Optical 3-D Measurement Techniques VIII, Gruen/Kahmen (Eds.), Zurich, July 9-12, 2007, Vol. I, pp. 319-327.

COMPARATIVE INVESTIGATIONS INTO THE ACCURACY BEHAVIOUR OF THE NEW GENERATION OF TERRESTRIAL LASER SCANNING SYSTEMS

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Abstract: Currently the second, or for some manufacturers even the third, generation of terrestrial laser scanning systems is available on the market. Although the new generation of terrestrial 3D laser scanning offers several new (geodetic) features and better performance, it is still essential to test the accuracy behaviour of the new systems for optimised use in each application. As a continuation of previous published investigations the Department Geomatics of the HafenCity University Hamburg (HCU Hamburg) carried out comparative investigations into the accuracy behaviour of the new generation of terrestrial laser scanning systems (Trimble GX and Leica ScanStation using time-of-flight method, Z+F IMAGER 5006 and Faro LS880 HE using phase difference method). The results of the following tests are presented and discussed in this paper: derived distances from point clouds of a 3D test field for accuracy evaluation of 3D laser scanning systems, accuracy tests of distance measurements in comparison to reference, accuracy tests of inclination compensation, influence of the laser beams angle of incidence on 3D accuracy, investigations into scanning noise and investigations into the influence of object colour on distance measurements.

1. Introduction

Laser scanning is on the way to becoming accepted as a common method of 3D data acquisition, finding its position on the market beside established methods like tacheometry, photogrammetry and GPS. Advanced technology and new features of 3D laser scanners have been developed in the past two years, introducing additional instrument features like electronic levels, forced-centring and on the spot geo-referencing. These elements are obviously equivalent to features that can be seen in total stations. Several authors have already reported on different approaches for investigations into terrestrial laser scanning systems. Nevertheless, standardized calibration methods of laser scanning systems do not yet exist. First investigations into the calibration of the IMAGER 5003 are described in [7]. Technical specifications provided by the system manufacturers are still not comparable. Therefore it may be difficult for users to choose the right scanner for a specific application, which emphasises the importance of comparative investigations into accuracy behaviour of terrestrial laser scanning systems.

First accuracy tests and practical experiences using the Trimble GS100 at HCU Hamburg are already published by [5] and [6]. Other investigations into the accuracy of different laser scanning instruments are reported by several authors [1], [3], and [4].

2. The terrestrial laser scanning systems used

The investigations into the accuracy behaviour of laser scanners were carried out by using the following laser scanning systems: Trimble GX, Leica ScanStation, Faro LS 880 and IMAGER 5006 from Zoller & Fröhlich (Fig. 1).

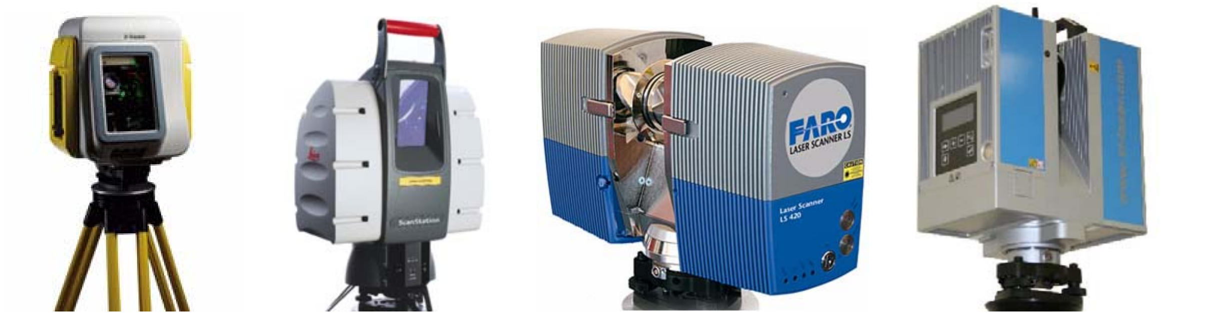

Fig. 1: Terrestrial laser scanning systems for investigation at HafenCity University Hamburg: Trimble GX, Leica Scan-Station, Faro LS 880HE, IMAGER 5006 from Zoller & Fröhlich.

