TERRESTRIAL 3D-LASER SCANNER *ZLS07* DEVELOPED AT ETH ZURICH: AN OVERVIEW OF ITS CONFIGURATION, PERFORMANCE AND APPLICATION

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ABSTRACT
This paper introduces the terrestrial 3D-laser scanner *ZLS07* which has been developed at the ETH Zurich. Besides its configuration, its performance in a 3D-reference field and the application of underground utility cavern acquisition for water and sewage engineering are presented. For utility cavern acquisitions, the *ZLS07* is guided headfirst through a manhole into the utility cavern. A full dome scan takes about 100 seconds and contains more than a million measurements. The *ZLS07* is designed as a robust and reliable laser scanning system which allows for measurements under rough conditions as they exist underground in utility caverns or tunnels.

1. INTRODUCTION

Nowadays, high precision terrestrial laser scanning (TLS) has become an additional surveying method in the field of engineering geodesy. A terrestrial laser scanner measures distances, horizontal and vertical angles to an object. The result of a scan is a 3D-point cloud. Well established manufactures for geodetic instruments and a few other small companies produce and sell terrestrial laser scanners for applications in engineering geodesy. Besides manufacturers, terrestrial laser scanners are constructed at universities for research purposes (Rietdorf, 2004 and Reimer, Wulf & Wagner, 2005). Laser scanning systems available on the market have different specifications and therefore, each laser scanning system is applicable for a specific area of applications. Up to now, there is no all-purpose laser scanning system available. Even though, there is a wide spectrum of available laser scanning systems, terrestrial laser scanners are currently used by only few specialized engineering companies.

Within the last year, the terrestrial 3D-laser scanner *ZLS07* has been developed at the Institute of Geodesy and Photogrammetry ETH Zurich (IGP). Main motivation for the development was the application of underground utility cavern acquisition in the field of water and sewage engineering, which was initiated by the surveying engineering department of the City of Zurich (Geomatik+Vermessung Stadt Zürich, GeoZ) (see section 5). Besides this application, the architecture of the *ZLS07* is based on a questionnaire which was evaluated at the beginning of 2006 by the IGP. Several engineering companies, which are potential users for terrestrial laser scanners, have been asked about TLS in general and why they have not yet invested in laser scanning technology. In addition to high initial cost, there is relatively little demand for laser scanning data according to the respondents. A result of the questionnaire is that the *ZLS07* should clearly be more economical than products on the market and make accessible new application areas for TLS.

In section 2 of this paper, the terrestrial 3D-laser scanner *ZLS07* is introduced. Section 3 deals with the axes calibration of the *ZLS07* and section 4 with the performance in a 3D-reference field. Finally, section 5 describes the application of underground utility cavern acquisition with *ZLS07* in the field of water and sewage engineering.

2. TERRESTRIAL 3D-LASER SCANNER *ZLS07*

The terrestrial 3D-laser scanner *ZLS07* (figure 1) mainly consists of the 2D-laser scanner SICK LMS200 (SICK AG, 2007) and a servo driven rotation table developed at the ETH Zurich. The configuration of the *ZLS07* allows a field of view by 360° horizontal and 330° vertical. Besides the criterion of an economical aspect of the *ZLS07*, the reliability and robustness of the 3D-laser scanner is a main requirement to its development. The *ZLS07* has to run reliably under different and rough conditions of the environment. As for example for the acquisition of underground utility caverns, the humidity can be very high and the temperature difference between inside and outside can exceed up to 15 °C. For applications in the field of tunnel construction, the laser scanner must be dust and shock resistant. Besides these requirements, the accuracy of the *ZLS07* should achieve 15 to 20 mm @ 10 m standard deviation for a single point (see section 2.3).

