Geometrical Building Inspection by Terrestrial Laser Scanning

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Key words: accuracy, evaluation, inspection, laser scanning, positioning, terrestrial

SUMMARY

The terrestrial laser scanning system Trimble GS100 was used in two projects for geometrical building inspection. In this paper, two projects, a water tower and an underground tunnel in Hamburg, are presented wherein geometrical building parameters and discrete points are derived from laser scanning data with the goal of inspecting existing buildings relative to construction plans. Using data acquired by laser scanning as-built measurements could be compared with building plans to determine deviations and possible collisions. The results achieved in these projects demonstrate clearly that terrestrial laser scanning data allows very extensive inspection of buildings due to the high geometrical quality of the point clouds. However, if increased precision (of better than 2mm) is required, the performance potential of the laser scanning system is limited. Since extensive CAD modelling was not necessary for these particular projects very fast results (up to a factor of 1:1 for the ratio of scanning to data processing) have been produced.

ZUSAMMENFASSUNG

Das terrestrische Laserscanning System Trimble GS100 wurde in zwei Projekten zur Untersuchung von Bauwerken eingesetzt. In diesem Beitrag werden mit dem Wasserturm und dem U-Bahntunnel in Hamburg zwei Projekte vorgestellt, bei denen geometrische Parameter des Gebäudes und diskrete Punkte aus Laserscanningdaten abgeleitet werden, um existierende Gebäude mit Bauplänen zu überprüfen. Anhand der mit dem Laserscanner gewonnenen Daten konnten Bauwerksplanungen mit dem Ist-Bestand hinsichtlich Abweichungen und Kollisionen überprüft werden. Die Ergebnisse zeigen, dass aus Laserscanningdaten abgeleitete Werte sehr umfangreiche Prüfungen zulassen, und dass jedoch bei erhöhten Genauigkeitsanforderungen (von besser als 2 mm) das System an seine Grenzen stößt. Da umfangreiche CAD-Modellierungsarbeiten nicht erforderlich waren, konnten sehr schnell Ergebnisse (bis zu Faktor 1:1 für das Verhältnis Erfassung/Auswertung) erzeugt werden.

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1. INTRODUCTION

Terrestrial laser scanning systems have been available on the market for about ten years and the last five years have shown laser scanning to be on the way to becoming accepted as a standard method of 3D data acquisition, taking its place beside established methods such as tacheometry, photogrammetry and GPS. In industrial as-built-documentation in particular terrestrial laser scanning systems have played an important role since their first availability as commercial systems. The major advantage of this measuring system is the complete and detailed 3D data acquisition of objects for many different applications. Particularly, the use of terrestrial laser scanning for 3D modelling and for deformation measurements, monitoring and analysis is increasing in the past years (Gordon et al. 2001, Kutterer & Hesse 2006, Schneider 2006, Tsakiri et al. 2006, van Gosliga et al. 2006, Lam 2006, González Aguilera et al. 2007, Gielsdorf et al. 2008). There are several publications on 3D object modelling, e.g. for a large dam using a Riegl LMS-Z420i equipped with a calibrated digital camera Nikon D100 (Alba et al. 2006), for a cooling tower using the time-of-flight laser scanners HDS2500 and HDS3000 (Ioannides et al. 2006), and for as-built documentation of industrial pipelines and historical architectural building using laser scanner data of a CYRAX 2500 (Sternberg et al. 2004). Kersten et al. (2005b) compared the Trimble GS100 and the IMAGER 5003 for indoor scanning and 3D modelling of two historical halls in the Town Hall of Hamburg. The comparison of practical performance in 3D modelling using different laser scanning systems, consisting of scanner hardware and its related software for data processing, in two different industrial as-built-documentation applications (transformer station and water conduits of a waste water treatment plant) is presented in Sternberg & Kersten (2007).

The laser scanning system Mensi GS100 has been used at the HafenCity University Hamburg since September 2003 in a variety of very different projects (Kersten et al. 2004, Kersten et al. 2005b, Kersten 2006) and in the first accuracy and system investigations with this laser scanner (Kersten et al. 2005a, Kersten et al. 2005b).

In this paper two projects, the water tower Sternschanze Hamburg (chapter 3) and an underground tunnel Gänsemarkt Hamburg (chapter 4), are presented wherein geometrical building parameters and discrete points are derived from laser scanning data with the goal of inspecting existing buildings relative to construction plans. Both projects were carried out in cooperation with the engineering office "Spanheimer Bornemann Ingenieure" in Hamburg.