Scanner/Criterion		**Trimble GX**	**Leica ScanStation**	**FARO LS 880 HE**	**Z+F IMAGER 5006**
Scan method		Time-of-flight		Phase difference	
Field of view [°]		360 x 60	360 x 270	360 x 320	360 x 310
Scan distance [m]		200	300	< 76	< 79
Scanning speed		≤ 5000pts/s	≤ 4000pts/s	120kHz	≤ 500000px/s
Angular resolution [°]	Vertical	0,0017	0,0034	0,009	0,018
	Horizontal	0,0017	0,0034	0,00076	0,018
3D scan precision		12mm/100m	6mm/50m	n.a.	n.a.
Camera		integrated	integrated	add-on option	add-on option
Inclination sensor		compensator	compensator	yes	yes

Table 1**:** Summary of technical specifications of the tested laser scanning systems

The technical specifications and the important features of these laser scanners are summarised in Table 1. The tested scanners represent two different principles of distance measurement method: Faro LS880 and Z+F IMAGER 5006 use phase difference method, while Leica ScanStation and Trimble GX scan with the time-of-flight method. In general it can be stated that phase difference method is fast, but signal to noise ratio depends on distance range and lighting conditions. If one compares scan distance and scanning speed in Table 1, it can clearly be seen, that scanners using the time-of-flight method measure longer distances but are relatively slow compared to the phase difference scanners.

Most of the presented investigations use spheres as test bodies to obtain the reference positions. The diameters of the used spheres were 76.2mm and 145mm, respectively. The spheres were of matt white colour and were checked for eccentricity and diameter. To obtain centre positions of the spheres, the point clouds representing the sphere were manually corrected for outliers. The fitting of the sphere geometry was performed using algorithms of the Trimble software Real-Works Survey and 3Dipsos.

3. Geometric investigations

3.1. 3D test field for accuracy evaluation of 3D laser scanning systems

Referring to the guidelines in part 2 of the VDI/VDE 2634 [9] the accuracy of 3D optical measuring systems based on area scanning shall be evaluated by checking the equipment at regular intervals. This can be achieved by means of length standards and artefacts, which are measured or scanned in the same way as typical measurement objects. One important quality parameter can be defined as sphere spacing error similar to that in ISO 10 360. Instead of calibrated artefacts in object space reference distances between spheres were used for the accuracy evaluation at HCU Hamburg. However, the precision of 3D laser scanning systems is composed of a combination of errors in distance and angle measurements, and in the algorithm for fitting the spheres/targets in the point cloud. The influence of these errors cannot be determined separately.

In order to evaluate the 3D accuracy of distance measurements derived from the sphere coordinates and of point cloud registration regarding the practical acceptance and verification methods of VDI/VDE 2634, a durable established 3D test field was used in the hall of building D at the HCU campus (Fig. 2). The volume of the test field is $30x20x12m^3$, including 53 reference points, which can be set up with prisms, spheres or targets. Just 43 points were used for this investigation. The points are distributed over three hall levels on the floor, on walls or on concrete pillars using M8 thread holes. The reference points were measured from four stations with a Leica TCRP 1201 total station. In a 3D network adjustment using the software Leica GeoOffice the station coordinates were determined with a standard deviation of less than 0.5mm, while the standard deviation of the coordinates of reference points is less than 1mm (local network). Specially built adapters with the same length as the used prisms guaranteed a precise, stable and repeatable set up of spheres or targets. Thereafter, spheres with a diameter of 145mm were installed on these reference points. These spheres were scanned with all four scanners from five scan stations for each system, where two scan stations were located at the ground floor, two at the first floor and the fifth station was placed on the second floor, so that a good geometric configuration for point determination could be guaranteed. For evaluation, all combinations of distances between all reference points were compared to those obtained from the centre of the fitted sphere of the point cloud. The minimum distance is 1.5m and the maximum distance is 33.1m, which is within the range of each scanner.

Fig. 2: Terrestrial laser scanner in the 3D test field scanning white spheres.

