Terrestrial Laser Scanning – Investigations and Applications for High Precision Scanning

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Key words: terrestrial laser scanning, investigating of laser scanners, applications, high precision scanning

SUMMARY

Nowadays, laser scanning has become an additional technique for geodetic applications. The use of laser scanners is continuously increasing. Different laser scanners of several companies are available. At the Institute of Geodesy and Photogrammetry (IGP) of the Swiss Federal Institute of Technology Zurich (ETH Zurich), experiences with several scanners were gained. Recently, the focus is on investigating and using the Imager 5003 of Zoller+Froehlich, Germany.

In the laboratories at the IGP, the Imager 5003 laser scanner has been investigated. A 52 m calibration track line allows to compare the measured distance with the nominal distance provided by an interferometer. Several tests were carried out on this calibration track line focussing on the distance accuracy. Further on, the eccentricity of the laser scanner was examined as well as the trunnion axis error. Some results of these comprehensive investigations will be presented.

The practical use of the Imager 5003 laser scanner has been tested on several objects. One of these objects, a chapel, represents an application in cultural heritage as a typical laser scanning application. Whereas the other object, a tunnel, demonstrates an application of engineering geodesy. First results of these two objects will be shown

ZUSAMMENFASSUNG

Laserscanning ist inzwischen eine anerkannte und ergänzende Technologie. Die Anwendungen für Laserscanning nehmen kontinuierlich zu. Verschiedene Laserscanner sind von diversen Herstellern verfügbar. Am Institut für Geodäsie und Photogrammetrie (IGP) der Eidgenössischen Technischen Hochschule Zürich (ETH Zürich) sind Erfahrungen bezüglich verschiedener Laserscanner gesammelt worden. Derzeit liegt der Schwerpunkt auf der Untersuchung und Anwendung des Laserscanners Imager 5003 von Zoller+Fröhlich, Deutschland.

In den Laboratorien des IGP wird der Imager 5003 untersucht. Eine 52 m Messbahn, die mit einem Interferometer ausgestattet ist, ermöglicht die Untersuchung des Distanzmesssystems. Weiterhin wurden Exzentrizitäten und der Taumelfehler überprüft. Einige Ergebnisse dieser umfassenden Untersuchungen werden aufgezeigt

Die praktische Anwendung des Imager 5003 wird an zwei Beispielen demonstriert. Eines behandelt eine Kapelle und stellt eine typische Anwendung für Laserscanning aus dem Bereich des Kulturerbes dar. Das andere Beispiel behandelt einen Tunnel und ist in den Bereich der Ingenieurvermessung einzuordnen.

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1. INTRODUCTION TO LASER SCANNING

Nowadays, terrestrial laser scanning has become an additional technique for geodetic applications. The use of laser scanners is continuously increasing. Different laser scanners of several companies are available. However, a classification of the laser scanners is quite problematical: on which point of view should the classification be based? Conceivable classifications concern the range or the principle of the distance measurement system or the point density or the point accuracy or the field of view.

1.1 Classification of Terrestrial Laser Scanners

Based on the raised question, a classification of terrestrial laser scanners will be discussed. First of all, there is no one universal laser scanner for all conceivable applications. One scanner is more suitable for indoor use and medium ranges (up to max. 100 m), another scanner is more suitable for outdoor use with long ranges (up to several 100 m). The decision which laser scanner is the right one depends on the application.

Terrestrial laser scanners can be categorized by the principle of the distance measurement system. Mainly, the distance measurement system correlates both to the range and to the accuracy. Therefore, this categorization implies a categorization by range as well as by accuracy. Most of the laser scanners are based on the time of flight principle. This technique allows measurements of distances up to several hundred of metres. Even ranges beyond one kilometre are achievable (e.g. Mensi, Riegl). The advantage of long ranges implies a less accuracy in the distance measurement (approx. one centimetre). Beside the time of flight principle, the phase measurement principle represents the other common technique for medium ranges. The range is restricted to one hundred metres (e.g. Zoller+Froehlich, IQSun). In opposite to the time of flight principle, accuracies of the measured distances within some millimetres are possible. For the sake of completeness, several close range laser scanners with ranges up to few meters are available. But, they are more for the use in industry applications and reverse engineering (online monitoring in construction processes). The used distance measurement principles are laser radar and optical triangulation. Accuracies less then one millimetre (tenth up to thousandth of millimetres) can be achieved. However, these scanners do not fit into the classification of "terrestrial" laser scanners. The table 1 summarizes the classification of laser scanners.