2. THE TERRESTRIAL LASER SCANNING SYSTEM MENSI GS100 FROM TRIMBLE

For geometrical building inspection the 3D laser scanning system GS100 from Trimble was used, which is manufactured by Mensi S.A., France. The system consists of a laser scanner, accessories (Fig. 1) and appropriate software for data acquisition and post processing. The optimal scanning range is between 2 - 100m. The panoramic view scanner (field of view 360^0 horizontal, 60^0 vertically) offers an uninterrupted panoramic capture of a scene of 2m x 2m x 2m up to 200m x 200m x 60m indoors or outdoors. The resolution of the scanner is 0.002gon (Hz/V). The laser point has a size of 3mm at 50m distance, whereby the standard deviation of a single distance measurement is 6mm. The distance measurements are performed by pulsed time-of-flight laser ranging using a green laser (532nm, laser class II or III). The system is able to measure up to 5000 points per second. In this investigation the Mensi GS100 with serial number 02-A-026 was used.

Fig. 1 shows the 3D laser scanning system Mensi GS100 (weight 13.5 kg) with accessories, consisting of a rugged flight case and a notebook for controlling the unit during data acquisition. The usage of an efficient power generator is recommended for field work, when mains power cannot be obtained.

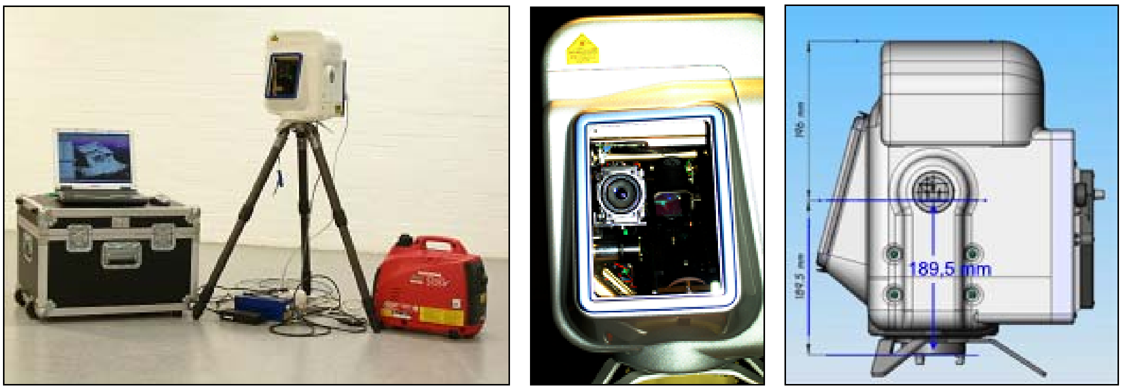

Figure 1: Terrestrial 3D laser scanning system Mensi GS100 at HCU Hamburg (left), view into the scanner showing the digital camera and the laser mirror (centre), dimensions (right)

A substantial component of the laser scanning system is the software. For data acquisition PointScape is used as a so-called field service program, which controls the scanner via a notebook. The post processing of the 3D point clouds is performed with Real Works Survey or with 3Dipsos. Both programs offer registration and geo-referencing of point clouds as well as multiple options for post processing. RealWorks Survey is mainly used for meshing of point clouds, computation of volumes, derivation of contours as well as for matching digital images with point clouds. The program 3Dipsos represents the engineering module, with which CAD constructions derived from the point clouds can be produced.

3. GEOMETRICAL DETERMINATION OF BUILDING PARAMETERS OF THE WATER TOWER STERNSCHANZE IN HAMBURG

The former water tower at the park Sternschanze in Hamburg (Fig. 2) was converted into a Mövenpick hotel. While preserving the external facade of the building the construction of the interior was carried out using pre-fabricated concrete elements. At the time of renovation planning the tower's interior diameter and axis could only be determined indirectly due to the current installation and construction work. After the core was removed from the tower a check could be made on whether the existing structure matches with the renovation plans. For this task terrestrial laser scanning can be offered as a suitable measuring method in order to efficiently acquire the geometrical data of the interior front (Fig. 2 centre). Furthermore the fit between the indirectly derived tower axis and the axis determined from laser scanning data can be measured and used to determine whether collisions will occur during the installation of the pre-fabricated concrete elements for each floor. Thus, this project tested whether terrestrial laser scanning can supply the necessary geometrical building parameters with the required accuracy.

