Optical 3-D Measurement Techniques VII, Gruen/Kahmen (Eds.), Vienna 2005, Vol. I, pp. 122-131.

# INVESTIGATIONS INTO THE ACCURACY BEHAVIOUR OF THE TERRESTRIAL LASER SCANNING SYSTEM MENSI GS100

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**Abstract:** Although terrestrial 3D laser scanning is being used increasingly for a wide range of applications, no laser scanning system on the market is suitable for all applications. Consequently, it is essential to test the accuracy and behaviour of new laser scanning systems for optimised use in each application. In this paper investigations at Hamburg University of Applied Sciences (HAW Hamburg) into the accuracy behaviour of the terrestrial laser scanning system Mensi GS100 from Trimble will be presented. Tests into the accuracy of point cloud registration and geo-referencing using reference distance measurements showed that there were significant discrepancies in the distances to spheres and to targets. In further investigations it could be indicated that the quality of the scanned point cloud is influenced by instrumental errors (trunnion axis error) and by the surface characteristics (colour, material and surface roughness) of scanned objects.

## 1. Introduction

Since the end of the nineteen nineties when the first terrestrial 3D laser scanner came on the market, the systems have achieved enormous technical advancement, so that they are established as 3D metrology beside, and also in addition to, well-known technologies such as photogrammetry and tacheometry. Due to improvements in hardware and software today's systems are able to record and accordingly evaluate complex forms and objects with a dense 3D point grid. Nevertheless, investigations into accuracy and efficient project implementation are very important for understanding and improvement, and for a broad market acceptance of such measuring systems. The Department of Geomatics of the Hamburg University of Applied Sciences tested the accuracy behaviour of the terrestrial 3D laser scanning system Mensi GS100 from Trimble in several investigations.

First accuracy tests and practical experiences using the Mensi GS100 at HAW 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 system Mensi GS100

The 3D laser scanning system GS100 is manufactured by Mensi S.A., France and consists of a laser scanner, accessories (Fig. 1) and appropriate software for data acquisition and post processing. The technical specifications of the system are summarized in [7]. 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 in 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.

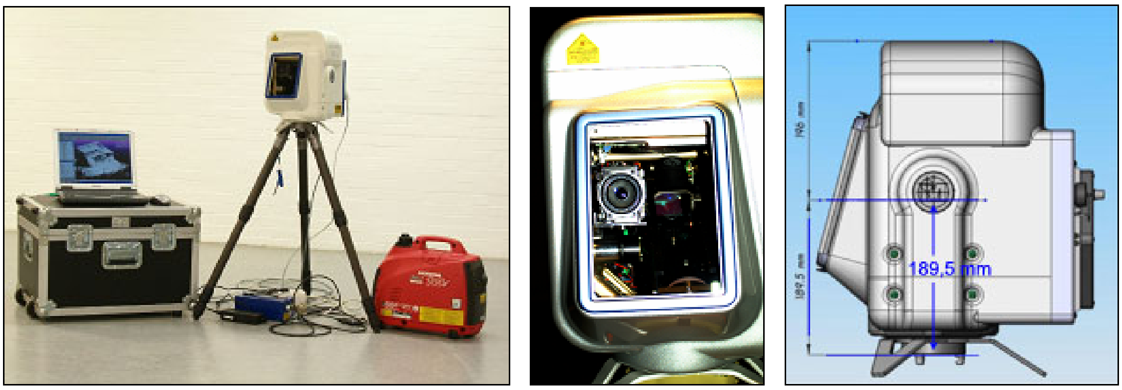


Figure 1: Terrestrial 3D laser scanning system Mensi GS100 at HAW Hamburg (left), view into the scanner showing the digital camera and the laser mirror (centre), dimensions (right)

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. Real Works Survey is mainly used for meshing of point clouds, computation of volumes, derivation of contours as well as for matching of digital images with point clouds. The program 3Dipsos represents the engineering module, with which CAD constructions derived from the point clouds can be provided.

## 3. Practical accuracy tests at HAW Hamburg

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

Referring 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 objects to be measured. 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 HAW 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 and of point cloud registration of the Mensi GS100 regarding the practical acceptance and verification methods of VDI/VDE

2634, a durable 3D test field was built up in the hall of building D at the HAW campus (Fig. 2). The test field consists of 53 reference points, which can be set up with prisms, spheres or targets. 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 nine stations with a Leica TDA 5005 total station. In a 3D net adjustment using PANDA 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.