The results of the 3D test field investigations are shown in Table 2, where all differences of scanned and reference distance for one station at the first floor and for all stations are summarised as the range Δd from minimum to maximum deviation value as an indication for the accuracy of each system. This range value is influenced by the measurement precision of the instrument and by the algorithm for the fitting of the sphere. The centre coordinates of all spheres were computed with the Trimble software RealWorks Survey after manual cleaning of the outliers. In accordance with VDI/VDE 2634 [9] the results were computed for one scan station at the first floor and for the registration of all scan stations in the 3D test field. The best result was a range from minimum to maximum of 41.8mm using the distances of all scan stations, which could be achieved with the Leica ScanStation, while with the other scanners a slight worse result was obtained (see Table 2). The Trimble GX scanner shows a better result for all scan stations than for one scan station due to the averaging of the computed sphere coordinates in the registration procedure (Table 2). The average value of all differences was less than +1mm for Faro and Z+F scanner, while this value was +4mm for Leica ScanStation and +6mm for Trimble GX scanner, which yields a systematic shift and which is clearly illustrated in Fig. 3.

Scanner	One scan station at first floor				All scan stations of 3D test field			
	# dist.	Δd min [mm]	Δd max [mm]	Σ Δd [mm]	# dist.	Δd min [mm]	Δd max [mm]	Σ Δd [mm]
Leica ScanStation	528	-13,8	24,5	38,3	780	-18,5	23,3	41,8
Trimble GX	378	-16,3	37,1	53,4	780	-16,0	31,3	47,3
Z+F Imager 5006	465	-23,5	22,0	45,5	780	-32,8	23,7	56,5
FARO LS880	528	-23,6	22,2	45,8	780	-41,1	30,7	71,8

Table 2: Comparison of 3D distances obtained from the 3D test field

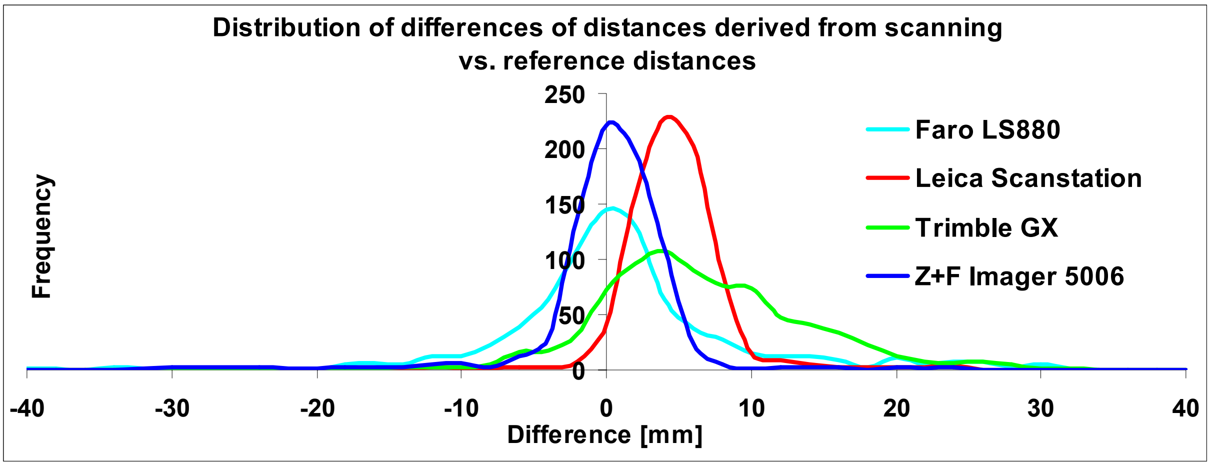

Figure 3: Distribution of differences for scanner vs. reference distances in the 3D test field

3.2. Accuracy tests of distance measurements in comparison to reference

Accuracy tests of distance measurements using reference distances derived from a precise total station were performed in distance ranges from 10m to 100m in steps of 10m. Reference distances were measured with a Leica TCRP1201 10 times before and 10 times after the scanning with the test scanners using averaging distance measurement mode. The differences between first and second measurement sequence were better than 0.3 mm. A standard deviation of 0.1mm was achieved for reference distances. Since all tested scanners use Wild-type forced-centring, it was possible to change prisms against scanner targets. By using special adaptors the centre of the scanner target could be placed in the same position as the prism centre.