The interior front of the tower (diameter 26m, height of 50m) could be almost completely scanned from five scanner stations. At two stations on the ground floor a special socket (Fig. 2 right), which was placed horizontally to the rotation axis of the scanner, was necessary to enable scanning of the entire interior from the ground to the top floor 50m above. At an additional station the lower part of the tower was scanned with a 360° panorama scan. For geometrical checking the upper section of the tower was also scanned from two stations at a height of approx. 47m. Finally, the individual scan stations were registered using eleven control points (eight white solid plastic spheres with a diameter of 76.2mm and three green targets), which were very well distributed on three levels of the tower interior. The coordinates of these control points were determined with a Leica total station TCRP1201 in the building coordinate system. After geo-referencing of the point clouds into this coordinate system the average deviation was 4mm at the control point coordinates.

Figure 2: Former water tower at Sternschanzen Park in Hamburg: view at the external facade (left), interior view (centre), scanner GS100 on the special socket on the ground level of the tower (right)

The data processing of the point cloud was carried out with the Trimble software RealWorks Survey 4.2 and 3Dipsos 3.0. In the first step of the workflow the tower axis was constructed in 3Dipsos from renovation planning data. After segmentation of the point cloud a cylinder was fitted into the interior tower geometry with a best-fit-method in such a way that no collisions occur. The perpendicular centreline of the cylinder was then compared with the planned axis, which yielded a difference of 25mm between both axes.

In the next step of the workflow, on the basis of the planning documents, both the tower axis and the target geometry were generated on this axis in the form of a cylinder using AutoCAD. The radius of the cylinder as proposed in the planning stage was used. This geometrical body was imported into the program RealWorks Survey (RWS) and superimposed in the point cloud. Now the point cloud was checked for collisions through comparison with the target geometry using the Surface Inspection Tools of RWS, whereby only points at the heights of the respective floors were considered. Within the upper part of the tower collisions of up to 60mm could be determined in particular areas. Collision surfaces could be represented using colour coding in a development of the cylinder as well as in a diagram. The diagram representation in Fig. 4 shows the completed target geometry as a red line (zero-line) and the point cloud as a green line with the differences between the two having been calculated as radial distances. In the areas, in which the green line is below the red line, collisions are detected. It is a disadvantage of this representation that the zero point of the best-fit cylinder is specified by the program. Thus, it is difficult to transfer detected critical areas to the object.

