DEFORMATION MEASUREMENTS AT HISTORICAL BUILDINGS WITH THE HELP OF THREE-DIMENSIONAL RECORDING METHODS AND TWO-DIMENSIONAL SURFACE EVALUATIONS

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Abstract: With the classical deformation measurement the objects are modeled by a number of measurement points which are distributed according to the deformation symmetrical as a grid or attached in 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 at ±1…2 mm. However, these procedures have the disadvantage that only the movement of the measurement points itself 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. In addition, 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. However, the survey projects in the churches differ in the Laser Scan System and in the kind of the evaluation. At the old church Pellworm only the current inclined position was determined from the measurements with the Mensi GS100 of the interior and the outside facades. 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.

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 measurement result in a standard deviation of the three dimensional position at ± 1…2 mm.

These procedures have, however, the disadvantage that only the movement of the measurement points is recorded. Movements between the measurement points, such as the torsion of the object, cannot be detected in this way.

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 [10], [4].

Deformation measurements with a laser scanner as a surface capturing system were carried out in the case of supervision of lock gates [8], [3], [6]. 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 Systems Mensi GS100 and IMAGER 5003

The systems available on the market distinguish very strongly with respect to their qualification for outside or inside measurements.

2.1. Hard- and Software

The 3D laser scanning system GS100 is manufactured by Mensi S.A., France, and the IMAGER 5003 is produced by Zoller&Fröhlich in Wangen, Allgäu, Germany. The most important technical specifications of the two systems used in this investigation are summarized in Tab. 1.

	Mensi GS100	**IMAGER 5003**
Metrology method	pulsed time of flight	phase differences
Field of view	360° horizon., 60° vertical	3600 horizon., 3100 vertical
Optimal scan distance	2 – 100 m	1 – 53.5 m
Scanning speed	up to 5000 points/sec	up to 500000 points/sec
Accuracy in distance (25 m)	6 mm (single measurement)	~ 6mm
Angular resolution	0.002 gon	0.020 gon
Divergence / Spot size in 25 m	0.06 mrad / 3 mm	0.22 mrad / approx. 11 mm
Calibrated video camera	RGB 768 x 576 Pixel	

Tab. 1: Technical specifications of the laser scanner Mensi GS100 and IMAGER 5003

The substantial differences between GS100 and IMAGER 5003 are specified as follows: The impulse time-of-flight method of the GS100 (wavelength 532 nm) permits the measurement of longer scan distances than the phase difference method of the IMAGER 5003 (780 nm), whereas the scanning speed of the GS100 is clearly slower due to the measuring method. The field of view is substantially larger with the IMAGER 5003 than with the GS100, thus it permits a higher flexibility of the system in interiors. On the other hand, the GS100 offers a higher angular resolution and a clearly smaller spot size of the laser beam at the object. Due to the integrated video camera, the GS100 offers the possibility for colour coding of the point clouds with RGB values.

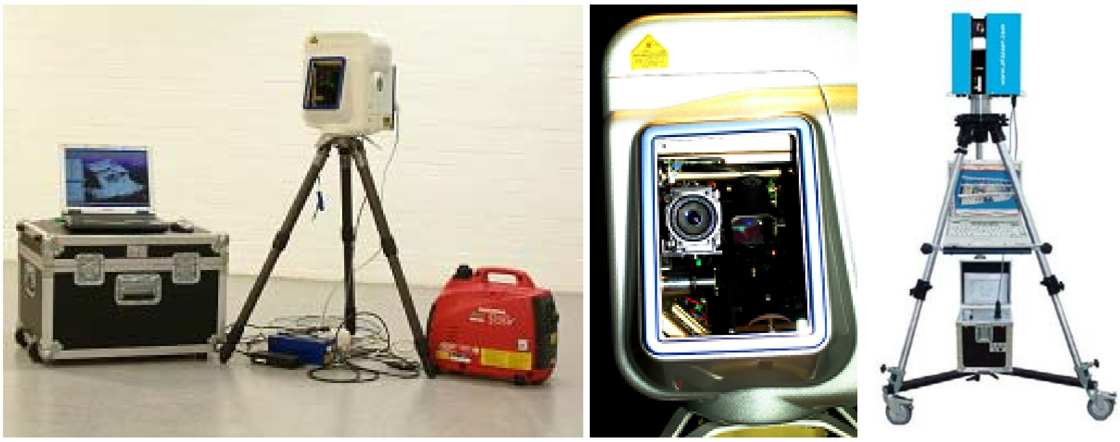

Fig. 1: 3D laser scanning system Mensi GS100 of the HCU with accessories (left), GS100 interior with digital camera and mirror (middle), IMAGER 5003 with accessories (right)

