last one has been realized with a survey made with traditional methods and reported to the global reference system.
- Besides has made the survey of the Sacristy's external surfaces, for which was used the photo-straighten technique. So the final 3D is not only an internal view of the architecture.

A topographical net is an important point to start every architectural survey, but in this case where we need to integrate data from different instruments and different technics, it assumes a particular significance. All the survey phases have been referred to an only one reference system thanks to a high precision network, measured by the University of Brescia. Every point of this net, made in 1996, has a monography with the position indicated by a picture and a sketch that allows to find it easy. Besides there are it's coordinates and those accuracies calculated by a least squares adjustment. All these informations are stored in a HTML structure into an interactive CD-ROM, that can be consulted by a common internet browser. The final 3D digital model is composed with 3D STUDIO MAX software, where have been imported all components of survey from different formats (.wrl; .bmp;.dwg.;dxf).

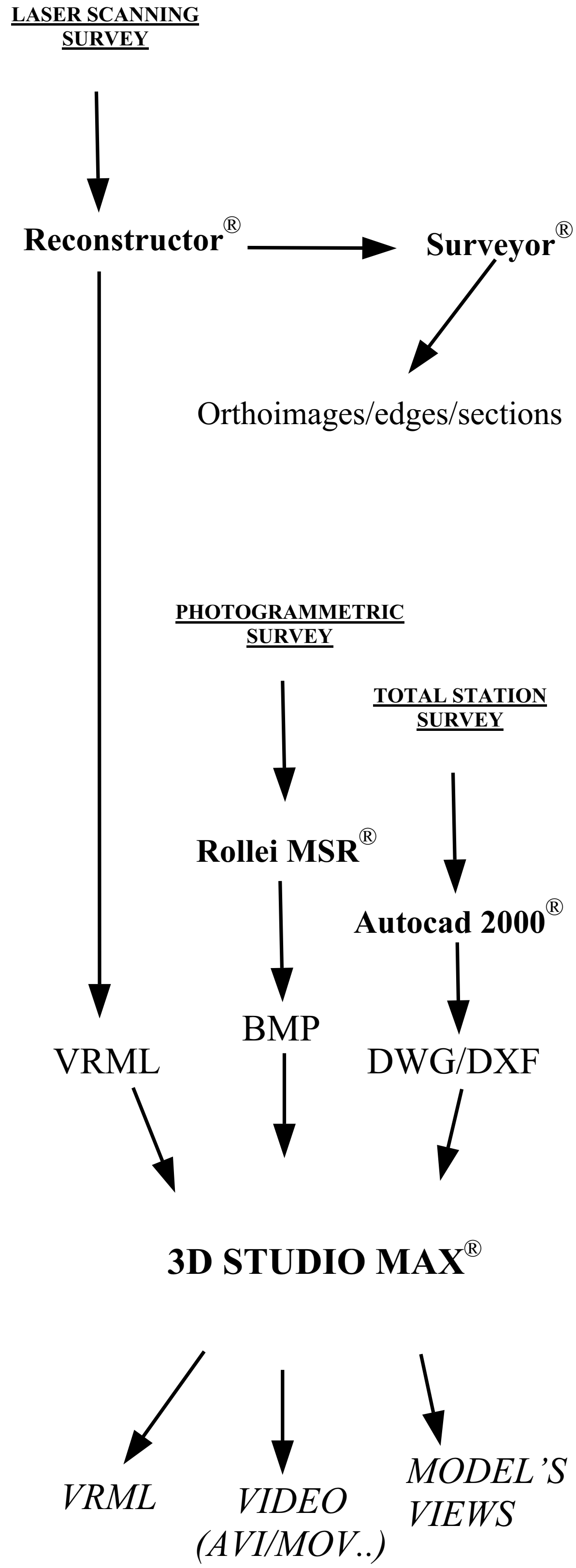


Figure 7. Chart of work procedure.

At this point has began the study about the methods of presentation and investigation of the 3D model, that could be sectioned with specifics tools to produce horizontal and vertical sections complete of orthoimages and 3D edges; otherwise it can be used as a support in the realization of a GIS or to realize a promotional multimedia CD.
An important role is assumed by new format code called VRML (Virtual Reality Modelling Language), that has been selected as the internet format to describe 3D environments. It is supported by most browsers and there are a few public demain plug-ins. VRML allows to study the 3D model in a way really interactive trough a simple instrument. Moreover, several tools, developed in java language, have also been implemented in order to demonstrate the high potential of the 3D models. These tools allow for example the meausurement of distance between points or simplify the 3D navigation by taking the user smoothly along a predefinied walkthrough.
How can be seen in the previous page chart, some important results have been obtained from laser scanning survey using *Surveyor* software. This tool allows to section 3D model and to export edges, orthoimages and section profiles. These informations can be imported in a CAD software to edit architectural plates.
3D studio software, where all the survey is stored, allows to make some interactive products like video and VRML that assume an important role for educational and promotional purposes.

5. CONCLUSIONS

This work wants to represent an example as a method of approach to the survey of a historical architecture, for which is generally very difficult find an only one investigation tool.
Instead, is more effective search for the correct compromise that integrates techniques even very different each other, but however easy to be effectively integrated in a result that covers an ample range of applications and that could be a support for technical staff, studious or simple tourists.
This work is interesting also because this place, during the XIX century, has been used as a barracks from the napoleonic army that has ransacked it and partially defaced: because of these events many decorations, particularly some capitals, has been removed. An interesting application of this survey will be the reconstruction of a comprehensive vision of the sacristy thanks to the introduction, in the virtual 3D model, the missed elements reconstructed on the base of those preserved.

6. ACKNOWLEDGEMENTS

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EXPERIENCES WITH LASER SCANNING AT i3mainz

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KEY WORDS: Architecture, Cultural Heritage, Laser Scanning, Scanner, Software, Modelling

ABSTRACT:

Since a year and a half i3mainz uses scanners for cultural heritage recording tasks. Three different scanners were used: CYRAX 2500 (time-of-flight laser), Mensi SOISIC (triangulation laser) and GOM ATOS II (structured light projection). These scanners are completely different regarding their principles of operation, specifications and typical applications. This paper will describe some projects, including problems experienced during scanning and postprocessing. Objects recorded include a cave, facades of a church ruin and a cenotaph.
Just scanning an object is mostly the easiest part of the job. Creating exact models consisting of irregular surfaces requires a high expenditure of work and time. However, the various software products provided by the scanner producers are often optimised for industrial purposes and not for the creation of triangulated meshes, as necessary for objects in architecture, arts and archaeology. In order to be able to create both, geometrically accurate and good looking models, more intelligent software has to be developed. It is concluded that laser scanning is an important new method for the recording of cultural heritage objects, which can complement or in certain applications even replace currently existing methods.

1. INTRODUCTION

In the past years laser scanning or 3D scanning in general has become more and more important for the recording of regular (e.g. industry, piping) and irregular surfaces (e.g. sculptures, architecture, archaeology). The question arose: Can 3D scanning replace traditional photogrammetry or tacheometric measurements? This paper will give an overview about current projects at i3mainz, where scanning was used as a single method or for additional data capture. Problems which appeared during both, scanning and processing, are described and possible solutions are suggested.

2. SCANNERS AT i3mainz

i3mainz was in the position to be able to purchase two laser scanners, the long-range scanner CYRAX 2500 by Leica Geosystems and the mid-range scanner Mensi SOISIC LD. Furthermore, the short-range scanner GOM ATOS II was used by a sub-contractor at the cenotaph project in Innsbruck (see 3.3). The following paragraphs will give a short introduction to each scanner with its principles and specifications.

2.1 Mensi SOISIC LD (S25)

The SOISIC LD scanner (it was renamed to „S25“ recently) is based on the plane triangulation principle combined with a cylindrical rotation. It is amenable to scanning both, smaller objects like statues, and larger objects such as archaeological sites, caves, rock walls, facades, plants, and so on. Since the SOISIC scanner has a relatively large base (as compared to other triangulation systems) of 0.8 m, it is possible to scan objects between 2 and 10 meters with better accuracy than other scanning products on the market. Due to the triangulation principle, the point accuracy decreases with the square of the object's distance. The standard deviation is 0.4 mm at 2.5 meters, 0.7 mm at 5 meters, 2.0 mm at 10 meters and 5.4 mm at 20 meters. These values were determined by scanning a planar surface with the i3mainz Mensi scanner, fitting a plane to the point cloud and evaluating the standard deviation of a single point.
An integrated stepping motor enables the scanner to rotate and capture a 320° field of view in the vertical direction. The scanning field in the base (horizontal) direction is derived from the camera's field of view and is about 46°. The scanner is able to record approximately 100 points per second. To process the resulting cloud of points for creating models, Mensi provides the 3Dipsos software. Here the points are managed, edited and filtered. Special modules allow the creation of triangulated meshes and regular objects for engineering purposes, as well as the management of imagery and mapping of photo textures onto the model.

2.2 Leica Geosystems (Cyra) CYRAX 2500

The CYRAX 2500 scanner is a time-of-flight scanner which is applicable for larger objects with distances up to 100 meters from the scanner. Possible applications are the recording of architectural facades, plants or landscapes. Our scanner has a more or less constant accuracy of 2 to 3 mm between 1.5 and 50 m range (determined with the method described above). The scanning speed is about 1000 points per second. Similar to Mensi's 3Dipsos, Cyra offers the processing software Cyclone. It is mainly designed for the creation of CAD-Models out of raw point clouds.

2.3 GOM ATOS II

The ATOS II scanner by GOM is a digitising system that works with white structured light. The light pattern is projected on the object's surface while two cameras record the reflected light. The scanner records 1280 x 1024 points in eight seconds. The scan volume may be anywhere between 0.6 dm^3 and 1.1 m^3. The accuracy (noise) is from 0.002 up to 0.02 mm (for max. measuring volume). Typical applications for this scanner are quality control, reverse engineering and rapid prototyping for small objects.

Figure 1. Scanners: Mensi S25 (top left), Cyrax 2500 (top right), GOM ATOS II (below)

3. PROJECTS

3.1 Caves

The survey and documentation of underground cave systems is a big challenge for conventional measurement methods. Due to the irregular shape of caves, laser scanning might be a proper technique to record them. i3mainz had the possibility to test the potential of laser scanning at the volcanic caves in the Eastern Eifel. There, in the Middle Ages, humans started to mine the basalt below the lava flows of the Wingertsberg volcano which erupted 200,000 years ago. The result was a huge system of underground caves. The Cyrax scanner was used for a demo project. The Cyrax scanner was selected, due to its good accuracy at distances of 10 to 20 meters and above. A disadvantage was the relatively small field of view (40° x 40°). For smaller caves it might be sensible to use the Mensi scanner instead, because it is capable of scanning a larger area of the cave in one scan (320° x 46°).
It should be noted that the Cyrax scanner is able to work up to eight hours by using two 12V batteries, while the Mensi scanner is dependent on permanent AC power supply. This makes the Cyrax scanner much more flexible, considering that the operation of the Mensi scanner with a power generator is not possible within a cave.
Figure 2 shows a model of the scanned part of the cave. Five viewpoints were used in this case. To connect the single scans, small spheres were placed at different positions and used as connecting points for the registration process. A medium point grid of 5 cm was chosen which was by far sufficient to document the cave's geometry. At the end the scan data was reduced to 25 % with the simplification software Qslim.
The main difficulty during scanning was, not to miss hidden areas. The cave was quite full of corners and pillars, so a lot of viewpoints are needed to capture all the surfaces without missing parts. Nevertheless, laser scanning appears to be the only useful method to document the complex geometry of a cave or a cave system. It is still a lot of work, but there is no other measurement technique that produces such detailed data within a comparable amount of time.
Additional tacheometric measurements for the spheres have to be used to determine a horizontal reference plane and a common coordinate system.

