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Abstract

In recent years, numerous measurement systems and techniques have become available on the market for three-dimensional (3D) surveying of objects. Largely due to the increasing need of 3D-data, fast area-wide 3D-measurement methods are in high demand. In the world of surveying and the field of engineering geodesy, terrestrial laser scanning has been established as a newer measurement method for fast, area-wide 3D-surveying. Terrestrial laser scanners measure distances and angles to objects without any contact. The actual geometry information of the scanned object has to be derived from a resulting 3D-point cloud in post-processing.

After the initial hype of terrestrial laser scanning, a slight disillusionment set in. Projects were not profitable or failed due to insufficient knowledge about laser scanning technology and its specifics. In addition, the hardware and software products available on the market often do not meet the requirements of specific applications. Thus, the selection of convenient applications for a particular terrestrial laser scanning system, the sensitivity in terms of environmental conditions, or the extensive post-processing of laser scanning data are just a few of the difficulties in using laser scanning technology. As a result, terrestrial laser scanning is rarely used for projects in engineering geodesy. Even though terrestrial laser scanning offers great potential, new fields of application have yet to be investigated.

This thesis originated from a project addressing the development of a qualified measurement system based on terrestrial laser scanning for the surveying of underground utility caverns in the field of water and sewage engineering. There was no convenient measurement system available on the market when the project started in 2005. There are three main objectives of this thesis: the development of a cost-efficient robust close-range 3D-laser scanning system largely for surveying underground utility caverns, the calibrations and investigations of terrestrial laser scanners with focus on the newly developed measurement system, and the development of new fields of application for terrestrial laser scanning. Moreover, this thesis contributes to the area of terrestrial laser scanning by offering better knowledge on its integration into engineering geodesy.

For the hardware development, the 2D-laser scanner SICK LMS200-30106 by Sick AG was selected and implemented as a distance measurement unit measuring distances and angles. This unit is well known and established in industrial applications and in the field of robotics. In addition, all components that were used for the close-range 3D-laser scanning system were selected according to predefined requirements. These requirements were strongly related to the application of the measurement of underground utility caverns. Furthermore, this thesis shows that an appropriate calibration of the close-range 3D-laser scanning system – the distance measurement unit specifically – allows its application in the field of engineering geodesy. Thus, appropriate calibration routines were developed, and intensive additional investigations of the measurement systems enabled the verification of the measurement accuracy and performance.

The close-range terrestrial 3D-laser scanner ZLS07 resulted from the development of a 3D-measurement system based on the terrestrial laser scanning technology. The ZLS07 is a robust and reliable measurement system that fulfills the requirements focused on surveying of underground utility caverns. Its specific limitations lie in the measurement range, accuracy, and angular resolution. However, the ZLS07 has been successfully established as a new measurement instrument at the surveying department of the city of Zurich. In addition to the hardware developments, an approach for automatic geometry modelling from 3D-point clouds was developed, tested, and discussed for post-processing 3D-point clouds of underground utility caverns. Furthermore, the ZLS07 was successfully used in other applications, such as the damage detection of an incinerator or the reverse engineering of technical constructions.
Zusammenfassung


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1 Introduction

1.1 Motivation

With the latest improvements in the development of terrestrial laser scanners, terrestrial laser scanning (TLS) becomes an important measurement technique for the field of engineering geodesy. Terrestrial laser scanners measure angles and distances to objects without any contact. TLS is a polar measurement method similar that of tacheometers. The result of a scan is a so-called three-dimensional (3D) point cloud, which is represented by thousands of single 3D-points. The actual geometry information of the scanned object has to be derived from the 3D-point cloud in a post-processing. Depending on the TLS system, the range of applications varies and will be augmented.

TLS entered the field of engineering geodesy at the beginning of this century. It was announced as a very fast and revolutionary measurement technique. After the initial hype, a slight disillusionment was observable. Projects were not profitable or failed due to insufficient knowledge about the TLS technology and its particularities. Furthermore, users struggled, for instance, with the selection of convenient applications for a terrestrial laser scanner considering the sensitivity in terms of the environmental conditions and the need to handle a huge amount of data. Developed with a better understanding of the new technology, gleaned from experiences in handling terrestrial laser scanners, and using more powerful computer systems, the second and third generation of TLS systems allow a more successful application of terrestrial laser scanners. Thus, it can be stated that nowadays TLS is established as an additional measurement technique in engineering geodesy. Nevertheless, TLS is scarcely used for projects in engineering geodesy.

At the end of the year 2005, a questionnaire was launched by the Institute of Geodesy and Photogrammetry (IGP) at ETH Zurich in Austria, Germany, and Switzerland to investigate the pros and cons of the TLS technology [ZOGG, 2005]. Thereafter, the results of the questionnaire formed the basis for new developments in hardware and software and for the exploration of new application areas. The questionnaire was sent to more than 170 engineering companies working in the field of engineering geodesy. Some of them were already using TLS; some were not. The interviews intended, among other aims, to determine the reasons that engineering companies were not working with TLS. The rate of return of the questionnaire was about 16%. In summary, 29 companies took part in the interview, 25 of which were yet not using TLS and four of which had already established TLS as an additional surveying method in their work processes.
The main statements against TLS given by engineering companies that did not yet use TLS were related to the high initial costs, the little demand for 3D-data in general, and the small range of applications. These statements represented 82% of all responses (total 52 responses; multiple responses possible) given in terms of not using TLS. Generally, the underlying reasons for all the statements against TLS tend to be limited knowledge of adequate applications for TLS. Moreover, the profitability of TLS relates to active operations of terrestrial laser scanners. The high investments are usually too high a risk for smaller engineering companies. Thus, no investments are made in TLS technology.

The results of the questionnaire additionally indicated awareness of the difficulty for engineering companies to develop new application areas for TLS. Due to lack of time in the everyday business, terrestrial laser scanners are often used for improper applications. Moreover, tacheometers have often been simply replaced by terrestrial laser scanners, often resulting in unprofitable projects. Thus, the development of adequate applications for TLS is a time consuming but indispensable process. In addition, terrestrial laser scanners from different manufacturers often use significantly different specifications, causing essential variations in applications. Purchasing a terrestrial laser scanner requires a clear perception of the range of application, so it is necessary to analyse the applications to select an adequate type of terrestrial laser scanner.

Strong motivations for this thesis have been the demand for a better knowledge and understanding of TLS and the need for new application areas of this fairly new measurement technology. In addition, an actual problem and a potential field of application of TLS had been introduced by GeoZ (Geomatik + Vermessung Stadt Zürich), the surveying department of the city of Zurich. A new measurement method had to be evaluated for the acquisition (surveying) of underground utility caverns in the field of water and sewage engineering. Largely for safety and productivity reasons, TLS was needed to replace the manual measurements taken by operators. Scanning of underground utility caverns required the development of a robust close-range 3D-laser scanning system that could be guided headfirst through a manhole into the underground utility cavern. There was no convenient TLS system available on the market when the project started in 2005. Thus, a new TLS system had to be developed to fulfil the requirements. Additionally, the hardware developments were driven by the results of the questionnaire, which was administered before starting the development.

In general, the possibility of developing a terrestrial 3D-laser scanner according to individual requirements and the on-site evaluation in collaboration with GeoZ has given impetus and motivation for this thesis. In addition, the thesis constitutes as another contribution to TLS in terms of its integration into engineering geodesy and the development of new applications for this newer measurement technology.

1.2 Aims of the Thesis

Since TLS has entered into the field of engineering geodesy, geodesists have been intensively engaged in this new measurement technology. Various studies and theses have addressed investigations into and calibrations of terrestrial laser scanners, for example [LICHTI et al., 2000a], [WUNDERLICH, 2002], [BOEHLER et al., 2003], [ZOGG, 2003], [RIETDORF, 2004], [STAIGER, 2005], [RESHETYUK, 2006], and [SCHULZ, 2007]. In addition, post-processing of TLS data is also an important field of research. For instance, the interpretation of 3D-point clouds and automatic detections of objects or structures are of high interests (cf. [KERN, 2003], [RABBANI, 2006], and [BRENNER, 2007]). However, geodesists rarely accomplish the development of new TLS systems or measurement systems in general because
specific applications require individual hardware and software developments or modifications. Terrestrial laser scanners are usually developed in the fields of robotics, for example, for autonomous vehicles (cf. [ARRAS et al., 2003] and [WULF and WAGNER, 2003]). In any case, the terrestrial laser scanners available on the market may not cope with the requirements for specific applications in the field of engineering geodesy. Thus, further developments of TLS systems or modifications are indispensable.

The aims of the present thesis cover three main aspects:

- The development of a cost-efficient robust close-range 3D-laser scanner for primary measuring of underground utility caverns under rough environmental conditions;
- The calibrations and investigations of terrestrial laser scanners, especially the newly developed measurement system;
- The development and achievement of new fields of application for terrestrial laser scanners.

These aims originate both from the results of the questionnaire completed by engineering companies [ZOGG, 2005] and the task of measuring underground utility caverns by the surveying department of the city of Zurich (GeoZ). Thus, the development of a robust, close-range 3D-laser scanning system is highly influenced by user recommendations for a new generation of terrestrial laser scanners and the acquisition of underground utility caverns. Moreover, the intent is to develop a TLS system whose costs are similar to or less than the latest generation of tacheometers.

1.3 Outline

Following this introduction, which focuses on the motivation for and aims of the present thesis, the thesis is structured as follows:

- Section 2: High Precision Terrestrial Laser Scanning
  This section gives an overview of TLS with respect to tasks in engineering geodesy. Beside the technical description of the different measurement techniques of terrestrial laser scanners, a classification of TLS within the field of engineering geodesy is proposed. TLS is compared with traditional and novel geodetic measurement methods. Furthermore, the quality of terrestrial laser scanners and the measurements are defined. Thus, the measurement system “Terrestrial Laser Scanner” is defined and described. Finally, the range of applications is discussed.

- Section 3: Development of Terrestrial Laser Scanner ZLS07
  Based on predefined requirements for a new TLS system, the terrestrial 3D-laser scanner ZLS07 was developed. This section is one of the main sections of the thesis and describes the components and configurations of the newly developed ZLS07 as well as its specifications. Moreover, the focus is on the definition and description of the measurement frame of the ZLS07. The data flow from the single sensors to the final result of a scan, the 3D-point cloud, is introduced.

- Section 4: Calibration of Terrestrial Laser Scanner ZLS07
  The calibration of the terrestrial 3D-laser scanner ZLS07 is an important task with regard to improvements of the measurement quality. Thus, this section focuses on the calibration of geodetic sensors in general and on the calibration of the ZLS07 specifically. For the ZLS07, the distance measurement unit, the axes systems, and the synchronisation of the different sensors are dealt with. The calibration configurations and routines are discussed and performed for the ZLS07.
• Section 5: Validation of Terrestrial Laser Scanner ZLS07
This section deals with investigations and validation of the terrestrial 3D-laser scanner ZLS07. In contrast to calibrations, investigations do not improve the measurement quality. Rather they specify the measurement quality of the measurement system. However, for the ZLS07, the angle measurement system and the wobbling of the vertical axis were specifically investigated. The 3D-measurement quality was specified in a 3D-reference field, which was designed and installed for investigating close- and mid-range terrestrial laser scanners.

• Section 6: Acquisition of Underground Utility Caverns
Thus far, the acquisition of underground utility caverns is considered to be the main field of application for the terrestrial 3D-laser scanner ZLS07. Additionally, the development of the ZLS07 was strongly influenced by this specific application. However, this section shows the acquisition of underground utility caverns in the field of water and sewage engineering and presents a solution based on the ZLS07. On-site evaluations, difficulties in the measurements, and the post-processing of the measurements are presented.

• Section 7: Automatic Geometry Modelling
Post-processing the data from terrestrial laser scanners is often a very time-consuming process. Automation is, therefore, required. This section presents an approach to automatic geometry detection specifically for scans of underground utility caverns.

• Section 8: Various Applications for Terrestrial Laser Scanner ZLS07
This section presents additional applications of the terrestrial 3D-laser scanner ZLS07 to the acquisition of underground utility caverns. Moreover, it presents a comparison with a commercial terrestrial laser scanner. Thus, a first application deals with damage detection inside an incinerator of a chemical plant. Scans were performed by the ZLS07 and then by the commercial terrestrial laser scanner Imager 5006 by Zoller+Froehlich [ZOLLER+FROEHLICH, 2008]. A comparison of the results of the two terrestrial laser scanners is presented. The second application deals with scanning of an overflow construction of a concrete dam, an application in the field of reverse engineering. The primary difficulty and challenge was the nearly inaccessible construction.

• Section 9: Conclusions and Outlook
This section summarizes the thesis with reference to the developments and findings. In addition, an outlook is given.
2 High Precision Terrestrial Laser Scanning

In recent years, airborne and terrestrial laser scanning has become a relevant technique for fast, precise, efficient, and contactless three-dimensional data capturing in engineering geodesy (cf. [INGENSAND, 2006]). Laser scanning, airborne and terrestrial, is based on the LIDAR [Light Detection and Ranging] technique, which was developed in the 1970s. The LADAR acronym stands for Laser Detection and Ranging and is a further developed technique with higher performance than the LIDAR technique [BACHMANN, 1979]. Laser itself is an acronym for Light Amplification by Stimulated Emission of Radiation. For measuring distances, a signal, for instance, sinusoidal, is modulated on the carrier wave. The time between emitter, object, and receiver is detected. The adoption of the LADAR technique in geodetic instruments was generally accepted by the 1990s for the reflectorless distance measurement. Later, airborne and terrestrial laser scanning were introduced. The breakthrough of a commercial operable geodetic instrument was achieved by airborne laser scanning at the end of the 1990s (cf. [BALTSAVIAS, 1999]). In addition, the first operable and commercial generation of terrestrial laser scanners was introduced at the end of the 1990s.

Regarding developments of terrestrial laser scanners for engineering geodesy, [WEHR, 1991] presents a 3D-measurement system based on LADAR technology at the beginning of the 1990s. In this system, a distance measurement unit is rotated around the horizontal and vertical axes. Thus, the adoption of terrestrial laser scanning (TLS) in engineering geodesy was launched. The main application areas were located in the field of building surveying and surveying of cultural heritage (cf. [WEHR, 1994] and [WEHR, 1997]). One of the first commercial terrestrial laser scanners for as-built documentation, the CYRAX, was presented by [WILSON et al., 1999]. The terrestrial laser scanner was announced as a portable 3D-laser mapping and imaging system. At the beginning of 2000, investigations of the first generation of commercial terrestrial laser scanners began (cf. [LICHTI et al., 2000a] and [LICHTI et al., 2000b]). In addition, first applications in the field of deformation monitoring (cf. [GORDON et al., 2001]) were performed by terrestrial laser scanners. In the following years, intense investigations of terrestrial laser scanners were performed, in particular, at universities (e.g., [WUNDERLICH, 2001], [WUNDERLICH, 2002], [BOEHLER et al. 2003], [KERN, 2003], [INGENSAND et al., 2003], [ZOGG, 2003], [RIETDORF, 2004], [RESHETYUK, 2006a], and [SCHULZ, 2007]).

In general, terrestrial laser scanners are considered to be highly developed these days, and, thus, terrestrial laser scanning is called precise terrestrial laser scanning. High scanning speed, high accuracy, and user-friendly operation are just a few remarkable features of the latest generation of terrestrial laser scanners. But each type of terrestrial laser scanner still covers a specific field of application. A universally applicable TLS system does not exist yet. Thus, the profitable operation of terrestrial laser scanners is difficult to achieve due to the limited possible applications. However, the range of applications for TLS has not kept pace with the development of terrestrial laser scanners, so the opening of new application areas is essential.

In the next section, precise TLS is classified within the field of engineering geodesy and within other geodetic measurement methods with the focus on having an efficient application. In addition, an overview of the main specifications of terrestrial laser scanners is given. The measurement system “terrestrial laser scanner” is discussed in terms of the measurement quality and the internal and external influences on the measurements. Finally, the range of applications is presented.
2.1 Terrestrial Laser Scanning in Engineering Geodesy

Basically, terrestrial laser scanners survey the object by measuring polar coordinates as slope distances ($d_S$), horizontal angles ($\beta$), and vertical angles ($\gamma$) with reference to the horizon of the instrument (Figure 2-1). An object is scanned within a couple of minutes. The result of a scan is a 3D-point cloud that contains thousands of measured points. Each single point is represented by at least three coordinates (X, Y, Z). In addition, the intensity I of the reflected laser beam is often registered as well and is referred to as a fourth dimension (X, Y, Z, I). However, terrestrial laser scanners act as a surveying method that mainly allows the three-dimensional capturing of a complex object. Hence, terrestrial laser scanners are established for reverse engineering or geometry comparison of scans from different measurement epochs, such as for quality control or deformation monitoring. Compared to other geodetic measurement methods, such as tacheometry or GNSS, TLS is not intended for staking-out, but the ScanStation 2 by Leica Geosystems [LEICA GEOSYSTEMS, 2008], for example, enables staking-out functionalities as well.

![Figure 2-1 Measurement elements (angles and distances) of a terrestrial laser scanner.](image)

In terms of TLS, the kinematic approach must be mentioned. Mobile platforms for mobile mapping are often equipped with 2D-laser scanning systems that continuously measure the environment while moving the platform (cf. [GLAUS, 2006], [GRAEFÉ, 2007], and [HESSE, 2007]). Additional sensors, such as GNSS, inertial systems, inclinometers, or odometers, define the actual position of the 2D-laser scanner. The laser scanning profiles can be located in a superior coordinate system, resulting in 3D-coordinates of the environment. A detailed overview of mobile-mapping systems is published in [EL-SHEIMY, 2005].

2.1.1 Measurement Methods in Engineering Geodesy

In engineering geodesy, tacheometry, GNSS, photogrammetry, and precise levelling are well established measurement methods. Precise levelling is largely used for height transfer and is not further described and mentioned here in conjunction with TLS. However, tacheometry, GNSS, photogrammetry, and radar interferometry are considered with respect to a classification of TLS in engineering geodesy. These measurement methods allow 3D-capturing of complex objects. Further, radar interferometry is being introduced into the field of engineering geodesy as well. Largely used for the determination of digital elevation model or for deformation monitoring in long-range applications, radar interferometry scans objects as well. However, it is a relative measurement method to determine deformations. The latest tech-
nology in 3D-measuring, the range imaging technology (RIM) will be mentioned even though it has not yet been adopted into the field of engineering geodesy due to its short range and its present insufficient accuracy for most applications.

**Tacheometry:** Polar measurement method. Tacheometers measure horizontal and vertical angles and, recently, slope distances to a target as well. The measurements are usually performed on predefined target points. In general, measurements by tacheometers are characterised by high accuracy within mm-range (distance and application depending) and low measurement frequency. The measurement range varies from a few centimetres up to several hundreds of metres. However, tacheometers allow swift staking-out of predefined object points on construction sites.

**GNSS:** Satellite-based measurement method. The main purpose of a Global Navigation Satellite System is the determination of the actual position, time, and velocity of a receiver. In terms of engineering geodesy, the GNSS allows the surveying of selective points. Furthermore, surveying by GNSS implies the precise measurement of the vector of two or more GNSS receivers. More details about GNSS and, in particular, GPS are found in [HOFMANN-WELLENHOF et al., 2001].

**Photogrammetry:** Image-based measurement method. Photogrammetry detects the geometry and position of an object from one or more images [LUHMANN, 2003]. Thus, photogrammetry is an indirect measurement method. The measurement sensor, the camera, is a passive sensor. The measurement range varies from a few centimetres up to several hundreds of metres. The measurement accuracy can vary from sub-millimetres up to several decimetres, depending on the application.

**Range Imaging (RIM):** 3D-measurements based on CMOS/CCD-method. Range imaging cameras are able to measure distances to the objects in their field-of-view in every pixel [KAHLMANN, 2007]. For each pixel of the camera, the 3D-coordinates can be calculated. A 3D-point cloud is provided by a single shot of the camera. The measurement range varies from a few decimetres up to about 50 m depending on the RIM-camera. The measurement accuracy is within the dm-range.

**Ground-Based Radar Interferometry:** Polar measurement method based on radar technology. The radar technology (RADAR = Radio Detection and Ranging) measures distances to objects based on electromagnetic waves in the microwave frequency range (cf. [HANSSEN, 2002]). The measurements are performed per pixel or per profile. Thus, the measurement of an area is realised by horizontal displacing of the radar interferometer or rotating the radar interferometer around the vertical axis. The ground-based radar instruments are quite complementary to terrestrial laser scanners (cf. [WERNER et al., 2008]). The areas of application lie in deformation monitoring and generation of digital elevation models. The measurement range of ground-based radar is up to several kilometres. Radar interferometry enables the monitoring of deformations by detection of phase differences between successive images acquired from the same viewpoint (cf. [WERNER et al., 2008]).

Recently, a tendency towards a sensor fusion and method fusion can be observed. The idea of sensor fusion is to combine the different measurement techniques into a single geodetic instrument. In addition, due to the large variety of geodetic instruments available on the market, an all-in-one solution is being called for. The first commercial products have already been introduced on the market. Tacheometry and GNSS, for instance, were combined in the Smart-Station by Leica Geosystems [LEICA GEOSYSTEMS, 2008]. Furthermore, photogrammetry and tacheometry were merged together in Topcon’s GPT-7000i [TOPCON, 2008]. However, a sensor fusion would enable the appropriate measurement technique for the particular application without the availability of several different geodetic instruments. In addition to sensor
fusion, method fusion is evolving as well. Surface models generated by TLS can be, for instance, overlaid by results of deformation information detected by radar interferometry. Data exchange, data formats, and data compatibility, therefore, have become highly important.

2.1.2 Classification of Measurement Methods

With respect to an appropriate implementation and application of TLS in engineering geodesy, it is important to classify and position this newer measurement method within the well known and established geodetic measurement methods. [WUNDERLICH, 2006], for instance, classifies TLS in relation to other measurement methods according to the number of points that have been measured (Figure 2-2).

![Figure 2-2 Classification according to point density (cf. [WUNDERLICH, 2006]).](image)

[LUHMANN, 2002] presents a classification of geodetic measurement methods with respect to the measurement accuracy and the size of objects to be scanned. Regarding TLS, it must be considered that terrestrial laser scanners are subdivided in close-, mid- and long-range terrestrial laser scanners (cf. section 2.2.1 and section 2.4). This classification depends on the maximum measurement range, which is coupled to the distance measurement principle. However, the size of objects has to be selected considering the available terrestrial laser scanner or vice versa (cf. section 2.4).

![Figure 2-3 Classification of geodetic surveying methods with focus on object geometry.](image)

Apart from the requested accuracy and the size of the object, the selection of an adequate measurement method depends on the object geometry, the results to be derived, and the geometry properties of the measurement method, respectively. Therefore, a classification of different geodetic measurement methods was proposed (Figure 2-3) according to the geometry properties of the measurement method. Thus, the geometrical aspect of the measurement method was considered in terms of selective, areal, and spherical measurement properties. In addition, the object geometries and the results to be derived can also be subdivided into selective, areal, and spherical elements. Spherical refers to the surveying of hollow parts, for example, interior environments. Therefore, the field-of-view (cf. section 2.2.2) of a geodetic measurement system is a crucial parameter. Thus, a panoramic measurement system is needed.
TLS is considered to be an areal and spherical measurement method specifically. The detection of selective information is possible but not in real-time. A post-processing of the measurements is needed. RIM technology is introduced in the classification for geodetic surveying methods with regard to future applications. However, currently, RIM technology has not yet been adopted in the field of engineering geodesy.