Figure 2: Mensi GS100 in the HAW 3D test field (left), sphere and target (centre) mounted on a reference point using special adapters, and scanned sphere in front and top view (right)

The reference points in the 3D test field were scanned with the laser scanner Mensi GS100 from five stations (two at ground floor and first floor each, one at $2^{nd}$ floor) in two days. Thereby, 28 reference points were scanned equipped with both, spheres and targets.

All scans of the GS100 were registered in Real Works Survey, where the average and maximum deviation to sphere and target centres was determined to 2.6mm (max. 4.8mm). In the comparison of the distances determined in all combinations between reference points, which were equipped with spheres and targets in each case, it could be stated that distances determined between spheres were systematically on average about 3mm longer than to those determined between targets. The results of the HAW tests are summarized in Table 1. In addition to the 3D test field the results of two practical projects (Cliff Brodten and Millerntorwache) are presented, where each reference network was measured by a total station Leica TCRP 1201 (±2mm and 2ppm, ±0.3mgon) with a precision of 1-2mm.

| Project | Type | # dist. | Distance | | # Neg. | # Pos. | $\Delta d_{av.}$ | $\lvert\Delta d_{av.}\rvert$ | Max. $\lvert\Delta d\rvert$ |
|---|---|---|---|---|---|---|---|---|---|
| | | | Min [m] | Max [m] | Corrections | | [mm] | [mm] | [mm] |
| HAW indoor 3D test field | target | 378 | 1,569 | 33,102 | 99 | 279 | 2,4 | 378 | 11,0 |
| HAW indoor 3D test field | sphere | 171 | 1,778 | 26,568 | 131 | 40 | -1,0 | 171 | 6,5 |
| Cliff Brodten, Baltic Sea | sphere | 21 | 27,490 | 105,901 | 19 | 2 | -5,0 | 21 | 12,2 |
| Millerntorwache, Hamburg | sphere | 15 | 3,026 | 21,206 | 11 | 4 | -6,4 | 15 | 32,8 |
| HAW testfield City Park | sphere | 28 | 76,035 | 200,408 | 21 | 7 | -6,7 | 28 | 28,8 |

Table 1: Comparison of 3D distances obtained from the 3D test field and practical projects

In a second temporary test field at the nearby city park the 3D positioning accuracy of the GS100 was tested for the maximum range of 100m. The test field consists of eight reference points equally distributed on the circumference of a circle with a diameter of 200m. The reference points were measured by the high precision instrument Leica TCRP 1201 from five stations. A precision of less than one millimetre for each reference point was obtained in the network adjustment with Leica Geo Office 2.0. The sphere was scanned three times on each reference point using the GS100 at the same scanning position (centre of the circle). All combinations of distances between the reference points were calculated and compared against those determined by the scanner (average position of three scans). The result of the test field city park is summarized in Table 1. All results in Table 1 show that the distances to spheres are systematically longer and to targets are systematically shorter than compared to reference distances.

### 3.2. Comparison of distances on a baseline

These above-mentioned results lead to a detailed investigation of GS100 distance measuring accuracy on a baseline. The baseline consists of eleven points, distributed equally on a distance of 100m. Reference distances were measured using the Leica TCRP1201. Each sphere and target was scanned three times in the sequence forward, backward and forward, respectively.

