

# Terrestrial Laser Scanning Applied for Reverse Engineering and Monitoring of Historical Buildings

Ivo MILEV and Lothar GRUENDIG, Germany

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## SUMMARY

A main advantage of terrestrial laser scanning is the possibility to nearly simultaneously acquire the geometrical positions of millions of object points in 3D. However this is also the main bottle neck of terrestrial laser scanning when it comes to data processing.

In this paper a new strategy will be proposed, presented and applied in order to show how to overcome the discrepancies. The modelling and processing will be done based on surface parameters which will be efficiently derived from point cloud measurements. It will be shown, that there is no need for a triangularisation of the points prior to a derivation of significant surface parameters. In such a way enormous data reduction will be achieved.

It becomes feasible to combine adjacent scans completely based on identical surface parameters derived from natural objects detected automatically in both scans. Natural objects may be used for geo-referencing as well.

Characteristic lines can be derived from the intersection of surfaces. Due to the high point density of the scan, an increased improvement of the accuracy of the surface parameters will be achieved even for small extensions of the detected surfaces. Then even deformation analysis of walls of buildings can be based on surface parameters. From the surface parameters and a defined boundary line and boundary plane also the volume under the surface can be easily determined.

It has to be taken into account that complex structures from the cultural heritage point of view require a structuring of the scatter points with emphasis on the preservation of monuments. The key elements of that modeling are feature lines. This necessary information can be obtained by analyzing of 3D Orthophotos of the objects.

Examples from building monitoring and the automatic determination of the volume of excavation are presented in order to demonstrate the efficiency of the concept. An additional advantage is the rapid and reliable data acquisition.

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## 1. INTERPOLATION FUNCTION

Repair and maintenance of historical architecture includes reinforcement of configuration, repair of figures and so on. For these tasks surveying information is needed. 3D laser scanning technology is one of the important technical methods to acquire spatial data. The architectural geometry is scanned quickly point by point; point clouds are registered and joined in order to generate the shape in the computer; finally a 3D model is reconstructed accurately. Construction drawings including ichnography, elevation, and cutaway can be produced. In addition, detailed structure and vignette can be obtained via close-range photogrammetry methods, which allow producing the orthoimage and line drawings. This technology is especially suited for surveying historical architecture where construction records are missing.

### 1.1 General Spline Definition

A main prerequisite for object representation is an efficient interpolation concept in order to correctly determine a best fitting surface function. Then the task to determine the volume between two surfaces would consist of a simple integration process.

To model a suitable interpolation an approximating function  $g : I \rightarrow \mathfrak{R}$  will be chosen. Based on supporting positions  $t_1, \dots, t_m$  a spline function  $f(t_i) = g(t_i), \forall i$  will be searched for. It is to be expected that for a sufficient number of supporting positions and for the corresponding sequence of nodes  $f(t) \approx g(t), \forall t$  holds. One criteria to guarantee the solvability of the problem is a regular distribution of the interpolation points. Alternatively a definite spline function  $g$  could be chosen in advance. Then the sequence of the nodes will be available and  $g$  can be evaluated, and used for the derivation of the control points of a B-Spline. Based on suitable supporting positions  $t_1, \dots, t_m$  the interpolation problem becomes solvable.

Choosing unit vectors of the right hand side of the system of equations for the interpolating problem the solution can be modelled by the Lagrange-function  $L_k$

$$\partial^{#j} L_k(u_j) = \delta_{jk}, \quad j = 1 : m \quad (1)$$

The Lagrange-function  $L_k$  decreases exponentially.

$$|L_k(t)| \leq \alpha \exp(-\beta |t - u_k|), \quad (2)$$

where  $\alpha, \beta$  are positive constants, depending on the sequence of the nodes and the distribution of the supporting positions. As shown in (Milev 2001) the solution of the general interpolation problem can be expressed by a linear combination of Lagrange-functions:

$$f = \sum_j L_j g_j \quad (3)$$

Due to the property of decrease of the Lagrange-function the interpolation process acts approximately local. This algorithm will be used in the functional patches during the modelling process (Milev 2006). For a better data handling the described spline approach is reduced to a NURBS representation in order to decrease the complexity.

## 1.2 Laser Data Processing

The applied concept has its base in optics, machine, electro technology and computer techniques for processing and modeling. The measurement and processing includes: scanning of the object outline point by point; gaining spatial coordinates and color information of points on the surface; joining the data to generate the shape in the computer and finally constructing the architecture model accurately.