All scanning distances of Faro LS880 and IMAGER 5006 were derived from scanned spheres with a diameter of 145mm, while for Leica ScanStation HDS targets and for Trimble GX green flat targets were used. For repeatability and reliability reasons each distance to sphere or target was scanned three times in the sequence forward-backward-forward with each scanner from the same position. Due to the limitation of scanning range Faro LS880 scans were checked to the distance of 60m and IMAGER 5006 scans to 75m. All major results of this accuracy test are illustrated in Fig. 4. There it is clearly indicated that the differences of the Leica ScanStation and IMAGER 5006 to the references distances are always less than 2mm, while for the Trimble GX the differences are also less than 2mm between 10-60m, but from 70 to 100m distance the differences increased to a systematic effect of 3-5mm. The differences of the Faro LS880 scans to reference were in the range of 1-5mm. Although Faro LS880 and Z+F IMAGER 5006 are capable of measuring up to 80m, it must be stated that even with highest resolution the number of 'hits' on the 145mm sphere is not high enough for distances beyond 50m to allow a precise fitting of sphere geometry. Additionally, it could be seen in several practical outside tests that signal to noise ratio rises on daylight circumstances for longer distances.

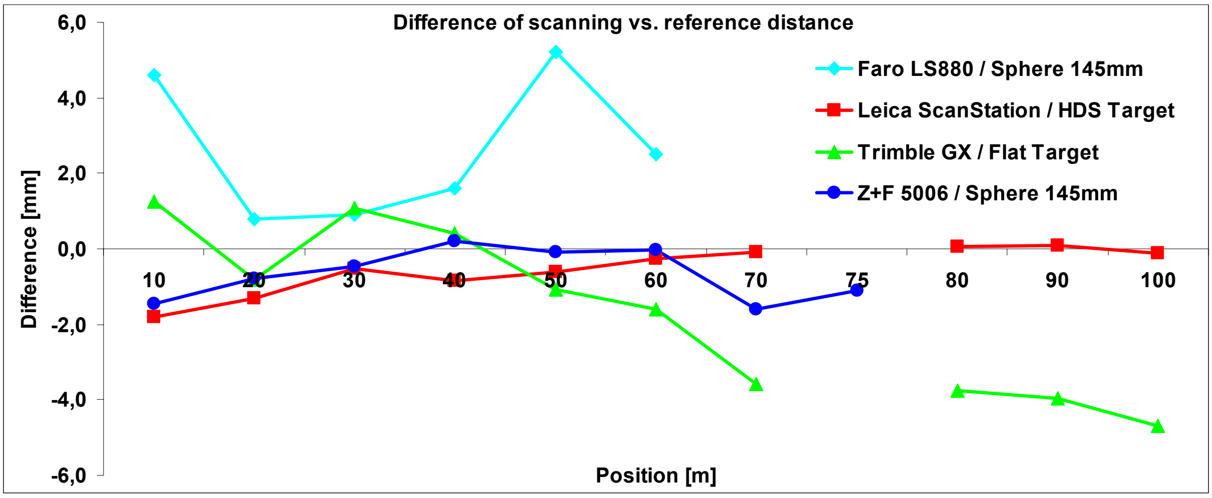

Figure 4: Comparison of the differences of scanning vs. reference distances

3.3. Accuracy tests of inclination compensation

All scanners in the test programme are equipped with an inclination sensor (see also Table 1), making it possible to level the scanner during measurements. Leica ScanStation and Trimble GX are able to compensate changes of main axis inclination during measurement, while Faro LS 880 uses corrections only for post-processing (in the registration of scans). The Z+F IMAGER 5006 uses the inclination sensor for gross error detection only, which indicates changes during the scanning. If the inclination sensor is switched on during scanning process, it is assumed for the time-of-flight scanners that the XY-plane of the scanner coordinate system is horizontal.

In order to check the accuracy of inclination compensation of each scanner, an outdoor test field was established using 12 spheres in steps of 30° on the circumference of a circle with a radius of 50m. Each sphere was set up on a pole and was adjusted to the same height by using a Wild N3 high-precision level instrument, while the tested scanners were set up in the centre position of the circle on a heavy-duty tripod (Fig. 6 left). While scanning the spheres, it is assumed that the centre coordinates of the fitted geometries (spheres) lie in-plane and that this plane is horizontal (Z =

constant). To check for movements of the scanner tripod during scanning, a Leica Nivel20 inclination sensor was fixed to the tripod, recording inclination in x and y direction in intervals of 5 seconds. The recordings of the Nivel20 showed no significant movements of the tripod during scanning.