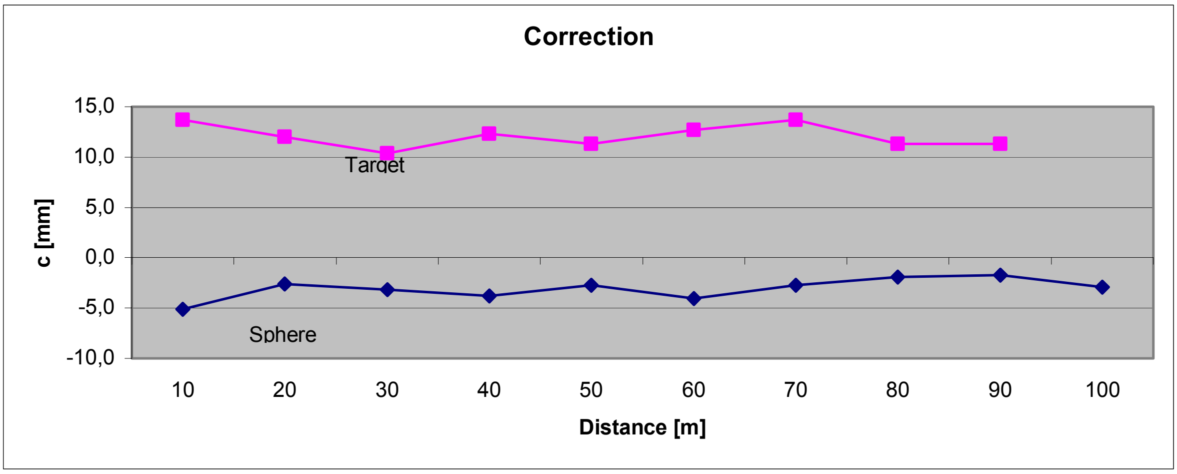


Figure 3: Comparison of scanner distances to spheres and targets vs. reference distances

The results from the baseline (see Fig. 3) indicate clearly that the derived distances to spheres and to targets include a systematic error in comparison to reference distances. The distances to the spheres are on average 3.1 mm too long, while the distances to the targets are on average 12.1 mm too short. These results confirm the differences between distances to spheres/targets in the 3D test fields. The systematic differences of the distances might be caused by the algorithms, which determine the distances from the point clouds (see Fig. 2 right).

Consequently, it can be recommended that an appropriate correction parameter for distance measurements will improve the results in 3D point measurements of the GS100. It is a matter for discussion with the system manufacturer how users will be able to set such a correction parameter in the soft- or firmware of the scanner similar to total stations.

## 4. Trunnion axis error

Ingensand et al. 2003 [3] report the trunnion axis error as an instrumental error of a laser scanning system, which is caused by mechanical characteristics such as a defective guide away of the axis, a fetch, and a defective mould of the contact surface. The trunnion axis error results from mechanical features of the instrument and is affected by the rotation around the vertical axis. The biggest influence for the trunnion axis error is given by the bearing of the vertical axis, i.e. various bearings generate various effects. In Figure 4 the trunnion axis error is illustrated as a difference to the mean trunnion axis. A critical aspect of the trunnion axis error is the heavy and uncentred mass of the GS100 (see Fig. 1). Since there are different possibilities of setting up the scanner on a tripod, several tests were carried out in the laboratory:

a) without tripod, scanner with instrument base (Fig. 5 left) fixed on a concrete floor (Fig. 5 right), b) scanner with instrument base fixed on a Leica surveying tripod (Fig. 5 centre), c) scanner with Leica tribrach fixed on a surveying tripod, and d) scanner fixed on Mensi GITZO tripod.

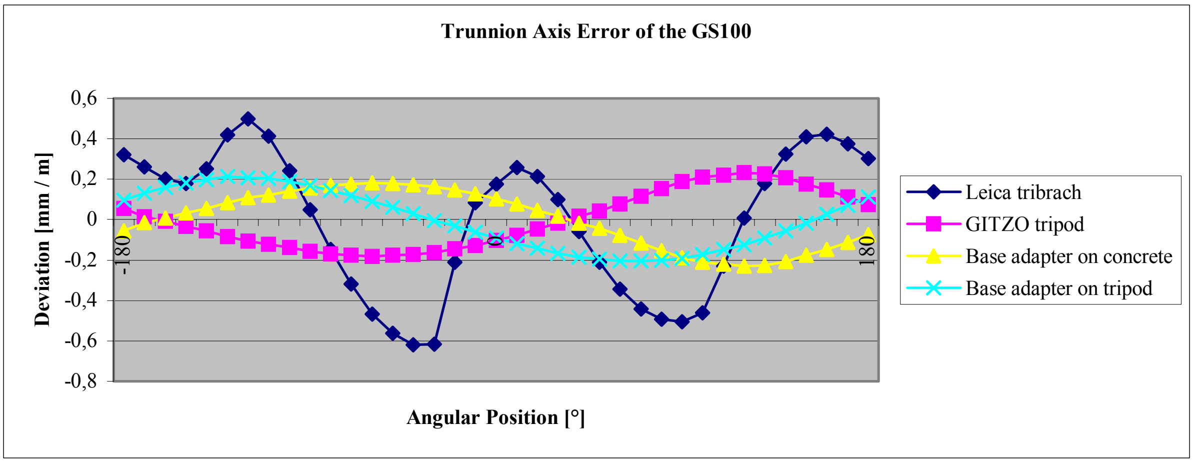


Figure 4: Different trunnion axis errors: scanner with instrument base fixed to concrete floor (yellow), same set up on tripod (turquoise), scanner with Leica tribrach (blue), scanner with GITZO tripod (pink)