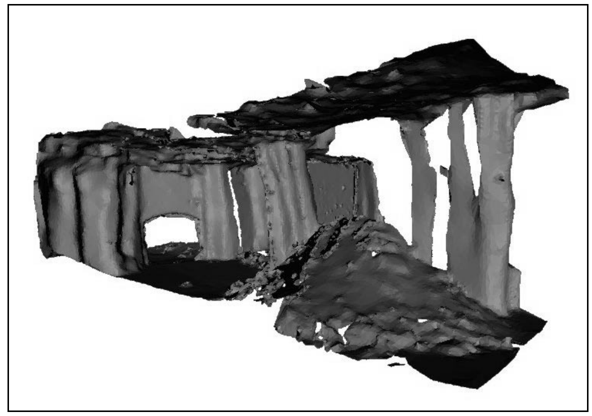

Figure 2. Polygonal model of the scanned cave

3.2 Church ruin

Another interesting application of laser scanning is the creation of digital surface models of architectural facades. i3mainz is working on a project with the intention to document the stages of construction of an old church which is remaining as a ruin. Close range photogrammetry was used to extract the stones' contours. Additionally, orthophotos had to be created. For this purpose, the facades were scanned with both the Mensi and Cyrax scanner. Since there was little space inside the church, the Mensi scanner with its 320° vertical field of view was used for the interior facades. Outside, the Cyrax could be used to scan a whole facade from a larger distance in one scan and under daylight conditions.
The point cloud of each facade was the basis to create first a regular lattice and then a DOM (digital object model) as input data for the creation of an orthophoto. The point cloud of the scanner was transformed to the global system by using identical points (edges of windows, projecting stones etc.).

Figure 3. Polygonal model as a basis for an orthophoto

This project, too, can be seen as an ideal application for laser scanners. Often, a simple rectification of the photos taken from the facades is not sufficient. Laser scanning provides a fast and easy way to get a detailed model of the surface for the creation of orthophotos.

3.3 Cenotaph

The cenotaph (empty tomb) of Emperor Maximilian I. is situated in the Hofkirche church in Innsbruck, Austria. It was created by various artists during the 16th century and is known as the largest and most important mausoleum of the Western World. The sarcophagus itself (2.5 x 4.5 x 2.0 metres) is made of black marble and bronze. It is ornamented with 24 finely carved alabaster reliefs (80 x 50 cm²) depicting scenes of Maximilian´s life. A life-size bronze statue of the emperor is kneeling on top of the sarcophagus as well as four smaller bronze statues (the four cardinal virtues), which are situated near the corners.

The first restoration attempt since the completion of the cenotaph (around 1568) started in January 2001 and is still in progress. During May 2002 there was a one-week break between two phases of restoration where the cenotaph was freely accessible, without any lattice or glass, for the first time ever. It had to be made the most of these few days by documenting this unique cultural heritage with state-of-the-art technology, before the cenotaph was hidden behind lattice and glass again, probably for the next 500 years.

Figure 4. Left: Cenotaph in the Hofkirche church of Innsbruck. (Photo: AEIOU) Right: Uncovered sarcophagus with reliefs

Measurements: In addition to traditional close range photogrammetry, carried out by an Austrian company specialised on this matter, i3mainz was engaged to record the cenotaph's shape with laser scanning methods. For this purpose two scanners were used. The idea was to use the Mensi SOISIC scanner to record the plain geometry, including marble parts (steps, frame and lid) and bronze statues. Scanning the alabaster reliefs with details smaller than one millimetre by using this scanner is not sensible. Instead, the GOM ATOS II scanner was brought into action.

A common coordinate system had to be created for the three measurements (photogrammetry, Mensi, GOM). Therefore, tacheometric measurements were carried out. Twenty special red spheres were placed on the cenotaph as connecting points to register the single point clouds from each scanner viewpoint. The spheres were measured by aiming at the left, right and upper contour and calculating the direction to the centre (the lower margins could not be measured due to the spheres' bases). The photogrammetrists placed their adhesive reflecting targets on the cenotaph. Eight observation points for the total station were selected around the cenotaph. After measuring angles to all targets (observation points, spheres, photogrammetric targets) and using a calibrated invar rod as a scale, a common net adjustment was computed, which resulted in 3D coordinates with a standard deviation of less than 0.5 mm.

Problems: In the planning phase of the measurements it was not clear, to what extent the material and colour of the object would influence the results of scanning. It was considered to spray the crucial parts with some kind of chalk or powder. The best conditions for both scanners, Mensi and GOM, are a dark environment and an object surface, which is bright and smooth. On site first the black parts of the cenotaph (marbled frame) and the bronze statues were tested with the Mensi scanner – with acceptable results. Some points were missed, but altogether the scanner worked very well as long as the sun was not shining directly onto the object. The GOM scanner had more problems with daylight and the black surface. The projected light pattern was completely absorbed by the marble, but the alabaster reliefs could be scanned properly, of course.

Scanning with Mensi SOISIC: The whole cenotaph was scanned with an average point width of 2 mm. For each pair of reliefs one scan was applied including the neighboured parts of the black marbled frame and the steps below the sarcophagus. By using this method, the important parts of the marbled frame were always scanned from two directions which leads to less hidden areas. Moreover, the scanner was placed on a scaffold to scan the upper part of the cenotaph with the lid and the five statues. Each scan contained at least four spheres for registration. All in all, 20 scans were applied during four days and nights. One single scan took up to six hours (3 - 4 hours as an average) depending on the size of the scanned area.

Figure 5 shows the registered point cloud of the whole cenotaph. Altogether, more than 10 million points were recorded, which is a large amount of data even for powerful PC's.

Figure 5. Registered point cloud of the cenotaph (shaded view)

Scanning with GOM ATOS II: Scanning the reliefs with ATOS II turned out more difficult than originally expected. To reach a maximum of accuracy and detail, the scanning volume has to be very small. In order to maximise the precision of the model, the reliefs had to be divided into several tiles - each part had to be scanned separately. This was possible by sticking special reflecting targets to the object and using those to stitch

the single scans together. Since it was not permitted to put anything directly onto the reliefs, adhesive tape was fixed on both sides, bridging over the reliefs without touching them, with the reflecting targets on it. Twelve scans per relief were applied from different directions. Despite the large number of scans, there were still many hidden areas in each relief (see Fig. 6). This was not avoidable due to the very detailed reliefs with lots of projecting parts.
A rough model of each relief can be processed directly on site. Due to the huge amount of data (approx. 150 Mbytes per relief) the polygonal models have to be reduced intelligently.

Figure 6. Part of a relief scanned with GOM ATOS II

Postprocessing: The first goal is to create a polygonal mesh using the registered Mensi point cloud. This will be used as a frame for the reliefs' scans, which are inserted in order to create a detailed and geometrically correct model of the whole cenotaph. The processing of the scanned data is still in progress.

4. SOFTWARE

Overview: Currently various software products for the processing of 3D point clouds are on the market. Many producers of scanners provide their own software (like Mensi and Cyra), but there are stand-alone products, too. Mensi's 3Dipsos and Cyra's Cyclone were mainly developed for engineering purposes. Cyclone allows the fitting of primitives to the point cloud, like planes, cylinders or spheres. 3Dipsos even provides a catalogue including different pipes, steelworks, flanges etc. which can be fitted to the point cloud. Additional catalogues can be imported to enable the user to create models for his own special application. As a result, a rough CAD model can be exported to MicroStation® or AutoCAD® for the final treatment.
In contrast to the field of plant engineering, the modelling of irregular surfaces is still making great demands on both, software and hardware. The central element of a 3D processing software for irregular surfaces is the creation of triangulated meshes. 3Dipsos offers two options: automatic triangulation, which means a real three-dimensional triangulation, and the triangulation by projection. The latter uses geometric reference surfaces like planes or cylinders, which act as projection surfaces for a 2.5D triangulation. In addition, 3Dipsos allows to use simple editing tools like filling of flat holes, smoothing, and the deletion or creation of single triangles. The options offered by Cyclone are very limited. It is not possible to create 3D meshes. Instead, a simple TIN mesh creation can be applied.

Demands on 3D modelling software: The crucial factor for the creation of accurate 3D models is the registration process. Both, 3Dipsos and Cyclone, allow the registration of several viewpoints by using identical points, which can be special spheres, reflecting targets (only Cyrax) or any geometric object. The best solution is achieved, if all scans are adjusted in one step. This is what the Cyclone software does: All targets with identical ID's are recognised automatically and an adjustment is computed. Additionally, different weights can be assigned to the targets. Mensi's 3Dipsos only offers the registration of two scans in one step with at least three targets, which can lead to large errors, particularly for large objects with lots of viewpoints. To avoid this, it is possible to import topographical coordinates (e.g. determined by a total station) for the identical points.
Another method is the registration by using overlapping areas of neighboured scans. This method is divided into two steps in 3Dipsos: Firstly, an interactive consolidation has to be applied by manually translating and rotating one scan with respect to the other scan to obtain a good relative position. After this, the automatic consolidation adjusts both scans with regard to minimised distances between both point clouds. This function is not included in Cyclone.
A satisfying solution would be a combination of an identical point adjustment and automatic registration of all point clouds.
After registering single scans to one point cloud, the points have to be edited. Outliers have to be detected and deleted. Possible reasons for outliers are scanning errors, due to light sources, dusty air or other scanning effects like errors at sharp edges or heavily reflecting areas. Additionally, in most cases it is sensible to reduce the noise of the point cloud, resulting from the scanner's inaccuracy. In case of large objects with huge data rates, the number of points should be reduced intelligently, depending on the object's surface.
If the point cloud is prepared sufficiently, a polygonal mesh can be created. For this purpose it should be possible to define breaklines which are considered during triangulation. After that, the software should be able to locate remaining errors like spikes or holes and repair them intelligently. Holes have to be filled with respect to the surrounding surface.
Another function that should be integrated in a 3D modelling software is the creation of NURBS surfaces. Especially objects with few details (like car bodies) can be described very well with this method.
A problem which appeared during the work with modelling software at i3mainz, is the direction of the normals. After scanning the cave with the Cyrax scanner (see 3.1) and importing the point data to 3Dipsos via an ASCII file, the information of the scanner viewpoint got lost and the normals of the triangles pointed to random directions. This leads to wrongly orientated triangles, which cannot be seen in the model. An intelligent function is needed to correct this.
During the whole process of working with scan data and creating meshes, it is imperative to check the quality of the data. Extensive quality control functions must be provided. It should be possible to verify the deviations between the created model and the original point cloud. Records must be created and statistical values must be calculated for every processing step like registration of the scans (geometry within each point cloud remains unchanged), reduction of noise, detection of outliers and so on.
Finally, the results of modelling have to be visualised. Tools must be provided to put suitable textures onto the models. This can be artificial textures from a catalogue or natural textures

taken from photographs. For the latter, image mapping procedures have to be offered, including the possibility of incorporating camera calibration values. It should be considered to include these functions into a 3D modelling software or, instead, a separate software product shall be used, which is specialised on visualisation of 3D models.