Each sphere was scanned consecutively three times with the highest possible resolution settings. The fitting of sphere geometries was performed using Trimble RealWorks Survey 5.1. Before sphere fitting, outliers were removed manually from the point cloud. The derived average Z-coordinates of all fitted spheres were compared to the reference horizontal plane for each scanner. Differences in Z vs. reference plane were obtained from the average Z-coordinate of each position in the circle and are shown in Fig. 5 (top), which is a clear indication that the compensation of inclination works almost perfectly for both time-of-flight scanners, while for the phase difference scanner it can be seen that scanning has been conducted in an inclined plane.

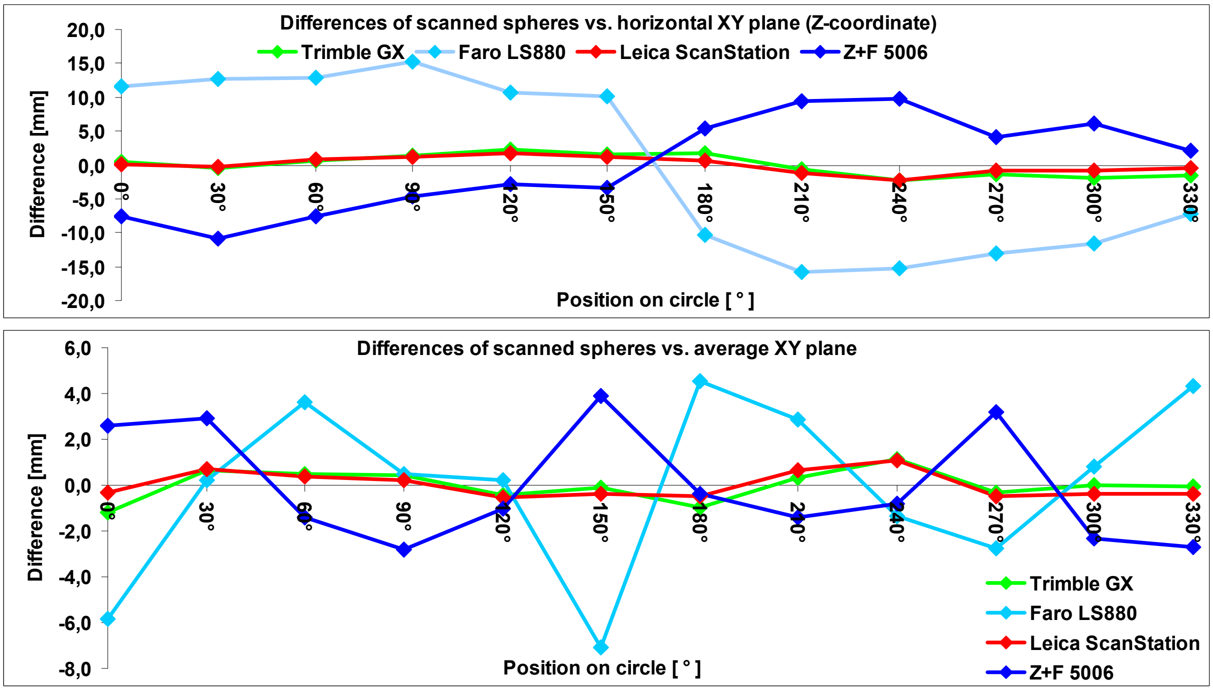

Figure 5: Test of inclination sensor in comparison: Differences of scanned spheres vs. horizontal XY plane (top) and vs. average XY plane (bottom)

Leica and Trimble scanner show maximum deviations of 2mm with a very minor sine oscillation, probably resulting from calibration error of the inclination sensor (Fig. 5 top). Faro LS880 shows huge differences up to 15mm, which may be influenced by the comparably low resolution (8mm / 50m) and the large signal to noise ratio of this scanner. The behaviour of the IMAGER 5006 is very similar to the Faro LS880, but the maximum value is 11mm less than the maximum value of the Faro scanner. In Fig. 5 (bottom) differences against an average plane fitted through the centre coordinates of the spheres are shown. Since all spheres were positioned on a plane, differences should be zero. The resulting differences may be interpreted as effects of a tumbling error of the trunnion axis, but especially for the Faro and Z+F scanners the results are influenced by the sphere fitting error due to the scanning noise on the longer distances. Further investigations have to be performed with bigger targets and/or smaller radius of circle.