### 1.2.1 Automated Plane Detection Based Registration

The detection of planes is done separately for each scan in the corresponding image matrix. Rows and columns of the image matrix represent the discrete vertical respectively horizontal angles of the points in the coordinate system of the scanner. Within an iterative process the image matrix is split into sub matrices. After each iteration step an adjusted plane is calculated approximating the points contained in the resulting sub matrices. The iteration process continues as long as a sub matrix stays planar or the stop criterion is reached (Gielsdorf, 2008). The identical planes in each scan pair are used for an automated registration process.

### 1.2.2 Surface Modeling

**Freeform surface**, or **freeform surfacing**, is used in modeling and other computer graphics software to describe the skin of a 3D geometric element. Freeform surfaces do not have rigid radial dimensions, unlike regular surfaces such as planes, cylinders and conic surfaces. They are used to describe forms such as turbine blades, car bodies, boat hulls and complex building forms. Any object is represented by a single real function of point coordinates. A point is outside the object if the function is negative, inside the object if the function is positive, and on the boundary if the function is zero (isosurface).

All the examples shown below use the proposed modeling method and are part of the processing software product SiRailScan.

## 2. REHABILITATION WORKS AND REVERSE ENGINEERING

“Reverse engineering is a process to achieve understanding of the structure and interrelationships of a subject system. It is the goal of reverse engineering to create representations that document the subject and facilitate our understanding of it – what it is, how it works, and how it does not work.”

### 2.1 Parish Hall Project

The project to be modelled via reverse engineering is a building that has not been used for the last 15 years but became now subject of a complete renovation. After removal of an intermediate roof a well preserved cylindrical inner roof construction appeared. As no plans existed and the shape of the roof was not trivial laserscanning of the object was chosen to generate plans of the actual 3D situation for the architect.

Scanning Stations	Points
	[Million]
Front	25
Back	25
Left	20
Right	20
Corner 1	22
Corner 3	22

**Table 1.** Scanning program

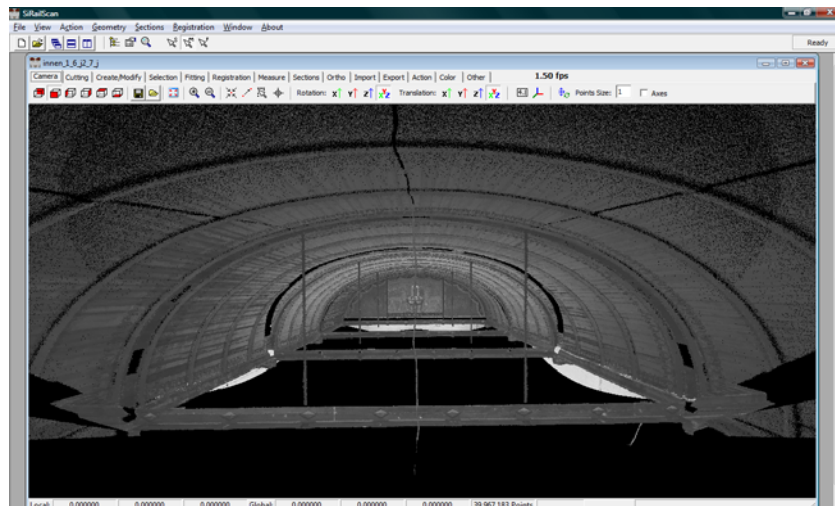
#### 2.1.1 Measuring Program

6 instrumental scanner positions were chosen around the building for modelling the outer shape of the building. Table 1 shows the amount of data gathered in those scans. The connection to the inner cylindrical hall was achieved by 2 scans taken from the window-sills. One scanner position was chosen in the middle of the hall generating a scan of maximal density (fig. 2). The information about colour which is very useful for a better identification of details was supplemented from free hand photographs (fig 1).



**Figure 1.** Coloured point cloud of the facade

The constructive conditions of the scanner which are based on a 360 degree rotated lens do not allow a direct hardware matching between point cloud and photo. The used coloring technology provides a high degree of flexibility during the whole project time.