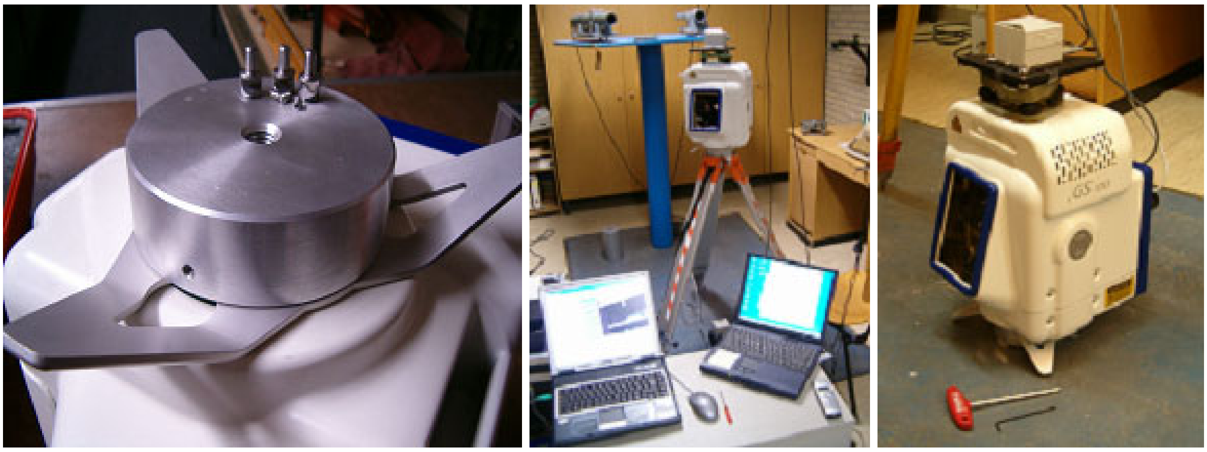

Figure 5: Special instrument base for the GS100 developed by HAW Hamburg and GS100 set up for the determination of the trunnion axis error (centre and right)

The trunnion axis error was determined using a Leica NIVEL20 inclination sensor, set up on top of the scanner's housing and centred in the rotation axis. The inclination in x and y direction was measured for one 360° rotation in 10° steps. Results in Fig. 4 show a clear sine oscillation with amplitudes of 0.2 mm/m. Amplitude of 0.6 mm/m (blue line) and the higher frequency is the result of the bad fitting of the used GS100 in the Leica tribrach. Additional tests with a Mensi GS200 using a standard modified base plate show a similar result for the Leica tribrach as the yellow curve in Fig. 4, i.e. the problems of unstable fixing of the scanner are already solved with the GS200. Several tests were performed to demonstrate the repetition of the errors, however the tests yield very similar amplitudes, but different phase angles. Reasons for this might be the uncentred mass of the scanner in combination with deformation effects of the scanners housing when rotating. In order to model a mathematical function for the harmonic sine oscillation further tests are necessary.

## 5. Investigations into the influence of surface characteristics on the quality of laser distance measurements

Furthermore, the influence of different surface characteristics and scan options during scanning with the GS100 was analysed. To separate the influence of the colour from the reflectivity and the surface characteristics, colour pattern sheets with reference RAL colours [8] and reflectivity values were scanned as well as commercially available coloured paper. Additionally, geometric bodies of different material and form were scanned, in order to examine how well geometrical primitives can be approximated into the point cloud with the software 3Dipsos.

### 5.1. Colour reference pattern

For the investigation of the separate influence of colours and brightness values on distance measurement a selection of colour pattern sheets (20cm x 20cm) were scanned at a distance of 8m with a resolution of 3.2mm. Additionally, an examination was made into whether an improvement in distance measuring accuracy can be achieved by an increase in the number of single point measurements (1, 10, 20). The colour matrix with the reflectivity reference values and the intensity received from the laser scanner are illustrated in Fig. 6. The light reference value is defined as the reflection degree of a certain colour between the black point (0) and the white point (100).