3.4. Influence of the laser beams angle of incidence on 3D accuracy

Among other effects the accuracy of a point cloud is dependant on the angle of incidence of the laser beam. One reason for this effect is the spot size and shape of the laser beam and the reflectivity of the object. The shape and its centre position influences the reflectance of the laser beam, which affects the precision of the scanned distance, and the 3D position of a scanned point within the point cloud. To evaluate the influence of the laser beam's angle of incidence on 3D accuracy of the point cloud a planar white stone slab with a dimension of 75 x 79cm^2 (Fig. 6 centre) was mounted in a metal frame and could be swivelled in this frame. The frame was equipped with a reading device to set the stone slab in defined angular positions with a precision of 5'. Additionally, four spheres (diameter 38.1mm) were fixed on the stone slab, thus swivelling together with the stone slab. The stone slab and the spheres were scanned with a resolution of 3 mm at an object distance of 10m. In total, ten scans were acquired in angular positions of the stone slab from 90° to 5°. Each plane, which was fitted in the resulting point cloud of the stone slab, was compared to reference points.

Fig. 6: Trimble GX on a heavy-duty tripod (left), swivelling planar white stone slab (centre) and white colour plate (right).

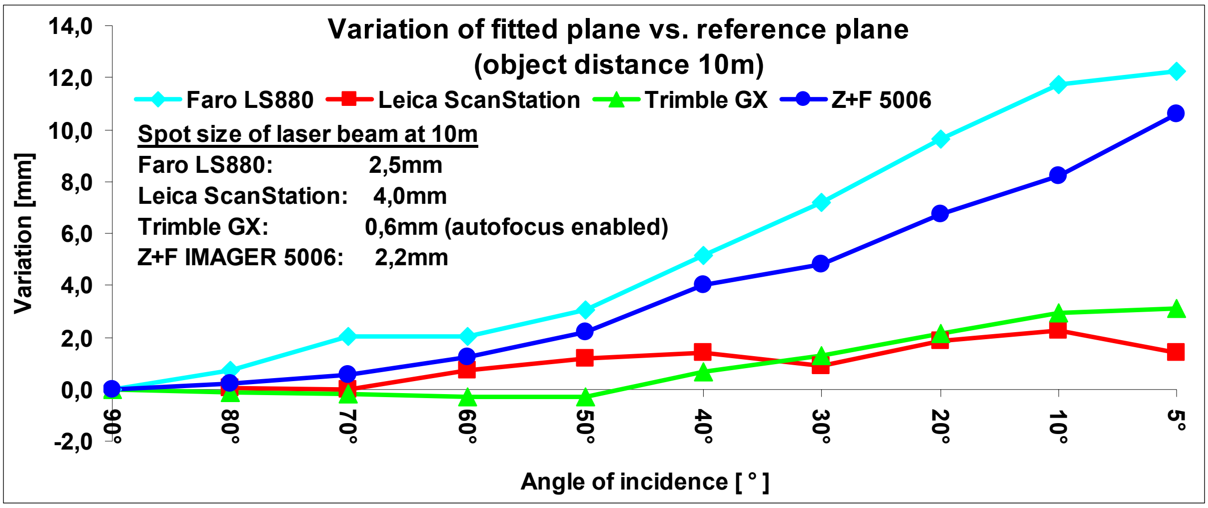

Figure 7: Influence of angle of incidence on 3D accuracy in comparison

Since the angular position of the stone slab has no effect on the point cloud of the spheres, the centres of the spheres were selected as reference points. Thus, the distance between the centre of the sphere and an average plane fitted through the point cloud representing the stone slab should be constant in an ideal case for each angular position of the stone slab. Nevertheless, it can be observed in Fig. 7 that the distance between the centres of the spheres and the computed plane is increasing with the decreasing angle of incidence. The time-of-flight scanners show minor effects of up to 3mm for an angle of incidence of 5°-10°, while the phase difference scanners achieve difference values of up to 12mm for the same angle. But generally, it can be stated that if the angle of incidence is less than 45°, significant influence on the accuracy of the point cloud can be expected. Further investigations are still necessary to check the influence of larger object distances.