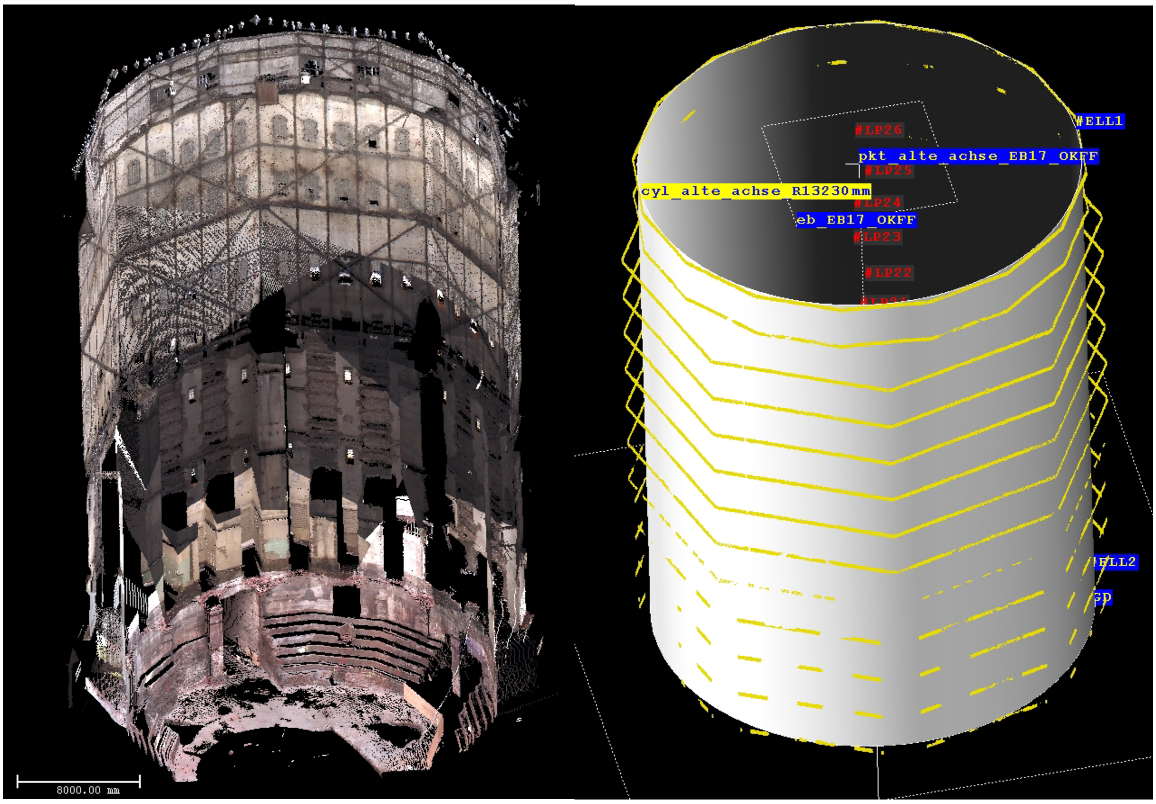

Figure 3: Entire point cloud of the water tower (left, depicted as RGB values) and segments of the point cloud (where the different floors are illustrated as yellow lines) with fitted target geometry (grey cylinder)

In a further step of the workflow horizontal planes, with a specified thickness equal to that of the floor, were extracted from the point cloud at the height of each floor level from 05 - 17 and then converted into polylines. The generation of these polylines was carried out automatically, although a small amount of manual post processing was necessary. The polylines were delivered in DXF format to the client for inspection of the planned pre-fabricated concrete floor elements.
After completion of the structural work of the floor levels 00 - 08 distance measurements were acquired for quality control of the floor levels 07 and 08 with the Leica TCRP1201. Hence, the interior diameter of the tower was determined between points, which could also be identified in the point cloud. A comparison of the distances between those determined geodetically by the total station and the same distances derived from the point cloud showed differences of 2mm on average (standard deviation 4mm).

