ADVANCED GEOMETRIC MODELING OF HISTORICAL ROOMS

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ABSTRACT

To support the maintenance and restoration of *Schönbrunn Palace* in Vienna, Austria, as *UNESCO World Heritage Site*, an Integrated Facility and Asset Management System (IFAM) is designed. The IFAM will be based on a topologically and geometrically consistent data foundation. For that reason, an adequate method for data acquisition and modelling is essential.

Conventional methods such as tachymetry or photogrammetry are restricted in their automation ability. Thus, they require a great amount of human interactivity during data capturing and modelling. Nevertheless, they enable a precise determination of linear structures at a certain level of generalization. But they are insufficient, considering data capturing and subsequent modelling of continuous surfaces. On the contrary, terrestrial laser scanning is well suited for acquisition of surface data. Unfortunately, most of the modelling methods currently used are not able to determine structure lines directly.

In this article, a method for direct determination of such structures from terrestrial laser scanner point clouds is presented. Starting from these initial structures, a topologically consistent boundary representation is derived. The continuous surfaces between these boundaries are modelled by a triangulation. The closed surface model is textured using high resolution colour images. This workflow is shown as applied in *Schönbrunn Palace*. Finally, qualitative and quantitative capabilities of different laser scanners are discussed.

1. INTRODUCTION

For documentation, management, and reconstruction of cultural heritage, high quality geometric modelling based on adequate data capturing methods is essential. We are currently investigating a workflow for capturing and almost automated modelling of historical rooms from terrestrial laser scanning (TLS) point clouds.

Numerous methods perform robust fitting of simple geometric primitives and subsequent intersection of these objects (e.g. planes, cylinders, ...), assuming that the objects can be modelled by simple geometries (e.g. Abmayr et al., 2004; Leica, 2005). This assumption might hold for new buildings, but it is not realistic for historical sites at all. Other methods are based on a triangulation of more or less thinned out point clouds to derive a closed surface description (e.g. Guarnieri et al., 2004). Models of that sort may be used for visualisation purposes, but have deficiencies concerning geometric accuracy and modelling of characteristic structures.

On the contrary, our approach is initiated by direct derivation of structure lines from the original point clouds. Subsequently, a consistent topological network of structure lines, a so-called boundary representation (BREP), is generated. The surfaces between theses boundaries are modelled by triangulation, derived from the original points and according to the complexity of the surface. The final model is consistent in topology and it can be used for visualisation as well.

Alternative data capturing methods like photogrammetry or tachymetry aim at the direct determination of structures (e.g. edges) causing a high degree of generalization during data acquisition and thus, requiring a great amount of human interactivity. Furthermore, these methods are insufficient for capturing continuous surfaces. However, photogrammtry is well suited for the documentation of surface textures.

In section 2, terrestrial laser scanners used in our experiments are described and a general introduction to our structure line determination method is given. Section 3 describes the current status of the semi-automated workflow used for modelling and visualization of historical rooms. In section 4 the quality of terrestrial laser scanners and possible applications of geometric models derived from TLS data are discussed. The paper ends with an outlook for future improvements of the workflow.

2. SENSORS AND THEORETICAL BASICS

The *Schönbrunn Palace* comprises various buildings and a park with different vegetation, altogether some 1.5 km². Currently, an Integrated Facility and Asset Management system (IFAM) is designed, which is intended to support the maintenance and restoration of *Schönbrunn Palace* as *UNESCO World Heritage Site* in an economic manner, and to increase the efficiency of the provided services (e.g. tourism) (Dorninger et al., 2005). The fundamental basis of this system are geometrically accurate and topologically consistent models of the facility, based on adequate data capturing methods.

2.1 Instrument Specification

In the following experiments, two laser scanners have been used: A Riegl LMS-Z420i (Riegl, 2005) and a Leica HDS 3000(Leica, 2005). Tab. 1 lists main specifications of both instruments (POB, 2005). According to this specifications, theLeica instrument is more appropriate for near range geometric data capturing due to its higher accuracy and the larger field-of-view. Nevertheless, the Riegl system is much faster and it supports an on-mount camera system for high resolution texture capturing.