Not only the software has to fulfil great demands, but the hardware, too. A powerful PC is needed to handle the huge amounts of data. The most important elements are a fast processor, a lot of RAM (at least 512 Mbytes, better one Gbyte or even more) and a powerful graphics card.

Table 1. Demands on 3D modelling software

General	• Ability of loading and managing large amounts of data (>> 1 Mio points) • Various import and export formats
Registration	• Adjustment of multiple scans in one step • Use of identical points • Use of overlapping areas • Use of additional measurements
Point cloud	• Automatic detection of outliers • Reduction of noise • Intelligent reduction of points
Mesh creation	• Definition of break lines • Intelligent 3D triangulation • Triangulation by projection • Intelligent polygon reduction
Mesh editing	• Automatic detection of outliers • Intelligent hole filling • Correction of normals • NURBS
Quality control	• Deviations between model and scan data • Records for every processing step

In addition to 3Dipsos and Cyclone, some other modelling software products were tested at i3mainz, including RapidForm by INUS technology and Raindrop Geomagic Studio. Both products are specialising in the creation and editing of meshes. It seems that Geomagic Studio meets most of the requirements mentioned in table 1. As compared to 3Dipsos, Cyclone and RapidForm, it is the most suitable software for 3D modelling of irregular surfaces.
Another new software product, 3Dveritas, will be made available to i3mainz for testing. The results of the evaluation were not ready for publishing at the deadline of this paper.

5. CONCLUSIONS

3D scanning is an important new tool for the documentation of cultural heritage objects. But it is not the "magic bullet" as it was deemed to be by many people, especially the producers, when the scanners appeared on the market. Without doubt, 3D scanners are very well suited for the measuring of irregular surfaces, probably it is the best method for such applications at all.
But it is not enough to see just the sheer collecting of data – laser scanning is unbeatable in that category. Rather attention should be paid to the postprocessing. The amount of energy and time to create an accurate and faultless model is many times larger than scanning time (roughly by factor 5 to 10 or even more). Both, software and hardware have to be improved, to relieve the postprocessing and to make laser scanning an economical option as compared to existing methods.

6. ACKNOWLEDGEMENTS

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zip

Ein Projekt im
Zukunfts-investitions-programm
der Bundesregierung

In September 2002 i3mainz will start a new research project "More efficient documentation in architecture, cultural heritage and archaeology by use of 3D scanners", which is financed as an aFuE project (Förderung anwendungsorientierter Forschung und Entwicklung an Fachhochschulen) by the German Federal Ministry of Education and Research.

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DIGITAL PHOTOGRAMMETRY AND LASER SCANNING IN SURVEYING THE "NYMPHAEA" IN POMPEII

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Commission V

KEY WORDS: Cultural Heritage, Close Range, Digital Photogrammetry, Laser Scanning, Surface Modelling

ABSTRACT:

A study currently carried out with archaeologists from Bologna University involves the restitution of the nymphaea existing in Pompeii (Naples, Italy); this task requires a long work using classical photogrammetric techniques. Different solutions were tested using digital photogrammetric systems, in terms of data acquisition (e.g. semi-metric vs digital cameras, Cyclop system), data processing (e.g. automated surface model reconstruction, monoscopic or stereoscopic plotting) and representation (e.g. orthophotos, adoption of cartographic projections), but this kind of object could be an interesting application also for laser scanning techniques. The decoration of nymphaea apsidal and front walls is particular rich in some cases, and deformation of surfaces are sometimes well evident, so the integration of the opportunities provided by close range digital photogrammetry and laser scanning could be a topic of interest. A multi-station laser scanner survey could permit to complete the planned activity in shorter time and with an adequate accuracy, with the production of a complete 3D model; this solution has been tested through the comparison with digital photogrammetric survey in terms of precision and reliability in restitution of the object size and shape, with the final aim to understand what kind of solution better supports the study and the accurate metrical documentation of the nymphaea. The paper presents the test currently carried out on two nymphaea.

1. INTRODUCTION

The research here described regards a project started in 1999, within a collaboration established between the University of Bologna and the Archaeological Superintendence of Pompeii. The project pointed out originally the study, restoration and valorisation of the Centenary Insula (IX,8), regarding an interesting house known as "of the Centenary" that would be scientifically recuperated and made available (Scagliarini Corlaita and Coralini, 2002).
In the frame of this project was successively activated a rigorous survey by digital photogrammetry of the most significant nymphaea of Pompeii. The nymphaea are elements of remarkable archaeological and also artistic value. Important houses of Pompeii were decorated with nymphaea. Like other structural elements they showed the social and economical status of house proprietary, so the pictures on walls and apsidal and the material used were sometimes particularly fine, giving artistic value to the objects. In Pompeii area about 15 examples of nymphaea are known, characterised by different geometry and structure. During 1999 and 2001 campaigns the surveys of six nymphaea were carried out, located in Centenary house, Grand Duke house, Small And Big Fountain houses, Wounded Bear's house, Scientist's house.
The nymphaea have been chosen with the aim to furnish almost an example of every architectural and decorative typology, so a preliminary phase was planned to study surveying and representation methodology appropriate for each specific typology based on the geometrical characteristics of nymphaea. The research in those phase regarded the survey and restitution through the utilisation of digital photogrammetric methods, evaluating alternative techniques by means of direct photogrammetric comparisons (Bitelli et al., 2001). The research is not concluded and in 2002 campaign further processing and data acquisition for other nymphaea is planned.
The photogrammetric restitution produced 3D object model and raster products. An high degree of detail was maintained in the image acquisition and plotting process, trying to preserve the richness of nymphaea apsidal and walls decoration in the graphical representation. Even the deformation of nymphaea surfaces are in some cases well evident.
In order to verify the reliability of different techniques of investigation with respect of richness and detail object description and eventual deformation detection, the integration of different close range digital photogrammetry techniques and laser scanning was planned. The latter is certainly an emerging technique for industrial and architectural applications, as well as in the field of cultural heritage and virtual reality based museums (Beraldin et al., 1999; Böhler et al., 2001; Monti et al., 2001).
A multi-station laser scanner survey could permit to complete the planned activity in shorter time and with an adequate accuracy, with the production of a complete 3D model.
The solution has been tested through the comparison with digital photogrammetric survey in terms of precision and reliability in restitution of the object size and shape.
The different techniques were pointed out to understand which solution could better supports the study and the accurate metrical documentation of the nymphaea in respect to geometrical and artistic typology.
The current work will be briefly described in the next paragraphs, taking as example the survey of the nymphaea of the "House of the Big Fountain" and of the "House of the Small Fountain" (fig.1).

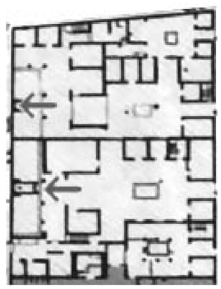


Fig. 1 – Sketch with the position of the nymphaea in the adjacents "House of the Small Fountain" (top) and "House of the Big Fountain" (bottom).

2. TECHNIQUES APPLIED

2.1 Photogrammetry

The subject of the surveys (the nymphaea in Pompeii) is generally of a relative small size, with different kind of geometric characteristics, from a very simple structure to quite complex surfaces.
For the photogrammetric image acquisition, and mainly due to handiness requirements, the choice has been for small and medium format semimetric cameras, but also a calibrated digital camera was adopted. In particular were used Leica R5 (24x36 mm) and Fuji 690III (60x90 mm) film based cameras with reseau (equipped with wide angle and normal lenses) and Nikon D1 digital camera equipped with a wide angle lens.
Normal and convergent photos were acquired, in order to apply classical stereoscopic plotting but also in some cases monoscopic non conventional techniques. A solution for a good stereoscopic coverage is represented by the use of the Cyclop system (Menci and Rinaudo, 2000). It is a single camera system (fig.2) that, simulating the use of a bi-camera, provides a specific software for mono- and stereo-restitution without requiring a topographic survey for ground control points determination.

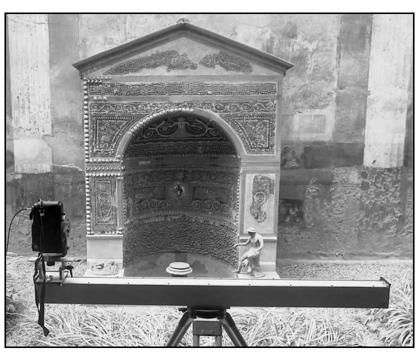


Fig. 2 - House of the Small Fountain: digital data acquisition using the Cyclop system.

To provide a solution for the exterior orientation problem, three different approaches are applied:

– a conventional topographical survey of the GCPs, using special retro-reflective targets and high precision total stations (with normal EDM or reflectorless system): this solution provides the best results in terms of accuracy, with error ellipses of few millimetres, for the point determination and for the absolute orientation;
– the scaling of the 3D model, derived from a relative orientation, by using distance measurements between well defined points;
– the employing of the Cyclop system as a bi-camera, with a base value of 1.20, 0.90, 0.60 or 0.30 m depending on the size of the object (therefore adequate to the case in question).

The orientation procedures (inner and exterior) are performed using a PC-based digital photogrammetric workstation (StereoView, Nikon Instruments) and also by an analytical stereoplotter (Digicart40, Siscam).
Different products were until now produced and their use considered with archaeologists:

– classical large scale three-dimensional vector restitution, either by analytical and digital stereoplotters;
– monoscopic restitution of the main structure using digital photogrammetric programs, aided by automatic correlation and epipolar constraints for homologous point collimation;
– design of profiles and sections;
– digital surface model determination, either by manual operation and by automatic matching procedures;
– digital rectified photos and orthophotos.