The discussed classification can be seen more in a general and rough way. In addition, classifications by instrumental properties affect a more technical grade. Differentiations of laser scanners in a technical way can concern

- the way of scanning (360 ° scans, scanning specific sections because of limited fields of view, scanning of profiles etc.),

- the deflection system (sweeping or rotating mirrors),
- the combination with other devices, mounted on the laser scanner (e.g. camera, GPS),
- etc.

Table 1: Classification of laser scanners

Measurement system	Range [m]	Range accuracy [mm]	Manufacturers (examples)
Time of flight	~ 1000	> 10	Mensi, Riegl, Cyra, Callidus
Phase measurement	< 100	< 10	Zoller+Froehlich, IQSun
Optical triangulation, Laser radar	< 10	< 1	Minolta, Leica

1.2 General Notes to Laser Scanning

Laser scanning means the deflection of a laser beam by moving (sweeping or rotating) mirrors, the reflection of the laser beam on object surfaces, and the receiving of the reflected laser beam. In opposite to measurements on reflectors, the accuracy of distance measurements depends on the intensity of the reflected laser beam. Physical laws describe the functionality between accuracy and intensity (Gerthsen 1993). Main parameters in these functions are the distance, the angle of incidence, and surface properties (Ingensand et al. 2003).

For calibration of total stations, specific procedures were developed in the last years. Instrumental errors as well as angular resolutions and distance accuracies can be defined. Unfortunately, the mechanical design of laser scanners is different to total stations. Most investigations cannot be applied to laser scanners. The measurements in two faces as well as the repetition of single point measurements are impossible. Further, a complicating factor is that most of the manufactures of laser scanners have no experiences in how to construct "geodetic" instruments and how to minimize instrumental errors. This leads to the conclusion that laser scanners have to be investigated from the point of geodetic metrology. Mostly in ways which are optimised for the specific instrument and which are unstandardised.

2. INVESTIGATION OF LASER SCANNERS

The IGP is using the laser scanner "Imager 5003" of Zoller+Froehlich, Germany. First experiences and investigations were carried out (Ingensand et al. 2003). Meanwhile, the laser scanner was updated regarding some instrumental properties (e.g. laser beam, deflection system). The experiences and investigations will be shown and compared to the previous investigations. Further on, new investigations were carried out, which are based on former experiments.

2.1 Eccentricity

In the following chapter, a comprehensive examination of the eccentricity of the laser scanner will be presented. In particular, three different investigations were carried out. These affect the

- eccentricity of the base cylinder,
- behaviour of rotation, and
- eccentricity of the scan centre

2.1.1 Eccentricity of base cylinder

The casing of the laser scanner is mounted on a base cylinder (figure 1). The casing (1) rotates on this base cylinder (2) and additional, the mirror (3) rotates in the gap of the casing.

Figure 1: Construction of the laser scanner IMAGER 5003 of Zoller+Froehlich – casing(1), base cylinder (2) and rotating mirror (3)

For identifying a possible offset, the direction to the centre of the base cylinder is derived and compared to the nominal direction. After converting the angular values in distance values, an offset of three tenth of millimetres with a standard deviation of one tenth of millimetres was derived in two perpendicular directions.

2.1.2 Behaviour of rotation

By rotating around the vertical axis, the orientation of the collimation axis has to remain constant. For verifying this condition, a target was mounted on the casing. The position of this target was calculated in specific positions by intersection. After plotting the positions of the target, the measured positions had to correspond to a circle (constraint: elimination of systematic errors, e.g. vertical axis error). The residuals of the positions to the adjusted circle were less than one millimetre.

Further detailed investigations of the orientation of the collimation axis are described in the chapter “trunnion axis error”. Based on variations of the orientation of the vertical axis during a rotation, a comprehensive discussion is given using Fourier analysis.