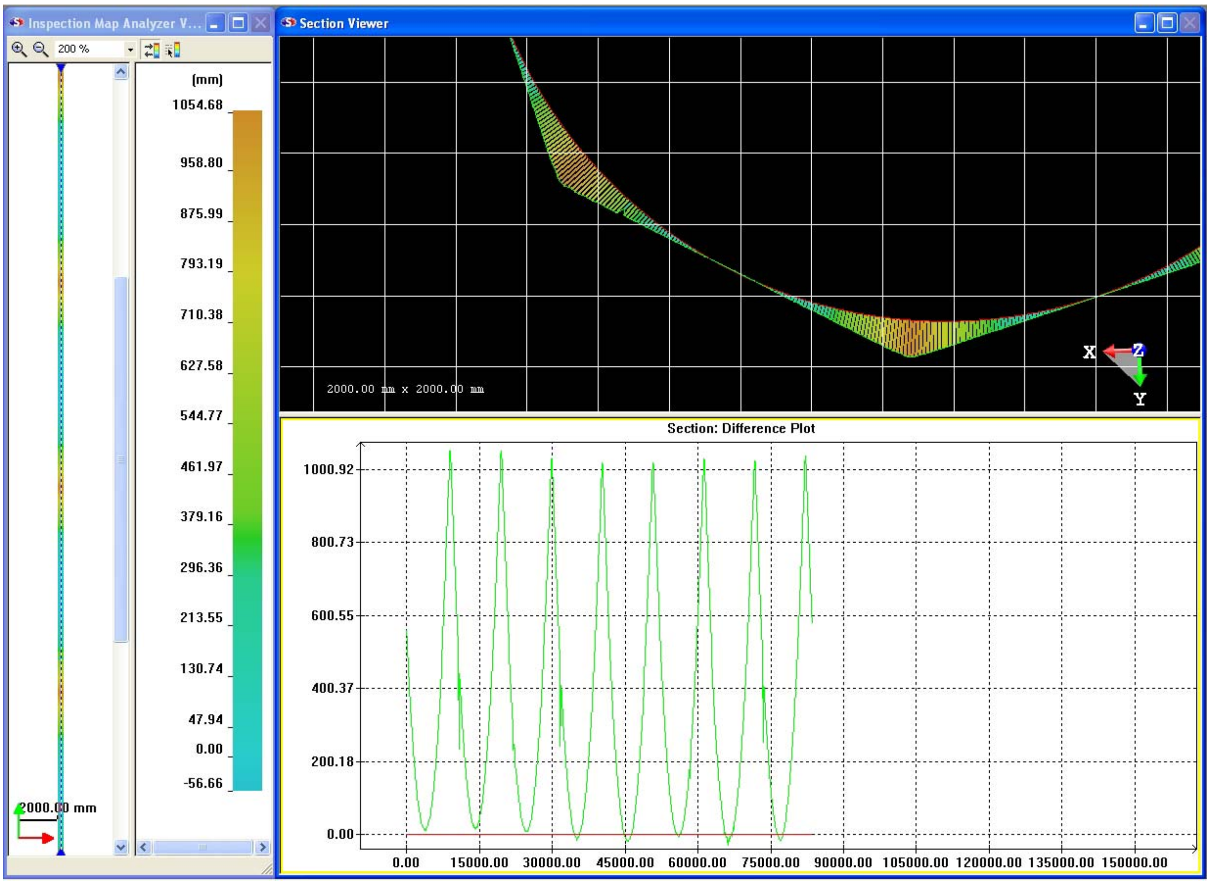

Figure 4: Collision detection with Surface Inspection Tool in RealWorks Survey

The data acquisition at the water tower was carried out in eight hours in total, whereby laser scanning was accomplished in six hours, while the geodetic control points were determined in two hours. The data post processing (registration and geo-referencing, determination of the axis, inspection of collisions, and generation of polylines) was completed in only seven hours. Thus, the ratio of scanning to data post processing was 1:1.

4. POSITIONING OF CONSTRUCTION ELEMENTS IN THE UNDERGROUND TUNNEL GÄNSEMARKT IN HAMBURG

A flange connection in an underground tunnel of the 'Hamburger Hochbahn' had to be sealed due to leakages and penetrating groundwater. The positioning of the center of the front surface of 240 flange pins was required with an accuracy of better than 3mm for the precise fitting of pre-fabricated flange sheet metals.

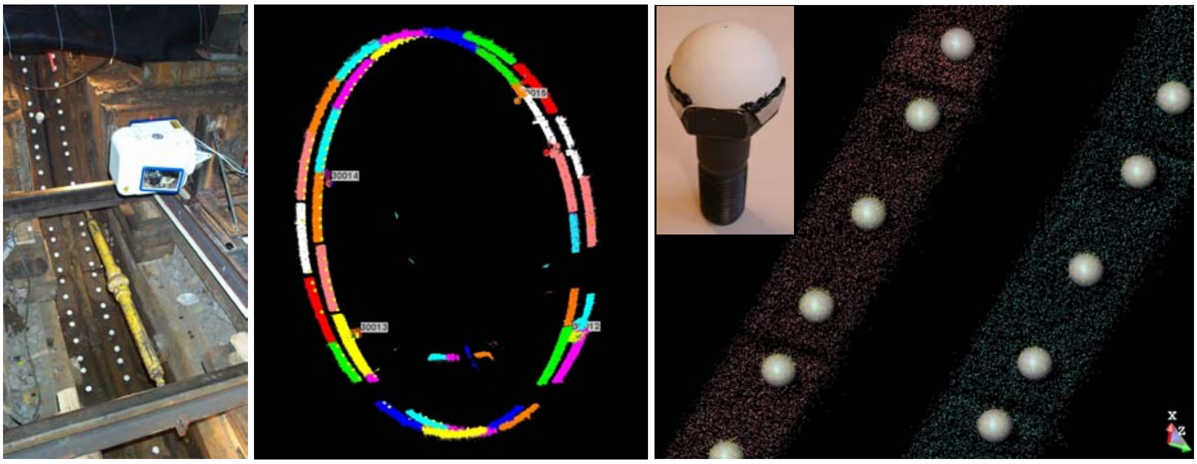

Figure 5: From left to right: Laser scanner GS100 on a special socket in the underground tunnel, colour coded representation of the different scans, hemisphere adapters and automatically fitted spheres

The investigation centred on whether the terrestrial laser scanner Trimble GS100 could supply the requested accuracy. Therefore, it was necessary to minimize the scanning noise through use of sufficient numbers of multiple measurements and through optimal reflectivity of the object surface. In addition a time slot of three hours was available in the nocturnal break of the underground railway, between 1 and 4am, for the scanning of the object. In order to be able to fulfil these constraints, the pins were signalised with specially manufactured hemispheres (halved table tennis balls on magnetic adapters, see Fig. 5). This target allows semi-automatic coordinate determination of the sphere centre using the 'Sphere Extraction Function' in the scanning software PointScape. Thus, the centre of each hemisphere represents the centre of the related front surface of the pin, which yielded the coordinates of the required points. In order to scan the entire flange in one setup, the scanner was mounted on a special socket developed at HCU (see Fig. 1 and Fig. 5 left) with a horizontal axis of rotation. Nevertheless, the signalised pins were scanned in sections (Fig. 5 centre) due to the limited number of available hemisphere adapters. Finally, the point cloud was transformed into the tunnel coordinate system using four control points. Additionally, the angle and the distance to 40 pins were measured with a Sokkia total station, in order to calculate their positions in the tunnel coordinate system as check points for quality control.