Fig. 1 shows both 3D laser scanning systems with appropriate accessories. The standard equipment of the GS100 is a solid transportation box and a notebook for controlling the measuring instrument during data acquisition. A useful addition of the system is an efficient generator for use in the field. The IMAGER 5003 is mounted on a mobile tripod and is supplied with a battery. Likewise, the control system of the scanner is a notebook.

2.2. Data Acquisition, Registration and Georeferencing

A important component of laser scanning systems is the software, with features summarized for both systems 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.

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. Each white sphere with a defined diameter was scanned separately with the GS100 before each object scan. The search of these spheres can be accomplished in the video frame of the digital camera. The calculation of the center coordinates in the local system scanner takes place semi-automatically and indicates the modeled sphere in the PointScape program (see fig. 2 left). 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 right).

Software	Mensi GS100	IMAGER 5003
Scanning	PointScape	Z+F LaserControl
Post Processing	RealWorks Survey for registration and geo-referencing, OfficeSurvey Modules	LFM Modeller for registration and geo-referencing, fitting of geometric primitives in point cloud
Post Processing	3Dipsos for registration and geo-referencing, fitting of geometric primitives in point cloud	LFM Server + Generator for data processing of huge point clouds

Tab. 2: Software for the laser scanning systems Mensi GS100 and IMAGER 5003

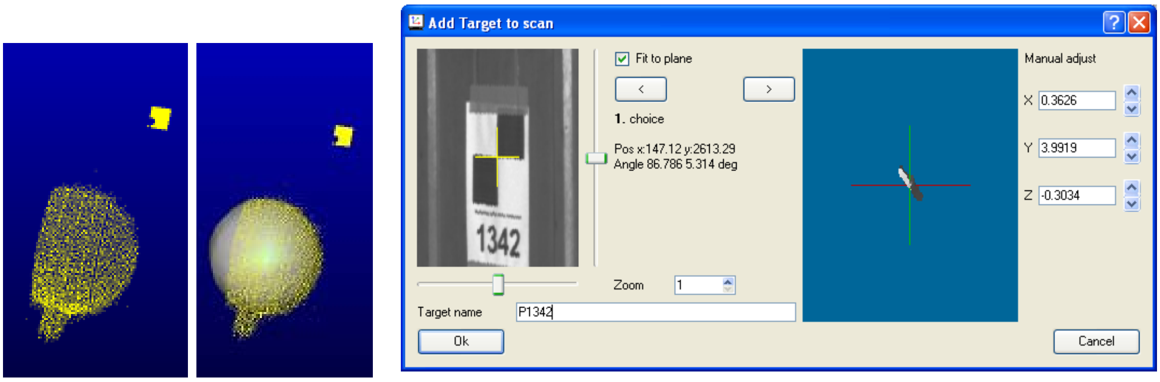

Fig. 2: Scan and automatic recognition of a sphere with PointScape (left) and target recognition with Z+F LaserControl (right).

Then the object can be scanned with the Mensi Scanner section-wise or as 360°-Scan with different solutions (min. 0.3 mm at 10 m distance). Also here, the video-framing supports the section determination.

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 [2]. Long-term and short-term changes in the ground, which result from the groundwater setting, lead 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.