2.1.3 Eccentricity of scan centre

The physical scan centre of the laser scanner has to correspond to the rotation centre of the laser scanner. Deviations between these two centres cause an offset in all measurements. For verifying this constraint, a field of reference points was surveyed. The laser scanner was put up on a reference point in the centre of this test field of reference points. After measuring the nearby reference points, the local scanner reference frame was transformed to the nominal reference frame of the reference points. Regarding the residuals two statements can be made:

- An offset of the scan centre can be determined and
- possible systematic effects in the distance measurements can be seen.

The results regarding the offset of the scan centre are the following. A significant offset cannot be verified. The residuals of the scan centre were less than one millimetre. The results regarding systematic effects of the distance measurements are discussed in the chapter "distance measurement system".

2.2 Trunnion Axis Error

2.2.1 Introduction and previous investigations

By rotating around the vertical axis, the orientation of the vertical axis has to remain constant. Otherwise, the current vertical axis has deviations to the nominal vertical axis. These deviations are defined as trunnion axis error (Matthias 1961). This error influences mainly the measurements in vertical directions, especially the co-ordinates in vertical direction.
Based on first investigations and findings of the trunnion axis error (Ingensand et al. 2003), further experiments were carried out. A summary of the first results is the following:

- A trunnion axis error could be seen.
- A precise mathematical description failed because of varying phase angles.
- Causes were assumed to be in the unbalanced system (approx. five kilograms between both sides of the casing, see figure 2)

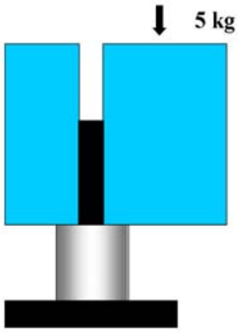

Figure 2: Eccentricity of the weight of the laser scanner (unbalanced system) of approx. 5 kg

The setup of the investigation was based on an inclinometer, which was mounted in the rotation centre in top of the scanner. The used inclinometer was the Nivel 20 of Leica Geosystems, which provided the measurement of inclinations in two perpendicular directions (x,y) at each measurement position within a small measurement range [-2; +2] mm/m by an accuracy of 1 μm/m. The original data (x,y) allowed to derive at each position the vertical axis (v). Afterwards, the mean vertical axis error (s) could be calculated. Deviations of the current vertical axis (v) to the mean vertical axis error (s) result in a trunnion axis error (t).

$$v = \sqrt{x^2 + y^2}$$

$$s = \frac{1}{n}\sum v$$

$$t = s - v$$

In case of a trunnion axis error, the derived new observations (t) describe a harmonic oscillation. Based on the Fourier analysis, the harmonic oscillation can be split up in frequencies, expressed by amplitude and phase angle. The frequency with the highest amplitude can be considered as trunnion axis error.

2.2.2 Results of new investigations

New investigations were carried out on a solidly built granite table. Thus, deformations of the table could be excluded. The aim was, to verify the influence of the unbalanced system. For investigating, the laser scanner was fixed on the table. Overall, four data series were surveyed with a time delay of several hours. In figure 3, the data series can be seen. Clearly visible are the harmonic oscillations in the graphs. Also, the graphs are quite identical.

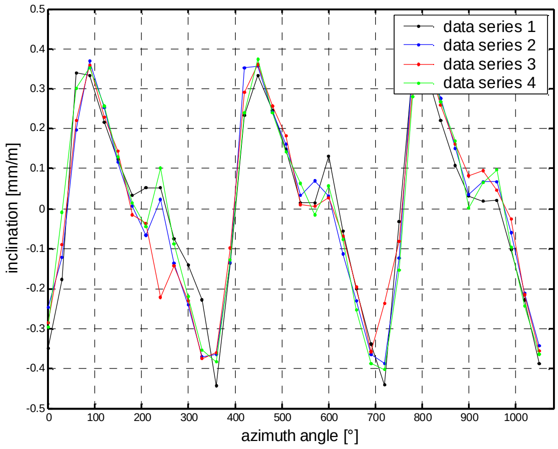

Figure 3: Derived observations (t) of the four data series

After Fourier analysis, the frequencies and their corresponding amplitudes were visible. A closer view to the interesting parameters is given in table 2.