	Riegl LMS-Z420i	***Leica HDS 3000***
wavelength	*1,550 nm*	*690 nm*
power	*1 mW*	*14-23 mW*
range	*2-800 m*	*1-100 m*
accuracy (single/ave.)	*±10 mm /±5 mm*	*±5 mm /±2 mm*
beam divergence	*10 mm / 50 m*	*≤6 mm /≤50 m*
min. increment (v/h)	*0.008° / 0.01°*	*0.05° / 0.02°*
angular accuracy	*0.002°*	*0.0034°*
field-of-view (v/h)	*0-80° / 0-360°*	*0-270° / 0-360°*
max. sampling rate	*8,000 pts/sec*	*1,800 pts/sec*
camera system (texture capturing)	*Canon EOS 1Ds* *11 Megapixel*	*CCD-sensor* *1 Megapixel*

Table 1. System specifications of 3D laser scanners (POB, 2005).

To determine an appropriate angular resolution measure, Lichti

(2004) proposed the effective instantaneous filed of view (EIFOV) that models the contribution of both, sampling increment and beam width. He determined an EIFOV of 5.2 mm for the Leica HDS 2500 (similar specifications as HDS 3000)and of 10.9 mm for the Riegl LMS-Z420i considering the minimum angular increment at a measurement distance of 50 m.

2.2 Determination of Structure Lines from Point Clouds

In the past ten years, airborne laser scanning (ALS) became more and more important for topographic data acquisition, as it enables a high degree of automation compared to conventional(non-matching) photogrammetric methods. However, characteristic features, i.e. linear structures, cannot be determined directly by the measurement instruments.

To overcome this, Briese (2004a, 2004b) proposed a semi-automated algorithm to derive such structures from ALS. In contrast to raster-based structure line extraction methods (cf. Brügelmann, 2004), this method allows a formulation of 3Dstructure lines based on the surrounding point cloud data. The developed modelling framework is based on pair wise intersection of robustly estimated local surface elements. It can be applied to ALS as well as to TLS data and allows an adaptation to any kind of point cloud data (e.g. determined by image matching). Fig. 1 shows the basic modelling concept.

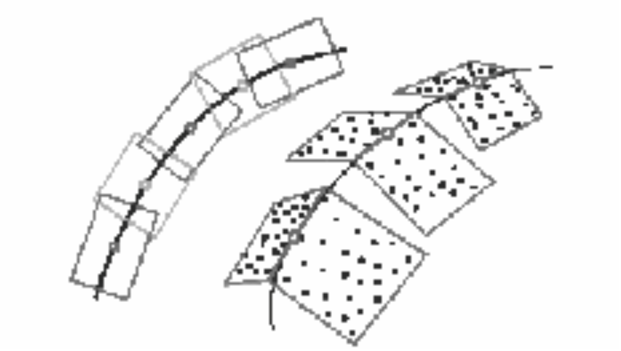

Figure 1. Basic modelling concept for the determination of structure lines with the help of intersecting patch pairs derived from surrounding point cloud data (Kraus, 2001, Briese, 2004).

In order to reduce the manual effort for the determination of initial values, a concept of line growing is implemented. This enables to determine a whole structure line based on one start segment or even based on one single point near the line. The determination of the surface elements can be performed in 2.5D as well as in 3D.

In the recent past, TLS became an attractive alternative to photogrammetry for close-range data acquisition, e.g. for capturing façades or the interior of rooms. Especially artificial objects are characterized by numerous sharp edges and linear structures. Thus, this method is predestined to be applied to modelling such objects. In order to reduce the complex 3D data selection problem in the surrounding of the lines in Cartesian coordinates to a simple 2D problem in the angular domain, polar coordinates are used (Briese, 2004b).

3. MODELLING AND VISUALIZATION

In this section, the semi-automated workflow for modelling and visualisation of one Bergl-room of Schönbrunn Palace is described. Johann Wenzel Bergl was a Bohemian painter working in the middle of the 18th century. The iconography of the paintings deals with the ideas of a baroque garden in combination with the absolutistic ideology of Habsburgs descent from the old Roman empire. The paintings are frescoes in the vaults and on linen on the walls and were created between1769 and 1779. These paintings are shown in Fig. 4 and Fig. 9.