3.1. Description of St. Salvator, The Old Church of Pellworm

The Old Church Pellworm was built in 1095 on a dwelling mound on the relics of a first wooden church. The neighboring tower was build in the 13./14. Century as a navigation mark with 52 m height. Until the heavy gale flood of 1362, Pellworm belonged to the mainland. After the flood Pellworm became an island. The tower collapsed in the year 1611 because it lost its unstable hold due to a basic break of the dwelling mound. The present ruin measures only 26 meters. In the year 1634, a disastrous flood destroyed the largest part of the island, 6000 of the almost 10000 inhabitants drowned. The Old Church Pellworm was not damaged during this disaster.

Today the church needs a basic structural renewal: the heating system, the roof frame, and particularly the masonry [1]. Some questions had to be clarified for the renovation: Moisture in the walls, the connection of the external wall to the masonry, the state of the subsoil, the current misalignment of the walls and curves in the ground plan. For this purpose the survey of the building was necessary from inside and outside. Also the inclination of the tower ruin was to be determined in order to be able to divert danger from the church. To answer these questions, an accuracy of ±1 cm was sufficient.

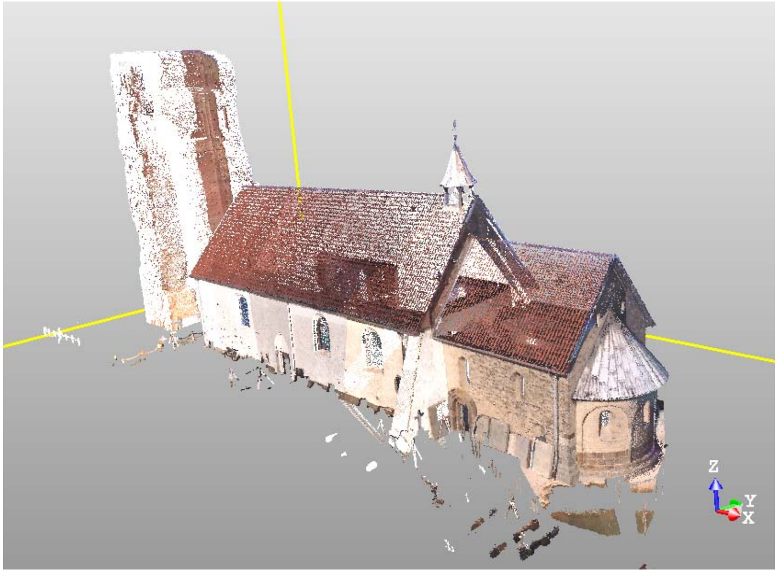

Fig. 3: Point cloud of the Old Church Pellworm registered from individual scans

3.2. 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 also 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 build instead of a side aisle. In the following centuries numerous static constructions were carried out, like a timber crossbar and masonry pillars. In 1880 the entire church was coated with machine bricks.

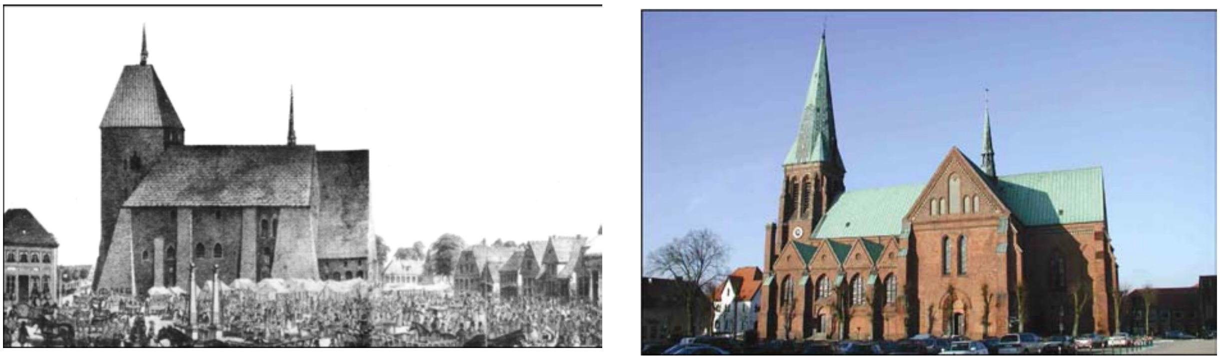

Fig. 4: Pictures of St. Johannis in the year 1820 and today [5]