Figure 2-4 Characteristics of TLS compared to tacheometry, GNSS and photogrammetry.

Another classification of geodetic instruments refers to the availability of the measurement data and geometry information. Thus, TLS, photogrammetry, radar interferometry, and RIM have to be considered as post-processing measurement methods. The results of the measurements have to be processed and interpreted after the surveying. These measurement methods are also referred to as indirect measurement methods. In contrast, the direct or real-time measurement methods, e.g., tacheometry or GNSS, deliver the results from selective measurements in real-time without the need of post-processing. In addition, real-time measurement methods enable staking-out functionalities. Figure 2-4 illustrates selected characteristics of the well-established measurement methods in engineering geodesy (tacheometry, GNSS, and photogrammetry) and TLS. The graduation of the different measurement methods is based on results observed during this study. However, the graduation is estimated based on empirical observation.

2.2 Specifications of Terrestrial Laser Scanners

Currently, a wide choice of terrestrial laser scanners is available on the market. Most manufacturers of geodetic instruments develop and produce their own TLS systems. Additionally, they often develop and offer different kinds of terrestrial laser scanners for different field of application. Figure 2-5 presents a partial overview of a few terrestrial laser scanners from well-known manufacturers.

Each TLS system has its own characteristics. The characteristics – for instance, the maximum measurement range or measurement accuracy – determine the field and range of applications for the TLS system. The main differentiating factor for TLS systems is the distance measurement method, which defines the maximum measurement range as well as resolution and accuracy of the distances to be measured. However, according to [STAIGER and WUNDERLICH, 2007], terrestrial laser scanners can be specified in terms of the appropriate applications according to the following main properties:
- Distance measurement
- Scanning resolution
- Field-of-view
- Measurement frequency, scanning speed
- Quality, which covers precision, accuracy, and repeatability of the measurements

Robustness, weight, size, operation, and controlling functionalities are just a few more specifications of terrestrial laser scanners that have to be considered when choosing a TLS system (cf. [WUNDERLICH, 2003]). The interfaces and control modules – an external laptop, for instance – are referred to as the operation and controlling functionalities of a terrestrial laser scanner. In general, however, a well-founded knowledge of the measurement technique and characteristics of terrestrial laser scanners is essential for interpreting and understanding the specifications of terrestrial laser scanners.

![Figure 2-5 Partial overview of commercial terrestrial laser scanners.](image)

The measurement methods of terrestrial laser scanners are described in detail in [WEHR, 1998] with reference to engineering geodesy. Moreover, [KERN, 2003] studies extensively the laser scanning measurement techniques. [RIETDORF, 2004] presents scanning measurement systems, in particular terrestrial laser scanners with corresponding distance measurement principles and angular measurement systems. In the following sections, the most essential measurement principles for TLS are summarised because they directly influence the main specifications of terrestrial laser scanners in terms of the distance measurement principle; the measurement range; the scanning resolution; the field-of-view; the measurement frequency; and the measurement accuracy, precision, and repeatability.

### 2.2.1 Distance Measurement

There are three main electro-optical measurement principles for determining distances between an emitter and an object: triangulation, interferometry, and time-of-flight (Figure 2-6). These three distance measurement methods are used in engineering geodesy. The time-of-flight method is further differentiated by the direct time-of-flight (pulsed time-of-flight) and the indirect time-of-flight (frequency-modulated continuous wave, amplitude-modulated continuous wave, and polarisation modulation). The pulsed time-of-flight and the amplitude-modulated continuous-wave method are implemented in most TLS-systems. In industrial metrology, for instance, the laser scanners are often based on the triangulation principle.
2.2.1.1 Electromagnetic Wave

Electromagnetic waves are used as carrier waves for the electro-optical distance measurements. The frequency range of electromagnetic waves is very broad. For electro-optical distance measurements in geodetic instruments (e.g., terrestrial laser scanner, tacheometer, RIM), electromagnetic waves within the bandwidth of visible light and near infrared are usually disposed ($0.4 \, \mu m < \lambda > 1.3 \, \mu m$). This relatively small bandwidth was selected due to its advantageous properties in the atmosphere close to the earth’s surface (cf. [HINDERLING, 2004]). In addition, for measurement systems based on radar technology, the wavelength $\lambda$ is between 8 mm and 1 m in the range of microwaves. This frequency bandwidth penetrates the atmosphere as well (cf. [DEUMLICH and STAIGER, 2002]). The permeability of the atmosphere depends on the dispersion and absorption of the electromagnetic elements on aerial molecules, on dust particles, and on water drops.

The electro-optical distance measurement is based on the modulation of the carrier waves, which allow the transition of a continuous or pulsed signal. With respect to the distance measurements of geodetic instruments, the signal modulation is used for determining the time between the emitting and receiving of the signal. Finally, the distance can be calculated based on the travelling time and the speed of light.

2.2.1.2 Time-of-Flight Methods

For the time-of-flight technique, the electro-optical distance measurement is based on the detection of the travelling time of light between an emitter, an object, and a receiver. Hence, the flight time of light for twice the distance $d$ is measured. The distance $d$ is calculated as:

$$d = \frac{c \cdot t}{2}$$

$d$  distance between emitter and object
$t$  flight time of light
$c$  speed of light in the medium

The electro-optical distance measurement is based on a laser beam that is used as a carrier wave for signal modulations. A laser can be strongly bundled and features a high coherence. The bundle of the laser beam, which can be described as the laser beam divergence, is a cru-
cial parameter in terms of measurement accuracy and precision of the electro-optical distance measurement. The laser beam divergence defines the footprint of the laser beam, which is distance dependant. The footprint corresponds to the spot size of the laser beam on the object surface (cf. [SCHLEMMER, 2004], [RIETDORF, 2004]). A more detailed description of electro-optical distance measurements can be found, for instance, in [RUEGER, 1996], [JOECKEL and STOBER, 1999], [DEUMLICH and STAIGER, 2002]. Furthermore, [BOSCH and LESCURE, 1995] present a compilation of selected publications with detailed focus on laser distance measurements.

For TLS, the pulsed time-of-flight method (direct time-of-flight) and the amplitude-modulated continuous wave method (AMCW) are widespread in use. A detailed description of the measurement principles can be found in [WEHR and LOHR, 1999]. The frequency-modulated continuous wave method (FMCW) and the polarisation method are rarely used for terrestrial laser scanners, but the FMCW-method is often referred to as radar technology.

**Pulsed Time-of-Flight (direct time-of-flight):** In pulsed time-of-flight, the distance is determined by measuring the time of a light pulse between the emitter, the object, and the receiver. The distance can be calculated according to (2.1). The resolution of the distance measurement \( \Delta d \) is directly proportional to the time resolution \( \Delta t \):

\[
\Delta d = \frac{1}{2} c \cdot \Delta t
\]  

(2.2)

The distance measurement resolution \( \Delta d \) of the pulsed time-of-flight distance measurement depends directly on the time. Therefore, the detection of the maximum signal of the received pulse is a crucial factor with respect to the distance measurement resolution and accuracy. The pulsed time-of-flight principle is used for distance measurements in conjunction with TLS of up to several hundred meters. The sampling frequencies range up to 50 kHz.

**Amplitude-Modulated Continuous Wave AMCW (phase difference detection):** By modulating, for instance, a sinusoidal or rectangular signal on the carrier continuous signal of the laser light, the travelling time \( t \) is directly proportional to the phase difference \( \phi \) between the received and transmitted signal.

The distance \( d \) is calculated according to:

\[
d = \frac{c}{2} \cdot \frac{\phi}{2\pi} T
\]  

(2.3)

\( d \) distance between emitter and object  
\( T \) period of the modulated signal  
\( c \) speed of light in the medium  
\( \phi \) phase difference between received and transmitted signal  

The distance measurement according to (2.3) is unique up to distances smaller than half the wave length of the modulated signal. The absolute range \( s \) is calculated as:

\[
s = \frac{1}{2} \left( N \cdot \lambda + \frac{\lambda \cdot \Delta \phi}{2\pi} \right)
\]  

(2.4)

with

\[
\lambda = c \cdot T
\]  

(2.5)

\( N \) ambiguities (number of waves)
The resolution $\Delta d$ of the distance measurement according to the amplitude-modulated continuous wave method is given by:

$$\Delta d = \frac{1}{4\pi} \cdot \frac{c}{f} \cdot \Delta \phi$$  (2.6)

Thus, the resolution depends on the precise determination of the phase differences $\Delta \phi$ and on the frequency $f$ of the modulated signal. Thus, the frequency $f$ defines the sensitivity of the distance measurement. For determining longer ranges, several frequencies are used for modulation. Hence, the lowest frequency defines the maximum range whereas the highest frequency affects the measurement resolution. Generally, the distance measurement according to the detection of phase differences in connection with TLS is used for distance measurements of up to 100 m. The sampling frequency achieves values of up to 600 kHz.

**Frequency-Modulated Continuous Wave FMCW (beat frequency, “chirp”-technology):**

For FMCW, the emitted laser light is modulated by a sine wave at varying frequencies and mixed with the reflected energy (cf. [HANCOCK, 1999]). The range is calculated by measuring the resulting beat frequency $B$. The frequency modulation is normally linear and follows a triangular waveform (Figure 2-7). The “chirp”-frequency changes linearly over time. For a triangular waveform, the distance between emitter and target is proportional to the beat frequency. Figure 2-7 shows the emitted frequency $f_e(t)$, the received frequency $f_r(t)$, and the resulting beat frequency $B$ with reference to the time $t$. The period of the “chirp”-frequency corresponds to the time $T_r$. The time difference $\Delta t$ is the difference between emitted and received signals. The distance to objects can be calculated according to [HANCOCK, 1999] as:

$$d = \frac{c \cdot \Delta t}{2} = \frac{c \cdot B \cdot T_r}{4 \cdot \Delta f}$$  (2.7)

$c$ speed of light in the medium  
$B$ beat frequency  
$T_r$ period of frequency sweep  
$\Delta f$ change in swept frequency

![Figure 2-7 Chirped waveforms and beat frequency B for FMCW-laser [HANCOCK, 1999].](image)

The maximum range can be calculated as

$$d_{max} = \frac{c \cdot T_r}{4}$$  (2.8)
For practical use of the FMCW-technique, the maximal range strongly depends on the sensor power and noise level (cf. [HANCOCK, 1999]). The FMCW-technique is not widespread in use for terrestrial laser scanners, but this technology is generally used for radar systems that are applied for long-range applications.

### 2.2.1.3 Triangulation

The distance measurement, according to the triangulation principle, is based on triangular relations between the known and unknown parameters. Moreover, it can be distinguished between active and passive triangulation. Passive triangulation is well known from geodetic measurements by tacheometers. Thus, two sensors observe the object to be measured. In contrast, for active triangulation, one sensor is a light source. The other sensor receives the emitted light. In the case of triangulation by a laser, the laser beam is projected onto the object and reflected to the receiver, a CCD-sensor. Figure 2-8 shows a schematic view of an active triangulation system. A laser beam is emitted and received by a CCD-sensor. The minimal and maximal distances \( d_{\text{min}} \) and \( d_{\text{max}} \) to be measured depend on the inclination \( \phi_0 \) of the CCD-sensor and the basis length \( b \) (cf. [BALTHASAR and HUMLER, 2008] and [DONGES and NOLL, 1993]).

![Active triangulation with a laser light and a CCD-chip as receiver.](image)

The distance differences \( \Delta d \) can be calculated as

\[
\Delta d = b \cdot \frac{1}{\cos^2(\phi)} \cdot \Delta \phi = \frac{b^2 + d^2}{b} \cdot \Delta \phi
\]

(2.9)

Thus, the distance differences \( \Delta d \) depend non-linearly on the angle of incidence. However, laser scanner measuring, according to the triangulation principle, usually uses a laser line instead of a single laser spot. Nevertheless, the distance calculations correspond to (2.9). In addition, a structured illumination of the scene is also widespread in use. Light patterns or sequences of patterns are projected onto the surface of the measuring object and recorded by a camera (cf. [BREUCKMANN et al., 2007]). In general, triangulation principles are used for industrial applications rather than in engineering geodesy. They are accurate within a sub-millimetre range. Laser scanners, according to the triangulation principle, are often used in conjunction with measurement arms (cf. Laser ScanArm by Faro [FARO, 2008]) or are optically tracked (cf. T-SCAN by Steinbichler [STEINBICHLER, 2008]).

### 2.2.1.4 Interferometry

In interferometry, electromagnetic waves are made to interfere with each other to determine distances. Inside of an interferometer, a laser beam is split into two beams. One beam passes to a moving reflector and the other beam to a fixed internal reflector. The two laser beams have the same amplitude and frequency due to the same light source. However, the reflected
laser beam is interfered with and produces an interference pattern due to phase differences. The distances are determined by analysing the interference patterns (cf. [RUEGER, 1996] and [DONGES and NOLL, 1993]). Interferometry is used in engineering geodesy for precise distance measurements within sub-millimetres. With respect to TLS, interferometry is not a relevant distance measurement technology.

2.2.1.5 New Distance Measurement Technologies

As mentioned previously, each distance measurement technology has its own advantages and disadvantages. Thus, a combination of these technologies would allow new characteristics of the electro-optic distance measurement, for example, higher accuracy for longer distances. Leica Geosystems, for instance, developed the so-called Pinpoint electro-optical distance measurement technology, which is a combination of the pulsed time-of-flight and the phase difference distance measurement technologies. The modulation frequencies are changed as a function of the number of target objects and their distances, and high modulation frequencies in the MHz to GHz range are emitted (cf. [BAYOUD, 2006]). [BAYOUD, 2006] states that the systems becomes selective with regard to the direct time-of-flight to hard targets and blind with regard to soft targets, such as rain, mist, or snowfall. Until now, the Pinpoint technology has been implemented only in tacheometers and not yet in terrestrial laser scanners. However, it will probably be a technology of TLS in the near future.

2.2.2 Angle Measurement and Deflection System

To provide distances and angles for the spatial surveying of the environment or objects, the laser beam of terrestrial laser scanners has to be deflected in horizontal and vertical directions with reference to the horizon of the instrument for a full 3D-surveying. The deflections are realised by optical mirrors that either rotate or oscillate horizontally and vertically (Figure 2-9). [RESHETYUK, 2006a], for instance, gives a detailed overview of laser beam deflection systems for terrestrial laser scanners. In addition, the nutating laser beam deflection, also known as Palmer scan (cf. [WEHR and LOHR, 1999]) is also used. Thus, the laser beam scans the environment helix-wise. Nutating mirrors are often used for areal laser scanning (cf. [FAVEY, 2001]).

Figure 2-9 Rotating, oscillating and nutating mirrors for laser beam deflection.

The orientation of the optical mirrors, the angle measurement, is detected by encoders. For terrestrial laser scanners, similar encoders are used as for tacheometers. [INGEN-SAND, 1998] gives a detailed overview of encoders in tacheometers and their functional principles. Accordingly, two different types of encoders can be distinguished for geodetic instruments:
- Incremental encoding (relative method)
- Binary encoding (absolute method)

For terrestrial laser scanners, the binary encoding is widespread in use [SCHULZ, 2007]. Nevertheless, incremental encoders are implemented for terrestrial laser scanners with high resolution within some milligons. Thus, the encoders limit the horizontal and vertical angle resolution of a terrestrial laser scanner. The resolution of terrestrial laser scanners depends on the horizontal and vertical angle measurement. However, the specification of the number of points per steradian, for instance, is a reasonable suggestion for the scanning resolution of terrestrial laser scanners, analogous to the resolution of flatbed scanners or CCD-cameras (cf. [INGENSAND, 2006]).

Another significant characteristic of terrestrial laser scanners is the field-of-view, which depends significantly on the deflection unit of the laser beam. The field-of-view defines the scanning area of a terrestrial laser scanner from a single setup position. Terrestrial laser scanners are classified according to the field-of-view in the following technologies:

- Profile scanners
- Camera scanners
- Panorama scanners

In addition, so-called “hybrid” terrestrial laser scanners are positioned between a camera and a panorama scanner. A “hybrid” terrestrial laser scanner can rotate around the vertical axis. Thus, a 360°-scan can be performed but with a limited vertical field-of-view. Figure 2-10, an upgraded version of the configuration in [RUNNE et al., 2001], presents an overview of terrestrial laser scanners with diverse fields-of-view. The profile scanner has been added as an additional field-of-view due to the increasing number of applications for kinematic surveying (cf. [GLAUS, 2006] or [ZOGG and GRIMM, 2008]). Profile laser scanners are largely used in combination with additional sensors for the localisation and orientation of the measurements within the environment.

![Figure 2-10 Field-of-view of terrestrial laser scanners (cf. [RUNNE et al., 2001]).](image)

The field-of-view is an individual characteristic for each type of terrestrial laser scanner. Typically, the field-of-view of a profile laser scanner is limited to a 2D-approach in a static mode. Profile scanners often cover a 180° or 360° 2D-area (Figure 2-10), and the orientation of the 2D-plane is arbitrary with reference to the environment. The kinematic approach enables the surveying of the third dimension. However, the field-of-view of a camera scanner is horizontally and vertically limited. A typical field-of-view corresponds to a scanning window of about 40° x 40°. A panorama scanner has the capability to scan an object with a 360° horizontal field-of-view. The vertical field-of-view is limited to approximately 310° due to the self-coverage of the instrument.
2.2.3 Measurement Quality: Precision, Accuracy, and Repeatability

Until now, there have been no standards in terms of the terminology for the measurement quality of terrestrial laser scanners, specifically, the resulting 3D-point clouds. Each manufacturer specifies its instruments individually. Thus, a precise and fair comparison of different laser scanners based on the specifications of manufacturers is difficult. In addition, the specifications of terrestrial laser scanners often do not allow for a conclusion with respect to the quality of the resulting 3D-point clouds. Nevertheless, an interest in standardisation exists on the part of the manufacturers (cf. [NIST, 2003], [NIST, 2005]). In any case, the quality implies a global system consideration and quantification. For the quality of a 3D-point cloud, the terms “single point precision” and “accuracy of modelled objects” have been introduced and used throughout this thesis. The definitions of these terms are based on the terms precision and accuracy as used by such standards organisations as ANSI, ASTM and ISO (cf. [ANSI/NCSL Z540-2-1997, 1997], [ASTM E456-02, 2002], [VIM, 1993]). In addition, repeatability is also considered to be a quality factor for 3D-point clouds and for terrestrial laser scanners.

**Precision:** Precision is defined, according to [VIM, 1993] and [ASTM E456-02, 2002], as the closeness of agreement between quantity values derived from repeated measurements of a quantity. It is usually expressed by a standard deviation.

**Accuracy:** Accuracy is defined, according to [VIM, 1993] and [NIST, 2005], as the closeness of agreement between a quantity value obtained by measurement and the true value of the measurand. The accuracy is inversely related to a systematic and random error and can be expressed by the RMS. The RMS itself includes components of variance (standard deviation) and bias (cf. [DEAKIN and KILDEA, 1999]).

**Single Point Precision:** The single point precision describes the standard deviations of the resulting mean absolute error for a single point of a 3D-point cloud, obtained by fitting a known object, e.g., a sphere with a known diameter, into the 3D-point cloud.

**Accuracy of Modelled Objects:** The accuracy of modelled objects, e.g., the centre coordinates of modelled spheres, corresponds to the standard deviation of the mean absolute error after transforming the centre coordinates into a reference field, which is measured by a tacheometer. The measured and the modelled reference points, respectively, are compared to a nominal value.

**Repeatability:** According to [VIM, 1993] and [NIST, 2005], repeatability is defined as the closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurements.

The single point precision and the accuracy of modelled objects describe the quality and characteristics of a 3D-point cloud, in particular. It must be considered that these descriptions of laser scanning characteristics highly depend on the reference object and its surface properties. For calibration and investigation purposes, a standard reference target must be used (cf. section 5.3.1 and section 5.3.2).

2.3 The Measurement System “Terrestrial Laser Scanner”

The quality of a terrestrial laser scanner and a 3D-point cloud, respectively, is of high interest for users. The quality of a resulting 3D-point cloud is described by the single point precision, the accuracy of modelled objects, and the repeatability (cf. section 2.2.3). However, the quality of a 3D-point cloud from a single scanning position, the quality of a complex 3D-point cloud composed from several scans with different scanning setups, and the quality of the 3D-
model that is derived from the 3D-point cloud must be distinguished. The quality of a complex 3D-point cloud depends on the scanner allocations for the scans, which can be considered analogous to a measurement network of tacheometers or the camera setups for photogrammetry. Furthermore, the quality of a composed 3D-point cloud depends on the used reference targets and on the registration algorithms. In addition, it must be taken into consideration that the reference network is often measured by tacheometers. Thus, the network accuracy influences the quality of the composed 3D-point cloud. However, the following details refer to the quality of a 3D-point cloud from a single scanning position.

To evaluate and estimate the parameters that influence the measurements and the quality of the 3D-point cloud, respectively, the measurement system has to be clearly defined. As mentioned above, the 3D-point cloud quality does not depend only on the measurement precision and accuracy of the terrestrial laser scanner. Rather, the environments and the objects also influence the quality of the 3D-point cloud. [STAIGER, 2005] states that the quality of a 3D-point cloud depends on the quality of the terrestrial laser scanner, the environment, and the object properties. In addition, the measurement configuration and the calculation methods in the post-processing are crucial parameters in terms of quality. Generally, it is important to consider the whole measurement system “Terrestrial Laser Scanner” for quality estimations and analysis of the resulting scan.

2.3.1 Configuration

The measurement system “Terrestrial Laser Scanner” consists of four main components:

- Terrestrial laser scanner
- Environment
- Object to be measured
- Measurement configuration

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**Figure 2-11 The measurement system “Terrestrial Laser Scanner”**:

Figure 2-11 illustrates the measurement system “Terrestrial Laser Scanner.” However, the terrestrial laser scanner, the environment conditions, and the object properties directly affect the measurements and the quality of the 3D-point cloud. Moreover, the measurement configuration and methodology constitute a crucial parameter. It is reasonable to distinguish between internal and external influences on the measurements of a terrestrial laser scanner. Internal influences refer to the terrestrial laser scanner whereas external influences relate to the environment conditions. In addition, [LICHTTI and GORDON, 2004] classify the measurement errors of terrestrial laser scanners in terms of internal and external errors. In terms of external errors, they specifically consider errors related to the registration of 3D-point clouds.
2.3.2 Internal Influences

The limitations and errors of a terrestrial laser scanner are referred to in terms of internal influences on the measurement. For instance, these errors originate in the distance measurement, the laser beam divergence, the angle measurement, the sensor synchronisation, and the geometric stability of the axes (e.g., wobbling of the vertical axis, cf. [ZOGG, 2003]). Additionally, a deficient calibration of the terrestrial laser scanners influences the measurements. Therefore, internal errors are a subject for calibration and investigation purposes in terrestrial laser scanners. The detection of these errors requires a well-known environment and known object properties as well as standard measurement configurations. The measurement limitations of the terrestrial laser scanner are subject to specifications.