3.1 Data Acquisition

For the acquisition of the room, a Riegl LMS-Z420i laser scanner with a Canon EOS 1Ds digital camera mounted on top of the scanner was used. The point clouds have been acquired with an angular sampling increment of 10 mm at 5 m measurement distance (~2 mio. points per 360°-scan). 360°-panorama scans were captured by 7 colour images at a resolution of 4064 by 2704 pixel and an overlap of 10%. 13retro-reflecting signals (cylindrical and flat) have been positioned for registration purposes.

Fig. 2 shows a map of the room. The four scan-positions used and the areas acquired from those positions are mapped as well. The first panorama-scan (SP1) has been acquired with a vertical rotation axis. It covers almost all walls and a great part of the floor (grey area). Two horizontal panorama-scans (SP2&4) have been acquired to cover the two window-axes and the ceiling(hatched area) and a fourth scan (SP3) was carried out with an oblique rotation axis to cover the remaining floor and parts of the walls (crosses) hidden in the other scans by the stove(represented by a circle).

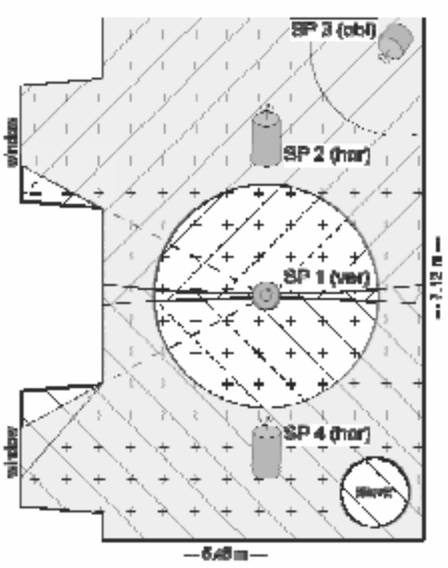

Figure 2. Map of the Bergl-room, showing the positions of the four scans and the areas acquired by these scans.

Capturing and registration of the point clouds and images has been carried out with the commercial software package RiSCANPRO (Riegl, 2005). For further processing, the following datasets were necessary:

- original point clouds in their scanner-own-coordinate systems (SOCS) in polar coordinates (~7 mio. points)
- transformation parameters from each SOCS to a common project coordinate system (PRCS)(the SOCS of SP1 was defined as PRCS)
- digital colour images (25 images)
- orientation of the images

For several reasons (e.g. multi-path reflections at the windows or at the chandelier), the original point clouds contained gross errors. Using a distance threshold and a neighbouring-distance-criterion, most of these erroneous measurements were detectable and have been eliminated (Fig. 3).

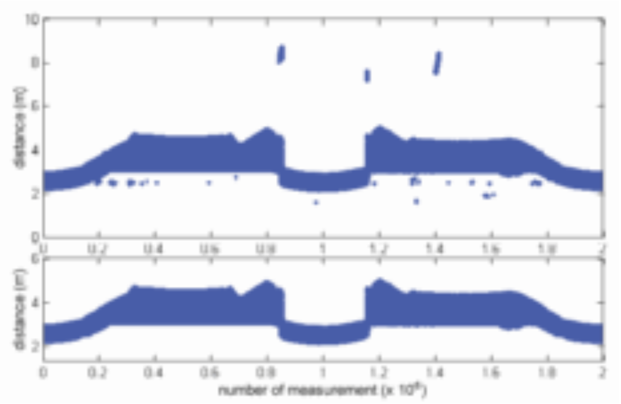

Figure 3. Measured distances from SP1
(top: incl. gross errors, bottom: after error elimination)

Fig. 4 shows a shaded relief after the elimination of gross errors and a coloured point cloud acquired at SP1.

Figure 4. Shaded relief (top) and coloured point cloud (bottom)of the 360°-panorama-scan at SP1 (polar coordinates)

By means of the 13 signals, the four scans have been registered with RiSCAN PRO. The mean standard deviation 0 of the registration is 4 mm.