Some examples are shown below, relative to surface modelling and derived orthophotos. Orthophotos, despite the difficulty of their application in architecture, provide a very powerful tool for restoration and documentation of monuments and materials; for their generation the capabilities of image matching procedures could be successfully exploited but they require appropriate a-posteriori manual editing (Baratin et al., 2000).
Figure 3 shows the results of a comparison between manual and automatic (without editing) DSM generation, at a 10 cm grid spacing, for the Small Fountain nymphaeum; the surface was

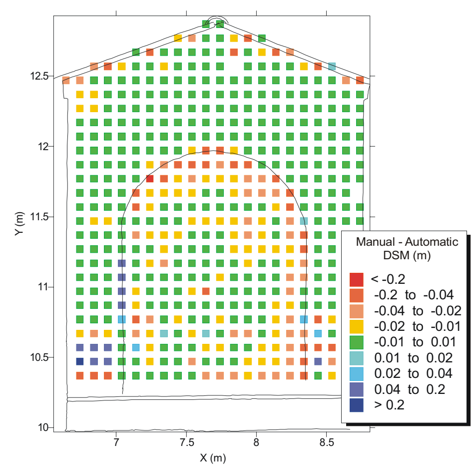
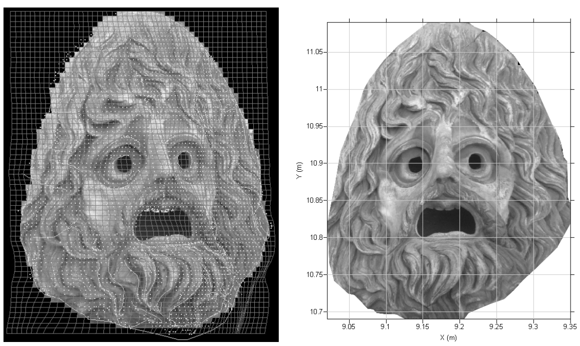


Fig. 3 - House of the Small Fountain: test for validation of automatic surface modelling (without editing) vs. manual DSM restitution on a simple mesh; values in m.

generated by the StereoView digital photogrammetric package. The same program, but in this case with some manual editing of the original 5 mm grid, was adopted for the surface modelling of the masks from the Big Fountain nymphaeum; the results for the left mask is shown in figure 4. The automatic 2 cm grid DSM, after some a-posteriori manual correction, has been the base for the orthophoto of the facades; a particular for the upper part of the Small Fountain front is represented in figure 5. Finally, figure 6 shows, using a simplified 3D reconstruction, the results of mosaic composition for the digital rectifications (software Rollei MSR rel. 4) of the walls located nearby the Small Fountain nymphaeum.



(a) (b)

Fig. 4 - Particular from the House of the Big Fountain: the mask on the left part of the nymphaeum. (a) Raster image depicted on the DSM obtained by automatic correlation, with grid and breaklines; (b) final orthophoto.

Fig. 5 - House of the Small Fountain: 1:25 digital orthophoto for the upper part of the front (reduced).

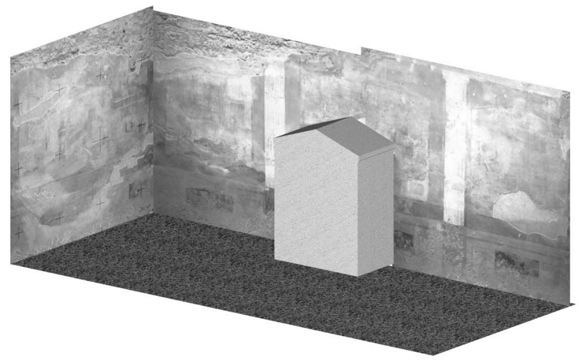


Fig. 6 - Mosaic of rectified images for the walls nearby the Small Fountain nymphaeum in a simplified 3D reconstruction.

2.2 Laser scanning

For the two above mentioned nymphaea a laser scanning survey was realized by using the Riegl LMS-Z210 system (fig. 7). This system can perform data acquisition for objects at a distance from 2 up to 350 metres, with a nominal accuracy in the distance of about 2-2.5 centimetres. Different systems could guarantee a better accuracy on short distances and could provide perhaps better results for an object of this dimension. In archaeological or architectural situations involving a large range of working distances this product could however allow a wider assortment of applications.

Fig. 7 - Big Fountain nymphaeum: laser scanning for a lateral station.

The system is able to acquire intensity, range and also RGB images for a scanning range of 370 gon (horizontal) x 88 gon (vertical), with a minimum angle step resolution of 80 mgon, either in horizontal and in vertical.

The definition of a Cartesian world reference system for the point coordinates, otherwise expressed in the polar system, can be performed in different ways:

- using the standard instrumental orientation;
- by a coordinate system described by a specific plane and one axis or, in alternative, the origin and the normal vector of a second plane (method useful for the registration of a single scan);
- by a manual modification (move/rotate) of the actual coordinate system;

- via reference points (method useful for registration of multiple scans);
- by automated techniques relying mainly on the recognition of the same flat areas on contiguous scans.

Three scans were realised for the Big Fountain with 80 mgon resolution, one central (4 frames averaged) and two laterals, and only a central scan acquisition for the Small Fountain.
In order to better compare the results of the photogrammetric and laserscanning process, the same targets, whose coordinates were determined by a topographical survey, were used for the exterior orientation in both the two approaches.
Figure 8 shows the phase of automatic localisation of the targets, based on their high intensity values, realized by 3D RiVIEW Riegl software for the nympheum of the "House of the Big Fountain"; the coordinates of the targets were supplied as a separate file. The automatic localisation, and the subsequent use for stitching together different scans, was successfully tested using the program Laser Scanner Registration 1.0 (Bornaz et al., 2002); the results, after a decimation of the cloud points, are shown in figure 9.

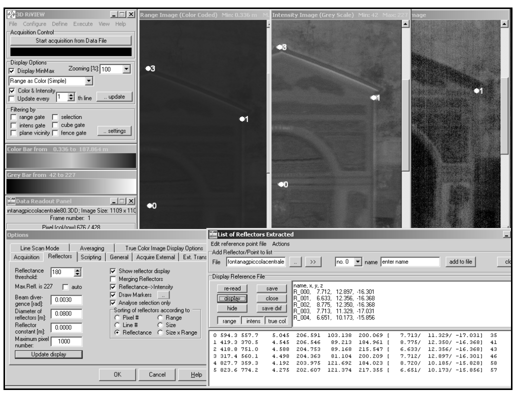


Fig. 8 - House of the Small Fountain: registering the scans by automatic identification and association of control points.

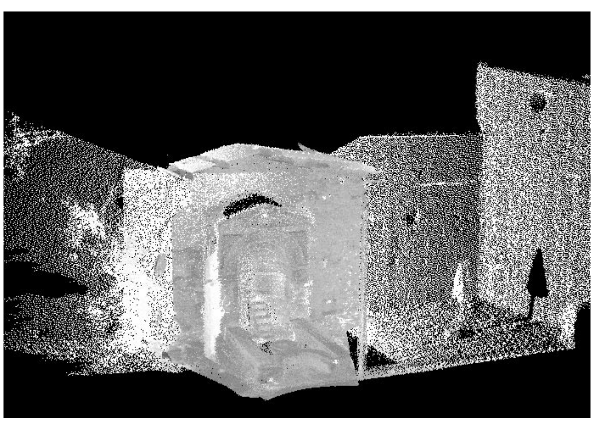


Fig. 9 - House of the Big Fountain, after automatic registration of three scans and subsequent point decimation.

The free visualisation software provided by the Riegl firm (or other programs) permits this combined cloud of points to be exported in .wrl format and easily explored by a VRML browser (fig. 10), and distances interactively and immediately measured between couples of points.
The successive step is the creation of the 3D mesh and the final 3D model, after a series of refinements that, as well known, in general require powerful software and hardware platforms.

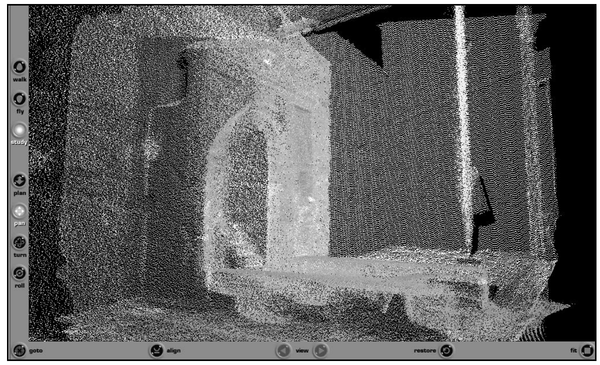


Fig. 10 - House of the Big Fountain, interactive exploration of the three co-registered point clouds by a VRML plug-in in a standard browser.

3. COMPARISON AND INTEGRATION OF THE TWO TECHNIQUES

During these experimentations, some preliminary tests were realized in order to verify the accuracy gained by different techniques.
Considering for instance about 40 differences in distance between couples of control points in respect to the values derived from the topographical survey we have:

Table 1 – Accuracy test: differences for absolute distances in respect to values obtained by total station surveying (values in meters).

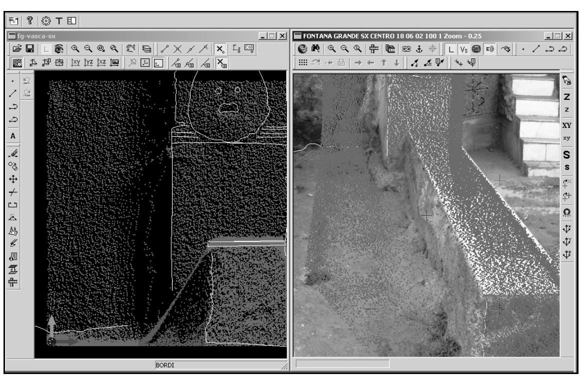
	mean	min	max	st.dev.
Photogrammetry (ROR+AOR)	0.002	-0.012	0.012	0.008
Photogrammetry (scaled model coordinates)	-0.002	-0.021	0.011	0.010
Laser scanning (instrumental coord. system)	0.004	-0.020	0.022	0.010

Taking in account the above mentioned limitations of this model of laser scanning for short distances and other experiences in literature, it appears that the accuracy provided by laser scanning systems is today well comparable with photogrammetry, and for some systems is better.
Some general considerations deriving from our experience can be briefly expressed.
The advantages of laser scanning, some of these in common also with photogrammetry, with respect to traditional surveying methods for archaeological sites and structures, and in general for cultural heritage preservation and documentation, could be briefly summarized as:

- short data acquisition time;
- very accurate 3D models obtainable from high density point clouds;

- non contact active sensing (no interference with excavation activities and no need to signalise the object);
- immediate results and easy measurements on the model.

Laser scanning peculiar characteristics are also the practicability of object replication (mould), and the support for virtual exploration and study via Internet, with a different approach in respect to photogrammetry and visual photographic reality (Bitelli et al., 2001).
In applications like those shown, laser scan could be a good solution to detect and model 'out of vertical' walls, providing a valuable support for structural monitoring and intervention.
On the other hand, archaeologists sometimes require from the survey a traditional product, in the form of a vector drawing with the main features well individuated, i.e. subordinate to a preliminary subjective filtering; the derivation of such a result from the laser model requires very powerful software and high skills where complex and not elementary geometrical shapes are involved, as is the case for numerous archaeological applications.
The choice of appropriate software is a crucial point for data processing, where strategies for data decimation and filtering, merging of cloud datasets and meshes, TIN tessellation, and finally generation of a polygonal model can produce quite different results (Fangi et al, 2001).
Photographic richness provided by photogrammetric image products is surely of high importance for archaeologists and architects, and true-colour imagery generated as a product of a laser scan, when available, is sometimes inadequate in quality and radiometric characteristics.
The integration of the two techniques, on the other hand, could provide very interesting results, starting from simple combinations: for instance, a stereoscopic model could permit the editing and integration of a incomplete laser acquisition (fig. 12), or the laser data could supply the coordinates for exterior orientation of photogrammetric images.



(a) (b)

Fig. 12 - House of the Big Fountain: (a) effect of shadowing and edges on laser data; (b) the errors are clearly visible and editable by superimposing the point cloud data on the photogrammetric stereoscopic model.