2.3.3 External Influences

External influences on the measurements by a terrestrial laser scanner are effected by

- the environment (e.g., refraction, air turbulences, meteo-conditions, obstacles, background of the object, and so on);
- the object (size, surface properties (roughness, reflectivity, penetration of laser beam), curvature (angle of incidence of laser beam), alignment, and so forth);
- and the measurement configuration (distance to object, object orientation with respect to line of the laser beam, point density, and so on).

Moreover, post-processing algorithms influence the quality of 3D-point clouds as well. Filter algorithms for noise reduction or transformation of 3D-point clouds into a common coordinate system affect the quality of 3D-point clouds.

2.3.4 Remarks

A detailed description of the influencing parameters on the measurements of terrestrial laser scanners is presented in [RESHETYUK, 2006a]. The errors in the measurements are subdivided into instrumental, object-related, environmental, and methodological groups. These subdivisions correspond to the classifications of internal and external influences on the measurements.

The very common consequences of internal and external influences on the measurements by a terrestrial laser scanner are mixed pixels or so-called “tail of a comet” (cf. [STAIGER, 2003]). Depending on the laser beam collimation, the properties of the objects being scanned, and the background properties, the laser beam may partially hit an object in front of another object. Thus, the detected distances are somewhere between the distances of the first object and the second object to the terrestrial laser scanner. This effect occurs more distinctly for terrestrial laser scanners that measure distances according to the phase difference principle (cf. section 2.2.1.2).

However, the definition of the measurement system “Terrestrial Laser Scanner” enables the evaluation and estimation of influencing parameters on the measurements by a terrestrial laser scanner. Measuring by a terrestrial laser scanner requires considering the whole measurement system to achieve an optimal 3D-point cloud quality. Furthermore, the quality of a 3D-point cloud strongly affects the post-processing algorithms, for example, those for filtering scanning noise, transforming the 3D-point clouds into a common coordinate system, or modelling 3D-objects.
2.4 Applications of Terrestrial Laser Scanning

Surveying tasks in engineering geodesy can be classified according to three main activities: surveying (also called acquisition), monitoring, and staking-out. In addition, the height transfer and determination are considered to be a fourth measurement task, which is largely achieved with precise levels. While TLS is a newer measurement method in the field of engineering geodesy, it is already well established for acquisition and monitoring purposes. Terrestrial laser scanners increasingly feature characteristics similar to tacheometers, such as setup over a known point or free stationing of the instrument. As mentioned before, staking-out functionalities are supported by just a few TLS systems currently available on the market.

Terrestrial laser scanners were developed largely for acquisition purposes. Their development was driven by applications used for the documentation of facility arrangements (e.g., pipes and power cables) of industry plants or of offshore platforms, the acquisition of objects for virtual scenes in the film industry, and the surveying of road surfaces under high traffic volume (cf. [STAIGER and WUNDERLICH, 2007]). Today, the range of applications has not changed significantly. The main focus for TLS still lies in acquisition purposes. In addition, applications for monitoring purposes have increased significantly.

Terrestrial laser scanners are widespread in use with numerous fields of application, such as architecture, cultural heritage, civil engineering, engineering geodesy, fashion, film, forensic, mechanical engineering, and transportation. The development of new fields of application is an ongoing process.

The fields of application and the objects to be scanned require an adequate measurement setup and, in particular, an appropriate terrestrial laser scanner and an appropriate measurement strategy, such as a largely kinematic or static approach (cf. [STAIGER and WUNDERLICH, 2007]). Because each terrestrial laser scanner has different specifications (cf. section 2.2), the field of application varies for a specific TLS system. Either an application requires a terrestrial laser scanner with concordant specifications, or a terrestrial laser scanner is qualified for a specific range of applications (Figure 2-12). Thus, the evaluation of a convenient terrestrial laser scanner is required. Until now, there has been no universally applicable terrestrial laser scanner available on the market to meet all requirements of the whole range of applications. Due to the limited availability of terrestrial laser scanners in engineering companies, projects are often achieved with a less than adequate terrestrial laser scanner, and unsatisfying results are the consequences.

Beside the measurement strategy of terrestrial laser scanners (whether static or kinematic), they are often classified according to measurement ranges with close-, mid- and long-range terrestrial laser scanners being differentiated. The measurement range of terrestrial laser scanners depends on the distance measurement principle, which can be considered a main characteristic of a terrestrial laser scanner (cf. section 2.2). Close-range is related to measurements
up to a distance of about 30 m, mid-range covers distances up to 300 m, and long-range refers to distances up to 1000 m and more. Figure 2-13 presents a classification of the main fields of application for terrestrial laser scanners based on the measurement strategy (static or kinematic) and the measurement range (close-, mid- and long-range). In addition, the range of precision is considered in relation to the applications.

In the following sections, two applications of the field of deformation monitoring are presented. For the first application – deformation monitoring in conjunction with load tests on a viaduct –, a mid-range terrestrial laser scanner with phase-difference distance technology was used. For the second application – the detection of snow drifts and settlements –, a long-range terrestrial laser scanner, which measures distances according to the pulsed time-of-flight principle, was applied.

Deformation Monitoring (mid-range application): In conjunction with future renovation work on the 33-year-old Felsenau viaduct, which is part of the Swiss highway A1 and one of the most remarkable concrete bridge structures in Switzerland (Figure 2-14), load tests were performed for evaluating the fatigue resistance and refining the analytical models. The bridge girder was, therefore, loaded with more than 100 tons. Apart from traditional geodetic measurement methods, the deformation monitoring was performed by the mid-range terrestrial laser scanner Imager 5006 by Zoller+Froehlich [ZOLLER+FROEHLICH, 2008]. The scanner was set up on the bridge girder of the viaduct. Scans of the carriageway were performed with and without the load. Thus, the scans for different load situations were compared to the initial situation (Figure 2-15). Deformation within mm-range could be detected. In [ZOGG and INGENSAND, 2008], a detailed description is given about the load tests and the results.
Detection of Snow Drift (long-range application): A test field was installed in the Swiss Alps close to Davos to detect snow drifts and settlements. The measurement range of more than 500 m required the long-range terrestrial laser scanner LPM-i800HA by Riegl [RIEGL, 2008] (Figure 2-16). TLS allowed the contactless measurements of the test field. Thus, no manual inspection was required. By comparing scans from different dates to the initial situation, a snow drift could be detected (Figure 2-17). Investigations showed that the measurement accuracy ($1\sigma$) was more than 10 cm (cf. [RUB, 2008]). A detailed overview of long-range TLS and further applications are published in [RUB and ZOGG, 2008].

2.5 Remarks

In general, the range of applications is widespread for TLS. Of course, the applications are more limited for a particular terrestrial laser scanner. Thus, the applications have to be chosen according to the scanner specifications and classifications. To cover a wide range of applications, several different types of terrestrial laser scanners have to be considered. In addition, terrestrial laser scanners have to be used for applications that are not realizable or are poorly realizable by well established geodetic measurement methods, such as tacheometry or GNSS. Knowledge gathered during this thesis allows inferring that TLS is not an alternative to traditional measurement methods. Rather, it complements the well established geodetic measurement methods. However, the need for staking-out functionalities of terrestrial laser scanners requires an implementation of tacheometer functionalities in terrestrial laser scanners. How-
ever, a tacheometer with scanning functionalities would probably be a more satisfyingly approach to this task, cf. Trimble VX Spatial Station [TRIMBLE, 2008]. Furthermore, the combined processing of data from different sensors has to be further developed. [SCHNEIDER and MAAS, 2007], for instance, present a fusion of TLS data and image data, which allows the use of the appropriate characteristics of the particular measurement data, e.g., for the self-calibration of the used measurement systems or the improvement of the integrity and accuracy of the 3D-data.

Beside the choice of an adequate terrestrial laser scanner for a specific application, the post-processing of the resulting 3D-point cloud is a crucial factor in terms of achieving results. Information extraction from a 3D-point cloud is the main task for the post-processing. [BRENNER, 2007] describes approaches for 3D-point cloud interpretations, with low-level and high-level interpretation and reconstruction of an object being distinguished. The point or edge detections are classified as low-level interpretations whereas the calculations of 3D-models are high-level interpretations. [WUNDERLICH, 2006] calls the interpretation of 3D-point clouds improvements and proposes three categories for 3D-point cloud improvements: CAD-modelling, numerical analysis, and texturing. CAD-modelling creates geometric objects from the 3D-point cloud based on triangulation; by adjusting geometric primitives such as patch, sphere, cylinder, cube, cone, pyramid, and torus; or by polyline fitting (cf. section 6.3.1). However, numerical analysis largely compares the 3D-point cloud with a nominal model, e.g., for quality control (cf. section 8.1). Texturing the 3D-point cloud is generally adequate for visualisation purposes. CAD-modelling is considered the most time-consuming approach to improvement of a 3D-point cloud.

In general, TLS is a geodetic measurement method with high potential in the near future. The demand for 3D-data (X, Y, Z) and subsequent 4D-data (X, Y, Z, I) will increase due to the need for 3D-data in online applications. Nevertheless, new developments of further applications of TLS are needed, including the improvements of hardware and software components. In the following sections, the development, calibrations, and investigations of the close-range terrestrial 3D-laser scanner ZLS07 are introduced. In addition, the application for the acquisition of underground utility caverns by TLS, specifically by the ZLS07, in the field of water and sewage engineering is presented.
3 Development of Terrestrial Laser Scanner ZLS07

The main reason and motivation for development of a measurement system based on the laser scanning technology originated in the specific application for the acquisition of underground utility caverns (cf. section 6). No terrestrial laser scanner, which was available on the market at the end of 2005 (at the beginning of this project), was suitable for this application. Splash water inside underground utility caverns and the difficult access are just a few difficulties. Additionally, a cost-efficient solution was postulated. The result of the development is the close-range terrestrial 3D-laser scanner ZLS07 (Zürcher Laser Scanner) (Figure 3-1). In addition to the acquisition of underground utility caverns, the ZLS07 is used for measurement and documentation of technical buildings in which the measurement accuracy is not a crucial parameter.

The following sections describe the terrestrial 3D-laser scanner ZLS07, with the focus on the implemented components and sensors. In addition, the model for the calculations of the 3D-coordinates – the 3D-point cloud – from the raw measurements is described, as well as the developed software for controlling the ZLS07 and processing the data. Finally, the result of a scan with the ZLS07 is presented.

3.1 Requirements

The requirements for the ZLS07 are strongly influenced by the intended and future application of the acquisition of underground utility caverns (cf. section 6). Nevertheless, the ZLS07 has to be a terrestrial laser scanner with a widespread use in terms of additional applications beside the acquisition of underground utility caverns. Furthermore, not only should the ZLS07 be a prototype, but also it should be operable in real conditions. The requirements guiding the development are as follows:

- Reliable in terms of operation under different environmental conditions
- Robust
- Splash-water resistant due to application in underground utility cavern
- Measurement range up to 30 m
- 360°-panorama scanner with a large vertical field-of-view
- Scanning speed: less than 10 min for a 360°-scan
- Measurement accuracy: cm-range
- Cost efficient
- Non-expert operation and data post-processing

Regarding cost-efficiency, the ZLS07 should be designed to be a low-cost scanner. Future purchase of a ZLS07 must be approximately 10% to 30% of the initial costs for commercial terrestrial laser scanners, which are assumed to be approximately 150'000 CHF. Hence, high initial costs are a crucial parameter for engineering companies when considering investing in laser scanning technology, according to [ZOGG, 2005].
3.2 Components of the ZLS07

The ZLS07 (Figure 3-1) is modularly constructed by using a rotation table developed at ETH Zurich, a distance measurement unit by Sick AG [SICK AG, 2006], and a wireless network CCD-camera by TCLINK International Co. [TCLINK, 2008]. For measurements taken by the ZLS07, the rotation table registers the horizontal position, and the distance measurement unit measures distances as well as vertical angles with respect to the horizon of the instrument. The CCD-camera is just for additional documentation purposes. Control of the terrestrial laser scanner is performed by an external computer system. The measurement range is 32 m for mm-resolution and 80 m for cm-resolution. Depending on the measurement mode, the intensity of the reflected laser beam can also be detected.

![Figure 3-1 Terrestrial 3D-laser scanner ZLS07.](image)

3.2.1 SICK LMS200-30106

The 2D-laser scanner SICK LMS200-30106 (Figure 3-2) is well known from industrial applications and robotics. Typical applications include sorting and classing objects, determining volume, preventing vehicle collision, automation processing, or navigating. Monitoring for security reasons is another very widespread application for the SICK LMS200-30106. The 2D-laser scanner, which generates a laser plane, can be connected to an alarm system. As soon as an object (human being or machine) enters into the laser plane, an alarm is activated. For object detection, the 2D-laser scanner is usually fix installed, and the objects pass by, such as for the collection of traffic data on highways.
In the field of robotics, the 2D-laser scanners by SICK AG are used for object acquisitions and for prevention of collision of mobile robots with obstacles in their trajectories (cf. [ARRAS et al., 2003] and [JENSEN et al., 2005]). The SICK LMS200-30106 is well known from applications for autonomous vehicles. The 2D-laser scanners are implemented for close- and mid–range controlling. The high measurement frequency of 75 Hz enables these applications. [REIMER et al., 2005], [WULF and WAGNER, 2003], and [WULF et al., 2004] present a continuous 360°-real-time laser scanner, based on the SICK LMS200-30106, which can be attached on moving platforms for mobile mapping and object recognition. The third dimension is acquired, whereas the measurement results of the SICK LMS200-30106 are just two dimensional. Another mobile platform with 2D-laser scanners is introduced by [BIBER et al., 2005]. Two 2D-laser scanners are used for geometry acquisition of the environment. A vertical 360°-profile is generated by the laser scanners and synchronised with the actual position and orientation of the mobile platform.

In recent years, the SICK LMS200-30106 is being more commonly applied in the field of engineering geodesy. Mobile platforms are often equipped by the 2D-laser scanners. [GLAUS, 2006] introduces a system for the kinematic acquisition of the catenary geometry and infrastructure in railway engineering. Two 2D-laser scanners are mounted on a trolley that is guided along the rail. Actual position of the trolley and the measurements of the laser scanners are registered. For the acquisition of tunnels, bridges, and road surfaces, [GRAEFE, 2007] presents a mobile multi-sensor platform that is installed on a van, from which the 2D-laser scanner acquires geometry and reflectivity information of the objects. The range of applications for the SICK-LMS200-30106 is widespread, largely due to the robustness, reliability, and high measurement frequency. However, measurement accuracy and range are moderate in comparison to high precision terrestrial laser scanners with similar measurement ranges (cf. Imager 5006).

### 3.2.1.1 Principles of Operation

The SICK LMS200-30106 measures distances based on the pulsed time-of-flight principle (cf. section 2.2.1) and angles. The emitted laser beam is reflected by objects in space, and the backscatter is registered in the receiver unit of the 2D-laser scanner (Figure 3-3). The emission and reception of the laser beam occurs through the same front window. The laser beam is deflected by a rotating mirror so that a laser fan is spanned in space with an opening of 180°.

The frequency of the rotating mirror is 75 Hz with an angular interval of 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, up to 13’500 distance measures are taken within one second.
3.2.1.2 Specifications

The main specifications of the SICK LMS200-30106 are summarised in Table 3-1, based on the manufacturer specification sheet [SICK AG, 2006]. In [YE and BORENSTEIN, 2002], investigations into SICK LMS200-30106 are described, and the product specifications are verified.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>angular range</td>
<td>180°</td>
</tr>
<tr>
<td>angular resolution</td>
<td>1°, 0.5°, 0.25°</td>
</tr>
<tr>
<td>distance resolution</td>
<td>1 mm for mm-resolution mode</td>
</tr>
<tr>
<td></td>
<td>10 mm for cm-resolution mode</td>
</tr>
<tr>
<td>maximal range:</td>
<td></td>
</tr>
<tr>
<td>mm-resolution mode</td>
<td>32 m</td>
</tr>
<tr>
<td>cm-resolution mode</td>
<td>80 m</td>
</tr>
<tr>
<td>laser beam divergence</td>
<td>0.286°</td>
</tr>
<tr>
<td></td>
<td>(laser beam footprint with a diameter of 15 cm at a range of 30 m)</td>
</tr>
<tr>
<td>systematic error</td>
<td>± 15 mm</td>
</tr>
<tr>
<td></td>
<td>(at range 1 m to 8 m)</td>
</tr>
<tr>
<td>statistic error (1σ)</td>
<td>5 mm</td>
</tr>
<tr>
<td></td>
<td>(at range 1 m to 8 m)</td>
</tr>
<tr>
<td>wavelength</td>
<td>905 nm (infra-red)</td>
</tr>
<tr>
<td>laser class</td>
<td>1</td>
</tr>
<tr>
<td>data transfer rate</td>
<td>max. 500kBaud</td>
</tr>
<tr>
<td>operating voltage</td>
<td>24 V</td>
</tr>
<tr>
<td>price</td>
<td>approx. 6’500 CHF</td>
</tr>
</tbody>
</table>

Table 3-1 Specifications of SICK LMS200-30106 according to [SICK AG, 2006].
According to the manufacturer [SICK AG, 2006], the statistical error corresponds to the standard deviation, which is calculated using at least 100 measurements on a target with defined reflectivity at a fixed distance and a defined amount of illumination. The systematic error is the sum of all the deviations over a defined extent of range and reflectivity, which cannot be reduced, even by using averaged values. Thus, the systematic error corresponds to an offset. For the angle measurement, the resolution is specified to minimum 0.25°. The angle measurement accuracy and precision is not specified by the manufacturer but was investigated in conjunction with the angle measurement system of the ZLS07 (cf. section 5.1).

In addition to internal systematic errors, the range measurement of the SICK LMS200-30106 depends on such object properties as reflectivity of the surface, angle of incidence of the laser beam on the object, measurement range, and transmission conditions between the scanner and the object. These parameters are well known and have been well investigated for terrestrial laser scanners that are used in the field of engineering geodesy (cf. [SCHULZ, 2007]). Nevertheless, it is difficult to describe standard specifications for the distance measurements of a terrestrial laser scanner without considering the parameters mentioned above. Therefore, additional investigations and calibrations of the distance measurement of the SICK LMS200-30106 were performed under laboratory conditions (cf. section 4.2).

The SICK LMS200-30106 offers the possibility of two different distance measurement modes: cm-resolution mode and mm-resolution mode. The maximum range depends on the number of bits reserved for the distance information in the data stream. For the cm-resolution, the maximum range is limited to 80 m due to the 13-bit width. For mm-resolution mode, the maximum range of 32 m is given by 215 bits. Furthermore, the maximum range for mm-resolution can be set to 8 m or 16 m for 13-bit or 14-bit width of the distance coding. For the ZLS07, the mm-resolution mode with a maximum distance of 32 m is generally used.

Apart from the distances, the intensity of the laser beam can also be detected by the SICK LMS200-30106, but it should be noted that the intensity can only be registered for 13-bit distances due to data-bit limitations on the data stream. The angular resolution of the SICK LMS200-30106 is limited to 1° in connection with the detection of intensity.

### 3.2.1.3 Data Structure

The 2D-laser scanner SICK LMS200-30106 is configured in the interlaced mode as standard configuration for implementation in the ZLS07. The scanning angle is 180° and the angular resolution 0.25°. In addition, the distances are registered in mm-resolution, and the maximum range is 32 m.

The data of the SICK LMS200-30106 are structured in the interlaced mode as follows:

<table>
<thead>
<tr>
<th>t_start</th>
<th>t_end</th>
<th>Pos1</th>
<th>Pos2</th>
<th>Pos3</th>
<th>Pos4</th>
<th>Pos180</th>
<th>Pos181</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>6.7 ms</td>
<td>0.00°</td>
<td>1.00°</td>
<td>2.00°</td>
<td>3.00°</td>
<td>179.00°</td>
<td>180.00°</td>
</tr>
<tr>
<td>13.3</td>
<td>20.0 ms</td>
<td>0.25°</td>
<td>1.25°</td>
<td>2.25°</td>
<td>3.25°</td>
<td>179.25°</td>
<td></td>
</tr>
<tr>
<td>26.6</td>
<td>33.3 ms</td>
<td>0.50°</td>
<td>1.50°</td>
<td>2.50°</td>
<td>3.50°</td>
<td>179.50°</td>
<td></td>
</tr>
<tr>
<td>40.0</td>
<td>46.7 ms</td>
<td>0.75°</td>
<td>1.75°</td>
<td>2.75°</td>
<td>3.75°</td>
<td>179.75°</td>
<td></td>
</tr>
<tr>
<td>53.3</td>
<td>60.0 ms</td>
<td>0.00°</td>
<td>1.00°</td>
<td>2.00°</td>
<td>3.00°</td>
<td>179.00°</td>
<td>180.00°</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Each row corresponds to a single scanning profile with 180 or 181 distance measurements. The number of distance measurements per scanning profile depends on the first position angle. If the profile starts at an angle of 0°, a scanning profile contains 181 distance measurements. For all other starting angles, 180 distances are measured for one scanning profile. The
nominal time for a profile, which corresponds to a 360°-rotation of the mirror, is set to 1/75 s. The columns headed Pos1...180|181 (180|181 stands for “180 or 181”) represent the actual position of the rotating mirror of the SICK LMS200-30106. For each mirror position, the actual distance is measured. The measurements are registered according to the following structure:

<table>
<thead>
<tr>
<th>$t_j$ [s]</th>
<th>$\Delta t$ [s]</th>
<th>$\alpha_j$ [°]</th>
<th>$d_1$</th>
<th>$d_2$</th>
<th>$d_3$</th>
<th>$d_{180}$</th>
<th>$d_{181}$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1466.710903</td>
<td>0.013333</td>
<td>0.00</td>
<td>395</td>
<td>411</td>
<td>445</td>
<td>...</td>
<td>477</td>
</tr>
<tr>
<td>1466.724237</td>
<td>0.013333</td>
<td>0.25</td>
<td>394</td>
<td>429</td>
<td>459</td>
<td>...</td>
<td>496</td>
</tr>
<tr>
<td>1466.737570</td>
<td>0.013333</td>
<td>0.50</td>
<td>421</td>
<td>446</td>
<td>461</td>
<td>...</td>
<td>454</td>
</tr>
<tr>
<td>1466.750903</td>
<td>0.013333</td>
<td>0.75</td>
<td>404</td>
<td>405</td>
<td>461</td>
<td>...</td>
<td>431</td>
</tr>
<tr>
<td>1466.764237</td>
<td>0.013333</td>
<td>0.00</td>
<td>462</td>
<td>455</td>
<td>424</td>
<td>...</td>
<td>421</td>
</tr>
</tbody>
</table>

The time differences $\Delta t$ are the differences between the starting time tags $t_j$ of two scanning profiles, which are equal to the nominal time for one rotation of the mirror (1/75 s). The time tag $t_j$ for the $k^{th}$-distance of a particular scanning profile $j$ can be calculated according to [GLAUS, 2006]:

$$t_j = t_j + \frac{(k-1)}{360} \cdot \frac{1}{75} \text{s} \quad (j \in [1,2,3,4]; k \in [1,2,3...180|181]) \quad (3.1)$$

The time tag $t_j$ corresponds to the time for the first distance of a particular scanning profile. The angle $\alpha_i$, which is the actual position of the rotating mirror, can be calculated as:

$$\alpha_i = \alpha_j + (k-1) \cdot \Delta \alpha \quad (j \in [1,2,3,4]; k \in [1,2,3...180|181])$$

with $\alpha_j = 0.25 \cdot (j-1) \text{mod} 4$ and $\Delta \alpha = 1^\circ \quad (3.2)$

The coordinates in the Cartesian coordinate system of the SICK LMS200-30106 are computed for a single distance and angle measurement (cf. section 3.4) according to the following:

$$ x_{\text{SICK},i} = \begin{pmatrix} d_i \cdot \sin \alpha_i \\ 0 \\ d_i \cdot \cos \alpha_i \end{pmatrix} \quad (3.3)$$

The distance $d_i$ is the distances measured by the 2D-laser scanner to the object. The angle $\alpha_i$ represents the actual position of the rotating mirror, which is defined in (3.2).