3.2 Determination of Linear Structures

The method for determination of linear structures described in sec. 2.2 has been applied semi-automatically. Therefore, it was necessary to digitise 2D approximations in the SOCSs as initial values for the computation of 2.5D structure lines. This has been carried out for every point cloud individually using polar coordinates. Therefore, several structure lines were determined multiple times. Transforming all detected lines into the PRCS enables to compare different versions of originally identical structure lines. The mean difference between lines detected in different scans (up to four) was 10 mm (max. difference: 20mm). Considering the uncertain definition of the structure lines, these differences seem to be caused by this uncertainty rather than by the registration. Fig. 5 shows structure lines derived from the point cloud acquired at SP1.

3.3 Structure Line based Room Modelling

The modelling process is performed in the Cartesian PRCS. First, different occurrences of identical lines are detected and their points are merged. Identity is fulfilled, if the mean distance between two structures is smaller than a given threshold (e.g. 5cm).

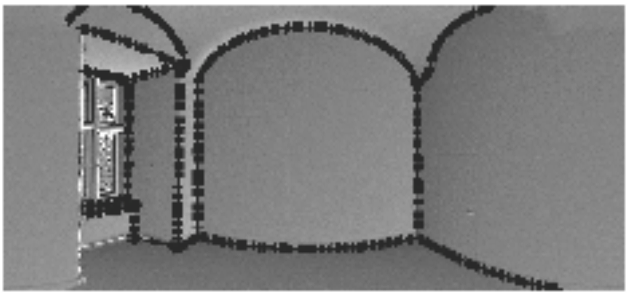

Figure 5. Result of the semi-automated detection of linear structures (part of SP1, polar coordinates).

Afterwards, the merged objects are replaced by a local 3Dregression line, if they can be modelled by a straight line according to a certain threshold (e.g. 2 cm). Structures which are not replaced by straight lines are thinned-out according to a given threshold (e.g. 2 cm). The mean standard deviation 0 of the generalised structures versus the originally detected ones is 5 mm. The result of this process is shown in Fig. 6 (transformed to SOCS of SP1 for visualisation purposes).

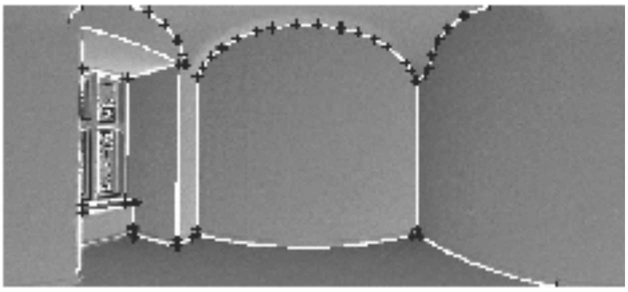

Figure 6. Structure lines after reduction of details according to given thresholds (part of SP1, polar coordinates).

As a matter of fact, multiple structure lines originally defining one corner of the room do not intersect, yet. In order to derive a closed boundary representation (BREP) with intersecting structure lines, the following method is applied.

The vicinity of the end points of structure lines (defined by a certain distance threshold of e.g. 5 cm) is investigated in order to find candidates for potential corner points. Final corner points are defined as mean positions of their respective candidates and the original endpoints of the structure lines are replaced by these unique corner points. In order to avoid displacements of long lines, the lines are subdivided in short segments of equal length of, for instance, some 50 cm. Then, on the one hand only the last segment is influenced by the displacement, and on the other hand, as an additional side effect, the triangulation network (described in the following section), can be built up more regularly.

Obviously this method introduces a modelling inaccuracy within the above mentioned threshold. Though appropriate for visualisation purposes, it is not satisfying from a geometrical point of view. Therefore, an alternative approach is presented in sec. 5.

Finally, some manual editing might be necessary. E.g., the skirting board is to small to be directly determined from the original point clouds. But, the vertical structure lines of the room end at the top of the skirting board. Thus, by connecting these points manually, the upper boundary of the board can be defined. The lower boundary has been determined automatically. In order to achieve topologically consistent faces(e.g. for future management in the IFAM), additional lines had to be added. These lines do not necessarily need to correspond to structures in the original room. In the Bergl-room, this was done in order to define a closed boundary of the ceiling. Fig. 7shows the BREP of the modelled room.