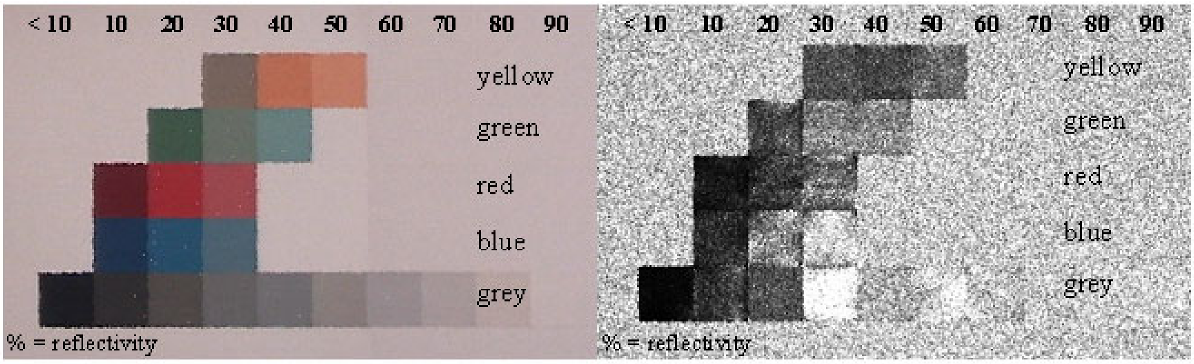


Figure 6: Colour reference pattern represented as true-colour (left) and as grey scale intensity image (right)

As expected, jet black (4%) and ruby-red (10%) show small intensity values (nearly black in Fig. 6 right) in the intensity-coded representation, while traffic grey (light reference value 30%), to be recognized as a bright surface in Fig. 6 (right), yields highest intensity of the reflected signal. A view on the light reference values and the intensities registered by the scanner (maximum 255) does not show any obvious correlation. However, there is a direct relationship between the scanned medium intensity and the standard deviation of an approximated plane (Tab. 2). As an example, deep black has the smallest average intensity of 11 and the highest standard deviation of 8mm, while traffic-grey has the highest intensity means of 250 and the smallest standard deviation of 2mm. Generally, the standard deviation decreases with an increasing light reference value within the different colour groups (see Fig. 7).

| RAL colour / reflectivity | Intensity LS Min. | SD [mm] |
|---|---|---|
| deep-black 4% | 11 | 8 |
| ruby-red 10% | 30 | 5 |
| signal-blue 10% | 51 | 5 |
| umbra-grey 10% | 66 | 4 |
| strawberry-red 20% | 68 | 4 |

| RAL colour / reflectivity | Intensity LS Max. | SD [mm] |
|---|---|---|
| tele-grey 60% | 203 | 2 |
| grey-white 67% | 206 | 2 |
| pastel-blue 30% | 213 | 2 |
| silk-grey 50% | 226 | 2 |
| traffic-grey 30% | 250 | 2 |

Table 2: Colours with the minimum and maximum intensity of the laser scanning including the standard deviation (SD) of each fitted plane [mm]

By an increase of the number of distance measurements from 1 to 10 shots for all colours the standard deviation of the approximated plane has been improved by a factor of 2, in some cases even by a factor of 3. A further increase of the single point measurements to 20 shots does not significantly improve the standard deviation of the approximated plane (Fig. 7).

