DEFORMATION MEASUREMENTS AT HISTORICAL BUILDINGS WITH TERRESTRIAL LASERSCANNERS

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Commission V, WG V/3

KEY WORDS: Deformation Monitoring, Terrestrial Laserscanning, Cultural Heritage Documentation

ABSTRACT:

With the classical deformation measurement the objects are modeled by a number of measurement points which are distributed according to the deformation symmetrically as a grid or attached at selected principal points of movement. The measurement points can be determined with a total station (angle and distance measurements) to a high precision with a standard deviation of the 3D - position of ±1…2 mm. However, these procedures have the disadvantage that only the movement of the measurement points can be determined. Movements between the measurement points, like the twisting of the object, cannot be detected this way. The interpretation is more difficult because historical buildings have a very rough surface with separate coarse stones, and the forms are often complex, e.g., multi-level church towers. New measuring instruments, like laser scanners, offer the possibility of a fast and approximately complete data acquisition of the buildings. It was to be considered if it is possible to derive changes from laser scanner data at different epochs. For the investigation, different churches in Schleswig Holstein were selected as suitable deformation objects. All churches are characterized by the fact that they were built on unfavorable ground (silt and peat). The density distribution of these materials is not homogeneous and therefore there are no setting movements but tilting of the buildings. In the cathedral of Meldorf a first measurement was performed with the IMAGER 5003 of Zoller&Fröhlich, and the changes were to be observed on a continuous base.

KURZFASSUNG:

Bei der klassischen Deformationsmessung werden die zu erfassenden Objekte durch eine Anzahl von Messpunkten modelliert, die je nach Art der zu erfassenden Deformation gleichmäßig als Gitter verteilt oder an ausgewählten Hauptbewegungspunkten angebracht werden. Die Messpunkte können dann z.B. mit tachymetrischen Verfahren (Winkel- und Streckenmessung) hochgenau mit einer Standardabweichung der 3D - Position von 1- 2 mm bestimmt werden. Diese Verfahren haben jedoch den Nachteil, das nur die Bewegung der Messpunkte selbst erfaßt wird. Bewegungen zwischen den Messpunkten, wie die Verwindung des Objektes, lassen sich damit nicht aufdecken. Bei der Interpretation wirkt sich zudem erschwerend aus, dass die historischen Gebäude eine sehr rauhe Oberfläche aus einzelnen groben Steinen haben und dass die Formen, aus den Sie aufgebaut sind, oft komplex, z.B. mehrstufige Kirchtürme sind. Neue Messmittel, wie Laserscanner, bieten die Möglichkeit einer schnellen und annähernd lückenlosen Erfassung der Gebäude. Zusätzlich soll betrachtet werden, ob es möglich ist, aus den Daten des Laserscanners zu verschiedenen Epochen auch Veränderungen ableiten zu können und ob diese neuen Systeme bei der Deformationserfassung auch wirtschaftlich eingesetzt werden können. Für die Untersuchung wurden verschiedene Kirchen in Schleswig Holstein als geeignete Deformationsobjekte ausgewählt. Alle Kirchen zeichnen sich dadurch aus, dass sie auf ungünstigem Untergrund (Schluff und Torf) erbaut wurden. Die Dichteverteilung dieser Materialien ist nicht homogen und somit finden keine gleichmäßigen Setzungsbewegungen sondern Kippungen statt. Die Messprojekte an den Kirchen unterscheiden sich aber Laserscansystem und in der Art der Auswertung. Beim hier beschrieben Messobjekt, dem Meldorfer Dom, erfolgte die Ersterfassung mit dem IMAGER 5003 von Zoller&Fröhlich. Die Veränderungen sollen fortwährend beobachtet werden.

1. INTRODUCTION

Signaled points on the object of measurement are used for the classical deformation measurement. Thus the measurement points model the object. With these points the entire object is supposed to be represented. All possible movements are supposed to be captured and to be distinguished. The entire body can incline or sink, however, it can also distort itself.

According to the kind of the deformation which is supposed to be controlled, the points are distributed uniformly as grid or they are attached at selected locations. The measurement points can be determined very precisely with a total station. Angle and distance measurements result in a standard deviation of the three dimensional position at ± 1…2 mm.