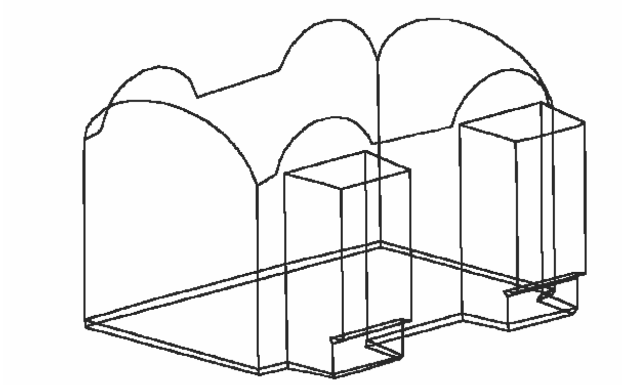

Figure 7. Boundary representation of the model.

3.4 Surface Modelling

Starting with the closed BREP model, 2.5D triangulations have been performed to model the continuous surfaces between all boundaries. For that reason, each topological face has been transformed to a Cartesian coordinate system with a z-axis normal to its mean surface. Ten topological faces have been defined to model the walls, one for the floor and one for the ceiling. The triangulation has been carried out using the CGAL-Library (CGAL, 2005). The boundaries were introduced as constraints. The surfaces were modelled by regular grid points derived from the original point clouds with the software application SCOP (IPF, 2005). A grid width of 25 cm was used for the ceiling and 50 cm for all other faces. In order to reduce the effect of the measurement noise, linear prediction (Kraus,2000) has been used for the interpolation. Fig. 8 shows the result of the triangulation (grey) together with the BREP model(black). The triangulation of the floor and the two walls in the background are not shown in this figure.

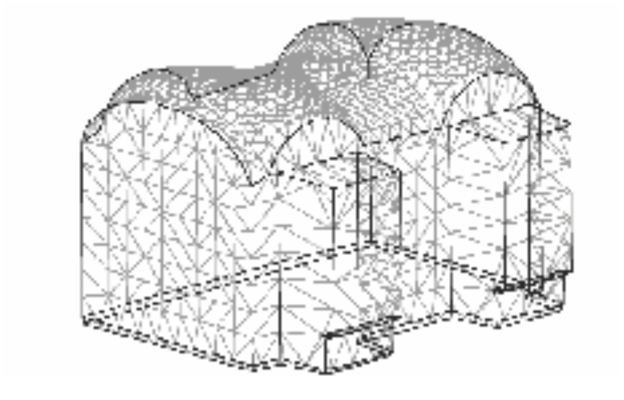

Figure 8. Boundary representation (black) and triangulated surfaces (grey) of the Bergl-room.

3.5 Visualisation

For visualisation purposes, a texture mapping was carried out using the software package Orpheus/Orient (IPF, 2005), which is originally designed for rigorous least squares adjustment in the field of photogrammetric point determination. Nevertheless, it supports the mapping of images with known orientation to geometrically defined surfaces, e.g. the result of a triangulation. Orpheus/Orient automatically selects the optimal texture source(i.e. image) to be mapped on the given surface. Finally, the result can be exported in Virtual Reality Modelling Language(Web3D, 2005). VRML can be displayed on common web browsers using adequate plug-ins. It can be transformed to the Extensible 3D (X3D) standard using appropriate tools (Web3D,2005). Fig. 9 shows a VRML-scene of the model.

Figure 9. VRML visualisation of the textured model.

4. DISCUSSION

4.1 Accuracy Estimation for Terrestrial Laser Scanning

The method described in sec. 3 directly determines structure lines from given point clouds. For modelling purposes, several simplifications have been applied. Tab. 2 summarises the thresholds used for generalisation, and the achieved accuracies.

