Digital reconstruction of archaeological objects using hybrid sensing techniques – the example Porta Nigra at Trier

Boochs F., Hoffmann A., Huxhagen U., Welter D.

i3mainz, Institute for Spatial Information and Surveying Technology

ABSTRACT

Digital reconstruction of archaeological objects may serve for different purposes and accordingly vary in the information provided. Simple web-based visualisations primarily need textural data combined with more or less accurate spatial geometry, classical documentations require complete and precise 3d-models allowing to eventually rebuild the object in case of damage, whereas basic research to the object itself, the history of its edification, the origin of the material used and the analysis of exiting damages demands a maximum of textural and geometrical information. In correspondence to these aims techniques for the data collection have to be selected, which will result in higher effort and higher demands to performance and versatility when more complex reconstructions are needed.
Looking at the actual technological progress, 3D-scanning, both structured light and laser based, and digital photogrammetry, for example, are providing possibilities to collect maximal information at a large spectrum. On the other hand, the potential of these new technologies sometimes will be overestimated, whereas effort and need for an adopted processing of data and a customised use of instruments often is underestimated. If therefor seems necessary to give a look into an interdisciplinary project of historians and surveyors dedicated to evaluate the value of these new sensing technologies.

1. INTRODUCTION

Several buildings and monuments, especially historic sites, have a certain history which has to be investigated. In the past, the most common proceeding has been analogue measurements assisted by simple tools and documentation media. Today, the work of art historians is still characterised by those methods.
An important benefit to analyse a monument is implemented by hand-based measuring methods which provide documentation for different levels of detail (geometry and text). Those surveys allow giving a variety of answers to the complex questions surrounding an ancient monument.
In the environment of monument conservation hand-based measurements are kindly regarded as standard. The procedure of those surveys makes use of the observers contact with the object and are usually leading into coloured analogue contour plans or digital raster information due to the applied simple measuring instruments.
In the field of surveying, the application of digital workflows is well progressed. In view of surveying engineers, data acquisition and its processing as well as the presentation of multimedia content is a well established practice – however, their use for the preservation of historical monuments is not well developed.
In this context modern technologies like Tachiometry, 3D laser scanning and digital photogrammetry have been tested at the Prota Nigra with regard to the requirements of historians, in order to show their potential for these aims. The presentation of the results is part of this paper which shows pros and cons of digitally acquired and handled geometric data for the use of monument preservation.

Figure 1: *The Porta Nigra in Trier, partly mapped with a digital surface model*

2. HISTORY

The Porta Nigra was built as the northern city gate of the city Augusta Treverorum (today's Trier) at the end of the

2nd century AD. At the time it had the name Porta Martis. Later it became the name Porta Nigra (black gate) because of the dark colouring of the sandstone caused by the weather. The durability of the construction method is of particular interest, because the building resists weather and enemies since more than 1700 years without the use of mortar. It's the only holdover of the roman city wall.
After the retreat of the romans, the Porta Nigra was unused for 600 years. Then, in the middleage (11the century), it was rebuilt to a so-called double church. In the upper floor was an abbey church, underneath a church for the people. About 1150 the archbishop extended the building with an apse at the Eastern tower. Nowadays, this polygonal choir is of art historical interest and ranks among the main works of the Romanesque architecture of the 12th century.
After the conquest of Trier by the French at 1794, the revolution troops took the roof of the church off and carried off the whole interior decoration. Because of the subsequent disrepair of the fane, the constructions of the middleage has been largely removed, except for the apse in view of static reasons. The basis of the building has been laid open to the level of the Romans time and all parts of the building have been roofed. Since 1986, the Porta Nigra is World Cultural Heritage of the UNESCO.