Table 2: Parameters of Fourier Analysis

Data series	Frequency 1 (period of 360°)		Frequency 2 (period of 180°)		Vertical axis error [mm/m]
	Amplitude [mm/m]	Phase angle [°]	Amplitude [mm/m]	Phase angle [°]	
1	0.256	317.4	0.176	291.1	0.475
2	0.276	321.3	0.165	291.9	0.424
3	0.271	324.7	0.144	288.7	0.420
4	0.275	319.5	0.174	293.0	0.432

The following results can be seen:

- The vertical axis error is quite constant.
- The significant frequencies are identical.
- The amplitudes are quite constant.
- The phase angles are quite identical.
- The resulting error is approx. 1.4 cm (frequency 1) in a maximum distance of 52 m.

Based on these new investigations it can be verified that modeling the trunnion axis error is only possible, if this unbalanced laser scanner is put up on solidly built things. Deformations of underlying objects are conceivable, even of tribrachs. The arising question is, what would happen, if the laser scanner is a balanced system (without eccentricities in weight)?

2.3 Distance Measurement System

Because the laser scanner was updated (e.g. laser diode, deflection system), new investigations of the distance measurement system became necessary. The investigations were applied on both "static" and "scanning" mode. "Static" mode means that the laser scanner can be used like a total station. The laser beam can be orientated towards an object, without rotations of the mirror. In comparison, the "scanning" mode means that an object is scanned with rotating mirror.

The results regarding the "static" mode will be compared to earlier investigations (Schulz 2004). The examinations were carried out on the calibration track line at the laboratories of the IGP. Over a length of nearly 52 m, distances were measured with an interferometer within an accuracy of a thousandth millimetre (one micron). These distances are of a factor thousand more accurate than the measured distances of the laser scanner. Thus, they can be treated as nominal distances.

2.3.1 Distance accuracy in the "static" mode

In several data series with different intervals (one, five, and ten metres), the distance measurement system was examined in the "static" mode. For this purpose, the laser beam was orientated towards a target in the way that the laser beam ran horizontally (deflecting mirror and target were nearly in the same height). A white paper with a black scale (for aligning the laser beam) served as target.

By examination the "static" mode, a set of thousand measurements for each range was stored (measurement frequency of 125 kHz, default noise). Based on these measurements, theoretical and empirical standard deviations could be derived. Further on, mean distances and the corresponding nominal distances were compared. Also, the differences between minimal and maximal distance of the thousand measurements for each position were calculated.

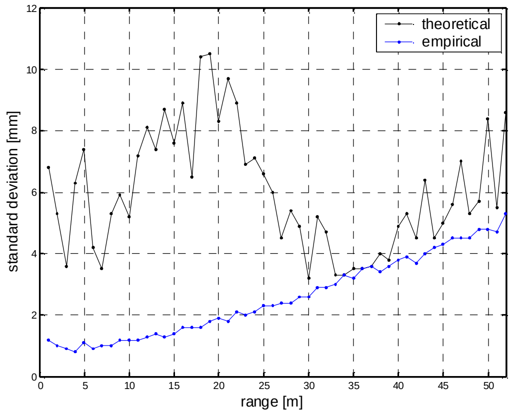

Figure 4: Theoretical and empirical standard deviations (interval 1 m)

The theoretical and empirical standard deviations (interval of measurements: one metre) are depicted in figure 4. In comparison to earlier investigations, the theoretical standard deviations lie within nearly ten millimetres over the whole measurement range. This improving accuracy results from two aspects. First, conceivable multipath effects were avoided by using a dark curtain behind the target in prolongation of the measurement direction. Second, the new laser diode has both an improved beam divergence (0.23 mgon) and a smaller laser spot size.

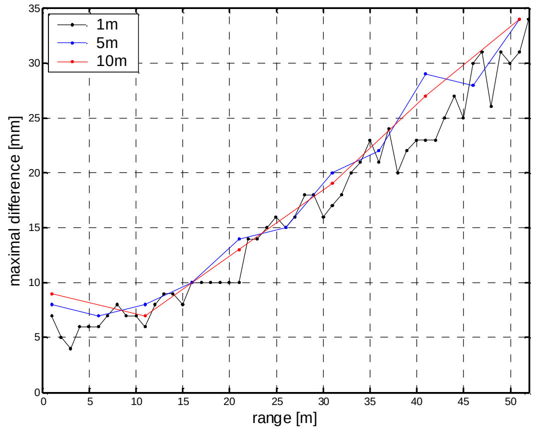

Figure 5: Differences between minimal and maximal measured distance (within thousand measurements)

In figure 5, the differences between minimal and maximal distance of the thousand measurements within each measurement position can be seen. Upon closer, the quite satisfying results of the theoretical standard deviations are relativised. The differences between minimal and maximal measured distances within each thousand measurements were increasing in correlation with the range. In farer distances, differences of more than ten millimetres are visible. They exceed more than 30 millimetres in a maximum range of 50 metres.