### 3.2.2 Rotation Table ETH Zurich

#### 3.2.2.1 Configuration

The rotation table (Figure 3-4), which provides the 360° horizontal rotation of the ZLS07, is developed and constructed at the ETH Zurich. Its main components are a DC-motor by Maxon Motor AG [MAXON MOTORS, 2007], a high precision gear with tangent screw similar to electronic hard drives, and an angular contact ball bearing (Figure 3-5). The angular contact ball gearing supports particularly high axial forces, allowing the ZLS07 to do a head-first scanning, which is important for the application of underground utility cavern acquisition (cf. section 6). Slip rings are installed to eliminate rotating power and data cables between the body and assembly.
The determination of the horizontal position of the rotation table is performed by an incremental encoder at the motor axis. This encoder counts the number of rotations of the motor axis. The resolution of the incremental encoder corresponds to 500 units per one rotation of the motor axis. The horizontal position of the rotation table is calculated from the gear ratio coefficient and the number of rotations of the motor axis. Largely due to cost-efficiency, there is no additional encoder implemented for the direct detection of the actual horizontal position of the rotation table.

The rotation table has an initial position that is realised by an index (reference pin and sensor). The motor is capable of approaching this initial position, which corresponds to the zero-direction of the horizontal circle for the ZLS07. Before starting a new scan, the rotation table performs an initialisation and turns to its zero-position. It should be noted that the index is always approached from the same direction to avoid inaccuracies caused by the worm gear. Hence, each scan starts with the same inner orientation of the rotation table ($\sigma_{\text{orientation}} = 0.0001^\circ$). The standard deviation for the inner orientation has been derived from the specifications of the motor and motor controller (cf. section 3.2.2.2).

### 3.2.2.2 Specifications

The resolution of the horizontal angular step width of the rotation table depends on the resolution of the incremental encoder, the gear ratio, and the number of teeth on the main gear wheel. The nominal number of impulses for a 360°-rotation of the rotation table axis corresponds to the gear ratio (1:750) multiplied by the incremental encoder resolution (500 per motor axis rotation) (cf. appendix A.1), resulting in a nominal 375'000 impulses. The minimal horizontal resolution of the rotation table results in 0.001° (one impulse of the encoder). Furthermore, the angular measurement accuracy of the rotation table is crucial in the measurement quality of the ZLS07.

The interface for controlling the DC-motor of the rotation table is realised by RS-232. The motor controller itself controls the rotation frequency of the DC-motor and reads the actual position. According to specifications [IMG GmbH, 2003], the absolute rotation frequency tolerance is set to 0.1% of the adjusted specified rotation frequency. This setting results in a
maximum position tolerance of 0.0072° and in a standard deviation of 0.0029° for the rotation table used with the ZLS07. The maximum rotation frequency of the motor axis is set to 7500 rotations per second in conjunction with the ZLS07, which corresponds to the scanning resolution low.

Table 3-2 gives an overview of major specifications of the rotation table implemented in the ZLS07.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>drive</td>
<td>Maxon DC-motor</td>
</tr>
<tr>
<td>motor controller</td>
<td>MCS7000 by IMG GmbH</td>
</tr>
<tr>
<td>gear ratio</td>
<td>750:1</td>
</tr>
<tr>
<td>minimal angular resolution (horizontal</td>
<td>0.0010°</td>
</tr>
<tr>
<td>resolution)</td>
<td></td>
</tr>
<tr>
<td>position accuracy* ( depending on rotation frequency)</td>
<td>0.0029° (1σ)** (** for 7500 rotations per second which corresponds to scanning resolution low for ZLS07)</td>
</tr>
<tr>
<td>bearing</td>
<td>angular contact ball bearing</td>
</tr>
<tr>
<td>operating voltage</td>
<td>12 V</td>
</tr>
<tr>
<td>price</td>
<td>approx. 2’000 CHF</td>
</tr>
</tbody>
</table>

*Table 3-2 Specifications of rotation table.*

Investigations into the accuracy of the rotation table were performed in conjunction with investigations into the accuracy of the angle measurement system of the ZLS07 (cf. section 5.1). However, the position accuracy of the rotation table is based on the specifications of the motor controller.

### 3.2.2.3 Data Structure

The data transfer between the rotation table and computer is realised by a serial RS-232 interface. The actual number of rotations of motor axis $N_{MA}$ is sampled approximately every 100 ms by the controlling software. Rotation numbers within these 100 ms are linearly interpolated. The time $t_k$ and the actual number of rotations of motor axis $N_{MA}$ are recorded according to the following:

$$t_k \ [s] \quad \quad N_{MA}$$

<table>
<thead>
<tr>
<th>$t_k$ [s]</th>
<th>$N_{MA}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1466.311580</td>
<td>2627</td>
</tr>
<tr>
<td>1466.411910</td>
<td>3130</td>
</tr>
<tr>
<td>1466.601449</td>
<td>4077</td>
</tr>
<tr>
<td>1466.653599</td>
<td>4338</td>
</tr>
<tr>
<td>1466.716880</td>
<td>4652</td>
</tr>
</tbody>
</table>

*The time $t_k$ is the time tag of the computer system that controls the rotation table. The actual horizontal position of the rotation table $HZ_{RT}$ is calculated afterwards according to (3.4).*
The nominal number of rotations of the motor axis is subject to calibration (cf. section 4.4). Figure 3-6 shows the number of rotations according to the time for different rotation frequencies of the motor axis. Hence, a horizontal 360°-rotation of the rotation table corresponds to approximate 375'000 rotations of the motor axis. In addition, the scanning resolution low of the ZLS07 equals to 7500 rotations/s, middle to 5000 rotations/s, and high to 2500 rotations/s.

\[ HZ_{\text{RT}} = \frac{360^\circ}{375'000} \cdot N_{\text{MA}} \]  

Figure 3-6 Number of motor axis rotations versus time.

### 3.2.3 CCD-Camera

A CCD-camera is installed on top of the ZLS07 primarily for documentation purposes and colouring of the 3D-point cloud (cf. section 7.3). The CCD-camera is a commercial low-cost network CCD-camera (approximately 200 CHF) made by TCLINK International Co. [TCLINK, 2008] (Figure 3-7).

The uncalibrated network CCD-camera has a VGA-resolution (640 x 480 pixels) with 256 colours. The camera supports the RTSP (Real Time Streaming Protocol), which enables a client to control a streaming media server remotely. The interface of the network CCD-camera is realised by Ethernet (IEEE 802.3) or wireless (IEEE 802.11). In conjunction with the ZLS07, the wireless interface has been implemented. The Ethernet interface would require additional cabling through the connecting slip rings of the rotation table of the ZLS07.
3.3 Configuration of Terrestrial Laser Scanner ZLS07

The 2D-laser scanner SICK LMS200-30106 (cf. section 3.2.1) is mounted on the rotation table developed by ETH Zurich (3.2.2). By rotating the 2D-laser scanner around the vertical axis, the third dimension of the object is measured by registering the horizontal position of the rotation table. 3D-coordinates are calculated from the 2D-laser scanner data and the data of the rotation table position (cf. section 3.4). For the ZLS07, two configurations are distinguished:

- Yawing configuration
- Yawing-top configuration

The yawing configuration is the standard configuration for the ZLS07, whereas the yawing-top configuration is largely for calibration purposes. The yawing-top configuration enables the measurement in two faces, allowing the calibration of errors of the laser axis and horizontal axis, analogous to the calibration of tacheometers (cf. section 4.3 and [DEUMLICH and STAIGER, 2002]). To minimise errors of axes, it is important to connect and adjust components mechanically in a way that the scanner axes are perpendicular to each other. Variances to the perpendicularity are minimised by mechanical adjustment and calibration routines.

3.3.1 Yawing and Yawing-Top Configuration

As mentioned previously, there are two different configurations for the ZLS07: the yawing and yawing-top configuration. 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 (Figure 3-8). The limitation of the vertical view is caused by the rotation table, which builds a scan shadow towards the tripod. The vertical limitation depends on the length of the vertical axis, which is subject to the particular application.

For the yawing-top configuration, the field-of-view is limited to 360° horizontal and 180° vertical (Figure 3-9). The laser fan spans a plane in the upper hemisphere of the laser scanner.
Development of Terrestrial Laser Scanner ZLS07

3. Development of Terrestrial Laser Scanner ZLS07

The full upper hemisphere is scanned by a 180° horizontal rotation of the rotation table. The yawing-top configuration allows two-face measurements like those of tacheometers (cf. [DEUMLICH and STAIGER, 2002]). This setup is chosen for the calibration of the horizontal and laser axes by measuring reference targets in two faces (cf. section 4.3). In general, a change of the configurations can be easily performed even on a construction site. Both software and hardware have been developed for both configurations.

The SICK LMS200-30106 is mounted eccentrically on the rotation table for both configurations because the centre of mass of the ZLS07 corresponds approximately to the centre point of horizontal rotation. This is important for minimizing the wobbling of the vertical axis. For the SICK LMS200-30106, the centre of mass does not correspond to the centre point of the rotating mirror, resulting in an eccentricity of the vertical laser fan compared to the centre of horizontal rotation of the rotation table. The eccentricity across the line of sight of the ZLS07 is defined by the mechanical construction. This offset was not subject to calibrations. Furthermore, the eccentricity along the line of sight, which corresponds to an additional constant of the distance measurement, was calibrated in conjunction with the calibration of the distance measurement (cf. section 4.2).

3.3.2 Design Features

In addition to the two configuration types for the ZLS07 (yawing and yawing-top configuration), there are other design features, in particular, two different types of vertical axes. There are a short and an elongated vertical axis. The vertical field-of-view changes depending on the length of the vertical axis.

Figure 3-10 ZLS07 with elongated (left) and short (right) vertical axis.

Elongated Vertical Axis: The vertical axis of the ZLS07 has been elongated to minimise the vertical coverage angle of the rotation table itself (Figure 3-10). This is an important aspect, especially for the yawing configuration, which is primarily used for the application of underground utility cavern acquisition (cf. section 6). The extension of the vertical axis (approximately 34 cm) increases the vertical field-of-view of the ZLS07. The vertical field-of-view is about 330°. A disadvantage is the amplification of errors due to wobbling of the vertical axis (cf. section 5.2).

Short Vertical Axis: A short vertical axis (approximately 7 cm) of the ZLS07 results in fewer errors due to wobbling of the vertical axis (Figure 3-10). In addition, the dimensions of the ZLS07 are more compact and allow application where the vertical field-of-view is not the cru-
cial parameter, e.g., for deformation or excavation monitoring in tunnelling. However, the vertical field-of-view is limited due to the rotation table, so objects close to the nadir of the ZLS07 can no longer be measured.

3.3.3 Sensor Synchronisation

In using more than a single sensor for data collection, data synchronisation is usually indispensable. Time tags have to be assigned to the measurement. Real-time multi-sensor platforms usually assign time tags onboard from an external time emitter controlled by real-time operating systems. Additionally, it is very common to use GPS time events “Pulse per Second” (PPS) for sensor synchronisation (cf. [STEMPFHUBER, 2004]). [HESSE, 2007], for instance, gives a detailed overview of different solutions for data synchronizing of complex measurement systems with a terrestrial laser scanner as an additional sensor.

For the ZLS07, the 2D-laser scanner and the rotation table deliver data for the calculations of 3D-point clouds of the object to be acquired. The two units build independent measurement components, whose data have to be combined for further calculations of the measurements. Synchronisation of the two units and controlling the ZLS07 while scanning are performed by an external computer system. No microprocessor for controlling the different units is implemented in the ZLS07, neither is a real-time operating system. The data of the two units have to be synchronised externally by the computer system. The synchronisation is realised by registering a time tag for each measurement. The measurements of both units are relocated in reference to each other by the registered time tag.

Time tags of the measurement system ZLS07 are assigned to the measurements of the rotation table and the distance measurement component by an external computer system. No internal controlling unit is implemented in the hardware of the ZLS07. The time tag is added to the measurements after reading the data from the interface. Thus, delays, interrupts, and latencies can be the consequences. These parameters influence the current time tags and their allocation. Due to the delays, interrupts, and latencies in data synchronisation, the nominal frequency of the rotating mirror of the SICK LMS200-30106 is used as a time tag for the 2D-laser scanning data as an alternative to the time tag of the computer system. Thus, two solutions for gripping a time tag for the data of the 2D-laser scanner can be distinguished:

- Time tag of computer system (microprocessor)
- Nominal frequency of rotating mirror of SICK LMS200-30106

The time tag of the computer system correlates with the frequency of the implemented microprocessor. The data from the rotation table and 2D-laser scanner receive a time tag that corresponds to the actual time of the computer system. For the ZLS07, a so-called QueryPerformanceCounter is implemented. The frequency of this timer is set to 1’193’180 Hz. The primary problems of using the time tags generated by the operating computer system are the delays, interrupts, and the latencies, which are difficult to detect. Even though the data from the 2D-laser scanner get the time stamp before being temporally stored in a buffer on the computer system, latency cannot be avoided between scanning and filling the buffer.

Alternatively, the nominal rotation frequency of the rotating mirror of the 2D-laser scanner SICK LMS200-30106 is used. According to the manufacturer’s product specifications [SICK AG, 2006], the nominal rotation frequency is set to 75 Hz. Thus, a laser profile is acquired every 1/75 s. Hence, the time $t_{scanning}$ for a defined number of profiles $N_{profiles}$ is calculated as:
\[ t_{\text{Scanning}} = N_{\text{Profiles}} \cdot \frac{1}{75} \text{s} \]  

(3.5)

As a standard setting for the ZLS07, the nominal rotation frequency (75 Hz) of the rotating mirror of the SICK LMS200-30106 is used as a time tag. A big advantage of time tags taken from the rotation frequency is the independency in terms of time delays due to gathering the data from the interface between the 2D-laser scanner data and the computer system. Also, [SCHULZ, 2007] and [HESSE, 2007] use the rotation frequency of the vertical laser beam deflection mirror of the Imager 5003 by Zoller+Froehlich [ZOLLER+FROEHLICH, 2008] as relative time tags for synchronising the laser scanner data with the actual position of the moving platform.

Nevertheless, both methods for time tag generation require a calibration to minimise errors due to synchronisation and time delays. An error due to bad synchronisation affects the angular measurements of the ZLS07, in particular, the measurements for the horizontal angles. A big advantage of a 360°-scanner compared to kinematic 2D-scanners on moving platforms [GLAUS, 2006] is that the measurements repeat themselves after a 360°-horizontal rotation without any changes of the environment and, thus, are used to calibrate the synchronisation, time delay, and latency problem of the ZLS07 (cf. section 4.4).

In computer science, there are latencies for all processes. Latency is defined as the time from an action to the reaction, for example, from a command to the execution. In conjunction with the ZLS07, the latency is defined as the time from the beginning of the triggering data to the allocation of the resultant time stamp. For all time-crucial applications, the latency has to be defined or calibration routines are needed to eliminate or minimise errors due to latency.

### 3.3.4 Overall Specifications of Terrestrial Laser Scanner ZLS07

The specifications of the ZLS07 are based on its calibrations and investigations that were performed at the ETH Zurich (cf. sections 4 and 5). Table 3-3 gives an overview of the main specifications of the ZLS07. It should be noted that the specifications are effective for the standard configuration, which corresponds to the yawing-configuration of the ZLS07 (cf. section 3.3) with the elongated vertical axis. Beside the scanning speed, the large vertical field-of-view is a special feature of the ZLS07 with an elongated vertical axis. Furthermore, the ZLS07 is developed as a robust and splash-water resistant laser scanner.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement range</td>
<td>32 m for mm-resolution of distance measurement</td>
</tr>
<tr>
<td></td>
<td>80 m for cm-resolution of distance measurement</td>
</tr>
<tr>
<td>Scanning resolution</td>
<td>low: 0.357° horizontal, 0.25° vertical</td>
</tr>
<tr>
<td></td>
<td>middle: 0.25° horizontal, 0.25° vertical</td>
</tr>
<tr>
<td></td>
<td>high: 0.125° horizontal, 0.25° vertical with intensity: 0.125°/0.5°/1° horizontal, 1° vertical</td>
</tr>
<tr>
<td>Scanning speed</td>
<td>13’500 points/s</td>
</tr>
<tr>
<td>Field-of-view</td>
<td>horizontal: 360° (maximum)</td>
</tr>
<tr>
<td></td>
<td>vertical: 330° (maximum; for elongated vertical axis)</td>
</tr>
</tbody>
</table>
Development of Terrestrial Laser Scanner ZLS07

<table>
<thead>
<tr>
<th>time for a 360°-scan</th>
<th>low: 50 s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>middle: 75 s</td>
</tr>
<tr>
<td></td>
<td>high: 150 s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3D-single point precision</th>
<th>15 mm (1σ) up to a range of 9 m (after calibration)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D-accuracy of modelled objects</td>
<td>12 mm (1σ) up to a range of 9 m * (after calibration)</td>
</tr>
<tr>
<td></td>
<td>(*by using a sphere-target with diameter of 15 cm)</td>
</tr>
<tr>
<td>CCD-camera</td>
<td>RTSP Network Camera</td>
</tr>
<tr>
<td></td>
<td>VGA resolution (640 x 480 pixels) with 256 colours</td>
</tr>
<tr>
<td>weight</td>
<td>11 kg</td>
</tr>
<tr>
<td>operating voltage</td>
<td>24 V</td>
</tr>
<tr>
<td>electric current</td>
<td>stand-by: 0.80 A</td>
</tr>
<tr>
<td></td>
<td>scanning: 1.25 A</td>
</tr>
<tr>
<td>user interface</td>
<td>notebook or tablet PC</td>
</tr>
<tr>
<td>data format</td>
<td>ASCII data file (data format: X, Y, Z, Intensity)</td>
</tr>
</tbody>
</table>

Table 3-3 Specifications of ZLS07.

3.4 Measurement Coordinate Systems

For measurements with the ZLS07, the 2D-laser scanner SICK LMS200-30106 (cf. section 3.2.1) and the rotation table (cf. section 3.2.2) acquire geometric information about the object to be scanned. The raw measurements are defined by distances and the vertical angles of the 2D-laser scanner and horizontal angles of the rotation table with reference to the horizon of the instrument. In addition to the temporal synchronisation of the data, geometric relations between the components and the raw measurements are required for the calculations of a 3D-point cloud, which results from a scan.

3.4.1 Homogeneous Coordinates

To transform the raw measurements of the 2D-laser scanner SICK LMS200-30106, which are measured in the local 2D-laser scanner frame (S-frame; S: scanner) (cf. section 3.4.2), into the frame of the terrestrial 3D-laser scanner (LT-frame; LT: local top), homogenous coordinates are used. They allow affine transformations which are easily represented by matrix multiplications. A translation, for instance, is represented by a matrix multiplication within the homogenous coordinate system. For the Cartesian coordinate system, a translation is described as an addition of vectors. The set of all homogenous coordinates is called projective space whereas the set of all Cartesian coordinates is called Euclidean space (cf. [HAERING and MASSARD, 2005]). The coordinate system of the ZLS07 is defined in a mathematical, “right-handed” frame.
A single 3D-point in the Cartesian coordinate system is represented by:

\[ \bar{x} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \tag{3.6} \]

To perform translations as matrix operations, the Cartesian coordinate system is expanded by an additional dimension. Thus, a single point is described in the homogenous coordinate system as:

\[ \bar{x}_H = \begin{bmatrix} rx \\ ry \\ rz \\ r \end{bmatrix} \tag{3.7} \]

with \( r \neq 0 \). To represent Cartesian coordinates as homogeneous coordinates, any value for \( r \) can be chosen. It is very common to set \( r = 1 \), which simplifies the transformation between Euclidean and projective space.

A comparison of a point in the projective space and in the Euclidean space is given in (3.8) according to [HAERING and MASSARD, 2005].

\[
\begin{bmatrix} X \\ Y \\ Z \\ W \end{bmatrix} \in \text{projective space} \leftrightarrow \begin{bmatrix} X \\ Y \\ Z \\ W \end{bmatrix} \in \text{Euclidean space} \tag{3.8}
\]

A transformation in the projective space is generally described as:

\[ U(X,Y,Z,W) = \begin{bmatrix} k_{1,1} & k_{1,2} & k_{1,3} & k_{1,4} \\ k_{2,1} & k_{2,2} & k_{2,3} & k_{2,4} \\ k_{3,1} & k_{3,2} & k_{3,3} & k_{3,4} \\ k_{4,1} & k_{4,2} & k_{4,3} & k_{4,4} \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ W \end{bmatrix} \tag{3.9} \]

with the 4x4-matrix \( K \), which is called a homogeneous transformation matrix. The transformation is an affine transformation, if \( k_{1,4}, k_{2,4}, k_{3,4} = 0 \) and \( k_{4,4} \neq 0 \). In [MARSH, 2005], the transformation matrices for translation, scale, and rotation are described in more detail.

**Translation**

The transformation matrix \( T \) describes a translation with \( \Delta x, \Delta y, \Delta z \) in the projective space:

\[ T(\Delta x, \Delta y, \Delta z) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \Delta x & \Delta y & \Delta z & 1 \end{bmatrix} \tag{3.10} \]

**Scale**

The scale matrix \( S \) in the projective space is designated as:
\[ S(s_x, s_y, s_z, s_w) = \begin{bmatrix} s_x & 0 & 0 & 0 \\ 0 & s_y & 0 & 0 \\ 0 & 0 & s_z & 0 \\ 0 & 0 & 0 & s_w \end{bmatrix} \]  

(3.11)

Usually the scale factor \( s_w \) is set to 1.

**Rotation**

The rotation matrix \( R \) describes the rotation around the corresponding coordinate axis. \( R_x(\phi) \) specifies the rotation around the x-axis by a rotation angle \( \phi \). The appropriate rotation matrices for rotations around the three coordinate axes (x, y, and z) are listed below:

\[
R_x(\phi) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\phi) & \sin(\phi) & 0 \\ 0 & -\sin(\phi) & \cos(\phi) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \]  

(3.12)

\[
R_y(\phi) = \begin{bmatrix} \cos(\phi) & 0 & -\sin(\phi) & 0 \\ 0 & 1 & 0 & 0 \\ \sin(\phi) & 0 & \cos(\phi) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \]  

(3.13)

\[
R_z(\phi) = \begin{bmatrix} \cos(\phi) & \sin(\phi) & 0 & 0 \\ -\sin(\phi) & \cos(\phi) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \]  

(3.14)

### 3.4.2 Yawing Configuration

The yawing configuration of the ZLS07 corresponds to the standard configuration for scanning. The 2D-laser scanner SICK LMS200-30106 measures polar coordinates (angles and distances), which are afterwards transformed into the Cartesian coordinates of the local measuring frame (S-frame) (Figure 3-11). Hence, the XZ-plane of the Cartesian coordinate system is spanned by the laser scanner fan. The Y-axis is perpendicular to this plane through the origin, which corresponds to the projection centre of the 2D-laser scanner. In addition, it is assumed that the Y-axis is perpendicular to the vertical axis of the ZLS07. Possible deviations are subjects for the axis calibrations (cf. section 4.3). Furthermore, the S-frame is a “right-handed” coordinate system. The angle measurements start at 0°, which corresponds to the direction of the Z-axis.