These procedures have, however, the disadvantage that the targets have to be placed all over the wall. This is time consuming and expensive. Another disadvantage is that only the movement of the measurement points is recorded. Movements of areas between the measurement points, cannot be detected directly.

A further problem arises during the observation of the measuring marks at the external walls of historical churches. During history 'covers' were built around some churches. Often the new external walls have no fixed connection with the old masonry.

The interpretation of the measurement is complicated because historical buildings have often a very rough surface of single coarse stones. Often they are built up from complex shapes, for example multi-storey church towers. The use of the laser scanner is suitable for capturing the structures of historical buildings very well, both for the exterior facade as well as the interiors (Sternberg, et al., 2004; Kersten et al., 2004).

Deformation measurements with a laser scanner as a surface capturing system were carried out in the case of supervision of lock gates (Schäfer, 2004; Hesse & Stramm, 2004; Lindenbergh & Pfeiffer, 2005). In these investigations, the relatively great changes could be determined well. The reason is certainly also the short-periodic use. Measurements in each case lasted one day on fixed stations. It was useful to work with a smooth plane as a comparison surface. With irregular bodies the epoch-wise comparison is clearly more difficult.

2. LASER SCANNING SYSTEM IMAGER 5003

The systems available on the market vary very strongly with respect to their qualification for outside or inside measurements. For outside measurements the Mensi GS100 is a suitable instrument, due to its large scan distance of up to 200 m (overscan). The Old Church Pellworm could be captured with this system from outdoor and inside with a standard deviation of about 10 mm (Sternberg, 2006).

2.1 Hard- and Software

The 3D laser scanning system IMAGER 5003 is produced by Zoller&Fröhlich in Wangen, Allgäu, Germany. Fig. 1 shows the 3D laser scanning system with appropriate accessories. The IMAGER 5003 is mounted on a mobile tripod and is supplied with a battery. The control system of the scanner is a notebook.

Fig. 1: 3D laser scanning system IMAGER 5003 with accessories

The key specifications of the IMAGER 5003 are specified as follows: The phase difference method permits only the measurement of short scan distances (< 25.2 m). The scanning speed of the GS100 is high due to the measuring method (7 min per station). The field of view is large with the IMAGER 5003 thus it permits a higher flexibility of the system in building interiors.

The most important technical specifications of the system used in this investigation are summarized in Tab. 1.

	IMAGER 5003 (Lara 25200)
Metrology method	phase differences (wavelength 780 nm)
Field of view	360° horizon., 310° vertical
Optimal scan distance	1 – 25.2 m
Scanning speed	up to 625000 points/sec
Accuracy in distance (15 m)	~ 2…4 mm
Angular resolution	0.020 gon
Divergence / Spot size (25 m)	0.22 mrad / approx. 11 mm

Tab. 1: Technical specifications of the laser scanner IMAGER 5003

2.2 Data Acquisition, Registration and Georeferencing

An important component of laser scanning systems is the software, with features summarized in Tab. 2. The software allows the control of the scanner via a notebook during the data acquisition phase, the registration and geo-referencing of the point clouds from different stations and a huge number of options for data processing to the stage that geometric primitives are fitted to the point cloud for CAD construction.

Software	**IMAGER 5003**
Scanning	Z+F LaserControl
Post Processing	LFM Modeller for registration and geo-referencing, fitting of geometric primitives in point cloud
Post Processing	LFM Server + Generator for data processing of huge point clouds

Tab. 2: Software for the laser scanning system IMAGER 5003

In order to be able to register the scanned point clouds of different scanner stations automatically, scanning targets were attached well distributed in the object space. The numbered targets with a black and white pattern for the IMAGER 5003 were scanned in each panorama scan. The semi-automatic computation is carried out subsequently in the software Z+F LaserControl and/or Light Formed Modeller (LFM) (see Fig. 2).