As depicted by other experiences, the use of laser derived DSM as a support for digital orthophoto generation do not directly provides satisfying results (see for instance figure 13 compared with figure 5), depending also on the object shape, data density, etc.; it requires at least an appropriate editing of the 3D model. Furthermore, complex shapes require multiple scans and an accurate survey planning.
In this context, photogrammetry could play a relevant role to complement laser surveys, in order to detect or correct erroneous or missing parts of the datasets and to describe discontinuities by means of breaklines and points.
3D texture mapping of the clouds of points can be performed by using calibrated instruments and cameras (Kern, 2001), and the combination of laser scanning and photogrammetric systems could produce a complete object modelling, with highly accurate geometric and colour characteristics.
In the next future the integration of these techniques will play therefore a fundamental role in surveying for cultural heritage recording.

Fig. 13 - House of the Small Fountain: particular of orthophoto obtained by using surface model provided by laser scanning.

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EXPERIENCES OF LASER SCANNING FOR CLOSE RANGE STRUCTURAL RECORDING

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KEY WORDS: Cultural-heritage, Laser scanning, Metric survey, Structural recording.

ABSTRACT:

Geomatics offers a wide range of solutions for close range measurement that can be applied to a disparate set of problems; however, survey workflows for projects are generally fixed to improve efficiency and standardise final deliverables. This paper will examine how one new survey technique, terrestrial laser scanning, may be introduced into a modern-day survey workflow. Terrestrial laser scanning is of great interest to surveyors, engineers, architects and archaeologists, and a wide range of scanning systems are now commercially available. The independent survey of two heritage sites within the UK has provided experience of laser scanning as a survey technique. Each survey utilised a different scanning system, namely the Riegl LMS Z210 to record a 14th Century tower and the Cyrax 2500 to survey part of an 11th Century priory. Both surveys also involved data derived from close range photogrammetry to allow a comparative assessment. Based on the experiences gained from these projects this paper highlights issues for consideration. It also comments on the complimentary use of different survey methods as an essential element for future survey practice.

1. INTRODUCTION

1.1. Motivation and methods for cultural-heritage recording

Measured survey is an essential process in many projects that deal with buildings or structures. This is particularly true when dealing with historic buildings and monuments where survey data helps architects, engineers and building historians to understand the significance of a building and its surroundings. This understanding allows informed decisions on issues such as repair, conservation or redevelopment to be made. The use of metric survey techniques are especially necessary when high accuracy measurement is required, for example on sites where major alteration may occur or where features may be permanently lost (Clark, 2001).

Understanding gained during the lifetime of a recording project is communicated through a system of reporting, archiving and publication; the contribution of the surveyor to this process is measured survey data in the form of floor plans, elevation drawings, sections, rectified photography, 3D CAD models and the periodic monitoring of surfaces or discrete points. The method used by surveyors to produce this information varies from project to project, but, in general, will involve at least one of three main techniques: hand recording, terrestrial survey or photogrammetry. Hand recording is performed by highly skilled professionals who produce annotated drawings and diagrams using tapes and grids. It is a specialist skill and normally applied to small, detailed areas or used to fill-in or augment survey data obtained by other techniques. The second available technique is terrestrial survey which includes the use of theodolite intersection, to record features and to provide control observations on which to base other techniques, in addition to the use of total stations for topographic site survey. It also includes, with the introduction of reflectorless EDM, the use of field portable CAD systems to simultaneously produce drawings and plans during measurement. The final technique at the surveyors disposal is image based measurement including photogrammetry and rectified photography. Image based methods are a long established tool for cultural-heritage recording. Imagery holds a great deal of information rapidly captured at a single point in time. Imagery, therefore, is a valuable source of archived data. Its application in this role can be seen after the fire at Windsor Castle in 1992 (Dallas et al., 1995) and during the restoration of Castle Howard (Thompson, 1962).

1.2. Survey workflow

When a public body such as English Heritage - the body responsible for conserving and enhancing the historic environment in England - commissions survey work it holds a responsibility to the tax-payer to demand good value and high quality. Practitioners are required to follow set specifications that provide objectives for the accuracy and quality of the final product. In order to meet these objectives the workflows used to implement survey techniques are well defined.

The workflow to produce a photogrammetric line drawing involves a number of different stages. Typically, once a target network has been established and photography has been taken the remaining work is performed off-site. Film based photography requires photographic processing including the developing, printing and replication of diapositives followed by an inspection of the results. The control observations would then be used to calculate target positions, and again the results would be inspected and documented to ensure the work is meeting the set specification. At this stage, many survey projects simply require the raw data to be archived for measurement at a later date, if required; however, the production of a line drawing still requires further processing stages. The first of these will most likely be the scanning of the diapositives for use in a digital photogrammetric workstation (DPW). Once the stereomodel has been satisfactorily orientated (subject to tolerances set in the specification) 3D vectors are plotted followed by further quality assurance (QA) procedures designed to ensure detail has been plotted faithfully and that the specified CAD layering system has been adhered to. The captured data can then be archived and digital drawings and paper plots prepared. The final stage is the delivery of the survey information in both paper and digital form (contained on a CD), probably via post. The originator of the work will then review the deliverables and perform a final QA phase.

The introduction of new techniques for metric survey requires new workflows to be developed and the definition of new appropriate specifications. How a new technique compares with traditional techniques also needs to be considered. This requires the critical evaluation of both the methods and resulting data. For cultural-heritage recording any technique that is capable of producing data similar to the current products of floor plans, elevation plots and sections should be considered for its potential to improve the efficiency of survey data acquisition or improve the quality and value of the final product. Laser scanning is one technique that currently shows potential for being used for cultural-heritage recording. This paper describes the use of two different laser scanning systems on separate historic sites and describes the experiences of data acquisition and processing in comparison to traditional techniques. It also discusses how laser scanning would fit into a contemporary survey workflow.

These projects were undertaken with a survey based approach to laser scanning, typified by the use of control data and the type of structures (e.g. subjects typical of the type that would be surveyed using current methods). The methodology used for the scanning in both projects can be likened to the photogrammetric flow-line described above. In addition to the collection of control data using terrestrial survey methods, the flow-line includes a registration phase (akin to stereomodel orientation) where the raw scans are brought onto a common coordinate system, data archiving phases and QA phases where the scan data is assessed for its quality. Unlike photogrammetry, however, no defined product exists for laser scanning and so for the projects described below the end-product was specified as point clouds registered to a common control scheme. The production of final end-products was then pursued following the data capture stage.

2. CASE STUDY 1: ASHBY-DE-LA-ZOUCH CASTLE

2.1. The Ashby Castle site

Ashby Castle was originally converted from a wooden Norman fort to a more substantial stone building in around 1160. After several changes of ownership its possession reverted to the crown in 1461, followed in a few years by the construction of many domestic buildings and the largest structure on the site, Hastings Tower. During the English civil war the castle was captured by parliamentarian forces and, in common with other captured fortifications of the time, Hastings Tower was rendered unusable (Batt, 2000). Preservation work began in the 19th Century and the castle is now in the care of English Heritage. The south façade of the remains of Hastings Tower was selected as a test site to be laser scanned; it is approximately 24 metres in height and over 10 metres wide. A considerable amount of depth is present on this façade as it includes not only the interior wall but also the remains of two wall end-sections which protrude up to four meters from the main wall, as shown in Figure 1. The most appropriate method of recording this structure for redevelopment or conservation activities would be digital photogrammetry based on a local site coordinate system, producing rectified photography, orthorectified photography, or line drawings. In this project features of interest include a fireplace at the top of the tower which would be inaccessible by current recording techniques without specialist equipment – measurement of these areas by photogrammetry would require access via a hydraulic lift or scaffolding. The tower is considered by English Heritage a typical United Kingdom cultural-heritage site that would require close range recording.

2.2. Laser scanning

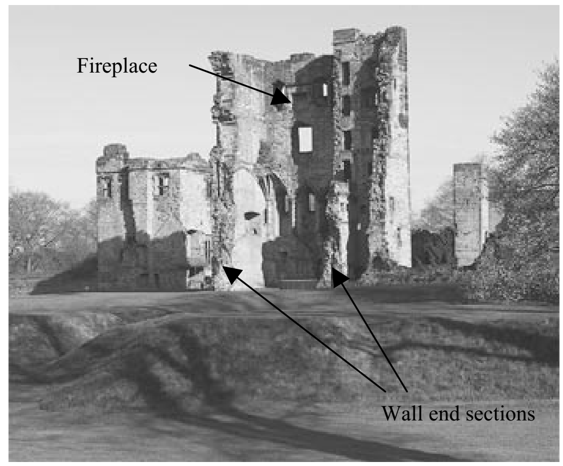

Figure 1. Hastings Tower, Ashby Castle.

The scanner used at Ashby Castle was a Riegl LMS Z210 instrument. It is a pulsed time-of-flight scanner with a maximum range of 450 metres depending on the reflectivity of the target (Riegl, 2002). In this project, emphasis was placed on a quantitative assessment of the instrument; therefore, scanning was performed at three different ranges from the face of the main façade 30m, 50m and 80m, rather than concentrating on collecting a complete description of the tower. As part of this evaluation process a large number of reflective targets were used to assess the precision and accuracy of the scanner - further details can be found in Mills and Barber (2002).

The remaining description considers the scans performed at 30m (in this case providing a scan with an average resolution, on the main wall, of 50mm). The instrument is quoted as providing a single point accuracy of approximately +/- 26mm. The size of the laser footprint at 30 metres is 90mm. In addition to the capture of XYZ data the scanner also records a RGB value for each point using a one pixel CCD sensor which allows the scan data to be viewed as a colour image in addition to an intensity image, based on the strength of the returning pulse (Figure 2), or as a range image. Scanner control is provided by a laptop computer running proprietary software with the progress of the scan displayed as a 2D image while the scan is running. The Riegl system offers an averaging routine whereby several individual scans can be performed and used to create one averaged scan. In this case 12 scans were used to create an averaged result. The resulting scan had a field of view of 80 by 50 degrees and consisted of over 300 000 points. Registration of the scan to a common coordinate system was made possible through the use of retro-reflective targets which were located on the local site grid using theodolite intersection from two stations.

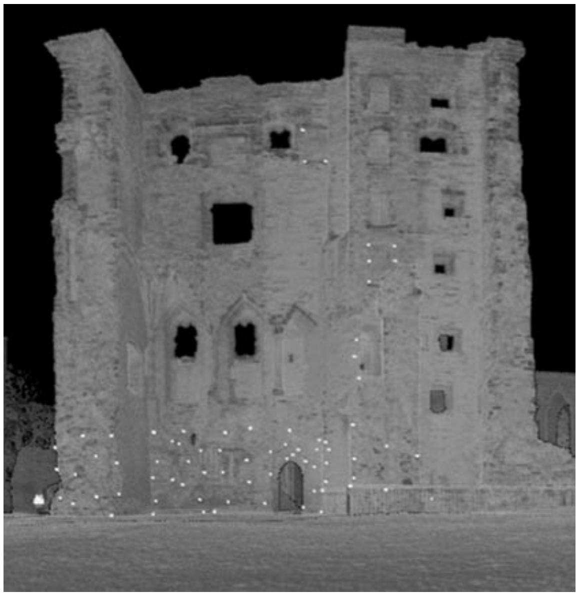

Figure 2. A sub-section of the intensity image produced by the Riegl LMS Z210 scanner.