**Figure 2.** Cylindrical roof of the hall

The measured point density for describing the roof form was 5 mm on the object and therefore led to 35 000 000 points. This density allows also the derivation of orthophoto products direct from the point cloud without requiring additional images. The transversal cuts were produced based on the modelled surface. The exact volume covered by the cylindrical roof was determined for modelling the acoustics.

## 2.2 Church Ruin Bethanien Tower

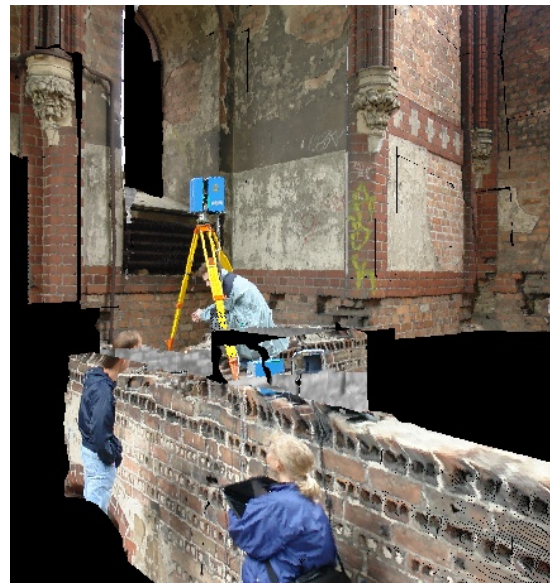
For documentation of the current condition of the church ruin “Bethanien tower” – Weissensee Berlin three different grades of processing complexity were applied:

- Point cloud with gray scale coded intensity - Figure 3
- Modelled gray scale point cloud
- Modelled point cloud with RGB interpolation-Figure 4

After 3D modeling a comparison between surface and point cloud was performed. Figure 4 shows the modeled and post colored 3D solid surface.



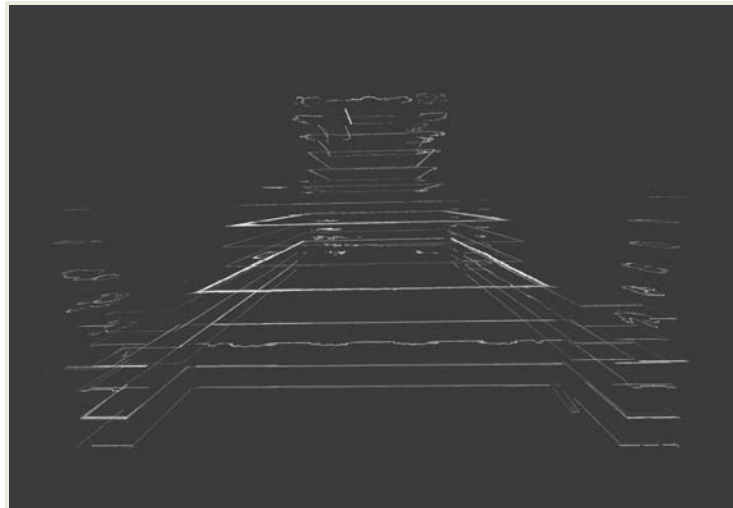
**Figure 3.** Raw gray scale coded point cloud



**Figure 4.** Colored 3D solid model of the wall

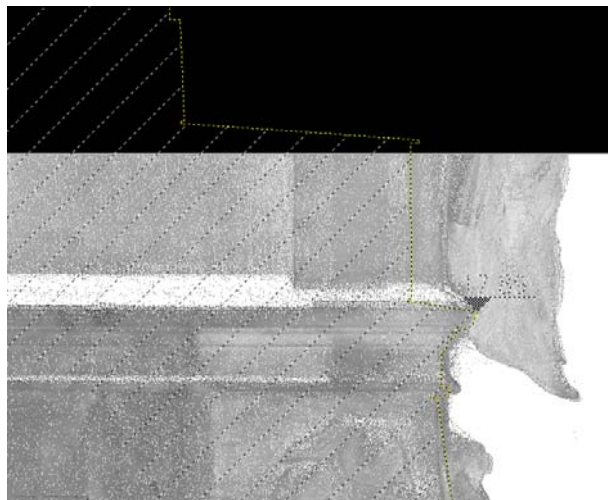
### 2.2.1 Line Drawings

Line drawings based on the orthoimage or vectorised sections can be produced following our concept. As shown in figure 5, the line drawings of horizontal cuts fulfill all measurement requirements. Drawings prepared in papers in digital form must be in the appropriate location in the document.