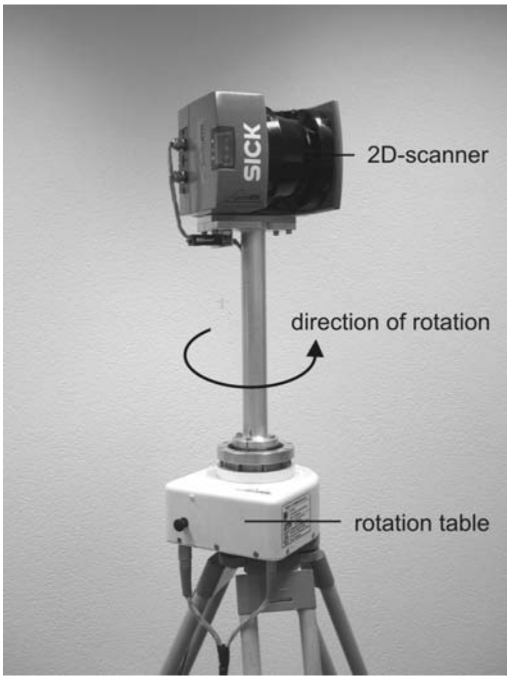

Figure 1: Terrestrial 3D-laser scanner *ZLS07*.

2.1 Components

2.1.1 Sensor. The 2D-laser scanner SICK LMS200 is used as sensor for distance and vertical angle measurements of the *ZLS07*. This sensor is well known from industrial applications and from robotics. Typical applications are, for example, sorting and classification of objects, volume determination or navigation purposes. Reimer et al. (2005) and Jensen et al. (2005) describe examples in the field of robotics. The SICK LMS200 is getting more commonly applied in engineering geodesy. Glaus (2006) introduces a system for the kinematical acquisition of the catenary geometry in railway engineering, which uses two 2D-terrestrial laser scanning systems.

The SICK LMS200 measures distances based on the time-of-flight principle. The maximum range is 80 m for cm-resolution mode and 32 m for mm-resolution mode. The *ZLS07* uses the 32 m range with mm-resolution mode as standard setting. The laser beam is deflected by rotating mirror in a way that a laser fan is spanned in space with an opening of 180°. The frequency of the rotating mirror is 75 Hz and the angular interval is 1°. By interlacing the laser fan by steps of 0.25°, the angular step width can be improved up to 0.25°. Due to the rotation frequency and the angular interval, 13’500 distances are measured within one second. According to product specifications of SICK LMS200 (SICK AG, 2007), the laser spot diameter increases up to 15 cm at 30 m. Furthermore, the product specification defines the standard deviation (1σ) of the measurements with 5 mm up to 8 m. The standard deviation is calculated by using at least 100 measurements on an object with a certain reflectivity at a certain distance with a certain amount of illumination. There is no distinction between an angular and distance dependent proportion.

2.1.2 Rotation table. The servo driven rotation table provides a 360° horizontal rotation of the *ZLS07* and is driven by a DC-motor. The gear ratio from the motor axis to the rotation axis of the rotation table is 1:750. The minimal horizontal resolution of the servo results in 0.001°. The determination of the horizontal position of the rotation table is performed by an encoder. This encoder reads the number of rotations of the motor axis since the rotation table has started. The horizontal position is calculated from the gear ratio coefficient and the number of rotations of the motor axis. The rotation table has a zero-position which is marked by an index. The motor has the feasibility to approach this zero-position.

2.2 Configuration

The 2D-laser scanner is mounted on the extended vertical axis of the rotation table. The vertical axis of the *ZLS07* has been elongated to minimize the coverage angle of the rotation table itself. This is an important aspect especially for the yawing configuration, which is used for utility cavern acquisition. The extension of the vertical axis increases the vertical field of view of the *ZLS07*.