For post processing of the scanned data all three software packages (PointScape, RealWorks Survey and 3Dipsos) from Trimble were used. In the first step the semi-automatic 'Sphere

Extraction Function' in PointScape was used for the determination of each sphere centre by picking one point on the related sphere in the point cloud. Thus, a sphere was fitted into the selected point cloud using a predefined radius. In the second step the geo-referencing of each pin was carried out by transforming the centre of each sphere into the tunnel coordinate system using RealWorks Survey. Moreover, these coordinates were compared with the check points determined by the total station. For the computed differences a standard deviation of 2mm for each 3D pin position was achieved, with outliers of up to 8mm also being detected. However, in the calculation of this standard deviation the precision of the total station was also included. In the third step an attempt was made to determine the deviations of the pins from an ideal circle of the tunnel using 3Dipsos. The circle was fitted into the entire selected point cloud using least squares adjustment. Therefore, the point cloud was segmented, so that it consisted only of the centres of the hemispheres. For the fitting of the circle of the tunnel flange the radius was not fixed; this parameter should be determined additionally using a circle in 3D space as a computation function. The advantage of this function is the calculation of the radius in an adjusted plane instead of a radius of a sphere. As a result of the fitting the radius, the flange centre and the normal-vector of the adjusted plane were determined. The 3D distance between the individual pins and the ideal circle could be generated in the function 'Distance to Entity'. The calculated coordinates were loaded for inspection in AutoCAD, where the distance from the pins (bolt heads) to the centre and the distance between two neighbouring pins were represented (Fig.6a). The determined radius was 2.470m with a standard deviation of 3.5mm. The obtained differences were in the range of –6.2mm and +17.2 mm.

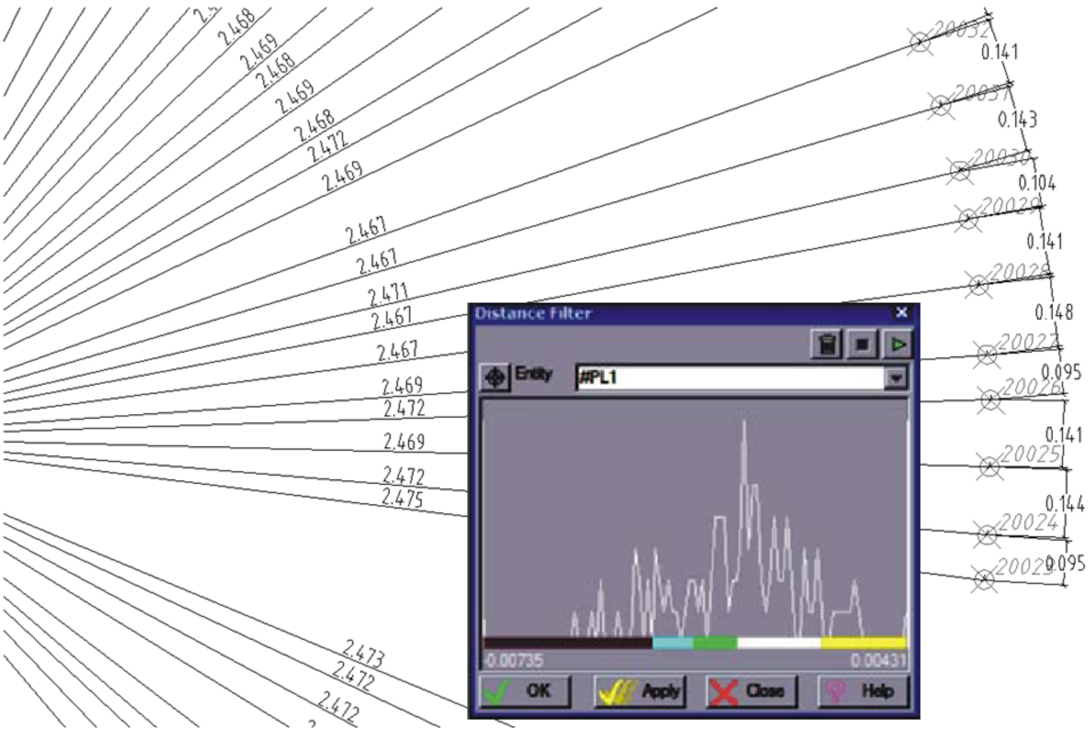

Figure 6: a) Representation of radius and distance between two pins in AutoCAD (background), b) distribution diagram of the difference between pins and plane in 3Dipsos (front)