3. TACHEOMETRY

Although often used for the complete surveying of objects the most important task of tacheometric measurements is the establishment of a stable and precise geometric frame. This allows to build up a base for all subsequent measuring techniques and was provided by a geodetic network derived from over determined measurements from inside and outside the monument. To these data a least squares adjustment was applied, verifying a sufficient accuracy for all observations (3D point accuracy of about 1mm).
As a first survey in the project tacheometry was used to record ground plots of the Porta Nigra, which obviously is one of the most easiest methods of geometric data acquisition.
The discussion of the results with art historians showed, however, that a data capture in the opinion of a surveyor, trying to find an idealized and generalized ground plot, is not acceptable for the use of a detailed building research analysis. It turned out, that in contrast to usual hand measuring methods that explicitly go into detail, the recorded results showed too large deviations to the buildings true shape.
As a result, this experience pointed out that the work of an art historian always demands for a contact with the object to investigate important and characteristic sections of the monument. For this reason, a collaboration of surveyors and art historians seems to the best choice to provide valuable and accurate measurement results.
The use of tacheometry in the context of a detailed building analysis helps at most for the geometrical registration of trivial building structures, at best in 2 dimensions. This could be done with the help of a specialized interpretation by experts.
Tacheometrical instruments have a big potential of geometrical accuracy. On the other hand, it has to be considered, that only a limited number of discrete points can be recorded. With increasing the number of measured points, the tacheometry gets economically unattractive compared to other techniques like 3D laser scanning and photogrammetry.
A great profit of tacheometry is the determination of reference points for the applied 3D laser scanning and photogrammetry. The targets can be acquired with the help of reflectorless distance measurements – a state of the art implemented in modern tacheometers.

4. LASER SCANNING

Laser Scanning Survey

Laserscanning is an increasingly popular measuring technology, allowing to simply generate the full geometry of even complex objects. We used a *Cyrax 2500 from Leica Geosystems* (*Cyra*), a so called camera-view-scanner with a 40°x40° field of view. The angle sensing is realized with two rotative mirrors which are situated in the optical path of the laser, which divert the rays in horizontal and vertical direction. Here, the reflectorless distance measurement is implemented with the time-of-flight principle. The scanning speed is about 1000 points per second.
According to manufacture's data the accuracy of a coordinate measurement is about 6mm@50m whereas the dependence to the characteristics of the surface must be noticed. Influencing factors can be color and roughness of the material as well as the convergence angle of the measurement beam and the geometry of the surface.
The effect of the material color is small and is situated within the measurement accuracy. Of greater influence is the reflectance characteristic of the surface, resulting in failures in case of low reflected energy. The roughness of the surface affects the measurements because the distance sometimes will be interpreted not correctly. Significant influence to the reliability and accuracy of the distance measurement has the convergence of the measurement beam and the geometry of the surface. *(Kern 2003, pp. 40-46)*
With the 3D laser scanner applied, almost the whole basement of the Porta Nigra could be acquired with a resolution of about 0.5 cm. Additionally a large section of the upper parts of the monument was recorded with a resolution of 1cm and also some parts of the apse. Altogether 51 viewpoints were needed to acquire in total about 132 million points. This corresponds to a space requirement of 5.1 GB on the data medium.
Significant problems occurred with regard to the dark, in some places nearly black surface of the monument. From a distance of 40-50m to the monument, the scanner acquired only few points, as the reflecting signal was too poor.

Another problem in this special case was the public-transit-traffic. During the acquisition we got to know, that the data which were matched from the eastern position of the Porta Nigra have been very noisy, because of the traffic amount in the adjacent street. The orientation of these point clouds resulted in a four times higher standard deviation as in those without these influences. One reason for that effect is the impact of vibrations on the instrument due to public service vehicle traffic.
To transform the point clouds in a reference coordinate system, reference points (*HDS*-targets, spherical targets) were fixed on the object and were coordinated with a reflectorless measuring tacheometer.

Analysis:
At first, all point clouds had to be freed from erroneous points which were measured on passing tourists or past the object. Afterwards a global registration was accomplished with the help of the reference points. These manipulations have been accomplished with the *Leica* software *Cyclone*.