To minimize errors of axis (visual axis, horizontal axis), it is important to connect the components mechanically in a way that the scanner axes are perpendicular to each other. Variances to the perpendicularity are minimized by mechanical adjustment and calibration routines. There are two different configurations for the *ZLS07*: yawing and yawing-top (figure 2a, 2b). For the yawing configuration, the laser fan covers a vertical profile from nadir to zenith. This configuration guarantees full dome coverage by the measurements. The field of view is 360° horizontal and 330° vertical. The limitation of the vertical view is caused by the rotation table which builds a scan shadow towards the tripod. With the yawing-top configuration, the field of view is limited to 360° horizontal and 180° vertical. The laser fan spans a plane in the upper hemisphere of the laser scanner dome. The full upper hemisphere is scanned by a 180° horizontal rotation of the rotation table. The yawing-top configuration allows two-face measurements. This setup is chosen for the calibration of the horizontal and visual axis by measuring reference targets in two faces.

Figure 2a: Yawing-configuration (field of view: 360° horizontal, 330° vertical).

Figure 2b: Yawing-top configuration (field of view: 360° horizontal, 180° vertical).

While measuring with the *ZLS07*, the horizontal position of the rotation table and the distances and vertical angles of the 2D-laser fan are registered. The synchronisation of horizontal and vertical position is derived by the clock rate of the computer operating system.

2.3 Specifications

The standard configuration of the *ZLS07* is the yawing-configuration (figure 2a) and it contains three different scanning resolutions: *low* (0.38° horizontal, 0.25° vertical), *middle* (0.25° horizontal, 0.25° vertical), *high* (0.125° horizontal, 0.25° vertical). Major specifications of *ZLS07* are summarized in table 1.

Field of view (horizontal) Field of view (vertical)	360° 330°
Max. angle resolution (horizontal) Max. angle resolution (vertical)	0.001° 0.25°
Max. Measurement range	32 m (mm-resolution mode) 80 m (cm-resolution mode)
Time for a full dome scan (360° x 330°)	Approx. 100 s
Weight	Approx. 11 kg
Single point precision (up to 9 m range)	15 mm (1σ)
Accuracy of objects modelled (up to 9 m range)	12 mm (1σ)

Table 1: Specifications of terrestrial 3D-laser scanner *ZLS07*.

The terms of single point precision and accuracy of modelled objects are used according to Schulz (2007). The single point precision describes the resulting mean error for a single point by fitting a known object, e.g. a sphere with known diameter, into the accordant point cloud. The accuracy of modelled objects, e.g. for centre coordinates of modelled spheres, corresponds to the mean error after transforming the centre coordinates into a reference field, which is measured by a total station. According to VIM (1993) and NIST (2005), the accuracy is defined as the closeness of the agreement between the result of a measurement and a true value of the measurand.

2.4 Software

The *ZLS07* is controlled by the software *KMScontroller* developed at the IGP. *KMScontroller* allows different settings for the laser scanner as resolution, field of view and distance mode. Furthermore, it controls the real-time synchronization of the rotation table and scanning data from the 2D-laser scanner, which corresponds to distances and vertical angles of measured points. The coordinate calculations of the 3D-point cloud out of raw measurements as distances, vertical angles and horizontal angles are realized by the post processing software *KMSprocessor*. The software allows for the implementation of calibration parameters. At this time, calibration parameters for horizontal and visual axis and the offset between scanner centre point and centre of rotations are established.

3. CALIBRATION OF ERRORS OF AXIS

For calibration of terrestrial laser scanning systems, two different methods have been established: system calibration and single component calibration. Further details about laser scanning calibration are described in Rietdorf et al. (2004) and Schulz (2007). First accomplished calibrations with the *ZLS07* are based on single component calibration. Therefore, the error of horizontal axis and error of visual axis have been determined. Furthermore, these errors result from the mechanical design.

The detection of errors of horizontal and visual axis of the *ZLS07* has been performed according to the procedure for total stations. The calibration is based on reference points. Because of the fact that laser scanners cannot target on a single reference point, reference targets are used, from which reference points can be deducted. Spheres with a diameter of 15 cm are used as reference targets. The reference point itself corresponds to the centre point modelled of a reference target (sphere). Thereby, the sphere with known diameter is adjusted into the point cloud of the scanned reference target according to the best fit algorithm based on the least square method.