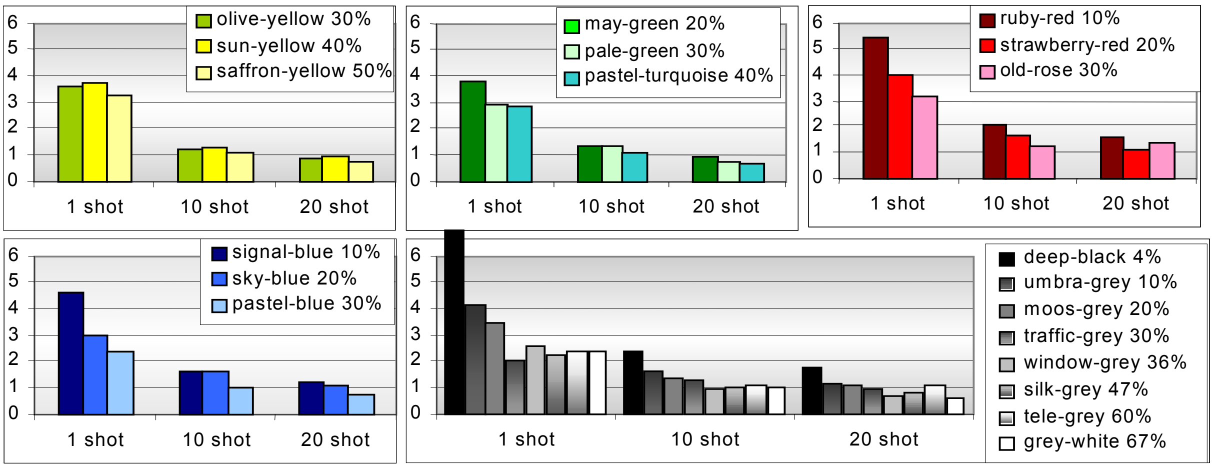


Figure 7: Standard deviation of different colour planes derived from point clouds

## 5.2. Rough coloured paper

For further investigations twelve different colour paper sheets of the size of 17cm x 17cm were scanned with four different scan options in 5m distance from identical positions: the resolution of 0.5mm for scan 1 and 2, and 5mm for scan 3 and 4. In the option 1 and 3 the scanning was performed with only 1 shot, while four shots were used for option 2 and 4. The focusing was set for all options to 'auto focus' and the scanning grid to 'best quality'.

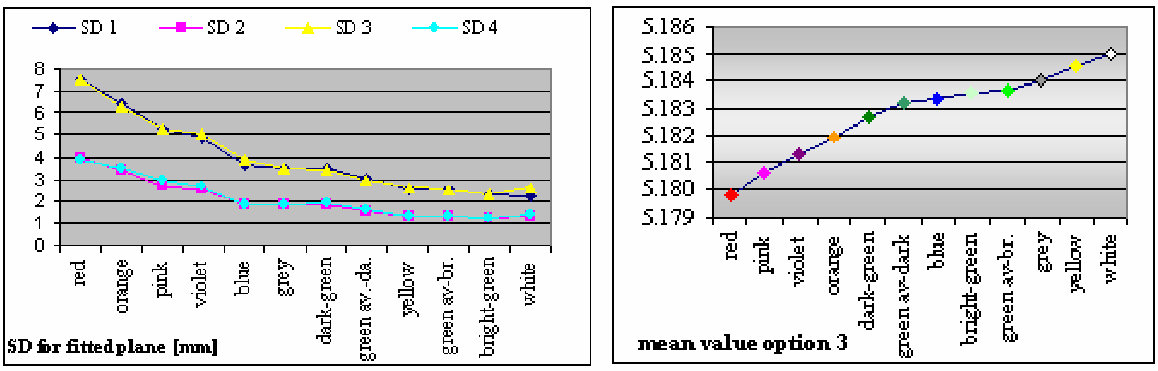


Figure 8: Standard deviation of each fitted plane (left) and distance to the scanner (right)

In all scan options a uniform behaviour of the dispersions could be shown for each colour. Red, orange and pink yield always the highest standard deviation with 3-8mm of an approximated plane, while for the colours white, light green and yellow only 1-3mm standard deviation could be achieved (see fig. 8 left). A correlation between the colour (and thus the intensity) and the standard deviation of the fitted planes could be shown. Apart from the standard deviation, e.g. 8mm with the colour red (see Fig. 8 left), an important aspect is also the dispersion of the individual measuring points, in particular if directly measured in the point cloud. Thus, the distance of some points to the centre axis of the approximated plane is more than 40mm in measuring direction within the point cloud of the red sheet in Scan 1 (blue: < 22mm, green: < 14mm).

As expected a higher scan resolution does not have any significant effect on the standard deviation of the measurement. However, an increase of the single point measurements from 1 to 4 yields a substantially lower dispersion. Thus, a reduction of the standard deviation by a factor of 2 (on the average 48%) has been achieved with this material, which corresponds to the theoretical consideration of $s_n = s_0 / \mathrm{Sqrt}\ (n)$ with n = number of measurements.