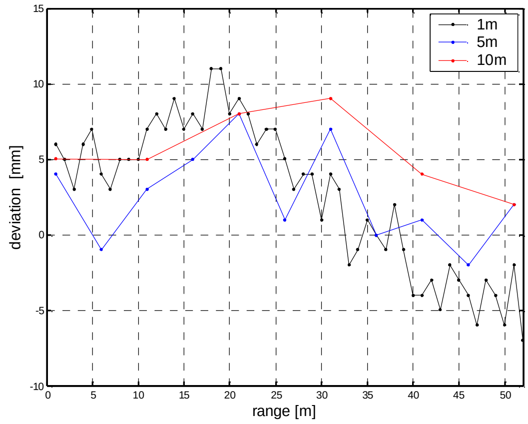

Figure 6: Deviations between measured distances (mean values) and nominal distances

The differences between nominal distances and measured distances (mean distance of thousand single measurements) are shown in figure 6. It can be seen that the deviations start at a value of nearly five millimetres, increase up to a maximum value by a range of nearly twenty metres and decrease. Some systematic effects can be assumed, e.g. addition constant and a negative scale factor.

Further on, the inner accuracy was tested. For this topic, the distances between each position to the previous position were computed. These distances were compared to the nominal distances (intervals of one, five or ten metres). The resulting differences are shown in figure 7. It can be seen that all differences are distributed with positive and negative signs within values of about four millimetres. In addition to figure 6, no systematic effects are visible except of a possible harmonic oscillation correlating to the fine frequency (half of the wave length of the fine frequency: approx. 3.3 m) of the phase measurement system.

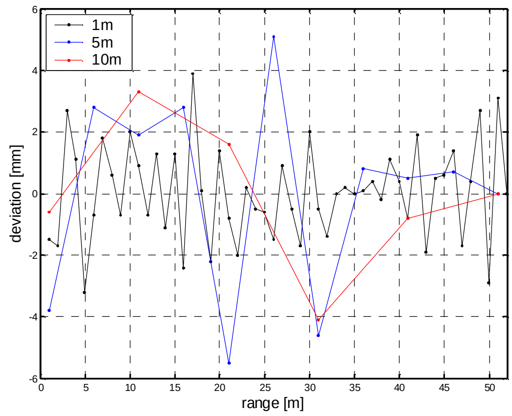

Figure 7: Deviations between the derived distances of two close-by positions of the target and the nominal distances (1 m, 5 m, or 10 m)

2.3.2 Distance accuracy in the "scanning" mode

Analogue to the investigations in the "static" mode, the "scanning" mode was examined on the calibration track line. Spheres with a white colour surface were observed instead of the white target with the black scale in intervals of one metre. The diameters of the spheres were at about fifteen centimetres (sphere 1: 15.14 cm) and twelve centimetres (sphere 2: 12.02 cm), which were calibrated before. All results are based on the "scanning" mode called "super high". This "scanning" mode has the highest point density. Depending on the point cloud, the centres of the spheres (centre points) were derived. The centre points were computed in two methods. In the first method, both the centre points and the diameters were estimated ("free" diameter). In the second method, the diameters were fixed and only the centre points were computed ("fixed" diameter). Then, the horizontal distances to the centre points could be compared with the nominal distances. Further, the heights of the centre points could be analysed in respect of the nominal heights of the calibration track line. For each position, the results were given including both spheres (sphere 1 and sphere 2) with fixed and "free" diameters.

In figure 8, the differences between the distances to the centre points and the nominal distances are depicted. Several conclusions can be drawn:

- An addition constant (approx. four millimetres) can be seen in all graphs.
- The results with fixed diameters are better than the results with "free" diameters.
- The deviations increase up from fifteen metres.