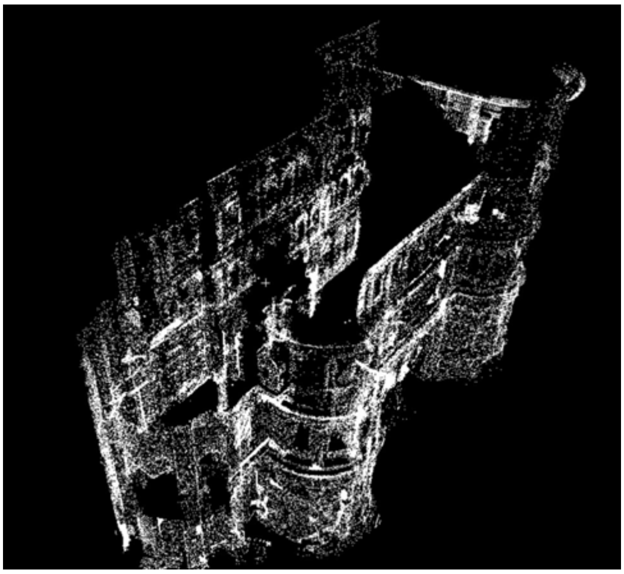

Figure 2: *3D point clouds after orientation*

The next modelling steps have been realized with the software *Geomagic* from *Raindrop* within smaller clouds of about 10 million points, in order to keep the workload for the hardware in acceptable limits during the following calculation.
The data had to be cleaned from meshes, which have been placed on the monument as protection against doves. This needed a high manual effort whereas it is not guaranteed that the data are clean of defects. A better solution would be to get off the dove meshes previously to get correct data.
After the cleaning of these obstacles, all outliers have been analysed and deleted with an automatic algorithm. This filter searches all points exceeding a certain distance to the point clouds, assuming a larger distance for wrong points.

Another kind of degradation is caused by the reflectorless distance measurements being used from 3D laser scanner. This is a random type noise, which is superimposed to the true distance measurement. It describes the deviation of the point from its true position. The deviation depends on the reflection characteristics and the geometry of the measured surface, as well as the angle of incidence of the measurement beam. The spot of the laser is not infinitive small, which means it hits the surface in a certain area. Especially at edges measurements cause a high noise, because only a part of the spot hits the edge. *Raindrop Geomagic* includes a filter to clean up the noisy data.
However, it has to be noticed that a loss of details results from a noise reduction. It is always a compromise between a smoothed and easy to model surface and the visibility of details. Unfortunately some important details like exact edges of the sandstone cuboids have been flattened, which downgrades the usage of the data for detailed building research. In this concrete aspect it is of importance how a scanner works. There are large differences between the technical characteristics of existing instruments, what might lead to strong variations in the quality of the data resulting in correspondingly strong variations in the potential for further usage.
After noise reduction, the point clouds have got orientated among themselves by means of a best-fit-algorithm. Afterwards all point clouds were merged to a single one. Additionally the quantity of points had to be reduced, as the density of points in the overlapping area was much too high. Because of a homogeneous density of points, one gets a homogeneous point cloud used to create a triangulated surface.
Despite a detailed editing, several holes resist in the surface. A time intensive manual post processing of the triangulation network is therefore needed. Only smaller holes on less curved surfaces can be filled automatically. As the surface is really irregular it is quite impossible to assume a correct course of the surface by an algorithm.
Such big holes emerged from shadows in view direction on one hand and on the other hand mostly due to the sparse density on the dark surface.
Finally a complete 3D model has been received representing the closed surface of the object. However, this surface model does not fulfil all requirements of art historians. They need a very detailed description as especially for areas of importance like edges and joints. But here the geometric accuracy and the level of detail necessary cannot be guaranteed. Because of the irregular surface, there is no sense to construct edges.
Nevertheless there are several advantages for the work of art historians like the possibility to quickly produce of a rough surface model allowing to give an object’s overview, as base for other measurement techniques as well as for the analysis of small scaled relations and proportions.