By rotating the S-frame around the vertical axis of the ZLS07 and translating the eccentricity of the origin of the 2D-laser scanner to the rotation centre of the rotation table, the S-frame is transformed into the L-frame (L: local). The L-frame is a “right-handed” frame. The Z-axis corresponds to the vertical axis of the ZLS07. The direction of the Z-axis in the L-frame is
from the zenith to the nadir of the ZLS07. In the application for underground utility cavern acquisition, The L-frame is a result of the ZLS07 being guided headfirst through a manhole into the utility cavern (cf. section 6).

Finally, the LT-frame corresponds to the “right-handed” frame of the ZLS07, with the Z-axis direction from nadir to zenith with reference to the vertical axis of the ZLS07. The X-direction in the LT-frame is equivalent to the X-direction in the L-frame.

Figure 3-11 Coordinate systems for yawing configuration.

A single point of the 3D-point cloud is calculated from the raw measurements of the actual horizontal orientation $\beta(t)$ of the rotation table and the distance $d(t)$ measured by the 2D-laser scanner, as well as the corresponding vertical angle $\gamma(t)$. The vertical angle $\gamma(t)$ corresponds to $180^\circ - \alpha(t)$ with $\alpha(t)$ as the rotation angle in the S-frame. A point in the S-frame is described by:

$$\mathbf{x}_s(t) = \begin{bmatrix} d(t) \cdot \sin(\alpha(t)) \\ 0 \\ d(t) \cdot \cos(\alpha(t)) \end{bmatrix}$$

(3.15)

where the rotating mirror of the SICK LMS200-30106 rotates in counter clockwise in terms of the origin to the positive Y-axis of the S-frame coordinate system. The point in the S-frame $\mathbf{x}_s(t)$ can be expressed in homogenous coordinates as:

$$\mathbf{\tilde{x}}_s(t) = \begin{bmatrix} d(t) \cdot \sin(\alpha(t)) \\ 0 \\ d(t) \cdot \cos(\alpha(t)) \\ 1 \end{bmatrix}$$

(3.16)

The point in the S-frame is transformed into the L-frame with a rotation (around vertical axis) and a translation (offset of eccentricity). The synchronization of the horizontal position of the
Development of Terrestrial Laser Scanner ZLS07

rotation table and the scanning data of the 2D-laser scanner is realised by a time tag. Each point in the S-frame receives its own time tag. The point in the L-frame $\bar{x}_L(t)$ is calculated by:

$$\bar{x}_L^T(t) = (\bar{x}_S^T(t) \cdot T_{SL}(\Delta x, \Delta y)) \cdot R_{S-L}(\beta(t)) \quad (3.17)$$

The actual horizontal orientation $\beta(t)$ of the rotation table is required for each point in the S-frame $\bar{x}_S(t)$. Furthermore, due to the eccentricity between the origin of the 2D-laser scanner and the rotation axis of the ZLS07 ($\Delta x$ and $\Delta y$), the translation parameters are needed for calculating the point coordinates in the L-frame.

The translation matrix is disposed as follows:

$$T_{SL}(\Delta x, \Delta y) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \Delta x & \Delta y & 0 & 1 \end{bmatrix} \quad (3.18)$$

The offsets $\Delta x$ and $\Delta y$ are defined by the mechanical construction of the ZLS07. The rotation of the S-frame around the vertical axis of the ZLS07 is described by a rotation matrix as

$$R_{S-L}(\beta(t)) = \begin{bmatrix} \cos(\beta(t)) & \sin(\beta(t)) & 0 & 0 \\ -\sin(\beta(t)) & \cos(\beta(t)) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.19)$$

Hence, the rotation angle $\beta(t)$ corresponds to the actual horizontal orientation of the rotation table and is a time-crucial parameter due to the continuous rotation of the rotation table.

Finally, the transformation of a point from the L-frame into the LT-frame is a 180°-rotation around the X-axis of the L-frame. It is described as:

$$\bar{x}_{LT}(t) = \bar{x}_L^T(t) \cdot R_{L-LT} \quad (3.20)$$

with

$$R_{L-LT} = \begin{bmatrix} \cos(\pi) & \sin(\pi) & 0 & 0 \\ -\sin(\pi) & \cos(\pi) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.21)$$

as the rotation matrix. In addition, the Cartesian coordinates are derived from the homogeneous coordinates of each point. Additional calibration parameters are implemented for the distance measurement and errors of axes (cf. section 4). Thus, the calibration parameters are implemented for the polar measurements of the ZLS07, analogous to tacheometers.

### 3.4.3 Yawing-Top Configuration

For the yawing-top configuration, the raw measurements of the 2D-laser scanner SICK LMS200-30106 are defined as well in the local measuring frame (S-frame) similar to the yawing configuration of the ZLS07 (cf. section 3.4.2). Therefore, a point in the S-frame is
calculated from the polar raw measurements (distances, angles) according to (3.15). Moreover, a point is defined in the homogenous coordinate system analogous to (3.16). The transformation of a point from the S-frame into the YT-frame (YT: yawing-top) is realised by one translation and three rotations. Figure 3-12 shows the yawing-top configuration of the ZLS07 with the corresponding coordinate systems.

For the yawing-top configuration of the ZLS07, the calculations of a point in the YT-frame from the raw measurements are described as:

\[ \vec{x}_{YT}(t) = \left( (\vec{x}_S^T \cdot T(\Delta y_{YT})) \cdot R_x \right) \cdot R_y \cdot R_{YT}(\beta(t)) \]  

(3.22)

The rotation \( R_{YT} (3.26) \) depends on the actual horizontal orientation \( \beta(t) \) of the rotation table and on the orientation of the ZLS07. The actual horizontal orientation is a time-crucial parameter. The translation \( T(\Delta y_{YT}) \) is defined in (3.23). This translation describes the eccentricity of the centre point of the 2D-laser scanner to the centre of rotation for the rotation table (cf. section 3.3.1). The eccentricity of the S-frame is given by the mechanical construction of the ZLS07 for the yawing-top configuration. Compared to the yawing-configuration (Figure 3-8), the yawing-top configuration (Figure 3-9) can be described by a single offset of the S-frame in Y-direction of the YT-frame.

\[
T(\Delta y_{YT}) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & \Delta y_{YT} & 0 & 1 \end{bmatrix}
\]  

(3.23)

The rotations \( R_x (3.24) \) and \( R_y (3.25) \) effect an alignment of the coordinate axes of the S-frame along the coordinate axes of the YT-frame.
The rotation for each single point around the Z-axis in the YT-system is calculated by (3.26).

The rotation angle $\beta(t)$ is time dependent and corresponds to the actual orientation of the ZLS07.

$\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & \cos(\pi) & \sin(\pi) & 0 \\
0 & -\sin(\pi) & \cos(\pi) & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}$

$R_y = \begin{bmatrix}
\cos\left(-\frac{\pi}{2}\right) & 0 & -\sin\left(-\frac{\pi}{2}\right) & 0 \\
0 & 1 & 0 & 0 \\
-\sin\left(-\frac{\pi}{2}\right) & 0 & \cos\left(-\frac{\pi}{2}\right) & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}$

$R_{yt}(\beta(t)) = \begin{bmatrix}
\cos(\beta(t)) & \sin(\beta(t)) & 0 & 0 \\
-\sin(\beta(t)) & \cos(\beta(t)) & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}$

### 3.5 Software

Two software tools are required to operate the ZLS07: KMS-controller and KMS-processor. This software was developed in conjunction with the development of the ZLS07 at ETH Zurich. Figure 3-13 gives an overview of the data flow from the scanning process by the ZLS07 to the import of the 3D-point cloud into commercial post-processing software, e.g., Cyclone by Leica Geosystems [LEICA GEOSYSTEMS, 2008] or Geomagic Studio/Qualify by Geomagic Inc. [GEOMAGIC, 2008]. The primary reason for splitting control and post-processing into two software packages is the time-consuming calculations of the 3D-point clouds. Operators can decide at the construction site whether they want to post-process the measurements immediately on-site or later back in the office.

The KMS-controller (cf. appendix A.2) largely controls the ZLS07 during the scanning process. Different measurement resolutions and measurement modes (32 m/80 m; intensity/no intensity) can be selected, as well as starting and stopping the scanning procedure. Furthermore, this software organises the data registration of the measurements according to the different components of the ZLS07.

The calculations of the 3D-point cloud are performed in post-processing by the software tool KMS-processor (cf. appendix A.2), which combines the measurement data from the rotation table and the 2D-laser scanner. Additionally, it implements the calibration parameters for the raw measurements. The KMS-processor offers the possibility of calculating 3D-point clouds or generating horizontal cross-sections from a 3D-point cloud. The result of the data processing with the KMS-processor is an ASCII-file with an X-, a Y-, and a Z-coordinate for each point. The intensity value of the reflected laser beam is processed and registered as a fourth
coordinate for each point. In case of no intensity data, a result that depends on the scanning mode (cf. section 3.3.4), a distance dependent value $I_D(t)$ is calculated as:

$$I_D(t) = \frac{d(t)}{1000} \cdot \frac{1}{D_{\text{max}}} \cdot 255$$

The maximum measurement range $D_{\text{max}}$ is set to 32 m or 80 m depending on the distance measurement mode of the ZLS07.

![Diagram of data flow from measurements to 3D-point cloud]

**Figure 3-13 Data flow from measurements to 3D-point cloud.**

### 3.6 Result of a Scan

The result of a scan by the ZLS07 is a 3D-point cloud (Figure 3-14 and Figure 3-15). Depending on the distance measurement mode (cf. section 3.2.1), the intensity of the reflected laser beam is registered as additional information for each single point. Figure 3-16 presents a 3D-point cloud with a distance dependent monochrome colouring. However, Figure 3-17 shows
the same section of the 3D-point cloud with a monochrome colouring based on the intensity values of the laser beam. In addition, the 3D-point cloud with intensity monochrome colouring has lower resolution due to the limited data band width of the SICK LMS200-30106 (cf. section 3.2.1). Nevertheless, areas with different reflectivity properties are detectable, such as, for instance, the entrance door into the scanned room (Figure 3-17). The door is clearly visible in the scan with intensity values whereas no areas with differences in reflectivity are observable in the scan without any intensity values (Figure 3-16).

For the visualisation of a 3D-point cloud, two possibilities are largely preferred: a 3D-point cloud in a 3D-viewer or a 2D-image of a cylindrical projection of the 3D-point cloud. However, while the 2D-image gives an overview of the acquired environment, the interpretation of the third dimension from the 2D-image is more sophisticated for users. In addition, the monochrome colouring of the 2D-image is analogous to the monochrome colouring of the 3D-point cloud. In conjunction with the operation of the \textit{ZLS07}, both visualisations can be performed. The post-processing software \textit{KMS-processor} allows the export of 2D-images that are monochrome coloured by intensity- or distance-dependent values (Figure 3-18).

An object is scanned within two to three minutes by the \textit{ZLS07}. The resulting 3D-point cloud of the \textit{ZLS07} corresponds to a 3D-point cloud measured by commercial terrestrial laser scanners. However, the characteristics of 3D-point clouds depend on the terrestrial laser scanner. Resolution, extension, and noise primarily characterise a 3D-point cloud, as well as accuracy and single point precision (cf. sections 4 and 5). Additionally, the arrangement of the single
points in the 3D-point cloud may influence further processing. Some commercial post-
processing software programs require gridded 3D-point clouds for full use of their options
and performance. With respect to these software features, the 3D-point cloud of the ZLS07
can be calculated and stored as a gridded or non-gridded 3D-point cloud.

![Figure 3-18 2D-image (*.bmp) of 3D-point cloud by cylindrical projection.](image)

### 3.7 Discussion

Several scanning tests have been performed by the terrestrial 3D-laser scanner ZLS07. Hence,
it can be concluded that the ZLS07 with the appropriate software represents a reliable, robust
and splash-water resistant laser scanning system. In addition, it enables the fast three-
dimensional acquisition of objects within two to three minutes. The maximum range is limited
to 32 m or 80 m, depending on the distance measurement mode. The vertical angular resolu-
tion is confined to 0.25° for the minimum whereas the minimal horizontal angular resolution
is 0.001°. A main advantage compared to TLS systems available on the market is the low ini-
tial cost of about 25'000 CHF (10% to 20% of initial costs for commercial terrestrial laser
scanners). In addition, the ZLS07 is a very adaptive system due to its modular composition.
Apart from the variation of the component configurations, such as for yawing and yawing-top
configuration (cf. section 3.3), changing of the length of the vertical axis allows for different
applications of the ZLS07. Moreover, the ZLS07 enables and establishes new applications for
TLS in general. The acquisition of underground utility caverns, for instance, can be efficiently
realised with the newly developed terrestrial laser scanner (cf. section 6).

The development and application of the ZLS07 reveal the 2D-laser scanner SICK LMS200-
30106 as an ideal distance measurement unit with respect to measurement frequency, robust-
ness, measurement range, and accuracy. However, the SICK LMS200-30106 has been used
by other institutes and universities for developments in the field of terrestrial laser scanning
with a focus on engineering geodesy. [HOVENBITZER, 2003], for instance, describes a ter-
restrial laser scanner for building documentation based on the SICK LMS200-30106, but,
among other differences, a step-motor is used instead of the DC-motor that is implemented for
the ZLS07. Thus, a 360°-scan takes about 40 to 60 minutes. On a construction site, in particu-
lar, scanning time is considered a crucial parameter and should be minimised so as not to in-
terrupt the construction process. Another terrestrial laser scanner based on the SICK LMS200-
30106 was introduced by [WULF and WAGNER, 2003]. That scanning system is used for
kinematic applications in robotics rather than engineering geodesy. Therefore, it performs a
very fast rotation around the vertical axis (about 10 s for a 360°-scan). However, there are
restrictions on the measurement resolution, accuracy, and precision due to the data synchroni-
sation between the scanner and servo drive.
4 Calibration of Terrestrial Laser Scanner ZLS07

Calibrations and investigations of geodetic instruments are important tasks for improvements and verifications of the measurement accuracy and precision of the instrument and the determination of its specifications. This thesis distinguishes between calibration and investigation. A calibration delivers calibration parameters that improve the measurement quality of the test specimen. In contrast to calibration, investigations mainly have information purposes. Investigations are often performed for specification verifications. However, both approaches compare the measurements to a nominal value or detect errors due to special measurement setups. The differences describe either the measurement precision and accuracy or the values for the improvement of the measurements, namely the calibration parameters. Furthermore, calibration functions can be derived from the results of the comparisons between actual and nominal values.

Following, the calibration of geodetic sensors is described in general, with the main focus on terrestrial laser scanners. For the terrestrial 3D-laser scanner ZLS07, the calibrations of the distance measurement unit, the errors of axes, and the synchronisation between the rotation table and distance measurements were performed. Thus, a detailed description and the calibration results are presented.

4.1 Calibration of Geodetic Sensors

4.1.1 Definition of Calibration

The calibration of a geodetic instrument is a very important procedure in minimizing systematic errors. According to [HENNES and INGENSAND, 2000], calibration refers to the detection and modelling of a calibration function for systematic errors. [XU and CHI, 1993] describe the calibration of sensors with four steps: modelling, measurement, identification, and correction. Usually, these calibrations are related to a single component and do not describe the characteristics of the whole measurement system, but characteristics of the sensors can be diversified. A formal determination of calibration is given by [VIM, 1993]:

A calibration is a set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system, or values represented by a material measure or a reference material and the corresponding values by standards.

Notes:

- The result of a calibration permits either the assignment of values of measurands to the indications of the determinations of corrections with respect to indications.
- A calibration may also determine other metrological properties such as the effect of influence quantities.
- The result of a calibration may be recorded in a document, sometimes called calibration certificate or a calibration report.

[GOTTWALD, 1998], [STAIGER, 1998], and [BRUNNER and WOSCHITZ, 2001], for instance, deal in detail with the calibration of geodetic instruments, such as tacheometers or levelling instruments. In general, a distinction can be drawn between verification, calibration,
investigation, and adjustment of a geodetic instrument. For this work, the distinction between calibration and investigation is of primary interest. For calibration of a geodetic instrument, two different types of calibration are distinguished:

- Comparison of the measurements with nominal values
- Special measurement setups that allow the detection of calibration parameters (e.g., two-face measurements by tacheometers)

Nominal values have to be defined by a measurement system within a higher accuracy and precision than the device to be calibrated. Furthermore, the calibration delivers results to improve the measurement system. Calibration values or correction functions are added to and implemented in the system. In contrast, investigation deals just with the testing of a measurement system. It is also very common to compare measurements to a nominal value. However, no calibration values or correction functions are derived and added to the measurement system. The investigations of geodetic instruments are established for the composition or verification of the instruments' specifications. Investigations in this work are related to performance evaluations of a TLS system.

Today, geodetic instruments, specifically terrestrial laser scanners, are very complex measurement systems. Different sensors interact with each other. Hence, the measurement results of the systems are composed of the measurements from the different sensors. The calculations are performed within the instrument with access to particular sensor data and calculation routines being hidden to users. Thus, the measurement system is kind of a “black-box” system. For calibration purposes, component and system calibrations can be distinguished (cf. [HENNES and INGENSAND, 2000]). For system calibration, the result of the measurement system is considered for calibration purposes, and the system output is of primary interest. In contrast, component calibration targets the calibration of a single sensor of the measurement system. However, the isolation of a sensor is sometimes hard to achieve. Additionally, external influences, such as temperature, must be taken into account. According to [HENNES and INGENSAND, 2000], component calibration does not consider interactions between sensors and components. Especially for complex measurement systems, it is difficult to evaluate these interactions; therefore, a “black-box” test is indispensable.

Calibrations and investigations require rigorous isolation of the system or of a single sensor from internal and external influences; such isolation is relevant to the significance of the results. The laboratory conditions ensure, at the least, constant environment conditions such as temperature and humidity. Thus, the thermal, mechanical, and electrical stability of the sensor can be investigated and calibrated.

### 4.1.2 Calibration of Terrestrial Laser Scanners

A TLS system consists of several sensors and components. The resulting 3D-point cloud of a scan is calculated from measurements of different sensors of the terrestrial laser scanner (e.g., for distance measurements or angular measurements). The calibrations by manufacturers and calculation routines deal with the raw measurements, and these processes are not accessible to customers. Thus, a calibration of specific sensors is meaningless for customers. However, if there is access to raw measurements, a calibration of specific sensors is valuable even though interactions between sensors can rarely be recorded.

In recent years, several universities and institutes have engaged in the calibration and performance tests of terrestrial laser scanning systems (cf. [ZOGG, 2003], [BOEHLER, 2005], [LICHTI et al., 2000a], [RESHETYUK, 2006a], [RIETDORF et al., 2004], and [SCHULZ, 2007]). It should be noted that investigations and performance tests represent the main activi-
ties as compared to calibration purposes. The implementation of a calibration function in laser scanning systems is a difficult task because internal measurement workflows are unknown to users. Furthermore, the interaction of different sensors of the measurement system is difficult to detect. Therefore, calibration of a terrestrial laser scanner should preferably be carried out by the manufacturers itself. Nevertheless, facilities for calibration, investigation, or testing of terrestrial laser scanners were built and the scanners investigated to capabilities by universities and institutes.

Standards for calibrations and performance evaluations of TLS systems do not exist yet. The need for standardisations is discussed in [CHEOK et al., 2006a]. Most manufacturers and independent institutes developed their own calibration and investigation procedures. Furthermore, standards for the description of terrestrial laser scanner specifications and characterisations are missing. ISO-standards, for example, do not exist; however, there are proposals and recommendations for future ISO standards (cf. [HEISTER, 2006] or [GOTTWALD, 2008]). Several working groups deal with standardisation protocols. For example, [CHEOK et al., 2006b] presented a status report on an indoor performance evaluation facility at NIST (National Institute of Standards and Technology, USA) for TLS systems and a terminology pre-standard, based on several workshops that had since been held at NIST (cf. [NIST, 2003], [NIST, 2005]). An important aspect of standardisation is the enabling of a fair comparison of instrument capabilities. Most manufacturers and independent institutes are, therefore, interested in standardisation. The specifications of terrestrial laser scanners have to be standardised as well. As mentioned in section 4.1.1, the calibration of traditional geodetic instruments can be achieved by either component-based or system-based calibration.

**Component Calibration:** The component calibration of terrestrial laser scanners deals with the calibration of single parts of the measurement system, for example, the distance measurement or the angle measurement. In addition, particular instrumental and non-instrumental errors are calibrated. However, a proper separation of the components of a TLS system is required. In addition, the system and the instrumental errors must be well known because, for each component calibration, a specific calibration routine has to be implemented. [SCHULZ, 2007] describes the component calibration for terrestrial laser scanners in general and for the Imager 5003 in particular.

**System Calibration:** In contrast to the component calibration, the system calibration considers the entire measurement system “Terrestrial Laser Scanner” (cf. section 2.3). Correction models for the resulting 3D-point clouds are the outcomes of a system calibration. These stochastic models contain parameters that describe the instrumental and non-instrumental errors. Thus, the stochastic models, the 3D-reference field, and the reference targets are essential parameters for the system calibration and influence the results. In [RIETDORF, 2004], a 3D-reference field based on planar patches as reference targets is described, as well as a stochastic model that allows the deduction of parameters that are relevant for terrestrial laser scanners (e.g., additive constant and scale for distance measurement, accuracy and precision of angle measurement, errors of axes). [RESHETYUK, 2006a] also describes the system calibration for TLS systems and, in particular, for terrestrial laser scanners measuring according to the pulsed time-of-flight principle. Standard reference targets provided by manufacturers are used. Additionally, the stochastic model is based on a 3D-Helmert transformation with additional parameters for the unknown instrumental and non-instrumental errors.

Generally, component calibration turns out to be a very complex and extensive calibration method whereas system calibration is a fast and efficient method. Nevertheless, the characteristic extraction of the components of terrestrial laser scanners is achieved by a component calibration rather than a system calibration due to the uncertainty of the stochastic models.
The functional models of components are often unknown. Thus, it is difficult to establish representative stochastic models.

4.1.3 Calibration of ZLS07

The ZLS07 is assembled from components like the distance measurement unit and the rotation table for the horizontal angle measurement. Calibrations are indispensable both for the single components and sensors and the complete measurement system. Due to the mechanical construction, errors have to be minimised by calibrations. For instance, errors of axes primarily originate in the non-high-level precision of the mechanical construction.

The calibrations of the ZLS07 were performed under laboratory conditions with constant temperature and humidity. Errors due to external influences were minimised. The calibration itself was designed as a component calibration, which enabled the detection and quantification of specific sensor errors (e.g., additive constant and scale of distance measurement, errors of axes). For each calibrated component of the measurement system (Figure 4-1), a calibration routine and its appropriate model were developed.