Thresholds:

thin out of non linear structures	20 mm
replace by 3D regression line	20 mm
define lines to be identical	50 mm
intersect lines (corner)	50 mm

Accuracies:

σ_0 of registration	4 mm
σ_0 of TLS points with respect to intersecting patches	5 mm
mean Δ of identical structures in different scans	10 mm
max. Δ of identical structures in different scans	20 mm
mean Δ of regression vs. original line	5 mm
mean Δ of thinned vs. original line	5 mm

Table 2. Thresholds used and accuracies obtained during data capturing and modelling of the Bergl-room (Δ = difference).

But how accurate are the originally determined structure lines? I.e., does a systematic error occur using different laser scanners, and to what extend would those lines correspond to photogrammetrically or tachymetrically estimated ones? In order to answer these questions, an experiment to determine the achievable accuracies of different laser scanner systems compared to conventional tachymetry and photogrammetry has been performed. Although this experiment is still under investigation, first results can be presented.

So far, point clouds, acquired by a Riegl LMS-Z420i and a Leica HDS 3000 (specifications: see sec. 2.2) have been compared. During the experiment an angular sampling increment of 10 mm at 5 m measurement distance has been used for both instruments. Fig. 10 shows a shaded relief of the test field, derived from a point cloud of a 360° panorama scan acquired by the Riegl scanner. It covers a stairway (centre), a big window (left), a half opened glass-door (right) and several plain faces (ceiling, floor, walls).

Figure 10. Shaded relief of the test-field acquired by a RieglLMS-Z420i scanner (polar coordinates).

The shaded relief in the area of the window (Fig. 11, left)clearly shows, that numerous laser shots either pass the window, or are totally reflected. Fig. 11 (right) shows the same area acquired by the Leica system. In front of the window, a signboard is standing and right of the window, there is a sign with a transparent plate fixed at the wall.

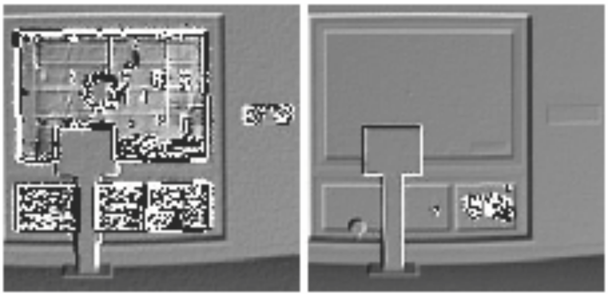

Figure 11. Laser interacting with glass (original measurements).left: Riegl LMS-Z420i, right: Leica HDS 3000

After the elimination of ranges longer than 15 m, it becomes obvious, that the Riegl scanner is able to acquire points at the glass surface, if the angle of the laser beam is almost normal to the surface (Fig. 12, left). In other cases, it acquires points outside the window. On the contrary, the Leica scanner provides a well defined surface model of the window (Fig. 12,right), though, at greater angles of incidence, points outside the window have been acquired as well (Fig. 11, right – lower, right corner)

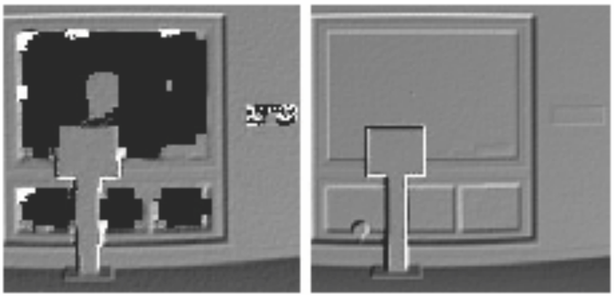

Figure 12. Laser interaction with glass (without ranges > 15 m).left: Riegl LMS-Z420i, right: Leica HDS 3000

The measurement accuracy of both instruments has been estimated by plane fitting to a planar region defined by some 70.000 points (sampling rate: ~9 mm, measurement distance:~2.3 m). The standard deviation σ_0 yields 7 mm for the Riegl and 2 mm for the Leica scanner, corresponding to the specifications given in Tab. 1 (sec. 2.1). As a matter of fact, point clouds determined by the Riegl scanner appear noisier than Leica point clouds.

In the test field, 21 structure lines have been determined. Fig.13 shows some of them superimposed to shaded reliefs of the original point clouds.