5. STRUCTURED LIGHT PROJECTION

Structured light projection is another scanning technique allowing to generate very precise and detailed 3D models. In order to show the potential of such a technology a high resolution recording of the memorial plaque of St. Hieronymus insides the monument has been performed. The size of the plate is 2.84m x 1.63m x 0.05m. As projector the *GOM ATOS II* was used, a digitising system that works with white structured light. The light pattern is projected on the object’s surface while two digital cameras record the reflected light. For good measuring conditions (bright object’s surface, few ambient light) 3D coordinates can be calculated for every pixel.
The scan volume can be changed by modification of the systems configuration. For this large object we used the maximum scan volume of 800mm x 640mm x 640mm, giving a point density of about 0.7mm for one measurement.
To record an object that is many times larger than a single scan volume it is necessary to define precise reference points for a global orientation of the individual scans. That was done by a photogrammetric triangulation. The photographs were taken with a calibrated *Fuji FinePix S1* digital camera (17mm lens), the subsequent evaluation was done with the photogrammetric software *ImetricS*, which detects the coded targets automatically and solves the bundle adjustment.
With the data of the reference points, the sensor can be moved as necessary to record all surface parts. The final result is a high-resolution 3D surface model which can serve for different aspects. One potential use could be the production of an accurate replication by means of molding tools Furthermore it is very well adapted, as opposed to the terrestrial laser scanning measurements, for the research of the historians due to the high accuracy. Drawback is the usability in just small areas and the high amount of data.

Figure 3: *High resolution 3D surface model of the memorial plaque of St. Hieronymus*

6. PHOTOGRAMMETRY

Photogrammetry plays a major role in terms of preservation of ancient monuments and architecture. On one hand the visual information in the images is of high value for an interpretation and on the other hand the geometric description is guaranteed. Furthermore images are easy to archive. The interpretation on a computer screen is possible by using effective computer systems with comprehensive functionality but they require mostly the knowledge of surveying technique. A fact, which needs to be reviewed during planning of a measuring campaign and which leads to a close collaboration between experts from various faculties.

Single image evaluation
In the range of architectural photogrammetry the method of single image evaluation is often used. The most widely-used method, which furthermore can be applied from non-specialised user, is the 2D photo rectification. The pixels of the images are reshaped to an rectified representation by means of a perspective transformation of points measured at the object. The result is a true to scale digital image with exact geometrical information. But the described method is only useful, when the recorded object is approximately flat. This is the case for house fronts which are the most likely application of this method.
Another simple usage is possible if the object contains more regular shapes like cylinders, for example. Then it is possible to compute a wrapped-off image of the measured picture with help of a resampling process. To use this method, the knowledge of the regular shape of the object as the interior and exterior orientation of the image are strongly needed to re-establish the relation between the position of the picture and the reference surface.
But also in general cases accurate results are possible when detailed information to the surface is available. Such a surface model can be derived from a 3D laser scan of the surface, for example. Then, the triangulated network represents the reference surface for a differential rectification. A product of this computation-consuming evaluation method are digital ortho-images which might be produced with high precision and valuable information, as . high resolution photographs can be rectified very accurately.
With methods from the virtual reality it is possible to map rectified images onto a point cloud or on a reference surface. With this, very impressive observation possibilities can be given.
Rectifications are used during the building survey as mapping basis or as a preliminary product for modelling work. They include a high density of information in terms of a pictographic representation, which should be used with certain reserves as they are often employed by non-specialized persons and are often underestimated in terms of accuracy.

Stereo image evaluation

For non planar objects a proper geometrical description needs a 3D data acquisition., what is supported by stereo photogrammetry. By means of two images and their known relative and absolute orientation it is possible to reconstruct object points by two intersecting rays. With his perception the observer gets a three-dimensional impression of the images and 3D coordinates can be determined like with analytic plotters. The result is a graphical representation of the object, reduced to significant contents in form of the representation of contour lines.