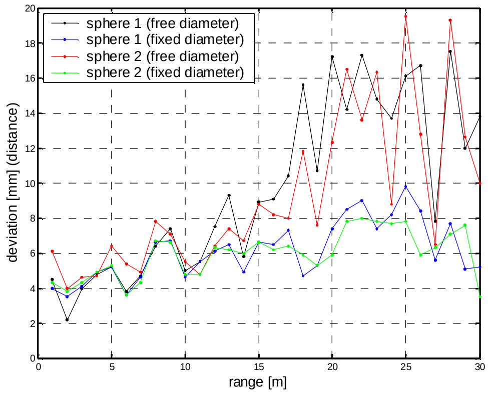

Figure 8: Deviations between the distances to the centre points and the nominal distances

Analogue to the "static" mode, the inner accuracy was surveyed. For each measurement, the distance of a centre point to the previous centre point was computed and was compared to the nominal distance (interval of one meter). The findings are depicted in figure 9. Up to fifteen metres, the deviations lie within two millimetres (positive and negative sign). In longer distances, the deviations increase with a harmonic oscillation. These results show two aspects:

- The spheres are well observable up to fifteen metres and the centre points can be computed quite reliably.
- An addition constant exists of nearly four millimetres.

In a further calibration procedure, the addition constant was determined with a value of four mm.

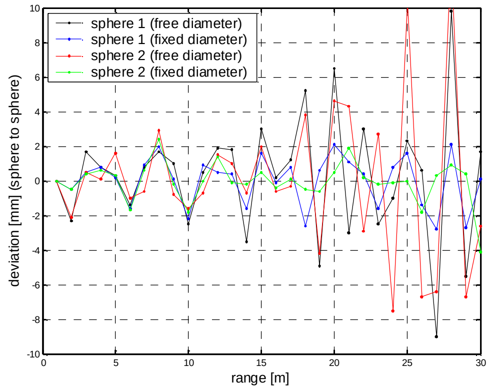

Figure 9: Deviations between the derived distance of two close-by centre points and the nominal distance (interval 1 m)

Additionally, the heights of the centre points could be compared to the nominal heights of the calibration track line. The deviations between computed heights and nominal heights are depicted in figure 10. It can be seen that the heights lie within one millimetre up to a range of fifteen metres. From this range on, the deviations increase with a harmonic oscillation. The conclusion can be drawn that the heights, which point to the accuracy of the vertical direction, are less problematical than the distances.

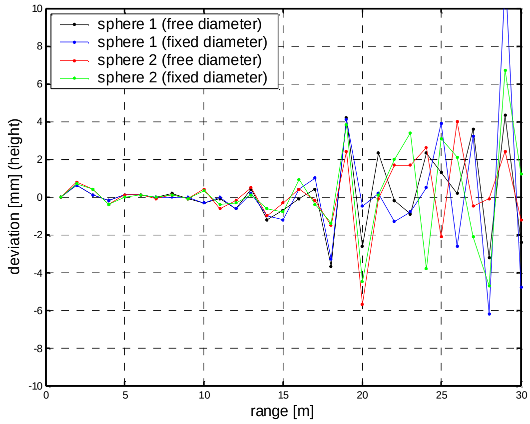

Figure 10: Deviations between the heights of the centre points and the nominal heights

The last investigation regards the diameter of the spheres. In figure 11, the deviations between “free” and “fixed” diameter of both spheres are compared. Thereby, the diameter is well estimated up to fifteen metres (deviations lie within four millimetres).

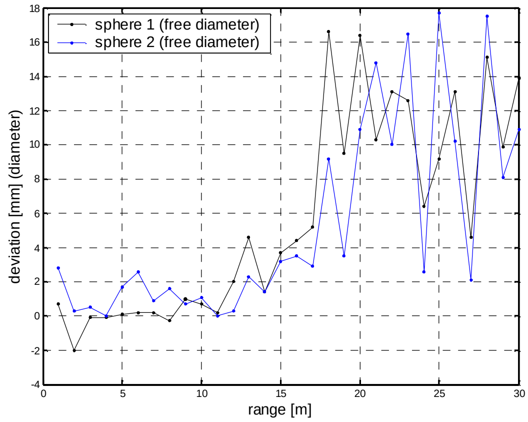

Figure 11: Deviations between derived diameters of the spheres ("free") and the nominal diameters of the spheres ("fixed")

The centre points were calculated by an iterative adjustment. The point with a significant distance to the surface of the sphere was eliminated. The adjustment was repeated, until either all points lay within a maximum distance to the surface of the sphere (e.g. five millimetres) or the unknowns (co-ordinates of the centre points) changed below a limited value (e.g. one tenth of millimetres).