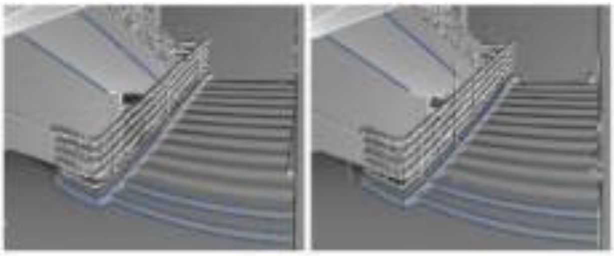

Figure 13. Structure lines, derived from Riegl LMS-Z420i (left) and Leica HDS 3000 (right) point clouds (polar coordinates).

From a quantitative point of view, the structure line detection worked almost equally on both datasets. Certainly, the mean standard deviations 0 of the lines with respect to the determined intersection patches differ: 5 mm (Riegl) and 3mm (Leica). Considering the EIFOV (sec. 2.1) of the two instruments, possibly more lines could be detected within the Leica point cloud, if a higher point density had been acquired. However, due to the low sampling rate of this instrument, this would imply very long acquisition times.

4.2 Further Remarks

Currently, numerous inhomogeneous datasets of Schönbrunn Palace exist (e.g. analogue and digitised maps, 2D and 2.5DCAD-models, cross-sections of several rooms, etc). These datasets are obviously of different quality and often cannot be merged easily. There is a demand for complete, consistent and accurate data capture and modelling in order to meet the requirements of a thorough documentation, including the utilization for IFAM and visualisation, but also for future applications.

Data from terrestrial laser scanning bear a great potential for automation and high geometric quality if appropriate methods for modelling are applied. In combination with adequate texture capturing (e.g. on-mount digital camera) it seems to be an optimum data acquisition method for capturing and subsequent geometric modelling of such complex historical facilities. The point clouds in combination with the images can serve as data source for multiple applications.

5. OUTLOOK

In this article the current status of a semi-automated workflow for geometric modelling and subsequent visualisation of point clouds, captured by a terrestrial laser scanner and a digital camera was presented. As this method is still underdevelopment, several possible improvements have been proposed. They are summarised in the following.

As described in sec. 2.2, the method for the detection of structure lines in TLS data is currently applied to 2.5D data in polar projection. Direct use of 3D Cartesian datasets is currently investigated. This will provide two advantages over the current workflow: The intersection angles of the individual patches will be smaller (often about 90°) with respect to those in polar projections, and all point clouds are processed in one single step(in the PRCS), thus, simplifying the modelling process, as each structure line is detected only once.

There is a certain drawback of the described approach concerning the intersection of structure lines in corners. Currently, two local patches are intersected in order to obtain elements of structure lines. In general, the intersections of individual lines to determine corner points leads to the problem of intersecting skew lines. A suggested workaround would be a least squares intersection of all involved patches thus obtaining one unique intersection point.

A further step towards full automation is the application of image data to determine initial values for structure line detection. Furthermore, the image observations can be considered within the structure line modelling procedure.

As described in sec. 3.4, the surfaces are currently modelled, using 2.5D triangulation. In the computer vision literature (e.g. Hoppe et al.) a number of highly refined methods for generating3D triangulations from point clouds by fitting surfaces are described. However, these methods have been tested on datasets quite different from the one described here, with visual quality as the most important criterion. We are currently investigating, how well such methods perform in the case of modelling historical rooms, where the accurate representation of the geometry is most important, and how they can be adapted to include previously determined structure lines.

So far, the modelling of objects with complex surface structures such as stoves, statues or stuccoes has been disregarded. Such objects raise two different problems: On the one hand, it is sometimes difficult to capture them from all sides. For that purpose, we are currently investigating an approach which uses a mirror to enable a "backside-scan" of objects. On the other hand, planar triangles are insufficient to model very complex surfaces. Briese et al. (2004) present an approach which is based on non uniform rational B-splines.

Finally, the experiment described in sec. 4.1 will be repeated with an improved set-up, according to the experiences from the first experiment. By the way, further instruments will be used and the modelling results of the laser scanner data will be compared to photogrammetric and tachymetric measurements.

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