4. Investigations into scanning noise

A test body consisting of different geometrical shapes (Fig. 8 right) was introduced to evaluate scanning resolution and noise resulting from edge effects. Edge effects may vary due to laser spot size and/or distance. The test body is a box with dimensions 75x75x20cm^3. Holes with different geometrical shapes such as circle, triangle, rectangle and wedge on the front side allowed scanning of the rear side. The box was scanned with a resolution of 2mm at a distance of 10m. Variations in the shape of the point clouds on the rear surface of the box are the result of the resolution performance of the scanner, which can only be inspected visually (Fig. 8 left).

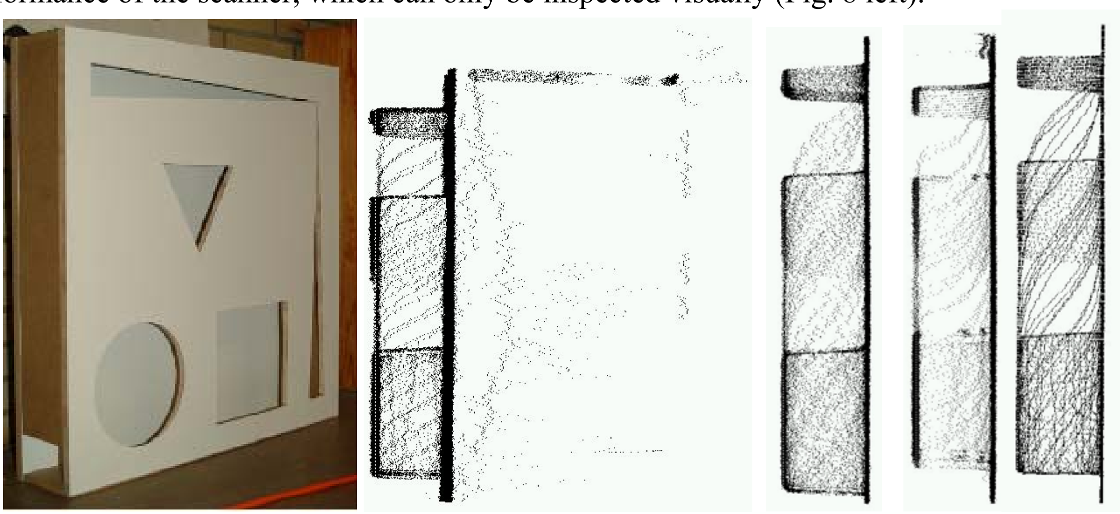

Fig. 8: Test body consisting of different geometrical shapes and resulting point clouds of four different terrestrial laser scanners: Faro LS880, Leica ScanStation, Trimble GX, IMAGER 5006.

5. Investigations into the influence of object colour

Investigations into the influence of object colour on the quality of laser distance measurements were carried out by using 22 different colour pattern sheets with reflectivity and standardized colour reference values (RAL). All colour sheets were scanned in a fixed position perpendicular to line of sight using a forced-centring device (Fig. 6 right). A scan resolution of 3mm at the object was selected at an object distance of 10m. A colour sheet is represented by an averaging plane fitted through the corresponding point cloud. Similar tests with the Trimble GS100 were already described in [5] and [8], while with the CYRAX 2500 are summarised in [2].

The variation in distances between the scanner and the centre of the averaging plane of each colour sheet are shown in Fig. 9 (top). As a reference plane the one derived from the point cloud of the RAL colour code White 9001 was used, but a significant effect of the object colour on the distance could be observed just for the Faro and Trimble scanners only. Furthermore, the range of noise in dependence on the object colour is shown in Fig.9 (bottom). Here it is obvious, that the colour of the object has no significant influence on the amount of measurement noise. The amount of noise varies between the four scanners. The Z+F Imager 5006 shows significantly less amount of noise. It is not known but it can be assumed that filters are applied on the scanned data.