2.3. Photogrammetry

As a comparison for the laser scanned data, photogrammetric data capture was also performed at Ashby Castle using a film based Wild P32 metric camera. Photography was taken at an average photo scale of 1:350 and was scanned onto Kodak's Photo CD format to allow it to be used in LH Systems SOCET SET DPW.

2.4. Profiles

The laser scan data was used to produce two longitudinal profiles through the façade. Profile 1 was placed across the left wall-end-section and comprised of an area of rough stone work. Profile two was located on the main façade across a small recessed window. Profiles were also collected using the scanned P32 imagery in SOCET SET. The recessed window area was in shadow at the time of photography and the second photogrammetric profile had to be broken at this point. Figure 3 shows the location of the two profiles. Figure 4 shows the two profiles using both scan (points) and photogrammetric (line) techniques. To provide an indication of the similarity of the profiles the laser scanner data was sampled at the collected photogrammetric data points, followed by the calculation of correlation coefficients. The profiles showed a high level of agreement with correlation coefficients of 0.99 and 0.97 for profiles 1 and 2 respectively.

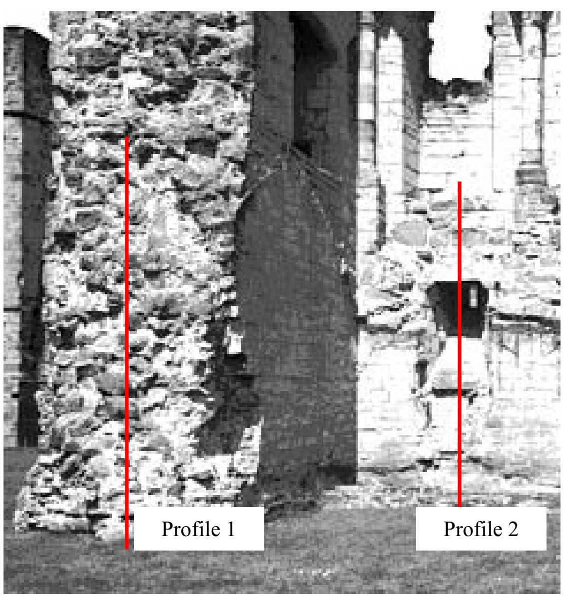

Figure 3. Profiles: Ashby Castle.

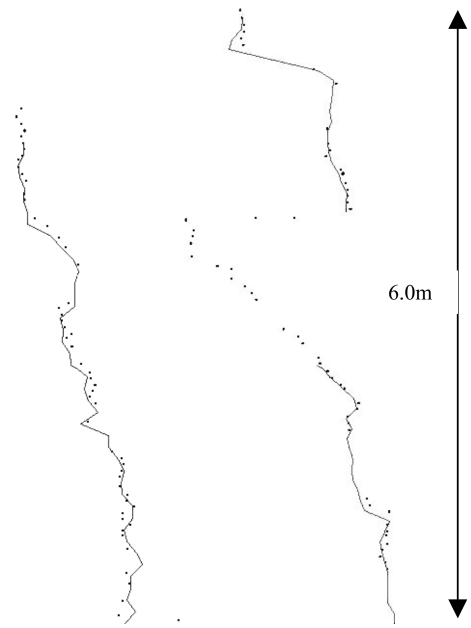

Figure 4. Profiles one (left) and two (right) from Hastings Tower.

2.5. Summary

It is clear that the laser scan data has been able to provide data in the recessed window area in profile 2 where photogrammetric data capture was not possible due to shadow.

However, although the point cloud contained a large number of points, the resolution of the scanning was found to be insufficient for the interpretation of small features of detail. This is especially the case for features at long distances from the scanner such as the fireplace at the top of the tower. It was also noticed that some data points were clearly incorrectly located, most notably at edges in the scene possibly due to multi-path or mixed-pixels affects. These points would need to be identified (preferably automatically) and removed from the data cloud in order to ensure they were not used in the final product.

3. CASE STUDY 2: TYNEMOUTH PRIORY

3.1. The Tynemouth Priory site

The site at Tynemouth has been an important religious centre and coastal fortification from the Seventh Century up until the present day. Two saints are buried within the walls of the Priory and two walls of the presbytery still stand to their full height of 22m (Hadcock, 1991). A small structure on the Priory site, the Prior's Hall (Figure 5), was selected to be scanned using a Cyrax 2500 laser scanner. The Prior's Hall was originally used to entertain the guests of the Prior and has undergone a complex process of development throughout its history, making it, as with Ashby castle, typical of many historic structures in the United Kingdom. Initially thought to be built around 1090-1140 it has seen structural additions and alterations in both the 13th and 14th Century. Interpretation of this development would be aided by accurate and complete survey data helping to improve the appreciation of the structure and, therefore, understanding of the building's significance. Additionally, recording areas of deterioration helps plan for maintenance work and determine the safety of the structure as it is fully accessible to the public.

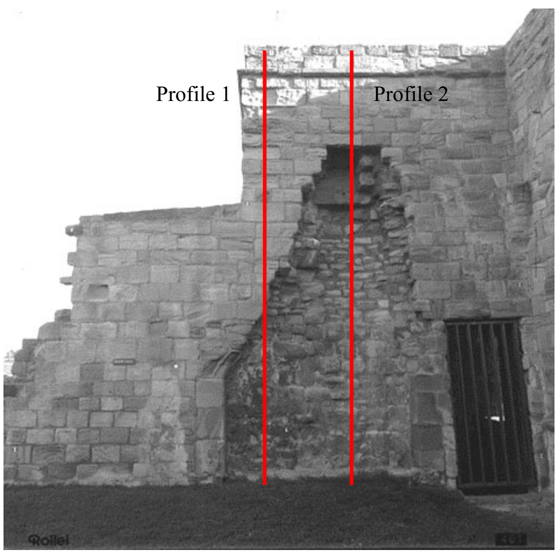

Figure 5. Priors Hall, Tynemouth Priory. The profiles collected using the laser scan and photogrammetric data are highlighted.

3.2. Laser scanning

Scanning was performed using a Cyrax 2500 scanner. This is also a time-of-flight system but has a quoted accuracy of 6mm - higher than Riegl LMS Z210. It has a highly collimated laser spot giving a footprint of 6mm at 50 metres (Cyra, 2002). As with the Riegl scanner the progress of the current scan is shown via the scanner software, although, unlike the Riegl system the Cyclone software shows the data being collected in an interactive 3D view – it was found that this allowed a fuller inspection of the areas being scanned. The Cyclone software is also the tool used to process the scan data and export it to CAD packages as required.

In this survey the main aim was a full record of the Prior's Hall referenced to the established local site grid. Three scans were used to record three of the four main aspects of the building consisting in total of approximately 690 000 scanned points. Overlapping areas of scan data were not required as the positions of the reflective targets used for registration were known. However, some overlap was made between scans to allow the efficient use of the targeted points (reducing the number of control points required) and improving the redundancy of the registration. It would have been preferable to complete the loop around the building, scanning all four aspects, to increase the strength of the registration; however, restrictions on site time did not allow this. In total, seven green reflective targets were used and were coordinated on the local site grid by intersection observations from at least two control points using a total station. At least four of the targets were present in each scan. The scanning and accompanying survey work took one day which includes the registration of the scans to the local site grid.

3.3. Photogrammetry

Conventional close range photogrammetry has been performed on the hall in a previous research project (Mills et al., 2000) and followed the standard English Heritage photogrammetric survey specification (Bryan and Blake, 2000) producing a line drawing at a standard plotting scale of 1:50 using a Zeiss P3 photogrammetric plotter. The imagery used to produce this drawing has also been used in SOCET SET to produce orthorectified photography and profiles.

3.4. Profiles

Figure 6 shows profiles manually collected using SOCET SET and extracted from the point cloud. The correlation coefficient for the profiles was 0.96 and 0.89 for profiles one and two respectively. As with Ashby Castle the profiles were broken in some areas due to shadow.

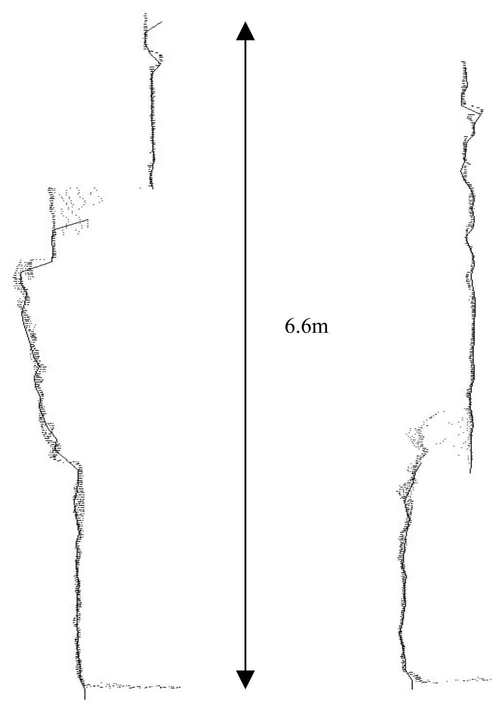

Figure 6. Profiles one (left) and two (right) from Priors Hall.

3.5. Summary

The slightly lower correlation between the two profile sets in comparison with the profiles collected at Ashby Castle is considered a reflection on the areas where photogrammetric data capture was difficult due to shadow or lack of surface correlation. It is clear that the laser scanning data has been able to provide a very clear profile in areas where photogrammetric points were unable to be collected.

The density of control points used for the laser scanning was much lower than that used to survey the hall by photogrammetry as the individual scans encompassed a wider field of view than the imagery and had no restriction on stereo coverage.

Figure 7 shows a meshed model of the eastern face of the hall and an image taken from a similar orientation. Certain features are more apparent in the scan data due to the angle of illumination – for example the corbel highlighted in Figure 7 is clearly visible in the meshed scan data but not the image. The ability to interact with the data to perform such interpretation is a clear benefit of scanning. The meshed model does, however, still require some editing before it can be considered a true representation of the hall.

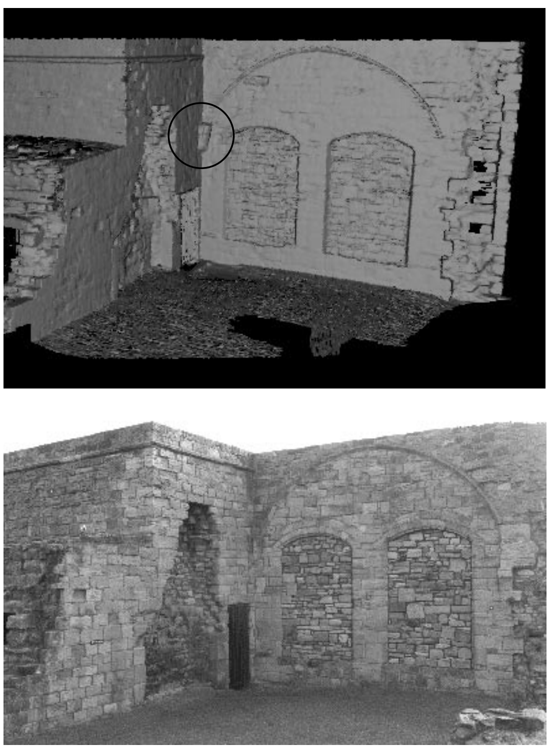

Figure 7. A meshed scan model (top) produced by the Cyrax 2500 and Cyclone software and a digital image (below) for comparison. Corbel is highlighted.