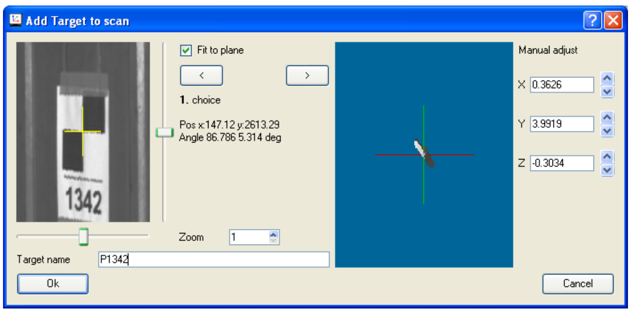

Fig. 2: Target recognition with Z+F LaserControl

3. OBJECTS TO BE SCANNED

Some of the churches at the North Sea coast of Schleswig Holstein were built before the year 1000 A.C. as Scandinavian wood churches. These churches were built on dwelling mounds (artificial embankments, in German: ‘Warften’), and the people used them also as protection in the case of tidal overflow. The subsoil below the churches is often unfavorable. It consists of bran, peat and watt sand. Fixed subsoil is not available before a depth of 20 meters (Brammer, 2004). Long-term and short-term changes in the ground, which result from groundwater setting, led to inclinations of the walls. The mass distribution and the misalignment of the churches is not known. The current condition of the church is often not documented, because many reconstructions were performed. A precise measurement of the volume body is needed to calculate the actual statics, the current mass distribution, and the forces. Laser scanners are suitable for the complete data acquisition.

Description of the Object St. Johannis, Cathedral in Meldorf

The church stands on a embankment approx. 14 m above mean sea level and was built in the 13th century. The tower was constructed as a navigation mark and was damaged by fires and collapses. But the tower was built up again and again. In 1490, the late-Gothic “Suederhalle” was built instead of a side aisle. In the following centuries numerous static constructions were carried out, like a timber crossbar and masonry pillars. But the movement of the “Suederhalle” in the south direction could not be stopped. In 1880 the entire church was coated with machine bricks. The pictures of the church (Fig. 3/ 4) from 1820 and 2003 shows the significant rebuilding of the building.

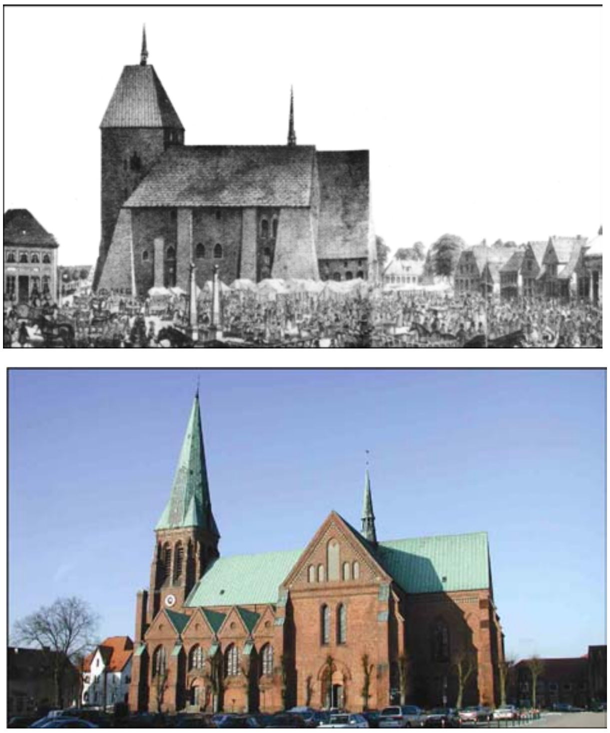

Fig. 3/4: Pictures of St. Johannis in the year 1820 and today (Lambrecht, 2003)

The inclination and cracking was not stopped yet, however, so that a comprehensive renovation has to be performed. In addition, the Suederhalle has to be rebuilt, creating a room in which church services can be held. This structural reconstruction also requires the demolition of a wall. In the scanning project, the church was to be captured in the current configuration, and a zero measurement was to be made in order to detect possible deformations due to the reconstruction.