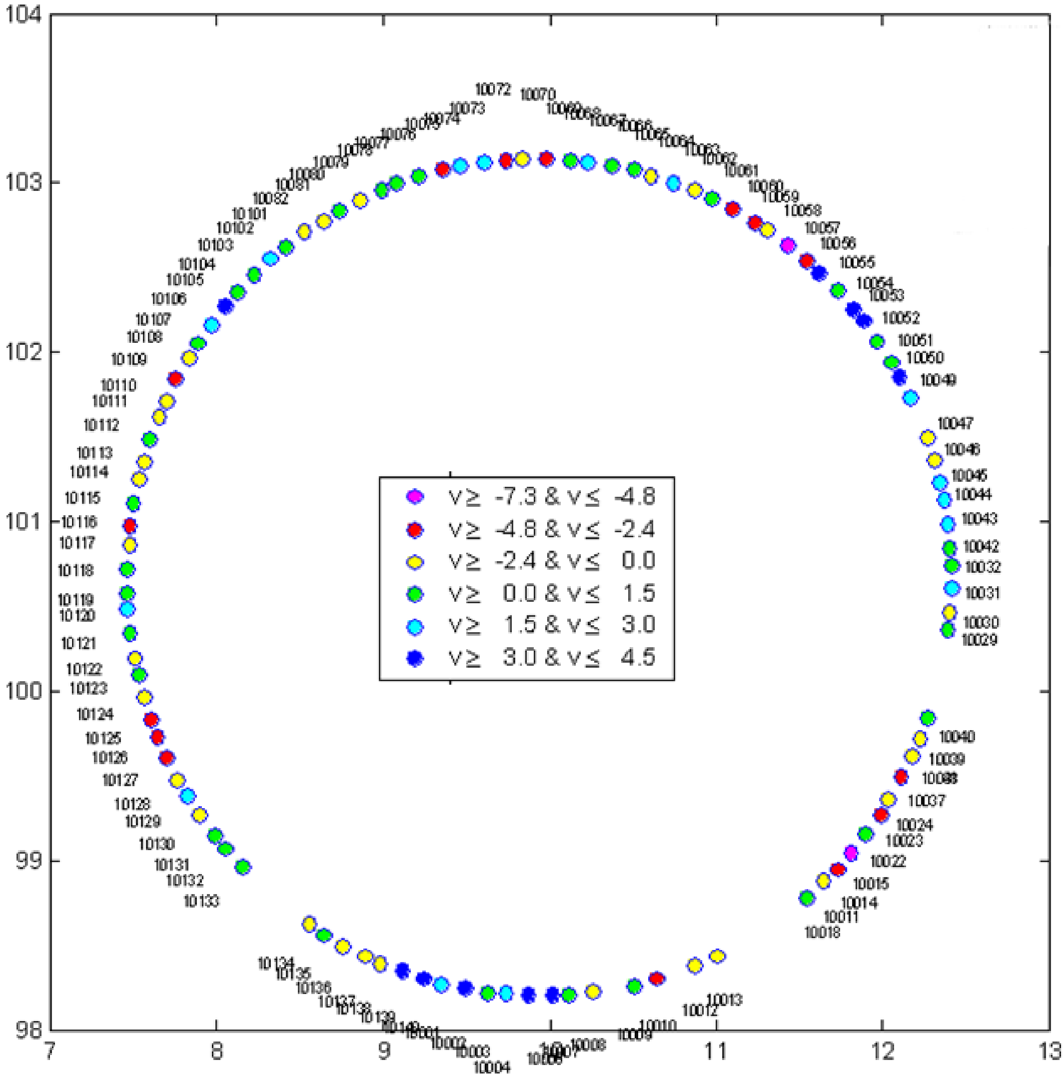

Figure 7: Differences between points (pins) and adjusted plane as a colour-coded representation in MATLAB (in mm)