4. DISCUSSION

Imagery is currently the most common method for cultural-heritage recording. It provides not only a geometric record (with further photogrammetric processing) but also a qualitative record of the subject, ideal for interpretation and investigation. The products from photogrammetric surveys are accurate and efficient, and the archive value of imagery is well acknowledged; allowing measurement of a subject well after it has been damaged or destroyed. Imagery, however, is not a direct method of geometric data capture and in some instances may have shortcomings, such as in complicated areas of relief where detailed stereo-coverage may be required to produce measurements, or in areas of shadow where lack of image correspondence may require intensive manual interaction (the measurement/editing of data points) or a complete failure to measure any data. The secondary processing stage also lengthens the time required to produce geometric information.

Laser scanning captures geometric data directly without the need for a secondary processing stage. The measurement of complex areas of surface detail is much easier with laser scanning than stereo photogrammetry – especially when dealing with sharp edges. Scanning captures a large amount of geometric data in a short length of time (typically 10-15 minutes per scan), however, the data captured is simply a dense collection of points as opposed to discrete points of interest. No intelligence is present within the data without further processing. Points can be incorrectly measured due to multi-path or mixed-pixel effects and these points need to be identified to ensure they are not used for modelling or measurement. The resolution of a laser scan needs to be matched against the features of interest to ensure that those features are visible in the resulting point cloud – the scanner selected must provide a resolution greater than the smallest feature to be measured. This is perhaps the most important question for laser scanning within cultural heritage applications. As many recording projects are performed for archive purposes and the features of interest may be unknown at the time of capture what is an appropriate resolution to scan at?

The desired resolution may, in part, be determined by the required product. Presently, this product may take the form of a meshed model and cross sections but will not be able to replace the advantages of image based products: high resolution archive data, ease of capture etc. It could, however, provide the surface models for orthorectified photography eliminating the need for lengthy photogrammetric surface extraction and editing. The interpretational value of a meshed 3D model with the ability to alter the light sources in real-time may also provide a new product opportunity.

Although in both of the projects described here registration between scans was performed using targeted points, registration of point clouds can also be performed through matching techniques, such as the Iterative Closest Point algorithm (Besl and McKay, 1992). This approach minimises the need for control points, however, some care would be required in providing sufficient redundancy for quality assurance checks. The matching of points in this way is similar to the use of surface matching within photogrammetric applications for the orientation of stereo-models (Rosenholm and Torlegard, 1988).

5. INTEGRATION OF SCANNING INTO THE SURVEY WORKFLOW

5.1. Desired result

The justification for the use of any new technique must be in its ability to provide added value and for better efficiency. Scanning is not, realistically, able to replace the current use of image based techniques at the present moment. However, it may improve the value and efficiency of survey work if scanning was used in conjunction with current techniques, in much the same way that image based techniques are presently combined with hand recording. Integration will take the form of combined results, where products are augmented with different techniques, or in the integration of methodologies to produce new and improved end products.

5.2. Integration of products

The basic integration of imagery with scan data includes the draping of scan data with imagery to improve interpretation and detail in complex areas. Sequeira et al., (1999) and Bernardini et al., (2001), are two examples that have used images to augment 3D geometry captured using laser scanners. Much of this work is aimed towards the visualisation, rather than the metric survey of objects and structures.

5.3. Integration of flow lines

A more complicated merging of workflows can be envisaged through the integration of observations to produce better estimates for object coordinates or to produce quality control information on the data captured by providing redundancy in observations. This would have to deal with occlusions in scan data (real occlusions caused by objects and false occlusions caused by lack of data) and the problems of matching corresponding high resolution features in scan and image data.

Photogrammetric networks typically require high density target networks and automated photogrammetric surface measurement often requires manual editing, especially across surface discontinuities. Laser scanning on the other hand deals well with surface discontinuities and has a much lower requirement on the density of target networks, but it does not provide as much information on surface texture or data as appropriate for use as an archive data source as image based methods. It would seem, therefore, that a complementary use of the techniques would provide a more efficient, better value product. Future survey flow-lines will use each technique to its strength – using laser scanning for object models and augmenting the main object models with stereophotography, especially in areas of high detail or areas at particularly risk.

6. SUMMARY AND CONCLUSION

This paper has identified the reasons and the methods for cultural-heritage recording and detailed the use of flow-lines to provide survey data of good value and high quality. In particular it has focused on how laser scanning could be used for cultural-heritage recording based on the experience gained during the survey of two typical heritage subjects using laser scanning and photogrammetry.

The paper noted that Laser scanning was able to capture data in areas where traditional photogrammetric techniques could not, such as in areas of shadow, and create profiles comparable to those produced by photogrammetry. It highlighted the reduced density of control points required for laser scanning work in comparison to photogrammetry and showed how use of a 3D meshed model with directed lighting can highlight different features to a standard photographic image.

It is acknowledged that image based survey techniques have an important role in cultural-heritage recording, providing a recognised archive product in their own right and established final products, however, survey workflows could be adapted to include laser scanning as a complementary technique aiming to improve the overall value and efficiency of survey work. The next stage in the acceptance of laser scanning for use in cultural-heritage recording applications would be the introduction of specifications to govern the use of laser scanning and define useful final deliverables for the end user.

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PHARAOH PEPI I.: DOCUMENTATION OF THE OLDEST KNOWN LIFE-SIZE METAL SCULPTURE USING LASER SCANNING AND PHOTOGRAMMETRY

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ABSTRACT

Two statues of Pharaoh Pepi I. are the oldest known life-size metal sculptures in the world. They are dated to about 2300 BC and were excavated in 1897. In 2001, after a several years lasting process of restoration, conservation and technological investigation, the statues were documented geometrically. The shapes of the sculptures were recorded using a 3D laser scanner. Special features like the seams between the copper sheets forming the statue and the rivets connecting them were measured using close range photogrammetry. A model was generated from the scanner data as well as a 3D vector map of the line features from the stereo images. Besides these single results, both were combined for visualization purposes such as video sequences of the rotating sculpture or a combination with reconstructed vanished parts of the statue like the loincloth and the crown.

INTRODUCTION

In 1897, amongst numerous other things two statues of Pharaoh Pepi I. were found in a temple of the ancient city of Hierakonpolis. They are dated to the 23^{rd} century BC and are considered to be the oldest known life-size statues made of metal. After a first restoration around 1900 AD, the statues were in the exhibition of the Egyptian Museum in Cairo. In 1996, a joint project between the Egyptian Museum Cairo, the Deutsches Archäologisches Institut, Abteilung Kairo and the Römisch-Germanisches Zentralmuseum Mainz in Germany started with the aim of the restoration, conservation and technological investigation of the statues. The bigger (fig 1) statue is about life-sized (178 cm), the small one about 78 cm high. The statues are made of copper sheets that are connected with a kind of rivets. To conclude the restoration project, the statues had to be documented geometrically.
Different demands were to be fulfilled: The shape and size of the copper sheets and the rivets had to be documented and to be plotted in maps from different views respective reference planes. Measurements, e.g. distances between certain surface points, shall be possible, even if not directly accessible. The documentation of the bigger sculpture was of higher importance as compared to the small one.

OBJECTIVES

Measurements of any kind between points of the surface of the model are easily possible using a digital model of the statue. Generating a surface model of this kind can reasonably be accomplished using the points measured with a laser scanner. This model can also be used for visualization purposes.
As the accuracy of the used scanning hardware was limited to about 0.7 mm, the smooth seams between the single copper sheets and the single rivets connecting them cannot be recognized reliably in the model. To achieve this part of the documentation, the corresponding parts of the statue were also recorded using close range photogrammetry. The resulting 3D

Figur 1. Statue of Pharaoh Pepi I.

vectors can be plotted in different projections (e.g. parallel projections from different sides of the sculpture).
The results of both methods can later be combined for generating various visualizations of the sculpture including the digital reconstruction of vanished parts of the statues like the crown or the loincloth, which originally were made of wood covered with a layer of gypsum colored in gold.
The small statue was recorded using the same techniques and procedures as with the bigger one. Problems occurred regarding the recording process: The statue is mounted onto a base of plexiglas and also it is fixed at the back with a plexiglas structure which could not be removed for the documentation process. As optical methods for recording are used, the refraction of the light passing through the plexiglas should be modeled for the data captured from the back of the statue, which seems to be anywhere between difficult and impossible. Thus, these data sets have not been processed until now.

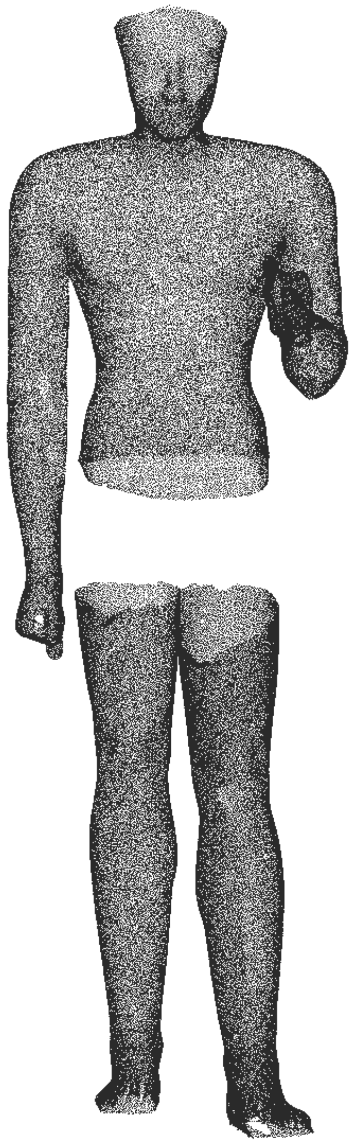

Figure 2. Registered point cloud from laser scanner.