In particular the Suederhalle is of great importance since the greatest movements were expected here. It is still unclear how to handle the misalignment of the supporting pillars during the renovation. There are two alternatives: Creation of the pillar in straight position or recreation under retention of the misalignment. The documentation of the church refers only to the interior so that the measuring distances are normally below 25 meters.

4. DATA PROCESSING OF THE LASERSCANS

4.1 Recording of the Present State

In order to be able to prove the changes due to the reconstruction, the accuracy with which the church is captured must be correspondingly good. The standard deviation of the position should be at the level of one to a few millimeters.
Due to the high accuracy demands, 11 fixed points were fixed in the interior of the church and measured with the precise total station Leica, TCRP1201. The standard deviation of the 3-D position is calculated after the adjustment to ± 0.5 mm.

The laser scanner IMAGER 5003 from Z&F with a maximum range of 25.2 m was used for the recording of the interior. 43 targets were measured for the registration of the individual scans with the total station. The standard deviation of the adjusted coordinates of the targets was ±1.3 mm.

The resolution of the IMAGER was set to ‘high’, for which a 360° scan yields a size of 10000 pixels x 5967 lines. This setting leads to a grid space of 16 mm x 16 mm at 25 m distance. Each of the 23 scans in total took 7 minutes with 1.2 million surveyed points.

The registration and georeferencing of the individual scans were accomplished in the two related programs Z+F LaserControl and LFM Modeller. Fig. 5 shows the used targets for registration and a selected area of a archway with a high point density for further modeling. The standard deviation was calculated from the three-dimensional residuals and was ±7 mm (LaserControl) respectively ±4 mm.

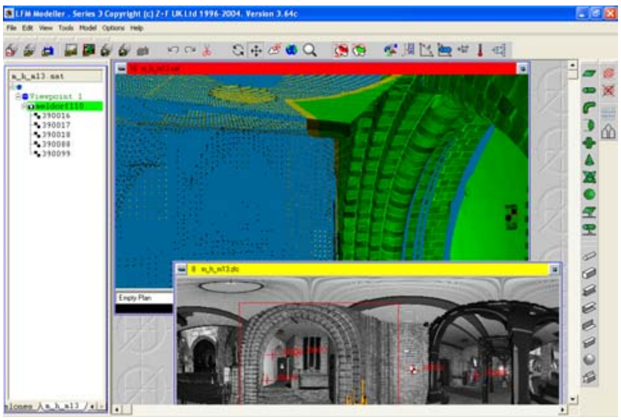

Fig. 5: LFM Modeller software

Finally all scans were registered in the software LFM Modeller, so that a homogeneous model of the church was created as a point cloud (Fig. 6).

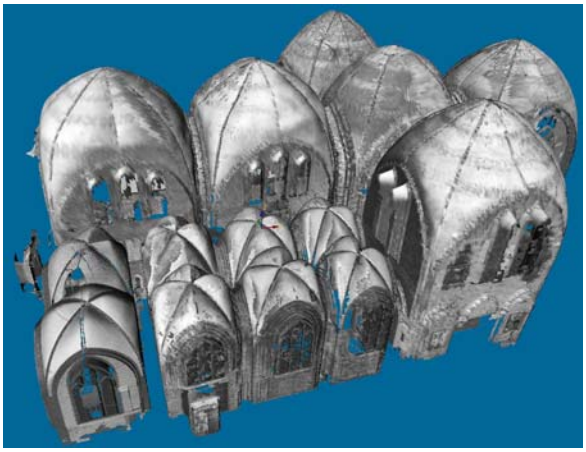

Fig.6: Registered point cloud of the cathedral in Meldorf

4.2 Evaluation and Results

For the as-built documentation of the present state the registered point clouds were processed with the software LFM Server and AutoCad. These programs support the generation of orthophotos and sections in the point cloud. The LFM Server software allows the export of selected point clouds to AutoCad. In AutoCad the final construction including the dimensioning is done manually. The two steps are shown in Fig. 7.