3.1 Calibration setup

Due to the limited vertical resolution of the *ZLS07*, the range between the scanner and the reference targets is set to approximately 6 m. A sphere with a diameter of 15 cm in a range of about 6 m is represented by around 70 single points. This allows a fitting of a sphere into the point cloud by the least square method. For the calibration setup, sphere 1 is situated in the horizon of the laser scanner whereas sphere 2 is scanned within a zenith angle of about 35°.

The two spheres are scanned by the *ZLS07* in the yawing-top configuration (see section 2.2), which allows the two-face measurement. By 360° horizontal rotation of the laser scanner, the two spheres are acquired in both faces.

3.2 Results

The error of horizontal axis and the error of visual axis are calculated as the mean value out of five sets of two-face measurements of sphere 1 and sphere 2. The results are listed in table 2.

Set Number	Error of visual axis *c* [°]	Error of horizontal axis *i* [°]
1	0.1881	0.2069
2	0.0283	0.2640
3	0.3278	0.3136
4	0.1878	0.3993
5	-0.1072	0.3763
Mean value	***0.1249***	***0.3120***
Standard deviation	***0.0249***	***0.0070***

Table 2: Error of visual axis and error of horizontal axis for terrestrial 3D-laser scanner *ZLS07*.

The results show the necessity to calculate a mean value out of several detections of error of visual axis and error or horizontal axis. The values, e.g. for the error of visual axis from a single set of measurements, have got deviations up to 0.2028° from the mean value.

Compared to errors of axis of a total station, the errors of axis of the *ZLS07* are 100 to 500 times as big as total station axis errors. These errors are mainly caused by restrictions for the mechanical fabrication of the *ZLS07*. The axes are not realized as precision axes. But the detection of the errors of axis allows corrections for post processing the laser scanning data. The calibration parameters are implemented in the post processing software *KMSprocessor*.

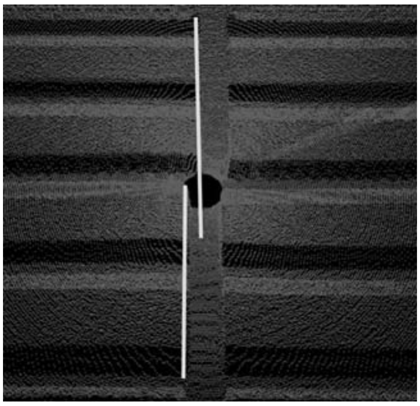

Figure 3a: Not calibrated point cloud (ceiling of a room). White line shows misalignment in the zenith of *ZLS07*.

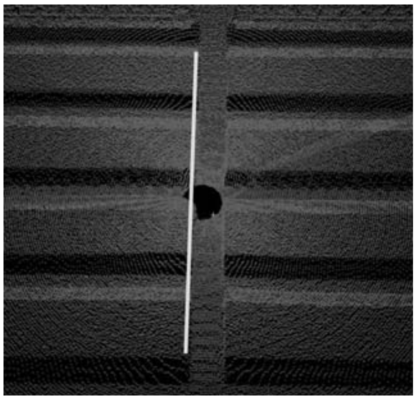

Figure 3b: Calibrated point cloud (ceiling of a room). The ceiling structure is aligned (white line alignment).

Figure 3a shows a section of a point cloud which is processed without any calibration parameters. The point cloud represents the ceiling of a scanned room and the black hole in the middle of the data corresponds to the zenith of the laser scanner. There is no data in the zenith due to the eccentric construction of the *ZLS07*. Ventilation slots, which are arranged in parallel and perpendicular position, represent the structure of the scanned ceiling. The point cloud processed without any calibration parameters shows a deformation of the rectangular structure close to the zenith. The white lines in figure 3a trace the ceiling structure and they should be linear to each other, but they are obviously not. Figure 3a shows a clear offset between both lines, whereas the white lines in point cloud in figure 3b are linear. No significant offset between both lines is visible. An obvious improvement of the point cloud geometry is detectable.