If the interactive evaluation is performed by surveyors, this might be critical due to the lack of specialized knowledge concerning the application. Therefore results are more valuable if the specialists for monument research do the interpretation themselves . This needs a close interdisciplinary collaboration between surveyors and historians in order to provide correctly oriented stereo images, because these technical steps might be too demanding for non surveyors

Multi image evaluation

High accuracy and feasibility is provided by a multi image evaluation. In opposition to the stereoscopic interpretation a defined geometric adjustment and not an exact number of images is needed. With the help of a triangulation all coordinates and orientations are calculated simultaneously. This well known photogrammetric task produces accurate object points which might be used for further steps and gives most reliable orientation values also being useful for following tasks like a 3D evaluation for example.

Interpretation of the Porta Nigra

The result of photogrammetric interpretations is mostly a CAD product. The user gets two dimensional plans and simple surface models being useful to show the results. Clear structured surfaces can be divided into their basic geometries with the help of which distribution of edges and contours is easy to understand.

The situation at the Porta Nigra is more complicated in this point of view. Continuous geometries are rare and nearly not existing for the view of a surveyor. The choice of significant points to document the characteristic geometry of the building must be done with the help of an expert.

A gapless digital 3D reconstruction model of the Prota Nigra can not be realised be any of the applied measuring techniques in an economic and scientific way. The combination of every technique's peak power is the key to a solid documentation of the monument, whereas high resolution photogrammetry can serve as base for further investigations. With the help of an high resolution image bundle it will be possible to find more sections of interest among guidance of experts of other profession. Those investigations could lead into a stereoscopic analysis at small-sized areas or to an evaluation of collected measurements at the building's surface.

Discussions with user from the preservation of monuments showed a necessary resolution of the images of at least 1mm/pix at the object to get a useful profit from the data. This only can be achieved by high resolution metric cameras. To show the potential we used a ICam28 from IMETRIC, providing high quality digital images (cf. Fig. 4).

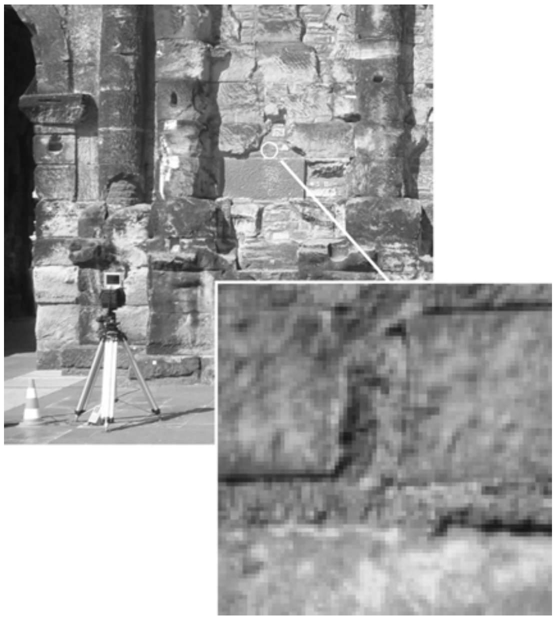

Figure 4: *Icam28 in action at the Porta Nigra, the resolution corresponds to 1mm/pixel at the object*

In addition, a combination of photogrammetry with an information system would give the possibility for a combined use of geometric data and content documentation allowing to simultaneously use geometric and semantic information.

7. CONCLUSIONS

All applied measurement techniques in this project have their respective strengths and their limitations as well. There is no overarching procedure for the digital reconstruction of archaeological objects. In fact a bundle of combinations of the several measurement techniques is needed to get a monument documentation of high quality. In the following, the strengths of the several procedures with regard to the particular tasks by means of the obtained cognitions of the Porta Nigra project are illustrated.

To establish a rough model of the whole object, as overview and base for following activities, photogrammetry and laser scanning can both be used. For further tasks and for the accurate evaluation of contours photos are needed anyhow. For that reason a photogrammetric evaluation for the creation of a grid model is to prefer for economical purposes, because the evaluation of the laser scanning data emerged as very time-consuming at complex buildings, like Porta Nigra.