Furthermore, an examination was made in 3Dipsos to check whether all pins fit into a plane. For assessment of the quality of fit, the features of the new, fitted object (e.g. standard deviation and normal vector of the plane) can be indicated. The fitting algorithm can create an improved fit by using a threshold value for the standard deviation. Apart from this numeric quality information the software offers visual interpretation of the results, which can be very helpful, in particular for the inspection of work pieces or other objects. With the function 'Distance to Entity' the distances from the individual points to the object are represented using colour coding and described in a distribution diagram (Fig. 6b). This diagram also displays the maximum distances in both directions. Nevertheless, this type of visualisation does not only facilitate the interpretation of the results, but also outliers can be easily eliminated in the distribution diagram, since the threshold values are manually adjustable. However, this representation is only available by screenshot, since storing of the colour coded point cloud is not possible in this software. In addition the spot size cannot be varied in this representation making individual points hard to distinguish. Further details on data processing and modelling of point clouds with the software 3Dipsos is described in Kersten et al (2005c). Moreover, for better analysis and visualization this step of data processing was accomplished a second time in MATLAB. Here, the processing can be repeated in two independent steps: (i) fit a circle in 3D into the point cloud, and (ii) fit a plane into the point cloud to determine the normal-vector and the differences between point cloud and plane. To display these differences between pins and adjusted plane colour coding was used as illustrated in Fig. 7.

A standard deviation of 2.3mm has been achieved for the adjusted plane, while differences between points and adjusted plane were in the range of -7,3mm and +4,5mm. However, these obtained differences are influenced by construction and measurement errors. Finally, the computation in MATLAB confirmed both results with a difference of less than 0.01mm: (i) the radius calculated with 3Dipsos, and (ii) the differences between points and plane.

The total time of data post processing (including the fitting of the spheres into the point cloud and its computations) was approximately 8h, which corresponds to a ratio of 1: 3 for scanning and evaluation time.

5. CONCLUSIONS AND OUTLOOK

In both projects terrestrial laser scanning has proven to be a suitable technique for 3D data acquisition of complex and irregular objects such as the interior of the water tower and the flange connection in an underground tunnel. Comprehensive 3D acquisition of the objects offered versatile possibilities for data processing using the tools RealWorks Survey and 3Dipsos. In the first project it was only necessary to generate simple geometry (coordinates, polylines) from the point cloud for the determination of the tower axis, for collision inspection and for further coordinate determination. Thus, efficient project processing with a ratio of 1:1 and 1:3 for data acquisition and evaluation, respectively, could be ensured. For the point determination an accuracy of up to 3mm was achieved in both projects, which did not completely meet the requirements of the underground tunnel project. It must be understood that special attention must be paid to the distribution of the control points around the object if such high accuracy is required. The low scanning speed had an unfavourable effect when scanning in high resolution with a time-of-flight system since a significantly longer time for scanning is needed. In this component there is still potential for optimisation of laser scanning systems that use the time-of-flight measurement method. Alternatively, a laser scanner with phase difference method such as an IMAGER 5006 from Zoller & Froehlich could offer a better performance for the second project in the underground tunnel due to faster scanning speed and better precision in such a short distance range between 3m and 10m. Unfortunately, this scanner was not available at that time.

In order to achieve an efficient project workflow, the flexibility could be increased by the use of so-called ‘third party software’ (e.g. MATLAB) during data processing, since the laser scanning system manufacture’s available tools do not facilitate processing for all of the required output functions. Finally, these tests prove that terrestrial laser scanning systems can be recommended for geometrical building inspections in the future, since the provided results were highly acceptable to the customer and further evaluations of this data are possible at any time on customer's request.

Advanced technology and new features of 3D laser scanners will be available on the market in the future, e.g. introducing additional instrument features like electronic levels, inclination compensation, forced-centring, on the spot geo-referencing, and sensor fusion (e.g. digital camera and GPS). Such improved laser scanning systems with an increased scanning range and with reduced scan noise will offer better performance for applications in geometrical building inspections.

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BIOGRAPHICAL NOTES

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Dipl.-Ing. Klaus Mechelke, born 1961, graduated as Dipl.-Ing. in Geomatics from Hamburg University of Applied Sciences in 1987. From 1987 - 1990 he worked as a lecturer at the Technical School in Addis Abeba, Ethiopia. Since 1992 he is a research and teaching assistant at the HafenCity University Hamburg, Department Geomatics.

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