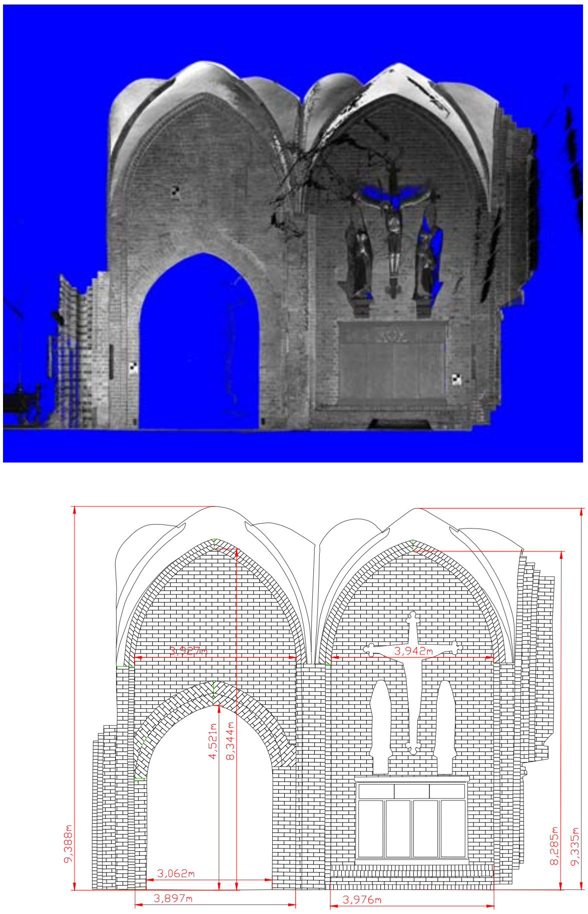

Fig. 7: Orthophoto and AutoCad Plan of Meldorf

In order to detect the change in Meldorf, the areas with the greatest changes are observed: the vaults in 14 meters above ground (Fig.8). If the inclination of the sidewalls keeps on continuing, the vaults will deform.

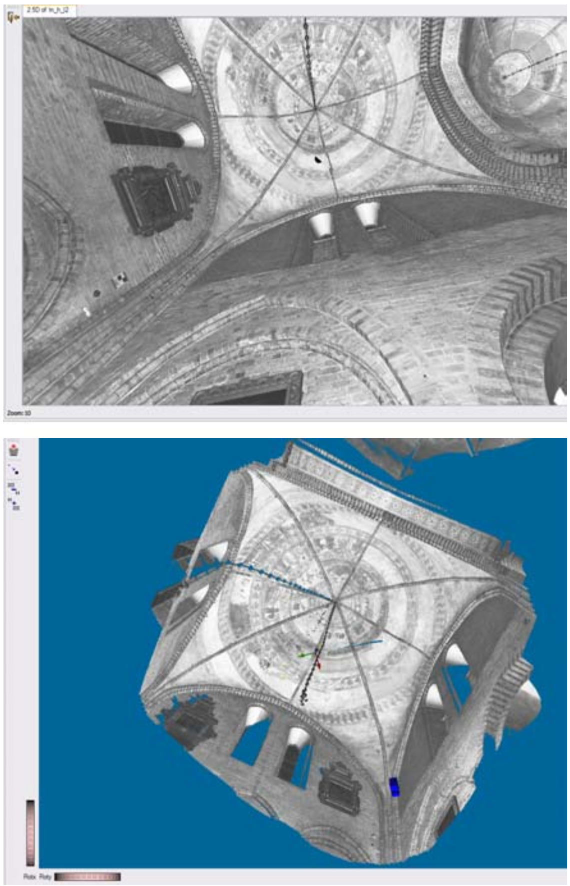

Fig. 8: Representation of the vault of the cathedral in Meldorf as point cloud: Orthogonal View Z+F LaserControl (top) and three dimensional point cloud Z+F (below)

For the determination of the deformation, different approaches were examined. This was already tested during the supervision of the Hamburg "Europa Passage" in 2004. The calculations there were easier, because at the "Europa Passage" smooth planes were compared epoch by epoch.

The possible methods can be distinguished in direct methods if the deformation time is short and the scanner does not move and indirect methods for longer observation periods.