![Figure 4-1 Overview of calibration scopes for the ZLS07.](image)

The following components and their effects on the measurements by the ZLS07 were calibrated and are described in the following sections:

- Distance measurement unit
- Errors of axes (errors of horizontal and laser axes)
- Synchronisation of horizontal position (rotation table) and distance measurements (distance measurement unit)

These components and their effects on the measurements of the ZLS07 are considered to be most importance in terms of measurement characteristics, although a calibration is indispensable.
4.2 Distance Measurement Unit

The SICK LMS200-30106 (cf. section 3.2.1), which operates according to the pulsed time-of-flight principle (cf. section 2.2.1), is the distance measurement unit for the ZLS07. The outputs of the SICK LMS200-30106 are distances assigned to corresponding positions of the mirror that deflects the laser beam. According to the manufacturer, there is no factory-made calibration of the distance measurement. Instead, the distance measurements are verified with regard to passing or failing the specifications. However, it is highly important in using the SICK LMS200-30106 to know the characteristics, accuracy, and precision of the distance measurement over the full measurement range so that systematic errors can be detected and removed from the distance measurements because a distance measurement calibration would improve the quality of distances. However, the repeatability of the distance measurements has to be investigated as well because it is essential for the implementation of the calibration parameters. Moreover, repeatability must also be guaranteed for the operation of the ZLS07.

In addition to the definition of calibration values for the distance measurements on a standard target (more than 90% reflectivity), the influence of the reflectivity of different reference targets on the distance measurement was investigated. The distance measurements for the calibrations were performed on a white target with a reflectivity of more than 90%. Bright-grey (approximately 70% reflectivity), grey (approximately 50% reflectivity), dark-grey (approximately 30% reflectivity) and black (less than 20% reflectivity) targets were used for the investigations of influences of measurements on surfaces with different reflectivity (cf. section 4.2.4).

4.2.1 Calibration Setup

For the distance measurement calibration, the calibration track in the calibration lab of the IGP was used. The maximal test range was 52 m. The reference distances of the calibration track were measured by the Hewlett Packard 5519A interferometer and compared with the distances measured by the SICK LMS200-30106. The resolution of this interferometer is 0.01 μm. The accuracy depends on the distance and can be calculated according to product specifications as

\[ \sigma_{\text{interferometer}} = 0.2 \mu m + 0.5 \cdot 10^{-6} \cdot \text{distance}_{\text{interferometer}} \] (4.1)

The climate environment did not significantly change during the measurement sessions. The temperature, pressure, and humidity were stable at 20.1°C, 967.3 mbar and 50%. The ZLS07 was set up at the end of the calibration track (Figure 4-2), and the reference target was installed on the trolley, which could be controlled remotely. While the measurement setup did not strictly conform to the Abbe-measurement principle for linear comparators, all the measurements were carried out after the evaluation of the influence. In addition, the calibration track is periodically calibrated by the IGP and the interferometer is calibrated every second year by the Swiss Federal Office of Metrology METAS. However, the intervals of the test measurements with the ZLS07 were set to 0.1 m and 0.2 m respectively. As mentioned before, a white paper target was used as standard target with a reflectivity of more than 90%.

The SICK LMS200-30106 offers no possibility for a static pointing of the laser beam on a target, as can be realised, for instance, for the terrestrial laser scanner Imager 5003 (cf. [SCHULZ, 2007]). Thus, the mirror, which deflects the laser beam, cannot be stopped at a predefined position, so the test setup for the calibration of distance measurement has to attend to this aspect. The laser beam of the SICK LMS200-30106 represents a kind of fan. The rotating mirror of the 2D-laser scanner rotates at 75 Hz. Within one rotation, 180 and 181 distances with different vertical angles are measured. However, a laser beam alignment was
needed for the distance calibration setup. The ZLS07 was horizontally adjusted in a way that laser beam number 90 perpendicularly hit the target and was aligned to the calibration track (Figure 4-2). The perpendicularity was achieved when laser beam number 90 travelled the shortest distance between ZLS07 and the target on the calibration track. The horizontal rotation of the ZLS07 was fixed, so only vertical rotations by the SICK LMS200-30106 could be performed.

Figure 4-2 Measurement setup for distance measurement calibration of ZLS07.

The distance $d_{\text{scanner}}$ between the ZLS07 and the target is calculated as a mean value from approximately 100 single distance measurements $d_k$. The number of measurements $n$ depends on blunders, which could occur during the measurements.

$$\overline{d}_{\text{scanner}} = \frac{\sum_{k=1}^{n} d_k}{n} \quad (4.2)$$

The distance differences $\Delta d$ between distance measured by interferometer and ZLS07 are calculated as

$$\Delta d = d_{\text{interferometer}} - \overline{d}_{\text{scanner}} \quad (4.3)$$

with

$$d_{\text{interferometer}} = \text{calibrated distance} - \text{distance(interferometer)} \quad (4.4)$$

The standard deviation ($1\sigma$) of the distance measurements at a specific target position is calculated as:

$$\sigma_{\text{observation}} = \sqrt{\frac{1}{n-1} \sum_{k=1}^{n} (d_k - \overline{d}_{\text{scanner}})^2} \quad (4.5)$$

A Gaussian distribution is assumed for the single distance measurements. For further evaluation of the distance measurement accuracy, the mean value of the distance measurements for specific target positions on the calibration track was of main interest.

### 4.2.2 Results

Several measurement sessions were performed with the ZLS07. Figure 4-3 shows the distance differences between distances measured by the interferometer and the SICK LMS200-30106
for three independent measured sets of data. Independent indicates a new start of the terrestrial laser scanner for each set of data. Similar behaviour and repeatability of the measurements can be concluded from the plots. For distances between 0 m and approximately 12 m, the distance differences $\Delta d$ are around -10 mm. There is a sort of peak at a distance of about 13 m. This effect could be caused by reflections of the laser beam. However, this peak was repeatable. For distances of more than 22 m, the distance difference $\Delta d$ increases to 10 mm.

As mentioned before, the distances of the SICK LMS200-30106 were calculated from approximately 100 single measurements for calibration purposes. In Figure 4-4, the standard deviations of the single measurements are presented. There are significant outliers at a distance of around 13 m. This corresponds with the peak of the distance differences at the same range. The standard deviations are below 8 mm for the full measurement range (32 m) except for distances of about 13 m. Standard deviations up to 12 mm occur. The appearing peak could be caused by the occurring laser beam waste or by inhomogenities of the phase front or of the receiving diode. Additional reflections of the laser beam in the lab could cause errors in the distance measurement. However, even the manufacturer did not have any explanations for the recurring effect. For future calibration setups, a surrounding cover of the target, e.g. a black cardboard tube, could possibly avoid any additional reflections of the laser beam.

The data sets of distance differences were used for further investigations. The main focus was on the detection of systematic errors, frequencies, and periodic variations. Hence, a calibration function for the distance measurement was modelled.
4.2.3 Calibration Function

By modelling a calibration function for the distance measurement, systematic behaviours and errors of the distance measurement were detected and minimised. For the analysis, a mean value data set was calculated from three data sets (Figure 4-5), enabling a representative data set for detection and discussion of systematic behaviours and errors.

![Figure 4-5 Mean value of three data sets of distance differences versus distance.](image)

The best known errors of electro-optical distance measurements are discussed in [RUEGER, 1996]. Therefore, additive constant, scale, short periodic variations, and non-linear distance-dependent variations are described as components of the instrumental corrections for the distance measurement. For both the ZLS07 and the SICK LMS200-30106, the distance measurements were analysed regarding these aspects.

4.2.3.1 Additive Constant and Scale

The additive constant describes the offset of the virtual electro-optical origin and the vertical axis of the instrument according to [RUEGER, 1996]. Even though the origin of the SICK LMS200-30106 is known from specifications [SICK AG, 2006], there are variations of the origin due to the mechanical construction of the ZLS07, the optical path length itself, and delays of electrical components.

The scale factor for the distance measurements is largely caused by the oscillator and by the emitting and receiving diode as internal effects [RUEGER, 1996]. External effects like temperature, humidity, or pressure can cause or reinforce a scale for the distance measurement, but it must be considered that the atmospheric influence of temperature, humidity, and pressure is not significant for distances up to 50 m. Nevertheless, temperatures can influence the whole distance measurement system in terms of the TLS system (cf. section 4.2.7).

The additive constant and scale are calculated by a linear regression of the data set. This linear regression is approached in the form of:

\[ f(x_i) = ax_i + b \]  

(4.6)

with \( a \) as scale and \( b \) as the additive constant of the distance measurement. The linear regression is calculated by minimizing the sum of errors according to the least-square method (4.7).

\[ \sum_{i=1}^{N} (f(x_i) - x_i)^2 = \min \]  

(4.7)
$N$ is the number of measurements. For the mean data set measured by the SICK LMS200-30106, the additive constant $b$ is calculated as -15.3 mm and the scale $a$ as 0.00079. The standard deviation for the linear regression is 3.8 mm. These values relate to the measurements of the ZLS07 in the YT-coordinate frame with the assumption of an ideal vertical axis. However, these results show that there is a significant additive constant, whereas the scale is marginal. In Figure 4-6, the additive constant and the scale are added to the original data.

![Figure 4-6 Original data and data corrected by additive constant and scale versus distance.](image)

### 4.2.3.2 Periodic Variations: Fourier-Analysis

Periodic errors often occur for distances measured according to the phase measurement principle. These errors are results of electrical or optical crosstalk due to systematic errors in the phase measuring system (cf. [RUEGER, 1996]). This kind of crosstalk does not appear for pulsed distance measurement systems. According to [RUEGER, 1996], they are free of crosstalk problems because the transmitted and received pulses are separated in time. The distance measurement principle of the SICK LMS200-30106 is based on the pulsed time-of-flight principle (see section 3.2.1). However, the distance differences between the terrestrial laser scanner and interferometer (Figure 4-6) indicate periodic variations.

![Figure 4-7 Frequency spectrum of distance differences.](image) ![Figure 4-8 Period spectrum of distance differences.](image)

For the detection of periodic variations from a time series of data, a Fourier-analysis is very common although other methods use heuristic approaches [MAUTZ, 2001]. For the analysis of the distance measurement characteristics of the SICK LMS200-30106, the Fourier-approach was implemented, the results of which are frequencies with related amplitudes. For the distance differences of laser scanner and interferometer, the amplitudes of corresponding frequencies and periods are shown in Figure 4-7 and Figure 4-8. There are three frequencies
with amplitudes greater than 1 mm. The greatest amplitude of 3.7 mm occurs with a frequency of 0.9836 m\(^{-1}\) and with a period of 10.167 m.

The Fourier-analysis of the data set results in a discrete frequency spectrum. The detection of frequencies is thereby limited because it depends on the data range and the size of the interval (Nyquist frequency, cf. appendix A.3). In Figure 4-7, the most significant frequency is surrounded by other frequencies with high amplitudes, thus indicating that it is difficult to extract the correct significant frequency from the data. The real representative frequency or period is somewhere between the detected frequencies. Figure 4-8 clarifies that this period can be somewhere in the range between 8 m and 30 m. But, the most significant frequency or period is considered to be 0.9836 m\(^{-1}\) and 10.167 m respectively.

**Figure 4-9 Standard deviation of residuals in terms of order of Fourier-coefficient.**

For modelling the data series, a Fourier-series based on sine and cosine terms was calculated with corresponding Fourier-coefficients (cf. appendix A.3). To determine the optimal order of coefficients for the Fourier-series, the standard deviations of the residuals are plotted in Figure 4-9, although the residuals are calculated for each data point to the model. The standard deviations strongly decrease up to a coefficient with order 10. For coefficients of higher order, there is no significant decreasing of the standard deviations.

**Figure 4-10 Data (distance differences), Fourier-series (order 10) and residuals.**

In Figure 4-10, the Fourier-series with the corresponding residuals is plotted. The order of coefficients is \(n = 10\). The standard deviation of the residuals of the Fourier-series with order
According to [RUEGER, 1996], non-linear distance-dependent errors are usually detected and modelled by a polynomial with \( n \)-th-degree. For this purpose, the polynomial \( p(x) \) is calculated by minimizing the sum of errors according to the least-square method. The polynomial \( p(x) \) with degree \( q \) can be expressed according to [BRONSTEIN and SEMENDJAJEW, 1999] as

\[
p(x) = \sum_{i=0}^{q} a_i x^i = a_q x^q + a_{q-1} x^{q-1} + \cdots + a_2 x^2 + a_1 x + a_0
\]

with the polynomial coefficients \( a_i \). The sum of errors has to be minimised:

\[
\sum_{i=1}^{N} (g(x_i) - x_i)^2 = \text{min}
\]

Figure 4-11 plots the data, the polynomial with degree 10, and the corresponding residuals. The standard deviation for the residuals, therefore, is around 2 mm. For polynomials with higher degree, the standard deviations increase enormously due to the threshold of the data set. The polynomial fitting fails in covering the full range of the investigated measurement range.

The electro-optical distance measurements depend, among other effects, on the surface properties of the object on which the laser beam is reflected. Hence, knowledge about the laser beam behaviours when measuring different surfaces is essential for proper application of the distance measurement system. However, additional investigations of the distance measurement on different surfaces were performed.

For the investigations of the distance measurement on different surface properties, targets with different colours and different reflectivity were used. As mentioned previously, the standard white target with a reflectivity of more than 90% was used as well as bright-grey (approximately 70% reflectivity), grey (approximately 50% reflectivity), dark-grey (approxi-
mately 30% reflectivity), and black (less than 20% reflectivity) targets. Figure 4-12 shows the difference between distances measured by interferometer and the SICK LMS200-30106. However, the measurements on the black target behaved significantly differently compared to the measurements on the other targets, although the maximum measurement range on the black target is 22.5 m compared to 32.0 m for the other targets. Additionally, there is a significant deviation for the black target measurements at a range of about 4 m. The results for the measurements on white, bright-grey, grey, and dark-grey targets show similar behaviours.

![Figure 4-12 Distance difference for different target reflectivity versus distance.](image)

In addition to additive constant and scale, systematic errors for different coloured targets are detectable as well. For the distance measurements on the white-coloured target, these errors are determined in section 4.2.3.

As for the distance differences for measurements on surfaces with different reflectivity, the standard deviations of the distance measurement show a similar behaviour except for the measurements on the black target (Figure 4-13).

![Figure 4-13 Standard deviation for the distance measurements versus distance.](image)

In general, it can be stated that the distance measurements and their accuracy depend on the surface reflectivity. Nevertheless, significant differences in measurement range and accuracy could only be detected for the black target with a reflectivity of less than 20%, indicating, however, a similar behaviour of the distance measurement over a large range of the colour spectrum.
4.2.5 Long-Term Stability

The performance of the distance measurement unit over a time period of several hours is represented by the long-term stability. Internal heating of the component can cause variances in the distance measurements. Furthermore, external or internal influences, e.g., temperature, can affect the distances. For the evaluation of the long-term stability of the SICK LMS200-30106, a target, which was installed at a range of about 3.4 m, was permanently scanned by the terrestrial laser scanner. The laser fan was adjusted on the target in a manner similar to the measurements on the calibration track. A white target with a reflectivity of more than 90% and a grey target with approximately 50% reflectivity were used.

Figure 4-14 Performance of distance measurement system over a time period of 2.3 hours.

Figure 4-14 shows the results of the long-term stability investigations for measurements on white and grey targets. Short- and long-term variations are noticeable. The short-term variations of the distance measurements are detectable within about ±5 mm, which corresponds to the specified standard deviation of the distance measurement of 5 mm at a range between 1 m and 8 m (cf. [SICK AG, 2006]). For the detection of a temporal drift or long-term variation of the distance measurements, the data were filtered by a median filter. Figure 4-15 presents the results after applying a median filter to the data. A temporal long-term drift of about 5 mm is detectable.

Figure 4-15 Long-term stability of distance measurement system (median filtered).
The investigations of the long-term stability show a long-term drift and short-term variations. The short-term variations correspond to the specified standard deviation of the distance measurement of 5 mm (1σ) for the SICK LMS200-30106. In terms of the long-term drift, the distance measurements are clearly influenced by a temporal parameter. Nevertheless, for applications used with the ZLS07, the long-term drift has not been specifically treated due to short-time operation.

4.2.6 Resolution of Distance Measurement

The resolution of a distance measurement system indicates the smallest distance difference that can be detected. Several authors, including [WITTE, 1986], [SPARLA, 1987], and [JOECKEL and STOBER, 1999] describe test arrangements for resolution investigations of electro-optical measurement systems. In [SPARLA, 1987], the main focus lies with the investigations of pulsed time-of-flight distance measurement. These investigations formed the background for determining the distance measurement resolution of SICK LMS200-30106.

![Figure 4-16 Standard deviation for distance measurement versus distance.](image)

The test setup was similar to the setup described in section 4.2.1, except for the measurement intervals. The target on the trolley of the calibration track was set up at a distance of about 5.5 m from the scanner and moved forward at intervals of 0.2 mm. For each position of the target, the distance was measured approximately 100 times by the SICK LMS200-30106. The standard deviations and the mean value were calculated for each target position. Figure 4-16 shows the standard deviations of the distance measurements. The mean standard deviation is about 3.1 mm.

Figure 4-17 shows the distances measured by the SICK LMS200-30106 versus distances measured by the interferometer. According to [WITTE, 1986], the comparison between nominal and actual distance measurement values describes a step function for instruments that feature a better resolution than their smallest display unit. For the SICK LMS200-30106, the relation between nominal and actual values specifies a linear correlation, and a noise is detectable. In Figure 4-17, a linear adjustment according to the least-square method is accomplished.

To define the minimal target movement that can be detected by the SICK LMS200-30106 within a statistical certainty of 95%, the mean standard deviation of 3.1 mm has to be multiplied by 1.96 [RADE and WESTERGREN, 1997]. This results in 6.1 mm for the minimal detectable target movement with a certainty of 95%. 
Figure 4-17 Distance by terrestrial laser scanner versus distance by interferometer.

4.2.7 Influence of Temperature on Distance Measurement

For the pulsed time-of-flight distance measurement method, the time can be measured by a quartz oscillator [JOECKEL and STOBER, 1999]. The oscillator generates a frequency that defines the runtime of the pulse, which is used to determine the distance. Errors in the oscillation frequency, e.g., drifts, influence the distance measurement in the meaning of a scale. Another possibility, instead of the direct time measurement, is the transformation of the time measurement into the charging characteristics of a capacitor, cf. distance meter DI3000 by Leica Geosystems [HINDERLING, 2004]. However, the quartz oscillator and the behaviours of a capacitor depend on temperature. An internal heating system can stabilise the internal temperature, but the external temperature still influences the internal temperature. A very common method for minimizing the influences of temperature on the distance measurement is a temperature calibration of the measurement system by the manufacturer. For the SICK LMS200-30106, there is no manufacturer-side calibration in terms of temperature and distance to the object. Thus, no calibration parameters are implemented for time and distance variations.

Figure 4-18 Standard deviations for distances (temperature range: -5°C to 15°C).

The influence of temperature on the distance measurement was investigated in the climate chamber of the IGP at ETH Zurich. This environment enables temperature conditions from below 0°C up to 40°C. The laser beam itself was adjusted on a target inside the climate
chamber. Even though there was a window for distance measurements out of the climate chamber, the laser beam was reflected at the window itself. This effect made the distance measurement impossible for longer distances. The distance to the target inside the climate chamber was approximately 2.5 m. For each temperature, eight data sets of about 100 distances each were acquired. The standard deviations for each data set were calculated. This test setup allowed for comparison with a reference distance.

Figure 4-18 and Figure 4-19 present the standard deviations of the distance measurement under different temperature conditions. For temperatures between -5°C and 15°C, the standard deviations are around 9 mm, whereas the standard deviations are around 6 mm for temperatures ranging between 20°C to 40°C.

![Figure 4-19 Standard deviations for distances (temperature range: 20°C to 40°C).](image)

It should be mentioned that the greater standard deviations for lower temperature can be attributed due to the humidity inside the climate chamber. By lowering the temperature, the humidity is increased. Water drops on the measurement unit due to condensation are the consequence. In addition, water drops, which were on the cover of the SICK LMS200-30106, influenced the distance measurement. Nevertheless, the investigations show no significant coherence between distance measurement and temperature. According to product specifications [SICK AG, 2006], there is no internal heating system implemented. The specified temperature range is between 0° and 50°. However, an additional external heating system could expand the temperature range from -12° to 50°.

### 4.2.8 Implementation

The results of the distance measurement calibration of the ZLS07 on the calibration track at the IGP show that an improvement in performance of the distance measurement is possible. The implementation of additional calibration parameters for the distance measurements by the SICK LMS200-30106 improves the measurements significantly. In addition, the distance measurement calibration allows the detection of an additive constant, which is caused by the configuration of the ZLS07 (cf. section 3.3). This constant describes the offset of the origin of the SICK LMS200-30106 in relation to the centre of the rotation table of the ZLS07.

The distance calibration of the SICK LMS200-30106 is implemented in the post-processing software KMS-processor (cf. section 3.5). The implementation is realised in a look-up table that contains the distances and the corresponding distance corrections. The interval of the look-up table corresponds to the calibration interval of 0.1 m. For distances in between, the distance corrections are linearly interpolated. The main advantage of a look-up table com-
pared to a calibration function is the direct use of the measured and detected calibration data. No parameterisation or modelling is performed, which could distort the actual calibration data.

To validate the distance calibration of the laser scanning system, a 3D-reference field was scanned by the ZLS07. Thus, a system investigation was performed with the knowledge of the distance measurement behaviour. Spheres with a diameter of 15 cm were used as reference targets. Afterwards, the centre points of the spheres were transformed into a reference coordinate system measured by a tacheometer (cf. section 5.3.3). Figure 4-20 shows the residuals in X- and Y-direction of a 3D-point cloud processed without any distance calibration parameters. The scale is 0.99885, and standard deviation $s_0$ is 4.8 mm. The standard deviation $s_0$ is the standard deviation of one single observation, which corresponds to a coordinate in one direction of the coordinate system. In contrast, Figure 4-21 presents the residuals of the 3D-Helmert-transformation for scanning data processed with additional distance calibration parameters. A scale of 1.00061 is calculated, and $s_0$ is 3.9 mm.

![Figure 4-20 Residuals of 3D-Helmert-transformation (no distance calibration parameters).]

![Figure 4-21 Residuals of 3D-Helmert-transformation.]

The results of the 3D-Helmert-transformation confirm an improvement of the distance measurement of the ZLS07 due to additional calibration of the SICK LMS200-30106. Furthermore, the implementation of the calibration parameters in a look-up table in the post-processing software KMS-processor is adequate (cf. section 3.5).

### 4.2.9 Discussion

The distance measurement calibration of the ZLS07 distance measurement unit – the SICK LMS200-30106 – significantly improves the quality of the measured distances. An additive constant of 15 mm was detected. However, this additive constant is basically caused by the SICK LMS200-30106 itself. In addition, it may contain an unknown portion which is originated by the mechanical construction of the ZLS07. The centre point of the SICK LMS200-30106 does not correspond to the centre point of the horizontal rotation (cf. section 3.3). This offset is known from the construction plans and accounted for the measurements and calculations of the 3D-points. Nevertheless, an unknown portion of this offset may occur and is included in the detected additive constant. However, this unknown portion depends on the vertical angle of the ZLS07. Thus, additional distance measurement calibrations for laser beams with different vertical angles would be required. In addition, the periodical variations in the distance measurement were evaluated by a Fourier-analysis. Compared to
polynomial fitting, the Fourier-series delivers better results based on the standard deviations of the residuals. The standard deviations for the Fourier-series are half the standard deviations for the polynomial fitting. A problem for the polynomial fitting is the threshold of the measurement range. The residuals close to the threshold go up to 120 mm and more.