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, so that a cubicle arises in which church service can be celebrated. These structural reconstructions 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 to be seen 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. Capturing and As-Built Documentation of the Old Church Pellworm

Since in Pellworm the outside measurements of the church including the tower was very important, the church was captured with the laser scanner Mensi GS100. This system offers measuring distances up to 100 m. A local control network with 11 points and 9 temporary targets was measured with the total station TRCA 1105+. In the interior 5 scans were carried out, and the external walls were captured with 9 scans. Both local measurements (inside / outside) were linked over the local area network. The registration and georeferencing was carried out with the Mensi software RealWorks.

First of all the scans of the interior were registered. During this registration no problem occurred, so that a standard deviation of the registration of ± 3…4 mm was reached. In a second step the scans of the external walls were registered. During the registration of the external areas a problem arose since the targets almost lay on one level. Because of that, greater differences were clearly visible at the church roof and at the tower. This was resolved with the production of natural targets (corners, window crosses, signs on the roof) to get further registration points. This led to a larger standard deviation in the registration of the outside area of approx. ±10 mm.

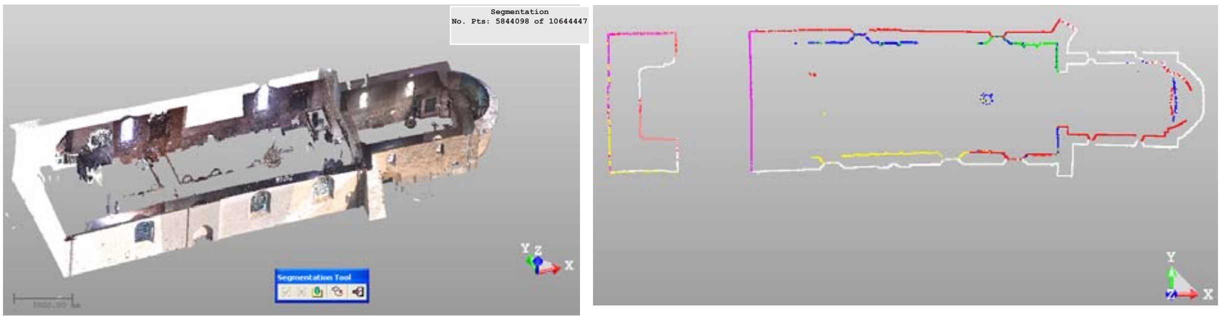

Fig. 5: Selected point cloud (left) and ground plan cut (right) from The Old Church Pellworm

The combination of the two independent georeferenced partial models facilitates a homogeneous model of the church as one point cloud. Cuts were constructed into the point cloud with RealWorks in order to produce two-dimensional plans in the ground plan and the elevation. The cuts in the point cloud were still finished in AutoCad in order to receive the dimensions and lines. It could be proved that in the current condition the tower is inclined away from the church.

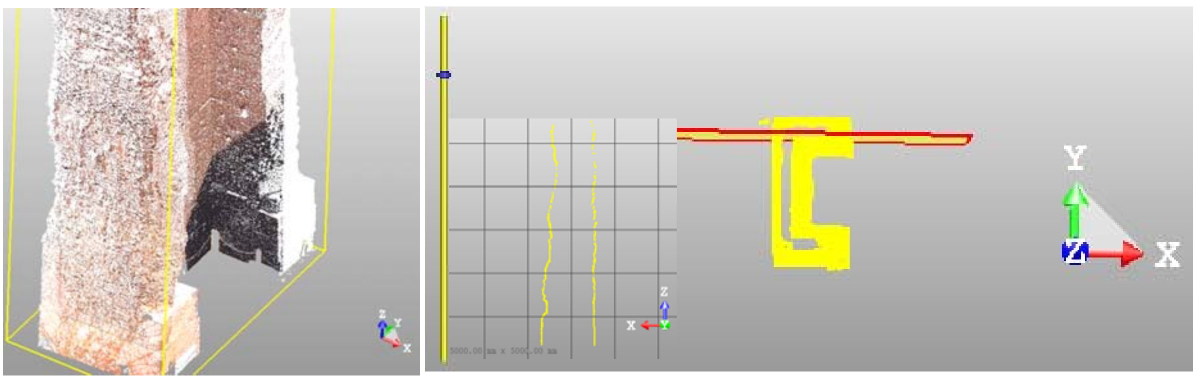

Fig. 6: Point cloud (left) and cuts through the tower of The Old Church Pellworm

4.2. Recording of the Present State and Calculation of Deformations from Repetition Measurements in St. Johannis, Cathedral in Meldorf