4. PERFORMANCE OF *ZLS07* IN 3D-REFERENCE FIELD

4.1 Setup

To test the performance of *ZLS07* by comparing modelled objects to references, a 3D-reference test field has been installed in the laboratories of the IGP. The dimensions of the test field were 14 m by 10 m by 3 m (length, width, height). Spheres with a diameter of 15 cm constituted the reference targets and were mostly installed on pillars. The centre points of the spheres corresponded to the reference points which were measured by total station. The scanner was set up on a tripod in the centre of the reference field and the scanning resolution was set to "high" (0.125° horizontal, 0.25° vertical). The vertical angular resolution of the *ZLS07* is the limited factor for maximum range between scanner and spheres. The maximum range between laser scanner and spheres is set to 9 m. This causes approximately 30 points on a sphere, which is enough to model the sphere according to least square method.

4.2 Results

After 3D-Helmert transformation of scanned reference points into the reference coordinate system, the residues of reference points are within expected range of 15 mm (figure 4). Additional to three rotations and three translations, a scale has been introduced as another variable for the adjustment. Figure 4 shows the 3D-reference field with residues for a scan respectively for the scanned and modelled reference points.

The test results show a σ_0-aposteriori for a coordinate of a reference point of 4.1 mm (mean value of 4 scans). The 3D-accuracy of a modelled object scanned by the *ZLS07* is calculated to 7.1 mm. The mean error is 9.0 mm.

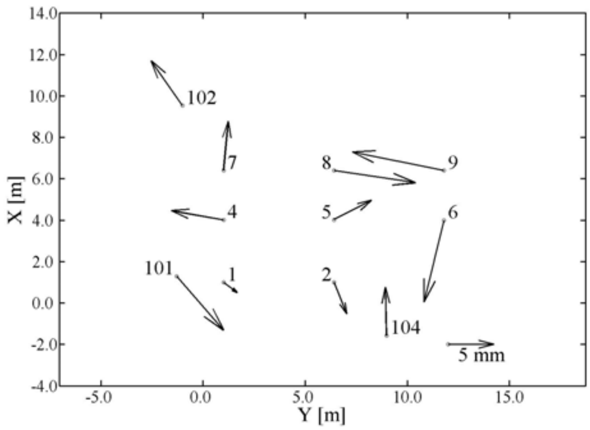

Figure 4: Residues of the scanned and adjusted centre points of reference spheres after transformation into the reference coordinate system. The scanner was set up on tripod between pillar 4 and pillar5.

5. APPLICATION: *ZLS07* FOR UNDERGROUND UTILITY CAVERNS

5.1 Configuration

A main application of the *ZLS07* is the acquisition of underground utility caverns in the field of water and sewage engineering. These special buildings control and connect inlet and outlet pipes. The geometry of these utility caverns is used for Geographic Information Systems (GIS) as infrastructure cadastral systems. The dimensions of underground utility caverns are up to 20 m or larger. But the standard dimensions are around 5 m by 5 m by 5 m. Usual access is a 3 to 4 m manhole (figure 5b).

Until now, the measurements of such utility caverns are achieved manually by operators with measuring tapes or laser distance meters. The operators have to climb down through the manhole into the underground utility caverns. This can be dangerous due to slippery conditions. Especially safety and cost efficient reasons caused the development of a utility cavern inspection configuration based on the *ZLS07*.

Figure 5a: *ZLS07* is mounted headfirst to a telescope tripod system which guides the laser scanner into the underground utility caverns through a manhole.

Figure 5b: View from aboveground into the underground utility caverns. *ZLS07* is in the right vertical position and ready to acquire the environment.

For the acquisition of underground utility caverns with the *ZLS07*, the laser scanner is mounted headfirst to a special telescope tripod (figure 5a) and guided through the manhole into the utility cavern. The laser scanner is ready to measure as soon as it arrives at the right vertical position. The operator controls the scanner from aboveground. No manual inspection is required anymore. By means of a 360°-scans, the whole environment is fully three dimensionally acquired.