A further important result was the fact that the fitted planes of the different colours were systematically shifted to each other by a total difference of more than 5mm between the white and the red sheet (Fig. 8). A similar result was achieved by Clark & Robson (2004) using the Cyrax 2500 [2], which works with the same laser light wavelength (532nm). However, in their investigations the deviations with up to 12mm were clearly larger and significantly higher than the manufacturer specifications.

### 5.3. Influence of the object material

For further investigations the influence of different object material on the point determination was evaluated beside different object colours, e.g. a traffic sign, a pylon, different wooden boards and polystyrene were scanned (Fig. 9 left) and the point clouds were processed.

Figure 9: Different object material: overview photo (left), point cloud of a traffic sign (front and side view) (centre) and point cloud of a pylon (right)

The wooden boards and the polystyrene were scanned with a resolution of 5mm/10m using single and quadruple point measurement. For the material "wood" an increase of the single point measurement does not cause a substantial improvement of the standard deviation of a fitted plane (bright wooden board: from 2.7mm to 2.2mm, dark central density fibre board from 5.0mm to 4.6mm). However, for the white polystyrene a significant improvement from 2.7mm to 1.7mm could be achieved by multiple point measurement.

The traffic sign was scanned with quadruple point measurement with two different resolutions (5mm and 2.5mm/10m). The dispersion in the point cloud and the standard deviation of the fitted plane is very high for both options (16.4mm and 14.4mm) compared to the wooden material. From the traffic sign only the red framework and black contents could be scanned, while the white surface obviously reflects the signal with a too high intensity, which yields a hole in the white part of the point cloud. Nevertheless, the pylon was completely scanned despite bad intensity values, with the exception of the black foot, as illustrated in Fig. 9 right.

## 6. Conclusion and outlook

The quality evaluation of the 3D distance measurements of the GS100 demonstrated that distances to spheres and to targets include a systematic error in comparison to reference distances, which might be caused by the algorithm for the determination of the distances from the point clouds. It is recommended to improve the algorithm or to use an appropriate correction parameter for distance measurements of the laser scanner. Investigations into the trunnion axis error of the GS100 showed clearly that a sine oscillation with amplitudes of 0.2 mm/m were detected, which influences the quality of the 3D point accuracy significantly (up to 20 mm/100m). Furthermore, it could be shown that the influence of trunnion axis error of the GS100 depends on the stability of the used instrument base and tripod.

In order to be able to make a differentiated statement about the accuracy of the distance measurements of the laser scanner GS100, investigations into the reflectivity (intensity) and the characteristics of the object surface (colour, texture or roughness, and material features, etc.) were performed at the department of Geomatics at the Hamburg University of Applied Sciences. All investigations showed a correlation between colour, intensity and dispersion of the points. Bright colours, e.g. green and yellow lead to a good point cloud quality, while red surfaces cause a high dispersion due to the green laser beam. Additionally, the surface texture (roughness) and the material features, e.g. the density, which affects directly the penetration depth of the signal, influence the point cloud quality.

Possible improvements of the scanned data by using colour information of the measured points, which could be determined with digital high-resolution cameras, are not sufficient due to the complex interaction of the influences of surface texture, material, colour, and angle of incidence. Practically, the different influences cannot be differentiated and separated.

The multiple measurements can also cause negative effects that are different from the demonstrated positive effects. For rough surfaces and for dark colours a multiple measurement leads to a reduction of the dispersion. However, for smooth surfaces and for an angle of incidence of $\alpha = 0°$ multiple measurement frequently leads to a wrong result of measurement and to a higher dispersion of the points.

Investigations for the geometry recognition of selected objects (geometrical primitives) clarify the problem as well, that the point measurements (scanning) are dependent on the material features of the scanned objects. The approximation of cylinders and spheres works quite well using 3Dipsos, while the approximation of individual boxes does not function. In principle, a higher automation is necessary for the data post processing, in order to be able to accomplish an efficient generation of geometrical information from the point clouds.

Various institutions, showing different results and quality aspects, performed investigations into several terrestrial laser scanners so far. However, few comparative investigations of the appropriate data processing software have been published. In future, evaluation of a laser scanning system (hardware and software) in practical use must be considered under the following criteria: applications (measuring tasks), objects and products to be obtained (e.g. 3D model, 2D plans or simple cuttings), accuracy, efficiency and interests of the user.

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