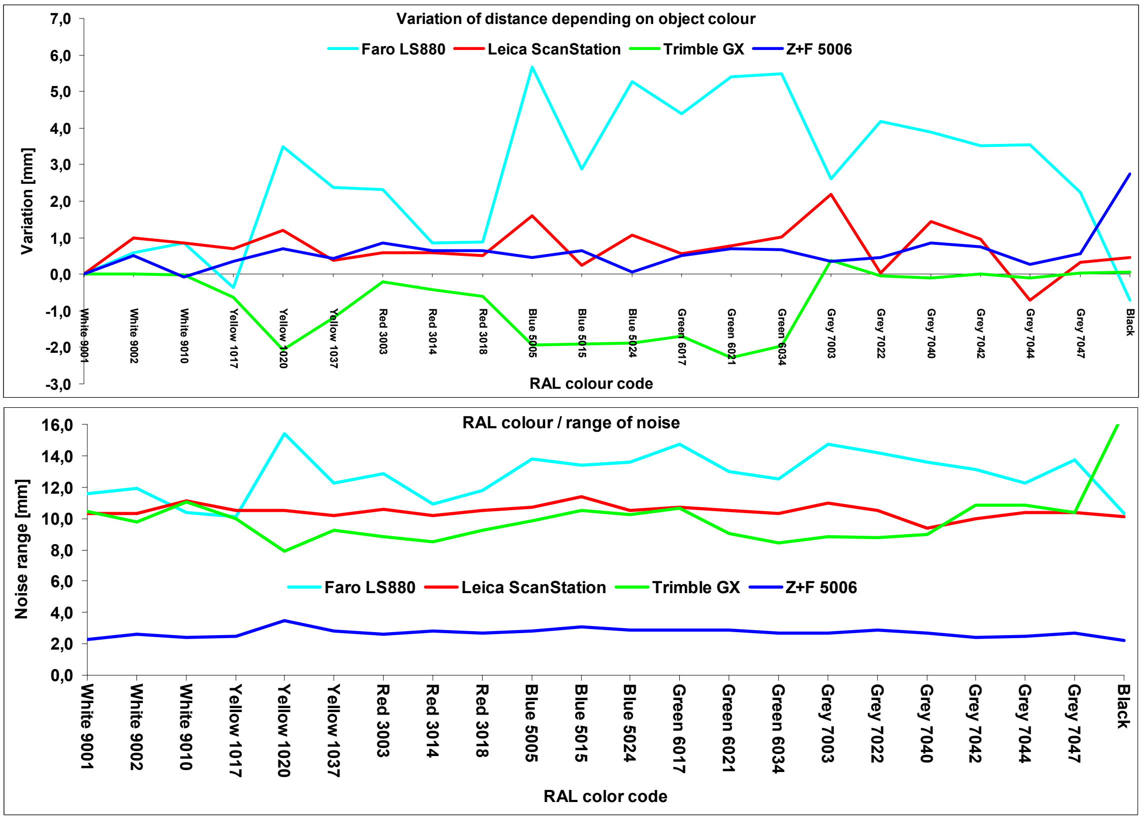

Figure 9: Influence of the object colour on laser scanning (top) and range of noise from object colour and from scanning, respectively (bottom)

6. Conclusions and outlook

The major results of different tests using the four current instruments of the new generation of terrestrial laser scanners are summarised in this paper. The investigations in the 3D test field showed that this range value (from minimum to maximum deviation value), which is influenced by the measurement precision of the instrument and by the algorithm for the fitting of the sphere, varied from 41mm to 76mm for the four scanners. In this test it could be demonstrated that only the time-of-flight scanners achieved a systematic shift of up to +6mm in the derived distances. The accuracy tests of distance measurements in comparison to reference distances showed clearly that the results met the accuracy specification of the manufacturer, although the accuracy is slightly different for each instrument. But, it could be seen in several practical outside tests that signal to noise ratio rises in daylight conditions for longer distances. In the accuracy tests of the inclination compensation it could be seen that the inclination of the time-of-flight scanners is successfully compensated, while the phase difference scanners show effects resulting from inclination of the turning axis. A trunnion axis error could not be proven. The influence of angle of incidence on 3D accuracy can be neglected for time-of-flight scanners, while phase difference scanners show significant deviations, if the angle of incidence is less than 45°. The accuracy is also not influenced by the spot size of the laser with respect to the angle of incidence. In the investigations into the influence of object colour on the quality of laser distance measurements it could be shown that the Faro and Trimble scanners show significant effects of some object colours on the accuracy of the scanning distance.

All investigations showed clearly that the used scanners are still influenced by instrumental errors, which might be reduced by instrument calibration. Therefore, it is necessary to define standards for investigations and tests of laser scanning systems to derive simple calibration methods for the scanners as usual for total stations, which can be applied by the user. These presented test procedures may be taken into consideration for the future discussion of the implementation of standardized test procedures.

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