In general, the SICK LMS200-30106 can be considered a reliable and steady distance measurement component. There are no significant relations detectable between distance measurement and change of temperature. For the test measurements in the climatic chamber, low temperatures caused condensation. Thus, water drops on the front cover window were the consequences and influenced the distance measurement. An external heating system for the front cover window of the SICK LMS200-30106 could solve this problem. Nevertheless, based on the test measurements, it can be stated that the temporal drift is not a crucial parameter for the distance measurements of the 2D-laser scanner. In fact, the short time variations of the measured distances are much more crucial. Standard deviations of about 5 mm to a range of about 10 m were detected for the measured distances. These results correspond to the product specifications from the manufacturer [SICK, 2006].

As for TLS in general, the measurement characteristic of the SICK LMS200-30106 depends on the surface reflectivity of the target and the angle of incidence of the laser beam. This behaviour has been documented in terrestrial laser scanners available on the market and has been well investigated (cf. [MECHELKE et al., 2007] and [SCHULZ, 2007]). A reflectivity-dependent calibration is not defined and implemented yet for the ZLS07 nor an additional distance calibration based on the angle of incidence for the laser beam on object.

The implementation of the calibration parameters is realised in a look-up table, which contains distances with corresponding correction values. The look-up table is established for a range up to 32 m with a resolution of 0.1 m. A linear interpolation calculates the corrections for distances in between. A look-up table is favoured over a modelling of the distance calibration function because a look-up table represents the real calibration parameters. Errors due to modelling can be minimised by implementing a look-up table. However, look-up tables are valid only for a certain period of time. Thus, periodic recalibrations are indispensable.

4.3 Errors of Axes

A terrestrial laser scanner is a polar measurement system and features similarities to a tacheometer. With reference to axes of the instrument, a tacheometer has three axes: a vertical axis, a horizontal axis, and an optical axis (line of sight). An additional laser axis can be parallel to the optical axis of a tacheometer for electro-optical distance measurements. However, the vertical axis provides a rotation in the horizon of the instrument for the measurements of horizontal angles. For the measurements of vertical angles, the optical axis and the laser axis respectively rotate around the horizontal axis. The ideal construction of a tacheometer should assume perpendicularity between these axes. Due to mechanical construction, the axes do not fulfil this requirement. The results are errors of axes. Furthermore, there are so-called wobbles of axes (wobble of vertical axis and wobble of horizontal axis) caused by variations of the axes during rotations. Mechanical fabrication or the mechanical components such as roller bearings of the axis can cause the systematic effects. The influence of the wobble of the vertical axis (cf. section 5.2) on the orientation of tacheometers, for instance, is described in detail in [Matthias, 1961].

The detection and elimination of the errors of axes are important for measurements by a tacheometer. The errors of axes influence the angular measurements. By measuring in two faces, the errors of horizontal and optical axes can be detected and eliminated. The only error that remains after measuring in two faces is the error of vertical axis. This error is caused by
poorly levelling of the instrument. Tacheometers typically measure in a horizontal measurement system. Thus, the implementation of tilting sensors minimises the error of vertical axis and enables the measurement in the horizontal measurement system. [STAHLBERG, 1997] precisely describes the influences of errors of horizontal and vertical axes on the angle measurements for tacheometers.

For terrestrial laser scanners, the axes are defined similar to the axes of tacheometers, but in contrast to a tacheometer, a terrestrial laser scanner has only a vertical axis, a horizontal axis, and a laser axis. There is no optical axis. Figure 4-22 shows the ZLS07 with its vertical axis \( v_A \), horizontal axis \( h_A \) and laser axis \( l_A \). In an ideal case, the axes achieve the following requirements:

\[
\begin{align*}
v_A & \perp h_A & (4.10) \\
l_A & \perp h_A & (4.11)
\end{align*}
\]

The errors of axes of the ZLS07 are caused largely by the mechanical construction. To minimise the influence on the measurements, a calibration of these errors was performed.

In general, a terrestrial laser scanner measures according to its own instrumental coordinate system. Later for post-processing, the 3D-point cloud is registered into a global coordinate system by using reference points, thus the vertical axis of a terrestrial laser scanner must not be vertically adjusted. The error of verticality does not affect the measurement accuracy of a terrestrial laser scanner. In contrast to tacheometers, terrestrial laser scanners usually do not measure in a levelled measurement system. The horizontal and vertical angles are referenced to the horizon of the instrument (cf. section 2.1). However, the implementation of tiling sensors in terrestrial laser scanners enables the measurements in a horizontal measurement system. However, the errors of horizontal and laser axis affect the measurements by a terrestrial laser scanner because there is no two-face measurement for TLS systems. Furthermore, it is important to calibrate the errors of axes. For the investigations of errors of axes in conjunction with the ZLS07, the influences on the angle measurements were performed according to [DEUMLICH and STAIGER, 2002].

[ZOGG, 2003], [NEITZEL, 2006a], and [SCHULZ, 2007] extensively performed and described investigations and calibrations of errors of axes for terrestrial laser scanners that operate according to the tacheometer measurement principle. The terrestrial laser scanner Imager 5003 was used for these investigations.
4.3.1.1 Error of Laser Axis

An error of laser axis occurs if the laser axis is not perpendicular to the horizontal axis. By measuring a reference target in two faces, which are positioned in the horizon of the instrument, the error of laser axis can be determined. The differences between the horizontal angles in the first and second face correspond to the double error of laser axis.

The laser axis error \( c \) is calculated according to [DEUMLICH and STAIGER, 2002] as:

\[
c = \frac{\beta_{II} - \beta_I - 200 \text{gon}}{2}
\]

\( \beta_I \)  horizontal angle in first face
\( \beta_{II} \)  horizontal angle in second face

The error of laser axis affects the horizontal angle. The influence \( f(c) \) of the error of laser axis on horizontal angles is given according to [DEUMLICH and STAIGER, 2002] by:

\[
f(c) \approx \frac{c}{\sin(\gamma)}
\]

\( c \)  error of laser axis
\( \gamma \)  vertical angle

It must be kept in mind that the equation (4.13) is an approximation for the effect of error of laser axis \( c \) on horizontal angles. A requirement for this assumption is that \( c \) is a small term in the amount of couples of centigons.

4.3.1.2 Error of Horizontal Axis

An error of horizontal axis occurs if the horizontal axis is not perpendicular to the vertical axis of the instrument. To detect this error, a reference point that is setup in a vertical angle of about 45° [\( \tan(45°) = 1 \)] from the instrumental horizon must be measured in two faces. It is important that the error of laser axis has been eliminated before detecting the error of horizontal axis. As for the error of laser axis, the differences between the horizontal angles in the first and second face correspond to double the horizontal axis error.

The error of horizontal axis \( i \) is calculated according to [DEUMLICH and STAIGER, 2002] as:

\[
i \approx \frac{1}{2} \left( \beta_{II} - \beta_I - \frac{2c}{\sin(\gamma)} \pm 200 \text{gon} \right) \cdot \tan(\gamma)
\]

The influence \( f(i) \) of error of horizontal axis on horizontal angles is given according to [DEUMLICH and STAIGER, 2002] by:

\[
f(i) \approx i \cdot \cot(\gamma)
\]

The equations (4.14) and (4.15) are valid only for small errors of horizontal axis \( i \), that is, a few centigon. For horizontal sight (\( \gamma = 100 \text{ gon} \)), there is no influence \( f(i) \) on the horizontal angles. The error of horizontal axis \( i \) influences the horizontal angles for sights with small vertical angles.
4.3.2 Calibration Setup

For the detection of visual and horizontal axes errors of a tacheometer, a target, which is setup in the horizon of the instrument and in a vertical angle of about 45°, has to be measured in two faces. The same measurement configuration can be used for terrestrial laser scanners (Figure 4-23). But the terrestrial laser scanners must meet the requirement of measuring in two faces. The ZLS07 offers the possibility for two-face measurements. For that purpose, the yawing-top configuration has been developed (cf. section 3.3). However, the calibration parameters detected by the yawing-top configuration of the ZLS07 were transferred to the yawing configuration even though the laser scanner configuration changed. The axes calibrations were performed without considering this fact in more detail.

Figure 4-23 Measurement setup for calibration of axis.

Because terrestrial laser scanners cannot point to a single reference point, reference targets from which reference points could be derived were used. Spheres were set as reference targets and were scanned by the ZLS07 in two faces. Due to the limited vertical resolution of the ZLS07, the range between the scanner and the reference targets was set to approximately 6 m. Afterwards, the centre point of a sphere was calculated by adjusting a sphere with a known diameter in the 3D-point cloud according to the least-square method (cf. section 5.3.1).

4.3.3 Calibration Results

The error of laser axis and the error of horizontal axis were calculated as the mean value from five sets of two-face measurements of sphere S1 and sphere S2. The results are listed in Table 4-1. They show the necessity of calculating a mean value from several data sets of errors of laser axis and errors of horizontal axis. The values, e.g., for the error of laser axis from a single set of measurements, deviate up to 0.2028° from the mean value.

<table>
<thead>
<tr>
<th>set number</th>
<th>error of laser axis $c$ [°]</th>
<th>error of horizontal axis $i$ [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1881</td>
<td>0.2069</td>
</tr>
<tr>
<td>2</td>
<td>0.0283</td>
<td>0.2640</td>
</tr>
<tr>
<td>3</td>
<td>0.3278</td>
<td>0.3136</td>
</tr>
<tr>
<td>4</td>
<td>0.1878</td>
<td>0.3993</td>
</tr>
<tr>
<td>5</td>
<td>-0.1072</td>
<td>0.3763</td>
</tr>
<tr>
<td>mean value</td>
<td>0.1249</td>
<td>0.3120</td>
</tr>
<tr>
<td>standard deviation</td>
<td>0.0249</td>
<td>0.0070</td>
</tr>
</tbody>
</table>

Table 4-1 Errors of laser and horizontal axes of the ZLS07.
Compared to the errors of axis of a tacheometer, the errors of axis of the ZLS07 are 100 to 500 times greater. These errors are caused largely by restrictions for the mechanical fabrication of the ZLS07. The axes are not realised as high-precision axes due primarily to economic reasons. Furthermore, the adjustment of the axis is faulty. However, the detection of the errors of axis allows for corrections in post-processing the laser scanning data. In addition, the influence of errors of axes on the measurements is minimised.

4.3.4 Implementation

The calibration parameters for horizontal and laser axes errors are implemented in the post-processing software KMS-processor (cf. section 3.5) according to equations (4.13) and (4.15).

![Figure 4-24 3D-point cloud without calibration parameters for errors of axes.](image1)

![Figure 4-25 3D-point cloud with calibration parameters for errors of axes.](image2)

Figure 4-24 shows a section of a 3D-point cloud that was processed without any calibration parameters. The 3D-point cloud represents the ceiling patterns of a scanned room. 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 (cf. section 3.3). The distance is approximately 2 m from the scanner centre to the ceiling. Ventilation slots, which are arranged in parallel and perpendicular positions, represent the scanned ceiling patterns. The 3D-point cloud processed without any calibration parameters shows a deformation of the rectangular structure close to the zenith. The white lines in Figure 4-24 trace the ceiling patterns and should be in line with each other, but they are obviously not. Figure 4-24 shows a clear offset between both lines, whereas the white lines in the 3D-point cloud in Figure 4-25 are linear. No significant offset between both lines is visible; thus, an obvious improvement of the 3D-point cloud geometry is detectable.

4.3.5 Discussion

The calibration of errors of axes provides a significant improvement of the measurement accuracy for the ZLS07. Measurements with small angles of zenith are particularly influenced by the errors of axes. The modular design of the ZLS07 allows the two-face measurement that enables the calibration of axes errors according to tacheometers. Table 4-1 summarises the calibration parameters for the errors of horizontal and laser axes.
For the detection of errors of horizontal and laser axes, the ZLS07 is considered a polar measurement system like a tacheometer. Furthermore, the calibration parameters were derived from the 3D-point cloud. Hence, a recalculation of the “raw” measurements was performed. However, a simplified measurement coordinate system was used without considering the eccentric setup of the 2D-laser scanner on the rotation table (cf. section 3.4).

4.4 Synchronisation of Rotation Table and Distance Measurement Unit

The main components of the ZLS07 are the rotation table and the 2D-laser scanner SICK LMS200-30106. Both components simultaneously acquire data. These data equal to the raw measurements of the ZLS07. A 3D-point cloud is calculated from the polar measurement elements, and each measurement consists of a horizontal and vertical angle and a distance. Thus, the synchronisation of these two components is a crucial parameter for the measurement quality of the ZLS07 (cf. section 3.3.3). A calibration of the data synchronisation is an important task to minimise errors due to time shift or latency. Time shift or latency depends on various parameters of this laser scanning system. The time relevant components of the ZLS07 consist mainly of the rotation table, the 2D-laser scanner SICK LMS200-306106, and the computer system, which controls the terrestrial laser scanner and the individual components.

For the purpose of calibrating the data synchronisation between rotation table and scanning unit, a simple advantageous characteristic of a terrestrial laser scanner with a 360° horizontal field-of-view has been used: it remeasures the environment after a 360°-horizontal rotation. However, it must be assumed that the objects to be scanned are not moving, a fact taken into consideration during the calibration setup. Based on a 360°-scan, the calibration parameters are defined. A room is scanned with additional overlapping areas at the beginning and end of the scan (Figure 4-26). The objects in the overlapping area of the scan have to be stable for the first and second acquisition. In addition, a stable setup of the terrestrial laser scanner is required. A position offset of a stable object in the overlapping area is interpreted as the error due to data synchronisation. This error is detected and a calibration value is calculated. The errors due to latency and time shift are interpreted as a horizontal angular shift. Thus, the calibration value represents an angular offset that is calculated from the deviation of the nominal number of rotations of the motor axis $NR_{nominal}$. The $NR_{nominal}$ is determined by the gear ratio and the number of teeth of the main gear wheel (cf. section 3.2.2). The calibrated number of rotations of the motor axis is described as $NR_{calib}$.

4.4.1 Calibration Setup

For the calibration setup, a room was measured by a 360°-scan with an additional overlapping area between the beginning and end of the scan (Figure 4-26); thus, the overlapping area was scanned twice within one scan with the ZLS07. A corner of the room was selected as a fixed and stable object and was used for the detection of the calibration value for the data synchronisation.

In a first step, the raw measurements of the rotation table and the 2D-laser scanner have to be processed with the nominal number of motor axis rotations $NR_{nominal}$ for a 360°-scan (cf. section 3.2.2).

$$NR_{nominal} = 375'000$$ (4.16)
In a second step, the calculated 3D-point cloud is separated into two 3D-point cloud sections: a first and a second overlapping area. The overlapping 3D-point cloud represents a corner of the calibration room. In both 3D-point cloud sections, two patches are fitted into the 3D-point cloud according to the least-square method. These patches represent the walls of the calibration room. In addition, they describe a corner section. A horizontal cross-section is rendered through the 3D-point clouds and the patches. The corner in the first 3D-point cloud section is represented by \( T_1A \) and the corner in the second section as \( T_1B \) and \( T_1C \) respectively (Figure 4-27). \( T_1B \) corresponds to the corner in the second scanned overlapping area in the case of \( NR_{nominal} \) being less than \( NR_{calib} \), and \( T_1C \) corresponds to the corner in the case of \( NR_{nominal} \) being greater than \( NR_{calib} \). These distinctions are crucial for the implementation of the calibration parameter due to different algebraic signs. The corner point coordinates are calculated by intersecting the two straight lines that represent the cross-sections of the adjusted patches.

\[
\lambda_{b,c} = \arccos \left( \frac{\left( \text{Scanner } T_1A \right)^2 + \left( \text{Scanner } T_1B \cdot T_1C \right)^2 - \left( T_1A \cdot T_1B \cdot T_1C \right)^2}{2 \cdot \text{Scanner } T_1A \cdot \text{Scanner } T_1B \cdot T_1C} \right) \quad (4.17)
\]
For the implementation of the angular correction, the angle $\lambda$ can be expressed as a number of motor axis rotations by:

$$NR_\lambda = \frac{NR_{\text{nominal}}}{360^\circ} \cdot \lambda_{B,C}$$  \hspace{1cm} (4.18)

Hence, the calibrated number of rotations of the motor axis $NR_{\text{calib}}$ is calculated for a $360^\circ$-scan of the ZLS07 as:

$$NR_{\text{calib}} = NR_{\text{nominal}} \pm NR_\lambda$$  \hspace{1cm} (4.19)

These numbers of rotations are essential for the implementation of the calibration parameter for data synchronisation. The horizontal position of the ZLS07 and the turn table is calculated according to the number of rotations of the motor axis since starting a scan. It must be noted that the initial horizontal position of the rotation table, the 0-position, is marked by an index. Before starting a new scan, the initial position is automatically returned to by the rotation table of the ZLS07.

### 4.4.2 Calibration Results

The calibration of the data synchronisation for the ZLS07 is performed for the scanning resolutions low, middle, and high (cf. section 3.3.4). The resolution depends on the time for a $360^\circ$-rotation of the rotation table. Thus, the error of the data synchronisation depends on the scanning time, which is related to the scanning resolution. In addition, the different resolutions may have different latencies. Thus, a calibration of the different scanning resolutions is indispensable. Table 4-2 gives an overview of determination of $NR_{\text{calib}}$ which is the mean value from a set of six calibration scans for each scanning resolution. The standard deviations (1 $\sigma$) of the mean values are approximately 14 rotations of the motor axis, which correspond to an angular horizontal error of around 0.013° for the rotation table.

<table>
<thead>
<tr>
<th>resolution (speed)</th>
<th>mean value of $NR_{\text{calib}}$</th>
<th>standard deviation (1 $\sigma$)</th>
<th>angular error [°]</th>
<th>$NR_{\text{nominal}} - NR_{\text{calib}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>low</td>
<td>374899.1</td>
<td>10.2</td>
<td>0.0097</td>
<td>110.9</td>
</tr>
<tr>
<td>middle</td>
<td>374892.5</td>
<td>14.4</td>
<td>0.0139</td>
<td>107.5</td>
</tr>
<tr>
<td>high</td>
<td>374917.8</td>
<td>14.2</td>
<td>0.0136</td>
<td>82.3</td>
</tr>
</tbody>
</table>

Table 4-2 Overview of calibration values for data synchronisation.

The standard deviation (1 $\sigma$) for the number of rotations can be interpreted as the random time uncertainty of the laser scanning system. For the ZLS07, this uncertainty can be up to 6 ms and indicates irregularities both of the rotation frequency of SICK LMS200-310106 and the motor drive of the rotation table.

Figure 4-28 shows the 3D-point cloud representing the calibration room although the area of main interest is the corner section of the room that was scanned twice within one scan. The corner section must lie in the overlapping area of the scan. Two patches are fitted into the 3D-point cloud according to the least-square method. The intersection of these two patches corresponds to an edge of the calibration room, which is used as a target for the calibration.
To identify the target clearly, a horizontal cross-section is performed through the 3D-point cloud (Figure 4-29). An angular offset is detectable in the overlapping zone. Points of main interests are the vertices, which are built by intersecting the straight lines. By comparing the coordinates of these vertices, the calibration parameters for the error due to data synchronisation are calculated.

4.4.3 Implementation

For the ZLS07, errors caused by the data synchronisation of the different components and the computer system systematically affect the measurement accuracy, in particular the horizontal angle measurements. The implementation of calibration parameters for the data synchronisation is indispensable. However, the correction and calibration parameter is defined in numbers of rotations of the motor axis that drives the rotation table and results from the calculation of the actual horizontal position of the rotation table (cf. section 3.2). The calibration parameter for errors in data synchronisation for a 360°-scan is implemented in the post-processing software KMS-processor (cf. section 3.5).

Figure 4-30 shows the cross-section of a 3D-point cloud processed with the nominal rotations of motor axis $NR_{\text{nominal}}$. Figure 4-31 represents the same 3D-point cloud processed with implemented calibration parameters. An improvement is detectable. Furthermore, the angular offset caused by insufficient data synchronisation is calculated at approximately 0.1°.
4.4.4 Discussion

The developed and described calibration method for the determination of errors in the data synchronisation can be performed in any room and does not need any further equipment. It must be mentioned that the calibration of the data synchronisation can be considered a system calibration rather than a component calibration. That is, apart from the main components of the ZLS07, such as the 2D-laser scanner and rotation table, the controlling and operating computer system (usually a laptop) is part of the calibration. All parameters and components that may influence the data synchronisation are included within this system calibration without individual factors being known. The repeatability of the results confirms the calibration routine. In general, the calibration has to be performed periodically, in particular after hardware and software modifications of the laser scanning system.

4.5 Review

The performed calibrations of the ZLS07 are effective in terms of quality enhancement of the measurements, and the measurement quality can be significantly improved by implementing calibration parameters. The distance measurement unit, the mechanical axes, and the data synchronisation of the ZLS07 were calibrated. The component calibration allows the specific detection and correction of significant errors. In addition, component calibrations focus more on the laser scanning system and rather than the measurement system “Terrestrial Laser Scanner” (cf. section 2.3). For the performed component calibration, the object and environment conditions do not significantly influence the calibrations due to known laboratory conditions.

A novel calibration setup and procedure for the detection of measurement errors due to inaccurate data synchronisation of the rotation table and 2D-laser scanner was developed and implemented. However, the introduced calibration routine is referred to as a component calibration although it includes several parameters and components that may influence the synchronisation of the data from the rotation table and the 2D-laser scanner. In addition, the operating computer system is included in the calibration process as well because it controls the data synchronisation between the two measurement units of the terrestrial laser scanner.

The calibration of a geodetic instrument implies the application of the calibration parameters to the measurements. The implementation has been accomplished either by calibration functions or by look-up tables that access the determined calibration values. For the ZLS07, the distance measurement calibration was implemented by a look-up table, whereas calibration functions were defined for the errors of axes and the data synchronisation. The look-up table allowed direct access to the calibration values with no data modelling. However, it must be stated that calibrations or resulting calibration values are temporally limited. Thus, recalibrations are indispensable. The period of recalibrations depends further on the behaviour of the instrument.
5 Validation of Terrestrial Laser Scanner ZLS07

Since the release of TLS systems in geodesy at the beginning of 2000, geodesists have been engaged in the investigations of this new measurement method and related systems that are on the market. Various proposals have been made for investigations of terrestrial laser scanners. One of the first investigations was performed by [LICHTI et al., 2000b]). In general, investigations are achieved under laboratory conditions (cf. [BOEHLER et al., 2003] or [SCHAEFFER and SCHULZ, 2005]). But in terms of purchasing a TLS system, it is reasonable for investigations to be conducted under conditions of the application use (cf. [FUSS et al., 2004] or [STERNBERG and KERSTEN, 2007]). In addition to different environments for the investigations, the investigation procedure and measurement setup can differ. Until now, there are no standards regarding test and investigation setups for terrestrial laser scanners. However, proposals for standardised investigations have been presented, for instance in [HEISTRER, 2006] and [GOTTWALD, 2008]. Furthermore, there are no standards for the specifications of the measurement precision and accuracy of terrestrial laser scanners. Nevertheless, for statements regarding accuracy and precision of a TLS system, it is important to investigate the system as a whole system. That is, a TLS system cannot be specified by investigations based on component investigations only. Rather, system investigations are essential through analysis of the 3D-point cloud. This aspect can be fulfilled with a 3D-reference field in which evaluations of the scanned reference targets are performed. Differentiations between system and component calibrations or investigations are described in section 4.1.