LASER SCANNING

The statues were scanned using a MENSI S25 scanner. This scanner can be used in a range between 2 m and 20 m and can reach an accuracy of about 0.3 mm for the closest distance under optimal conditions. It is a triangulation scanner that sends out the laser beam at the one end of the scanner base and records the 3D position of the reflected point using a digital camera at the other end. The base for this scanner is about 80 cm. The opening angle in this plane is about 45°. Additionally, the scanner can rotate around its horizontal axis and in this way has a vertical opening angle of 320°. The accuracy of a point measurement is dependent on the distance to the object due to the triangulation concept of the scanner. The scanner can measure with a rate of 100 points per second at most.
As the calibration of the scanner was not optimal for closest distances at the time of recording the sculpture, the accuracy of the derived surface model can be expected to be about 0.5 mm. This should be sufficient for measurements to be taken at the model, e.g. the distance between certain points on the statue, but this model does not allow an accurate reconstruction of the sculpture, which was not intended in this case, anyhow.
One challenge in scanning complex 3D objects like this statue is to cover the complete surface with the scanning process. This is supported by software tools allowing the visualization of the scanned point clouds, usually supplied by the scanner's manufacturer with the software controlling the scanning process itself. It is highly recommended to do further checking by triangulating the surface to visualize possible holes that are often not easily to recognize by just inspecting the point cloud.
The process of scanning the bigger sculpture took about 6 days. The working hours of the single days were short due to the opening hours of the museum and the fact, that the scanner was not allowed to be operated unattendedly during night time. In this time, altogether about 1.8 million points on the surface of the statue were scanned from 29 different observing points. The scans were performed with a mean point grid on the surface of the statue of about 1.0 mm for every single scan. This point grid is densified considerably as the surface is usually covered in multiple scans from different directions. With regard to the accuracy of the scanner and the time for scanning, an even more

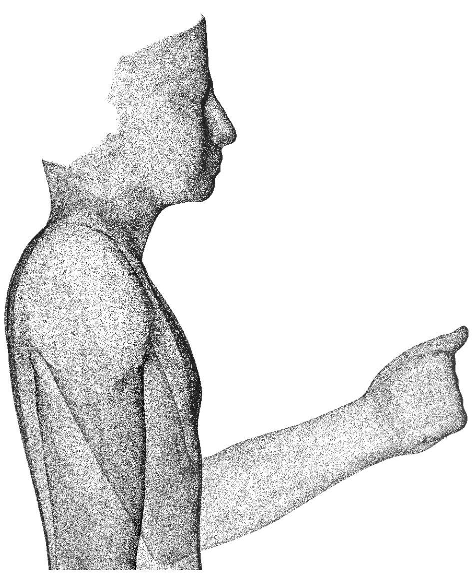

Figure 3. Detailed view of point cloud.

dense grid would not result in any improvement.
The quality and the processing speed of all following steps of treatment of the measured points are strongly dependent on the software used for this purpose. MENSI provides the 3Dipsos software which is designed primarily for engineering projects with the extraction of CAD-features from the point cloud. The treatment of irregularly shaped surfaces including triangulation and model generation is possible but is not always very effective.
The single scans are registered into a common coordinate system using red spheres placed around the sculpture. The center of each single sphere is modeled in the software and the points of the scans are transformed using these positions of the spheres as common tie points. At least three spheres are needed for every observing point. The accuracy of these transformations is limited to the accuracy of the positioning of the points and thus, especially in close range applications, often not sufficient, therefore. The point clouds of the single scans were registered more accurately using the point clouds themselves for the calculation of the transformation parameters, as provided by the 3Dipsos software. The result of this registration process was an oriented point cloud of the statue. Because of the overlapping scans of parts of the surface, the density of the points had to be reduced using a spatial sampling resulting in a point spacing of 1mm. The resulting model consists of about 1.000.000 points on the surface of the statue (fig 2, 3). The following steps are the elimination of wrong points, e.g. occurring at edges, and the smoothing of the point cloud.
3Dipsos provides two different approaches for the triangulation of the point clouds. Firstly, a true 3D triangulation which requires a regularly spaced point cloud. The second method uses projection surfaces like planes, cylinders or spheres, and performs a 2.5 D triangulation on this reference surface. This can be useful for building the mesh, e.g. for a part of an arm, but on the other hand leads to single mesh arrangements that must be stitched together to achieve a complete model of the statue.
The time needed for the generation of the complete model was a multiple as compared to the time needed for scanning. Reasons for this are firstly the poor calibration of the scanner which led to a higher noise in the recorded points and secondly the software that provides only basic support for the generation of triangulated surface models and thus is not optimal for this task. The noise in the data itself also led to a higher effort in time for the model generation, as a higher effort is necessary in the preliminary treatment of the point cloud (cleaning, filtering) prior to the modeling of the surface.

PHOTOGRAMMETRY

The parts of the statue containing seams between the copper sheets and rivets were recorded with stereo models using an analogue middle format camera Rollei 6008 metric.
For the orientation process of the single stereo models, point markers were stuck onto the statue. 16 convergent images were taken in addition to the stereo images. The distances between selected marked points were measured directly to introduce a scale into the following calculations.
After measuring the image coordinates of all marked points in all images, a bundle adjustment was calculated to determine the 3D position of the marked points . The coordinates of the points could be determined with an accuracy of about 0.3 mm.
The features on the statue were plotted using an analytical plotter Zeiss P3 with MicroStation® as connected CAD-system. The features to be plotted were attributed very simply using different layers for rivets, rivet holes, the contours of missing parts of the statue, the construction holding up the statue and other details like the remains of the crown or the loincloth. The final 3D vector data set can be viewed and plotted in various projections showing the metric correct position of these features in the plots (fig 4).

Figure 4. Vector plot.

VISUALIZATION

For all further visualization tasks, 3D Studio Max®, a 3D visualization and animation software, was used. The data transfer was realized using Wavefront OBJ and AutoDesk DXF formats.

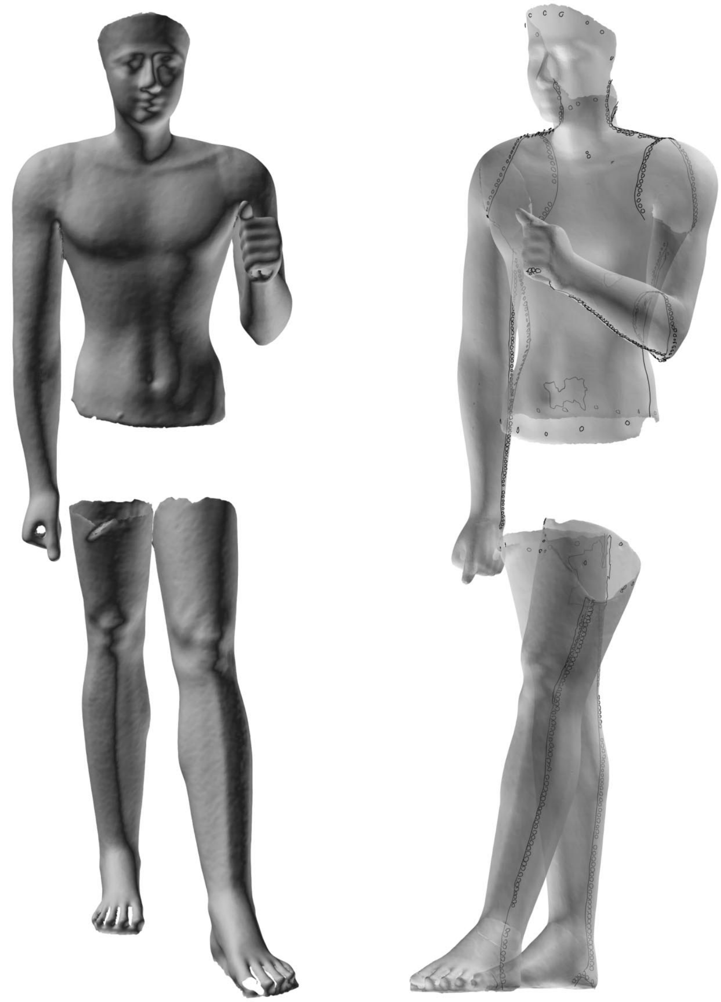

Figure 5. Left: Shaded view of the sculpture's model. Right: Combined with vector features.

With the full set of functionalities, many different visualizations can be performed. A simple one is to assign a texture to the sculpture that is similar to the current or supposed original appearance of the sculpture and show it from different directions. Video sequences, e.g. rotating the camera position around the sculpture, can easily be generated in this way. Such an animation assists the observer in achieving a good 3D impression of the object.

The vector data can be emphasized when combined with the surface model. By assigning semi-transparency to the model's surface, the position of seams and rivets can be viewed in 3D even though these features are not visible in reality (fig 5).

Additionally, parts of the sculptures that have vanished in the past can be reconstructed digitally and switched on and off for viewing. Thus, the most probable original impression of the sculpture can be generated without changing the real sculpture itself. The crown and the loincloth of the sculpture were created using photos of comparable objects from other sculptures.

MEASUREMENTS

Using the model of the sculpture, measurements can be performed that are not possible with the sculpture itself. Using rather simple software tools, point coordinates or distances between points can be measured as 3D distances or differences parallel to selected coordinate axes. Points without direct connection in between can be used easily.

Thus, measurements can now be done without the need to use the real sculpture itself with sufficient accuracy. This will be an advantage when the sculpture will be in the exhibition of the museum again, or not accessible at all to scientists interested in further investigations.

CONCLUSIONS

The used approach for the geometric documentation of the statue of Pepi combines the prospects of the two methods used. The documentation of the seams and rivets with close range photogrammetry represents established standard technologies. The digital surface model of the sculpture generated from laser scanner points allows measurements on the one hand and is suitable for various kinds of visualizations, in addition. The digital reconstruction of perished parts as well as animations can be made using these data.

The accuracy of the digital model is not sufficient for an exact reconstruction of the sculpture, which was not an objective of

this project. In such a case, another scanner with higher accuracy using different techniques (e.g. structured light projection) should be used. The size of the sculpture and the accuracy needed is near the limits of the used scanning hardware.
Comparing the simple line drawing of the seams and rivet features only (fig 4) with the combination of 3D model and line drawing (fig 5) shows the much higher information content of the latter. It is much easier for the observer to relate the line features with the corresponding areas of the sculpture and at the same time see all features, even those actually hidden by the sculpture itself.
The digital representation of the sculpture can additionally be used for measurements and visualizations distant from the sculpture itself which can only be accomplished with such a virtual 3D model.
Further results and visualizations of the sculpture will be published in a separate report covering the whole process of its restoration, conservation, technological investigation and documentation.

PROBLEMS

Various problems occurred, respectively had to be solved during this project. Beginning with the on-site work the temperature during the scans was at the limit of the hardware specifications. The scanner can be operated at temperatures up to 40° C; the actual temperature inside the scanner was 39° C sometimes. In the worst case external cooling is possible using a ventilator.
The limited opening hours of the museum lead to an extension of the recording time, but were not a problem in general. An important factor for the recording time is the scanning rate of about 100 points per second at best. This is quite slow as compared to ranging scanners or light projecting systems. The most important advantage is the accuracy in the range between 2 m and 10 m, which is unrivaled at present.
The fact, that the calibration of the scanner was not optimal for close range applications in spite of a manufacturer's calibration immediately before the project, led to a reduced accuracy of the scanned points and a higher expense for the generation of the model.
The software used is workable for generating irregular object models, but far from optimal. The current situation is that optimal packages are not available at present (cf. Böhler et. al., 2002).
The whole equipment including the scanner itself, tripod, power transformer, etc. in a transportation box has a complete weight of about 150 kg. It was shipped from Germany to Egypt by airfreight. The time for transportation and possible delays must be considered as a period when the scanner cannot be used for other projects.

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zip
Ein Projekt im
Zukunfts-
investitions-
programm
der Bundesregierung

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