5.2 Field campaign

In collaboration with GeoZ, the IGP performed tests with the *ZLS07* for the acquisition of underground utility caverns. Besides standard objects with a single inlet and outlet pipe, complex special buildings with slider plates and large extensions up to 25 m were scanned. Apart from the scanning results, a main interest was to test the time for the setup and the practicability of the laser scanning system for prospective application in water and sewage engineering.

5.3 Results

The on-site test shows an efficient and reliable method for the measurement of underground utility caverns compared to the traditional acquisition methods as measuring tape or laser distance meter. The setup for the tripod and laser scanner inclusive scanning time for a single object takes about 25 minutes. The time corresponds to the time by traditional methods, but the laser scanning data is more detailed.

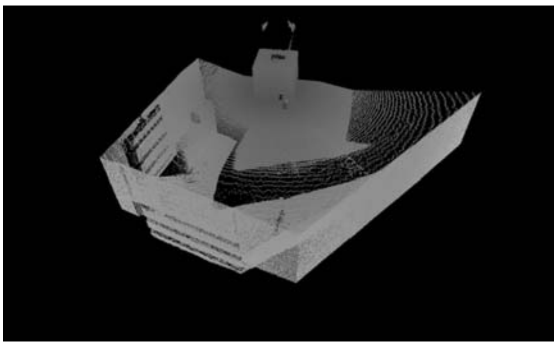

Figure 6a: Point cloud of an underground utility cavern with manhole where the scanner was guided through.

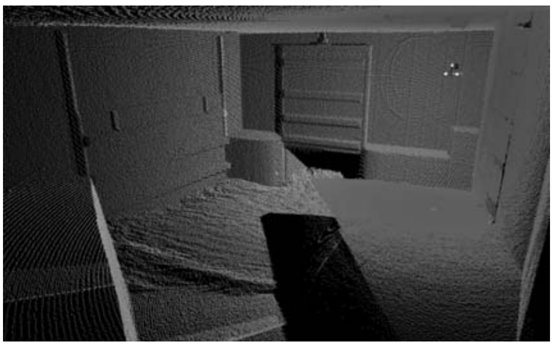

Figure 6b: Inside view of an underground utility cavern with two slider plates and a gully.

The results of the scans are point clouds of the underground utility caverns (figure 6a, 6b). The point cloud represents the entire 3D-structure of the environment. By point to point measurements, the dimensions of the utility caverns are well detectable.

The digitalisation of the point cloud is a convenient method to get vector data out of the point cloud. A fast method to generate a ground plan is for example the digitalization with a CAD-software. More details are described in Zogg et al. (2007).

6. CONCLUSIONS

The terrestrial 3D-laser scanner *ZLS07* works reliably and achieves the requirements for its development. Performance tests of the *ZLS07* in a 3D-reference field confirm the accuracy requirements even though the *ZLS07* shows significant errors of axis due to mechanical construction. A calibration is indispensable. Furthermore, there are systematic errors and a scale factor in the distance measurements. The component calibration allows the detection of specific instrumental errors.

Main application of the *ZLS07* is the acquisition of underground utility caverns in water and sewage engineering. Tests in cooperation with GeoZ provide satisfying results. The 3D-laser scanner enables the registration of the third dimension in the field of utility caverns acquisition. The limitations of the *ZLS07* are mainly set to its measurement performance in the cm-range, to its limited range of 32 m for the mm-resolution mode and to the vertical resolution which is set to a minimum of 0.25°. Nevertheless, the *ZLS07* opens up new application areas for TLS and constitutes an alternative solution to commercial laser scanning systems not least because of the economical aspect due to low initial costs for a *ZLS07*.

Besides additional sensors as digital camera or inclination sensors, the length of the vertical axis will be reduced as improvements of the *ZLS07* for other applications than utility caverns acquisition. Minimizing the length of vertical axis diminishes effects of errors of axis as errors of trunnion axis. Furthermore, new application areas like detection of excavation in tunnelling or volume detection of melting furnaces will be established for *ZLS07*.

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