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 in 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. One scan 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. The standard deviation was calculated from the three-dimensional residuals and was ±7 mm (LaserControl) and ±4 mm.

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

4.3. Evaluation and Results

For the as-built documentation of the present state the registered point clouds were processed in the software LFM Server and AutoCad. These programs support the generation of orthophotos and sections in the point cloud.

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

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.

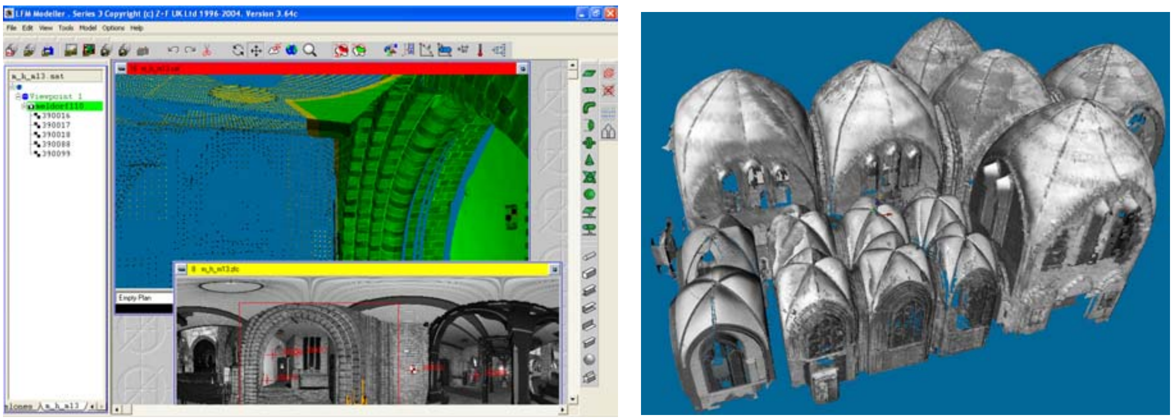

Fig. 7: LFM Modeller software and registered point cloud of the cathedral in Meldorf

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 [8] und [3]. There the results were quite good since the changes were very fast and the laser scanner remained on a fixed station. Further possibilities as cuts and the fitting of planes were calculated similar to the approaches by [6]. 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 derived.

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 produces a great variation of 95 cm and no thin line. In the LFM Modeller the generation of cuts is only possible in the 'preview', here the point cloud is very thinned out. The program RealWorks from 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 with the ASCII format. Also here the result was not usable.