The conclusions of the investigations in the "scanning" mode are the following:

- In general, the results are quite good up to distances of fifteen metres.
- The use of "fixed" diameters increases the accuracy.
- For practical applications it is recommended to restrict the measurement range for scanning spheres up to fifteen metres.
- Further on, more the quality than the quantity of the points on the spheres influences the results.

3. APPLICATION OF TERRESTRIAL LASER SCANNING

Mostly, an object has to be scanned from different view points. Afterwards, the aim is to register single point clouds to one common point cloud. This operation is called registration. For registration, homologous points (tie points) or objects (e.g. spheres, cylinders) are required.

In the following examples, spheres with diameters of approximately twelve centimetres and fifteen centimetres (see chapter 2 "Investigations regarding the 'scanning' mode") were used. Thereby, in each scan at minimum three spheres were visible. The spheres can be changed by reflectors. Thus, it is possible to integrate the local scanner frame to existing reference frames.

3.1 Example 1: Chapel of "Neubrueck", Switzerland

The first example shows the chapel of "Neubrueck" (Switzerland). It represents a typical application for cultural heritage. The chapel was scanned from all four side and additionally

one scan is made in the interior. The scans were registered by using spheres. Based on the registered point cloud, further information can de derived. Mathematical information (e.g. volume, distance) as well as a 3D-model are conceivable.
In the following figures, the point cloud (figure 12a) and a rough 3D-model with textures (figure 12b) are shown

Figure 12a: Registered point cloud

Figure 12b: Rough 3D-model of the chapel (with textures)

3.2 Example 2: "Muehlebach"- tunnel, Switzerland

The second example shows the "Muehlebach"- tunnel (Switzerland). In addition to the first example, it represents a high precision application for engineering survey. Investigations of the tunnel (e.g. deformation analysis, tunnel profile, rail track) could be of interest. The tunnel was scanned in shifted scans (approx. ten metres by a length of the tunnel of nearly one hundred metres). From each view point, separated scans of the tunnel tube and the spheres were surveyed.

In figure 13a, the high detailed point cloud is shown. Clearly visible are details like catenary, wall and rail track. The whole tunnel tube is presented in figure 13b.

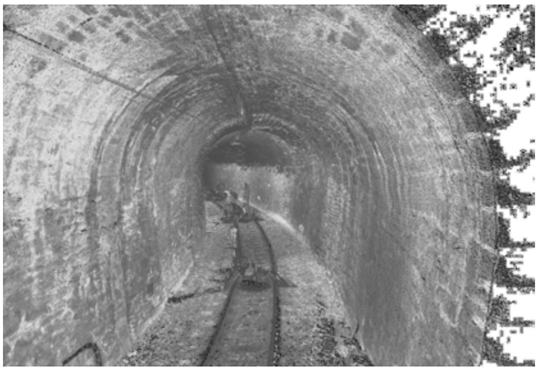

Figure 13a: Detailed view of a tunnel section

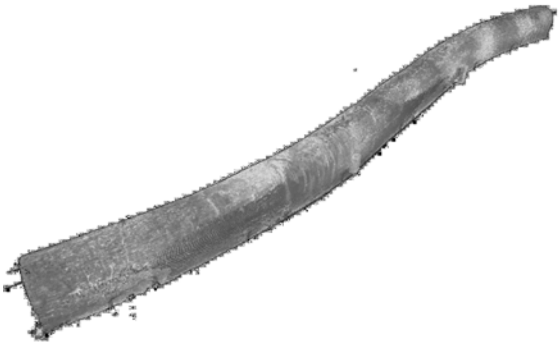

Figure 12b: The whole tunnel tube

4. CONCLUSION

Comprehensive investigations regarding eccentricity, trunnion axis error and accuracy of the distance measurement system were done. Thereby, conclusions of the distance accuracy both in "static" and in "scanning" mode were drawn. Further on, some results were compared with the results of former investigations. In general, the findings are quite good. However, for applications in high precision scanning it is important to investigate the laser scanner in respect of instrumental and methodological errors.

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BIOGRAPHICAL NOTES

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