In the first case the direct comparison could be made with the observation of the laserscanner: the horizontal angle β, the vertical angle ζ and the range R. Because of the fixed position of the scanner, the two angles should be identical for both observations. Only the differences in the range shows the deformation. But this range measurement is distorted by measurement noise and systematic errors.

The direct comparison of the angles and the range of the laserscan measurements were also used in a simulation of long term investigations of (Teskey et al., 2005). Here the observed points in the two epochs are clearly defined targets.

For the observation of long-term deformation with laser scan data the following indirect methods could be used:

- Comparison of grid points
- Comparison of linear structures like cuts
- Comparison of surfaces – in the simplest case a plane

The first step in each case is the transformation of the point cloud into the same coordinate system. Often it is helpful to use the object coordinate system to simplify further calculations. This reduces in the first case the comparison of the resampled grid points p(x,y,z) possibly to only one component.

In the second case cuts could be generated at the same position and e.g. the change of the tilting could be calculated or the change of the form can be determined, for example the distortion of a circle to an ellipse.

The simplest case of a surface comparison could be using planes. Here the comparison would be carried out with the normal vector of the plane. The difference between the normal vectors of the two observation epochs shows the direction and the magnitude of the deformation. For bigger objects it is useful to create smaller plane regions, generated by manual or automatic segmentation.

All these methods of the indirect comparison were tested at the "Europa Passage" in Hamburg, where planes are observable. In the first step a regular grid was calculated in the point cloud and the grid points of each epoch were compared. This is similar to the approaches of (Schäfer, 2004; Hesse & Stramm, 2004). There the results were quite good since the changes were very fast and the laser scanner remained on a fixed station. Further possibilities, such as cuts and the fitting of planes were calculated similar to the approaches of (Lindenbergh & Pfeiffer, 2005). The changes of the normal vector of the plane was used as a deformation criterion. The deformation of the Europe passage was below 5 mm and the observation period was over 4 months, so a change could not be detected.

In Meldorf some of these procedures dropped out due to the irregular faces so that cuts and free-formed surfaces were mainly considered here.

The cuts were produced in three software programs since various problems occurred. The program Z+F LaserControl (version 6.6.1.0) produces not a thin line but a wide band with a noise up to 95 cm although the thickness of the slices were reduced to 5 cm. In the LFM Modeller the generation of cuts is only possible in the 'preview', here the point cloud is rather thinned out, so that no reliable comparison between two epochs could be done. The program RealWorks of Mensi can process only a restricted number of points, so that the point clouds first had to be thinned out with e.g. the spatial sampling. A lot of time was spent for the exchange of the point clouds presented in the ASCII format. The contour lines with a height distance of 25 cm and a thickness of the slices of 2 cm are shown in Fig. 9 top. The dimension of the vault is about 10 m. Also here the result was not usable in this form for further evaluations. The cutting tool produces only point clouds and no single line, an automatic comparison of two different cuts is not possible.

The surface modeling was attempted as a triangulation again with the programs Z+F LaserControl and LFM Modeller. The result was unsuitable due to missing setting options and/or it could not be computed at all. Therefore the triangulation was carried out with the software RapidFormXOScan by Inustech. The algorithm used by RapidForm is similar to the TRIADS algorithm, with a region growing algorithm based on triangles with one given initial triangle. The meshed triangles from RapidForm are displayed in Fig. 9 below as a smooth surface.

The smoothed triangulation surface as a result of the computations is plausible and further usable. Further scans could be combined by means of a global registration with overlapping areas of the point clouds or with meshed surfaces. In this way a seamless smoothed surface model was created with a standard deviation of the surface points of ± 3…4 mm.

Further evaluations could be done in two ways. First approach is the comparison of global georeferenced surfaces of two epochs and the calculation of a difference model. Main advantage is the easy processing of this model as a standard tool in the programs, main disadvantage is the influence of the inaccuracy of the georeferencing. The second approach is the examination of two local best fitted surfaces. Due to the movement of the sidewalls, the vaults should be modify the form. A circular form should change to an ellipsoidal form.