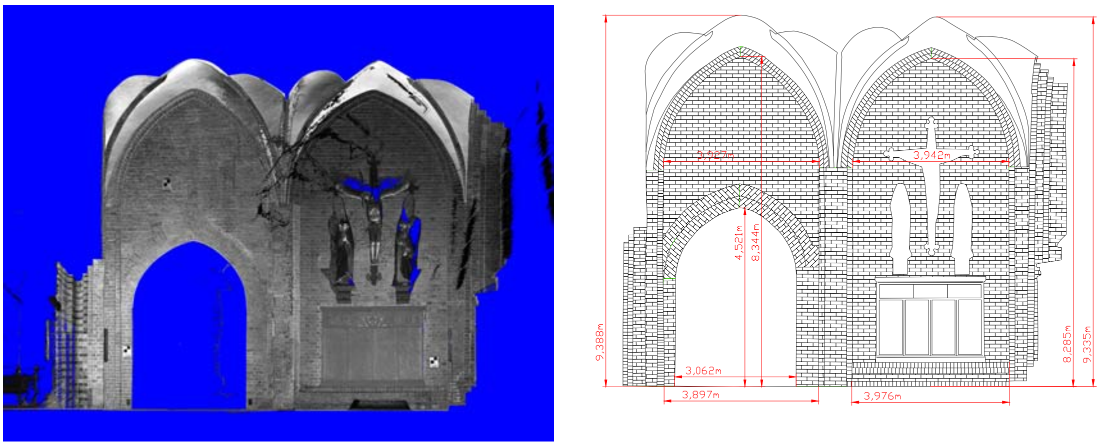

Fig. 8: Orthophoto and AutoCad Plan of Meldorf

The surface modelling 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 free-formed 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.

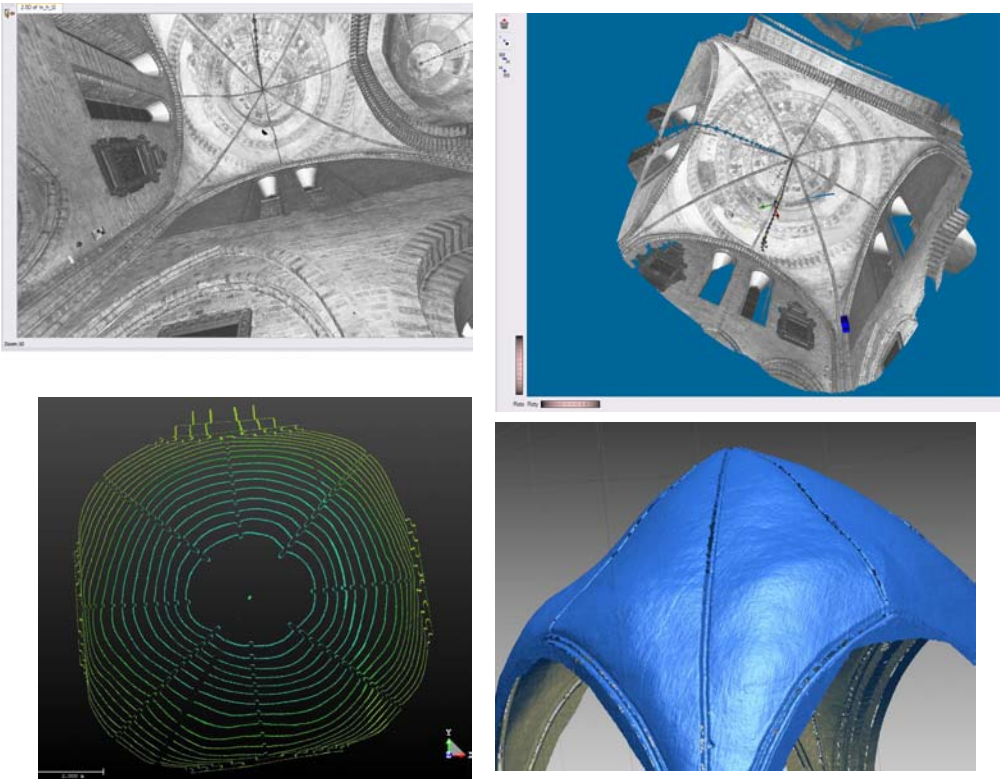

Fig. 9: Representation of the vault of the cathedral in Meldorf: Orthogonal View Z+F LaserControl (left up), three dimensional point cloud Z+F LaserControl (right up), level lines from RealWorks (left below), meshed surface RadidForm (right below)

The next measurement of the deformation is planned in approx. 4 years. Until then there will be a further improvement of the scanner evaluating software and the free formed surfaces (for example NURBS algorithms [11]). These allow the differencing of free formed surfaces. The relation of the working time of 1:4:2 for measurement, pre processing, and evaluation respectively will improve still further.

5. Summary and Outlook

With the laser scanner is it possible to create very quickly an as-built documentation and a construction of simple cuts. The measuring time at the church of Pellworm was 2 days, the end was determined by the departure of the ferry boat from the island. 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 proved. 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 demanded, like deformation analyses in tunnels [7].

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