**Figure 5.** Horizontal Sections through the point cloud

The sections shown on Figure 5 are produced in an automated way with a section step of 10 cm. This “tomographical” method to build sections is only possible if the measured data density is based on the laser scan technology. The huge amount of data captured allows for a flexible data processing based on different requirements as the object is completely represented.



**Figure 6.** Gaps between Ortho image and CAD simplification

For a creation of drawings the reflection of building parts based on the main axes is not recommendable. The stone made facade parts are individual. A “copy and paste” method for generalization of elements is not usable. Figure 6 shows the differences between the reflected CAD drawing and the laser scan based - georeferenced ortho image.

### 2.3 Rehabilitation works at the Mew Palace Sanssouci Potsdam

The **New Palace** is a castle on the western side of the park Sanssouci in Potsdam. It was built between 1763 and 1769 under the reign of the Prussian king Frederic the Great.



**Figure 7.** Horizontal Sections

The old anker construction has to be replaced with a ne steel frame construction. This prefabricated bended balks must to be fit inside the architraves inside a belt within 2 cm

Figure 7 shows a section after registration and georeferencing in the object coordinate system. The geometrical situation is visible now because the architraves are laid open for the first time after the construction works 200 years ago.



**Figure 8.** Vertical section through the roof with architraves

In order to determine the actual geometrical shape of the architraves (fig. 8) the only feasible measuring technique is laserscanning. The geometrical complexities and the planed accuracy for the new steel beams require a complete 3D documentation (see fig. 9). This can not be achieved using any other standard measurement technique.





**Figure 9.** Architraves

### 2.3.1 Planning products for Cultural Heritage Purpose

The end products derived from laser scanning are as shown below:

- Horizontal and vertical cuts
- Extracted feature lines
- Orthophotos
- Facade planes
- Extraction of feature lines
- True lengths

All these products are provided in common CAD data formats. The difference is the best description of the real geometrical conditions. The stones were handmade and of course uniquely for itself.

This project shows that the laser scanning method provides unique results in difficult restricted areas of construction engineering and also best covers the needs of projects from cultural heritage.



**Figure 10.** Actual conditions of the structure

### 3. CONCLUSIONS

The technological concept shown above allows one to describe complex surfaces by appropriate parameters without using triangulization. Converting the derived spline function into a NURBS is a useful simplification of the functional patches model. Storage space and visualization time are reduced considerably.

The solution concept allows the derivation of longitudinal and transversal sections through the modelled surfaces and raises the accuracy due to smoothing of the measuring noise.

The results achieved provide the information for simulations which are needed for constructing and for acoustic calculations. Surveying of historical architecture based on 3D laser scanning technology can not only reduce the time for field work and improve the efficiency but also provides additional products such as 3D models for visualization, and construction drawings based on new reverse engineering techniques.

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## BIOGRAPHICAL NOTES

**Dr. Ivo Milev**, born 1963. Graduated in 1988 as Dipl.-Ing. in Surveying and Mining Engineering from Technical University of Sofia. Obtaining doctorate degree in 2000 from Technical University of Berlin. Since 1998 Head of Engineering Surveying Development Group of technet GmbH Berlin

**Prof. Dr. Lothar Gruendig**, born in 1944. Graduated in 1970 as Dipl.-Ing. in Surveying and obtaining doctorate degree in 1975, both from University of Stuttgart. Since 1988 Professor of Geodesy and Adjustment Techniques at the Department of Geodesy and Geoinformation, Technical University of Berlin.

## CONTACTS

Dr.-Ing. Ivo Milev  
Technet GmbH  
Maassenstrasse 14  
10777 Berlin  
GERMANY

Tel. : +49 30 23625885  
Fax : +49 30 2154027  
Email: [ivo.milev@technet-gmbh.de](mailto:ivo.milev@technet-gmbh.de)  
Web site: [www.technet-gmbh.com](http://www.technet-gmbh.com)

Prof. Lothar Gruendig  
Technische Universitaet Berlin, Sekretariat H20 , Strasse des 17. Juni 135  
10623 Berlin  
GERMANY

Tel. : +49 30 31422375  
Fax : +49 30 31421119  
Email: [gruendig@inge3.bv.tu-berlin.de](mailto:gruendig@inge3.bv.tu-berlin.de)