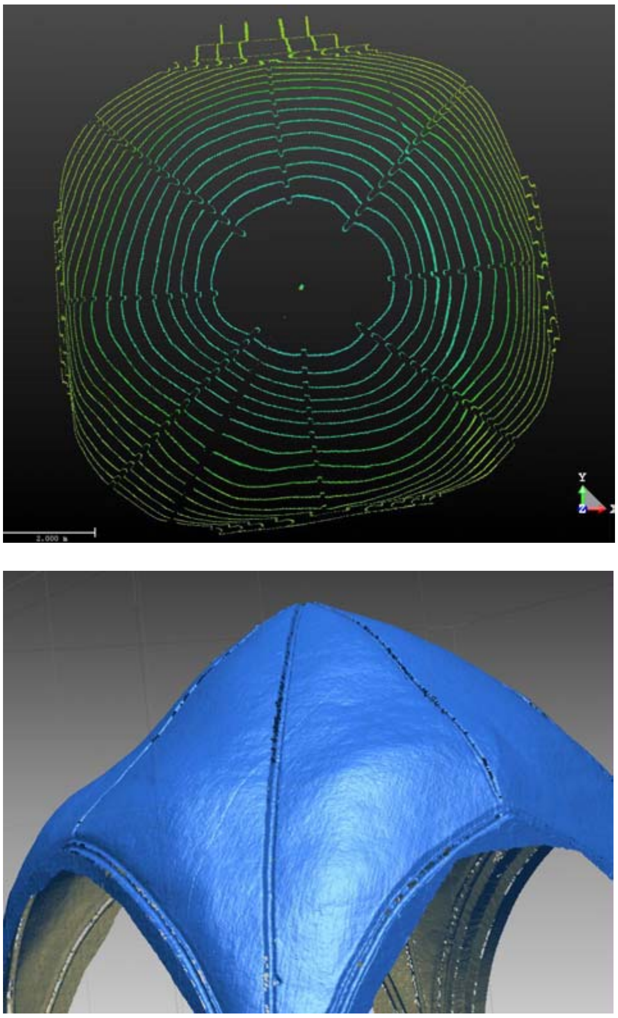

Fig. 9: Representation of the vault of the cathedral in Meldorf as model: contour lines from RealWorks (top), meshed surface from RapidForm (below)

The next measurement of the deformation is planned in approx. four years. Until then there will be a further improvement of the scanner processing software and the free formed surfaces, for example NURBS algorithms (Teutsch, 2005). These allow the differencing of free formed surfaces. With NURBS (non uniform rational B-Splines) it is easy to compare the surfaces of two epochs with the normal vectors or the curvature of the surfaces. This leads to a significant accuracy increase. The standard deviation of the surface is half the standard deviation of the single point. (Grimm-Pitzinger, 2005). In this case the standard deviation could go down to a level of ± 1...2 mm.
The relation of the working time of 1:4:2 for measurement, preprocessing, and final processing, respectively, will improve still further. The working times in the preprocessing will be reduced, due to a semi-automatic registration and a simplified export / import of point clouds between different programs in the near future.

5. SUMMARY AND OUTLOOK

With the laser scanner it is possible to create very quickly an as-built documentation and a construction of simple cuts. The evaluation took place within one day. As a result 4 slices at different levels were produced parallel to the z-plane and 7 slices parallel to the x- and y-plane.

Here an advantage of this flexible processing procedure was demonstrated. New cuts can be defined very quickly and simply also in the future.

The generation of cuts and orthophotos is very elegant with the LFM software, the duration is, however, also clearly higher. The software requires a training and a telephone link to the program developers.

During the computation of deformations, the use of surfaces appears promising. Not single points but the object as a whole are considered. Just in this field improvements are still to be expected in next time. The use of third party software is vital here. The complex question formulations are solved only by specific software programs, and these are not integrated in the internal laser scanner processing software yet.

At this time, the accuracies cannot yet be achieved, however, as in the case with the classical deformation measurements. For applications that can work with a standard deviation of ± 3…4 mm, recording and processing with the laser scanner are an alternative, in particular when simple inspections are required, like deformation analyses in tunnels (Mechelke et al., 2006).

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