The advantage of 3D laser scanning is the detailed modelling for the complex, irregular surface for small scales. In addition more accurate analyses of proportional relations of several parts of the building can be done. Even the comparison of floor situations can be done as well. Height relations of arches and cupolas are good to interpret, at least in fact of the possibility of observation in different perspectives. For those analyses a partly acquisition of the Porta Nigra is recommendable.
If the requirements demand for a more accurate modelling of the surface's structure at large scaled space, such as ornaments or original vestiges of processing, the use of the high-resolution structured light projection is needed.
For additional analyses, concerning the purpose of building research, the results of laser scanning are not useful. The required details can not be detected, a disadvantage in contrast to the other measurement techniques applied. In addition, the geometrical accuracy does not achieve the historian's resolution requirements of the monument of 5mm at critical areas like edges and joints.
Advantage of photogrammetry and structured light projection is the comparatively short working time at the object. The analysis can take place in the office. Especially photogrammetry provides the opportunity to control image data capture and the subsequent photo triangulation by a geodesist, while the analysis and the consequent interpretation might be done by a briefed historian.

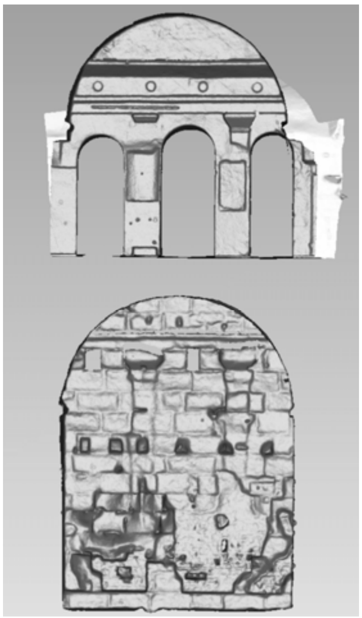

Figure 5: *3D model of vertical intersection between apse and roman construction useful for coherence and proportion evaluation*

In spite of all modern measuring techniques it should never be forgotten, that the contact to the user (historian, conservator etc) never can be left off. A lot of relevant details concerning the purpose of building research can only be detected in contact to these specialists. These details are often acquired with a hand-based measurement or plotted into a 2D contour plan.
The different methods of measuring techniques for building documentation have to be seen from different angles and according to different requirements. From the high resolutive modelling of small building details up to the extensive documentation of geometrical and attributive data by hand measuring methods or the complete recording of the building it is important to proof the purposes and constraints of the acquisition at the beginning of any activity in order to get a result of high quality.
There is a strong correlation between content wise completeness and geometrical accuracy. The best geometrical accuracy is not sufficient when the data extracted doesn't match the needs of the specialist as well as a qualified specialised evaluation doesn't help without the adequate geometrical relation. The outcome of this is the imperative commitment to a interdisciplinary and methods combining strategy of monument surveying, within which the building survey is done in closely teamwork between the professional groups, which are interested in the result, and the specialists of the applied methods. *(Weferling 2002, pp. 149-152)*

REFERENCES

GOM Optical Measuring Techniques, 2005, *User Manual*.

Hoffmann A., Welter D., 2006, *3D-Aufnahme der Porta Nigra mit unterschiedlichen Messverfahren unter denkmalpflegerischen Gesichtspunkten,* Diploma thesis at Universitiy of Applied Sciences Mainz.

Kern F., 2003, *Automatisierte Modellierung von Bauwerksgeometrien aus 3D-Laserscanner-Daten*, Dissertation at Technical University at Brunswick, Geodätische Schriftenreihe der Technischen Universität Braunschweig, Nr.19.

Marbs A., 2002, *Experiences with Laser Scanning at i3mainz*, CIPA, Heritage Documentation - International Workshop on Scanning for Cultural Heritage Recording, pp. 110-114, Corfu, Greece.

Weferling U., 2002, *Bauaufnahme als Modellierungsaufgabe*, Dissertation at Brandenburg Technical University at Cottbus, Retrieved 2002 from Deutche Geodätische Kommission at Verlag der Bayerischen Akademie der Wissenschaften, München