For the terrestrial 3D-laser scanner ZLS07, both component- and system-based investigations have been performed. The focus of the investigations described is as follows:

- Horizontal and vertical angle measurement (angular measurement accuracy)
- Wobbling of vertical axis
- System investigations by determination of the 3D-measurement quality

In terms of component investigations, the terrestrial laser scanner was tested with respect to the angular measurements (horizontal and vertical angular measurement) and the wobbling of the vertical axis. Due to the extended vertical axis of the ZLS07, errors caused by wobbling of the vertical axis particularly influence the horizontal and vertical angle measurements. In addition to component calibration setups, a 3D-reference field was installed in the basement of the IGP for the system investigation of the ZLS07. In addition, the ZLS07 was compared with the terrestrial laser scanner Imager 5006, which represents the latest generation of mid-range laser scanning systems, with respect to the measurement accuracy. All the investigations were performed under laboratory conditions.

5.1 Angle Measurement System

The angle measurement system of a terrestrial laser scanner provides the angle information for objects. The accuracy of the angle measurement system, therefore, influences the measurement accuracy of the whole laser scanning system. The angle measurement system can be divided as follows:

- Horizontal angle measurements
- Vertical angle measurements
For the ZLS07, the horizontal angles are measured by the rotation table (cf. section 3.2.2). The vertical angles correspond to the angles measured by the 2D-laser scanner SICK LMS200-30106 (cf. section 3.2.1). The horizontal and vertical angles refer to the instrumental horizon and the vertical axis of the instrument (cf. section 2.1). Thus, the synchronisation between the rotation table and 2D-laser scanner (cf. section 3.3.3) is essential and influences the angle measurement accuracy.

In contrast to a tacheometer, a terrestrial laser scanner cannot directly measure angles and distances to a predefined target. For most terrestrial laser scanners, the laser beam cannot be adjusted on a target. Thus, the angle measurements have to be derived from the scanner targets used in the Cartesian coordinate system. In general, sphere-targets were used for the investigations. The centre points of the sphere targets were adjusted and modelled according to the least-square method with the known diameters of the sphere-targets (cf. section 5.3.1). Finally, the polar coordinates were derived from the Cartesian coordinates of these centre points. However, it must be noted that the quality of the sphere centre points depends, among others things, on the adjustment algorithms used. Thus, the investigations of the angle measurement system of the terrestrial laser scanner, in terms of accuracy and precision, have to be regarded as approximations that include adjustment models as well.

Below, the investigations of the angle measurement system in terms of accuracy and precision are described. A set of measurements by the ZLS07 was used for the exemplary detection of the quality of the angle measurements. The accuracy and precision are defined for the horizontal and vertical angle measurement system of the ZLS07. In terms of accuracy of the angle measurement system, the measured values are compared to nominal values. Though, a mean absolute angular offset can be detected as a systematic error. However, the precision of the angle measurement system corresponds to the standard deviation of the angular offsets.

5.1.1 Test Setup

For the investigations of the accuracy and precision of the angle measurement system, a reference test field was installed in the laboratories of the IGP (Figure 5-1 and Figure 5-2). The ZLS07 was set up on a pillar in the centre of the reference field. Spheres with a diameter of 15 cm represent the reference targets, installed on pillars at a distance of about 3.5 m from the scanner. The coordinates of the reference targets were measured by a tacheometer. However, the accuracy (1σ) of the reference target centre was less than 1 mm for horizontal position and height. The coordinates of the reference targets were used as the nominal values for further calculations.
Several scans were performed with the scanning resolution high (0.125° horizontal, 0.25° vertical). The resulting 3D-point cloud was used for further calculations. Polar coordinates such as angles and distances were deduced from the Cartesian coordinates of the centre points of the sphere-targets. These were compared to the nominal polar coordinates of the reference targets to determine the accuracy and precision of the angle measurement system.

For the calculation of the accuracy and precision of horizontal angle measurements, the angles $\beta_{ik}$ were deduced from the 3D-point cloud according to:

$$
\beta_{ik} = \arctan \left( \frac{\Delta x_i}{\Delta y_i} \right) - \arctan \left( \frac{\Delta x_k}{\Delta y_k} \right)
$$

$i, k$ sphere number

The horizontal angle measurement accuracy is defined as the difference between the detected angles $\beta_{ik}$ [cf. (5.1)] and the nominal values based on the reference coordinates. The standard deviation of the angle differences is reported as the precision of the angle measurement system.

Similar to the accuracy and precision of the horizontal angle measurement system, the measured vertical angles $\gamma_i$ were compared to their nominal values. In advance, the 3D-point clouds were transformed into the reference coordinate system according to a least-square adjustment based on the 3D-Helmert transformation of the eight reference points (cf. [LUHMANN, 2003]). Figure 5-3 presents a side view of the measurement setup. Finally, the vertical angle $\gamma_i$ was calculated with reference to the levelled instrument horizon as:

$$
\gamma_i = \arcsin \left( \frac{\Delta z_i}{\sqrt{\Delta x_i^2 + \Delta y_i^2 + \Delta z_i^2}} \right)
$$

Figure 5-3 Configuration (side view) of the angle measurement investigations.

### 5.1.2 Results

Table 5-1 shows the results of the determination of the angle measurement accuracy and precision of the ZLS07. The standard deviations $\sigma_{\text{horizontal}}$ and $\sigma_{\text{vertical}}$, which correspond to the angle measurement precision, are calculated for each set and overall measurements and angular offsets, respectively. A set corresponds to one scan of the reference field with eight spheres as reference targets. The angular offsets designated as $\text{mean}_{\text{horizontal}}$ and $\text{mean}_{\text{vertical}}$ correspond to the mean absolute values of the angular offsets for each reference target. The angular offsets represent the angle measurement accuracy. The overall standard deviations are about 0.045° for horizontal and vertical angular offsets, whereas the vertical angle measurement is slightly more precise. An angular deviation of 0.045° corresponds approximately to a lateral deviation of 8 mm at a range of 10 metres.
5.1.3 Discussion

It can be summarised that the accuracy and precision of the angle measurement system of the ZLS07 is in the same range (0.04°) for the horizontal and vertical angle measurements. Nevertheless, these values represent just a range of the accuracy and precision of the angle measurement. The calculations enclose errors due to centre point modelling of the sphere-targets and the transformation of the 3D-point cloud into the reference coordinate system for the detection of accuracy and precision of the vertical angle measurements system.

[SCHULZ, 2007], for instance, investigated the accuracy and precision of the angle measurement system of the terrestrial laser scanner Imager 5003. The accuracy for the horizontal and vertical angle measurement system is detected in a range of about 0.01°, which corresponds approximately to the same accuracy range of the ZLS07. Moreover, the angle measurement precision of the Imager 5003 is about 0.001°. This is a factor of 40 times better than the angle measurement precision of the ZLS07. However, as mentioned before, the accuracy and precision of the angle measurement for the ZLS07 are around 0.04°. Furthermore, it can be stated that the combination of the two-angle measurement systems – the rotation table and the 2D-laser scanner – are reasonable due to the similar ranges of accuracy and precision of the angle measurements.

5.2 Wobbling of Vertical Axis

The ZLS07 is designed as a panorama scanner with a horizontal field-of-view of 360° (see section 3.3.4). A rotation of the distance measurement unit around the vertical axis is required. For a terrestrial laser scanner, it is not essential that the vertical axis aligns to the vertical direction; however, the wobbling of the vertical axis is a crucial parameter. Thus, several investigations have been performed by different universities to detect the wobbling of the vertical axis for terrestrial laser scanners (cf. [ZOOG, 2003], [NEITZEL, 2006a], and [SCHULZ, 2007]).

According to [MATTHIAS, 1961], the wobbling of the vertical axis for tacheometers is related to the fact that the vertical axis does not keep its position in space while rotating the alhidade. Reasons for this fact can be found in the construction of the axis, errors in the roundness of the bearing balls, or the influence of lubricant. In general, wobbling of the vertical axis is based on the mechanical constructions of the terrestrial laser scanner.

The normal of a horizontal plane corresponds to the vertical axis. In case the error of vertical axis has been eliminated by levelling, the horizontal plane stays horizontal by rotation around its normal. If not, the plane and its normal perform a wobbling of the vertical axis, which influences the inclination of the horizontal plane. The inclination changes can be measured by inclination sensors. For terrestrial laser scanners, an inclination sensor, e.g., NIVEL20 by

<table>
<thead>
<tr>
<th></th>
<th>mean$_{\text{horizontal}}$ [°]</th>
<th>$\sigma_{\text{horizontal}}$ [°]</th>
<th>mean$_{\text{vertical}}$ [°]</th>
<th>$\sigma_{\text{vertical}}$ [°]</th>
</tr>
</thead>
<tbody>
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<td>0.0350</td>
<td>0.0466</td>
</tr>
<tr>
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<tr>
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<td>0.0480</td>
<td>0.0361</td>
<td>0.0427</td>
</tr>
</tbody>
</table>

Table 5-1 Accuracy and precision for angle measurements by ZLS07.
5 Validation of Terrestrial Laser Scanner ZLS07

Leica Geosystems [LEICA GEOSYSTEMS, 1988], is mounted on the alhidade and measures inclination changes while rotating the alhidade. In order not to influence the inclination measurements by kinematic forces, the alhidade is turned to a specific position, and the inclination is measured in a static mode. [MATTHIAS, 1961] and [GERSTBACH, 1976] describe test setups and computations of the wobbling for geodetic instruments, such as specific tacheometers.

The wobbling influences the horizontal and vertical angles measured by ZLS07. Thus, the result of a scan with the ZLS07, a 3D-point cloud, contains angular errors due to the wobbling of the vertical axis.

5.2.1 Test Setup

The inclination sensor NIVEL20 by Leica Geosystems [LEICA GEOSYSTEMS, 1988] was used for the measurements of inclination variations. According to manufacturer specifications, the measurement resolution is 0.001 mrad, and its linearity error is set to 0.005 mrad + 0.5% of measurement value. The NIVEL20 measures inclination variations in two directions that are perpendicular to each other. A special construction enables the mounting of the NIVEL20 on the ZLS07 (Figure 5-4). The inclination sensor was set up so that inclination variations were measured along ($v_{\text{along}}$) and across ($v_{\text{cross}}$) the laser beam direction of the ZLS07. But, the current mounting of the NIVEL20 on the ZLS07 is suboptimal. An alignment of the centre of mass of ZLS07 and NIVEL20 has to be intended. In addition, the cable guiding should be realized from above the scanner. The terrestrial laser scanner itself was set up on a steel pillar to minimise external movements, which could influence the inclination measurements. Furthermore, the tests were performed in the laboratories of the IGP, where the climate environment remained stable.

![Figure 5-4 Inclination sensor NIVEL20 mounted on ZLS07.](image)

At horizontal positions (hz-position) of 0°, 30°, 60°, ..., 360°, the inclination changes were measured several times. Finally, three independent sets of inclination values were acquired. Each set of data contained inclination values for horizontal positions with a resolution of 30° and a range up to 1080°, corresponding to three full horizontal rotations of the ZLS07.

5.2.2 Results

The result of the inclination measurements are presented in Figure 5-5 and Figure 5-6. The measurements are raw measurements that contain additional inclinations because the terrestrial laser scanner cannot be precisely levelled. This approach is effective for tacheometers as well. In addition, the three data sets – set 1, set 2, and set 3 – can be considered independent.
sets of measurements. A new measurement setup was achieved for each data set. The data themselves show systematic behaviours with a trend of sine and cosine oscillation.

For the detection of wobbling of the vertical axis, the inclination values of each data set have to be reduced by the influence of imprecise levelling of the terrestrial laser scanner. This influence performs a sine oscillation with a period of $2\pi$ and an amplitude that directly corresponds to the levelling. An additional sine oscillation with a period of $4\pi$ could occur caused by the angular contact ball bearing. [MATTHIAS, 1961] describes a simple method to extract the error due to wobbling of the vertical axis from the inclination values. [NEITZEL, 2006b] uses an approach following the Gauss-Markov-model. A third approach is the detection of harmonic oscillations by Fourier-analysis (cf. [SCHULZ, 2007]).

![Sets of inclination measurements by Nivel20 along measurement direction.](image1)

![Sets of inclination measurements by Nivel20 across measurement direction.](image2)

By considering the inclination data sets as a kind of data time series, the Fourier-analysis is used. Figure 5-7 and Figure 5-8 show the frequency spectrums with related amplitudes for the three data sets of inclination values along and across the laser beam direction of the ZLS07.

![Frequency spectrum. Inclination along the measurement direction of ZLS07.](image3)

![Frequency spectrum. Inclination across the measurement direction of ZLS07.](image4)

The most significant frequency and its amplitude are originated in the levelling of the terrestrial laser scanner and do not correspond to the wobbling of the vertical axis. Furthermore, the second significant frequency describes the wobbling of the vertical axis. The periods and amplitudes of the wobbling of vertical axis are summarised for the three data sets in Table 5-2.

<table>
<thead>
<tr>
<th></th>
<th>period [rad]</th>
<th>amplitude [mrad]</th>
</tr>
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</tr>
<tr>
<td>set 2</td>
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<td>3.2289</td>
</tr>
<tr>
<td>set 3</td>
<td>3.2289</td>
<td>3.2289</td>
</tr>
</tbody>
</table>

**Table 5-2 Periods and amplitudes for the wobbling of vertical axis.**
Validation of Terrestrial Laser Scanner ZLS07

Figure 5-9 Residuals (Fourier-analysis) along the measurement direction of the ZLS07.

Figure 5-10 Residuals (Fourier-analysis) across the measurement direction of the ZLS07.

Figure 5-9 and Figure 5-10 show the residuals $\text{residual}_{\text{along}}$ and $\text{residual}_{\text{cross}}$, respectively, of the inclination data according to the Fourier-series $f(x)$ (cf. appendix A.3) with coefficients of order 1 (5.3). Thus, the inclination data are diminished by the error of the vertical axis due to levelling. The residuals correspond to the wobbling of the vertical axis along or across the measurement direction of the ZLS07.

$$f(x) = a_0 + a_1 \cdot \cos(x \cdot k) + b_1 \cdot \sin(x \cdot k) \quad (5.3)$$

The calculations of $a_0$, $a_1$, $b_1$, and $k$ are subjects of the Fourier-analysis.

Figure 5-11 Residuals for inclination data along the measurement direction of the ZLS07.

Figure 5-12 Residuals for inclination data across the measurement direction of the ZLS07.

The residuals of the calculations according to [MATTHIAS, 1961] are presented in Figure 5-11 and Figure 5-12. The calculations are based on an approach of fitting a sine-oscillation into the measurements to eliminate errors due to an un-levelled terrestrial laser scanner. The observation equation for the inclination values is described as:

$$v_{r,(\text{along}/\text{cross})} = v_{\text{vert}} \cdot \sin(\beta_{\text{vert}} - \beta_r) + v_r \cdot \sin(\beta_{\text{vert}} - \beta_r) + (n_0 + 1) \quad (5.4)$$

- $v_{r,(\text{along}/\text{cross})}$: inclinations measured by NIVEL20 (along/across laser beam direction)
- $v_{\text{vert}}$: difference between zenith of the instrument and plumb-vertical direction
- $v_r$: vertical angular movement of vertical axis (wobbling)
- $\beta_{\text{vert}}$: horizontal angle between zenith of instrument and plum-vertical direction
- $\beta_r$: horizontal angular movement of vertical axis (wobbling)
- $\beta_r$: horizontal position $r$ of terrestrial laser scanner
- $n_0$: zero point offset
The residuals correspond to the wobbling of the vertical axis along or across the measurement direction of the ZLS07. In [MATTHIAS, 1961], the calculation of a mean square wobbling error $v_{\text{mean}}$ is proposed. It is calculated as:

$$v_{\text{mean}} = \sqrt{\frac{\sum (v_r \cdot v_r)}{r_{\text{max}} - 3}} \quad (5.5)$$

with $r_{\text{max}}$ as number of inclination measurements.

<table>
<thead>
<tr>
<th></th>
<th>$v_{\text{mean}}$ (Fourier-analysis) [mrad]</th>
<th>$v_{\text{mean}}$ (Matthias-analysis) [mrad]</th>
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<td></td>
<td>along</td>
<td>cross</td>
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<tr>
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</tr>
<tr>
<td>set 2</td>
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</tr>
<tr>
<td>mean value</td>
<td>0.094</td>
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</tr>
</tbody>
</table>

The mean square wobbling error of the vertical axis is presented in Table 5-3, which contains the results of the calculations according to Fourier-analysis and according to Matthias-analysis. The results show similar values for the different computation methods. Obviously, the wobbling along the laser beam direction is smaller than across.

### 5.2.3 Discussion

The investigations on the wobbling of the vertical axis show that the vertical axis of the ZLS07 features a detectable wobbling. Investigations in this field for terrestrial laser scanners were previously performed by [ZOGG, 2003], [NEITZEL, 2006b], and [SCHULZ, 2007], all of whom describe the wobbling of the vertical axis of the Imager 5003. It can be stated that the wobbling of the ZLS07 has a similar range as the Imager 5003. Compared to tacheometers (e.g., [MATTHIAS, 1961], [GERSTBACH, 1967]), these two terrestrial laser scanners show 20 to 50 times greater wobbling. Investigations of the HDS 3000 by Leica Geosystems [LEICA GEOSYSTEMS, 2007] at the IGP show behaviours of wobbling of the vertical axis like tacheometers. However, the range of the mean square wobbling error lies within 0.004 mrad compared to approximately 0.100 mrad for ZLS07.

The influence of the vertical axis wobbling on the angle measurement of the ZLS07 can be calculated according to [DEUMLICH and STAIGER, 2002]. For the measurement of vertical angle, the influence is:

$$\Delta \gamma_i = \text{residual}_{\gamma_{\text{along}}} (\beta_i) \quad (5.6)$$

The vertical angle correction corresponds to the residual of the inclination value $v_{\text{along}}$ along the laser beam direction at the horizontal position $\beta_i$. On the other hand, the wobbling of the vertical axis influences the horizontal angles with:

$$\Delta \beta_i = \text{residual}_{\gamma_{\text{cross}}} (\beta_i) \cdot \cot (\gamma_i) \quad (5.7)$$
The influence on the horizontal angle additionally depends on the vertical angle $\gamma_i$. It must be noted that all the inclination measurements for the detection of the wobbling of the vertical axis were performed in a static mode. The horizontal positions were approached, and the inclinations were measured afterward. The behaviour of the vertical axis of the ZLS07 during a dynamic scan has not been investigated yet. Kinematic investigations would assume a high frequency inclination sensor with a high precision and a high resolution. Nevertheless, kinematic influences have to be separated from inclination variations due to wobbling of vertical axis.

In general, the results of the investigations of vertical axis wobbling for the ZLS07 are repeatable and not random. The wobbling can be modelled as a sum of harmonic oscillations that are determined by Fourier-analysis. Additional influences of the verticality of the vertical axis of the instrument with respect to the plumb line have not been investigated yet in conjunction with the wobbling of vertical axis.

A correction of the angle measurements is possible but not realised yet for terrestrial laser scanners. Thus, the 3D-point cloud is distorted by the wobbling of the vertical axis depending on the vertical angle. The horizon of the instrument, for instance, performs distorting sinusoidal oscillations. However, all the wobbling cannot be eliminated in any manner by a functional model. A better solution compared to a model of the wobbling would be the implementation of a dual axis compensator, which registers the inclination values for each scanner position, or the implementation of a better axis construction with more precise bearings.

### 5.3 3D-Measurement Quality

The verification of the 3D-measurement quality (single point precision and accuracy of modelled objects) of a TLS system, in particular the ZLS07, is an important aspect regarding its appropriate applications. The end-user of a terrestrial laser scanner, e.g., a survey engineer, has to know about the single point precision and 3D-accuracy of modelled objects of the resulting scan (cf. section 2.2.3). He is not necessarily interested in the characteristics of the single components; rather, the 3D-point cloud and its quality are of primary interest. Up to now, there have been no generally accepted regulations for specifications of TLS systems. Manufacturers specify their products individually and report different specifications. This fact makes a comparison of different TLS systems very difficult or impossible for end-users. Furthermore, the quality of the product of a scan, the 3D-point cloud, is still not defined. In most cases, manufacturers just specify the distance measurement quality.

[HEISTER, 2006] discusses the problem of not having standards for TLS specifications and proposes a test procedure, which is based on reference objects, for instance, spheres, that are arranged in a test area. The size of the objects and the test area depend on the maximum and the typical measurement ranges, respectively. This test setup enables a qualitative prediction of the result of a scan, the 3D-point cloud. Qualitative indicators, therefore, indicate the deviation of the object size to the nominal value, the deviations between the distances of two objects, and the flatness of a scanned plane. [GOTTWALD, 2008] presents a field procedure for investigating terrestrial laser scanners. The procedure is based on an ISO-standard for geodetic sensor systems such as precise levels, tacheometers, or GNSS-systems. Moreover, the described field procedure contributes to the development of a future ISO-standard for terrestrial laser scanners.

However, [RIETDORF, 2004], [RESHETYUK, 2006a], and [MECHELKE et al., 2007] describe a reference field for the investigations and calibrations of TLS systems, although the main goal is the detection and quantification of instrumental errors by system investigations.
However, as mentioned previously, the main interests for end-users are the quality of the 3D-point cloud and not of single components, like distance or angle measurement. Based on this conclusion, a 3D-reference field was installed in the basement of the IGP at ETH Zurich. The main purpose of the ETH 3D-reference field is the quality tests of terrestrial laser scanners with focus on its results, the 3D-point clouds.

Different types of reference targets were installed in the ETH 3D-reference field. Spheres with a diameter of about 15 cm and truncated pyramids with a top plate size of approximately 30 cm by 30 cm were used as reference targets. Truncated pyramids were used and investigated as an alternative to sphere-targets largely for calibration purposes. The main advantages of a truncated pyramid compared to a sphere-target are the better production of targets of a large size (more than 50 cm extension) and the better angles of incident of the laser beam on oriented targets.

Below, the use of different reference targets as spheres and truncated pyramids are described and discussed. Additionally, the characteristics of targets, which were scanned by the ZLS07 at different ranges, are considered. This is an important aspect for the selection of appropriate targets in a 3D-reference field. Finally, the setup of the ETH 3D-reference field and testing results for the ZLS07 and the Imager 5006 are specified.

5.3.1 Sphere-Targets

For TLS, different reference targets are used. In addition to sphere-targets, so-called flat targets are in use. Usually, each manufacturer for terrestrial laser scanners provides its own reference target. In general, reference targets are applied to register 3D-point clouds from different scanner stations. Another main purpose of reference targets is the connection of a scan to a survey network measured by a tacheometer (geo-referencing).

Because terrestrial laser scanners are not able to acquire a specific reference point, the reference points have to be derived from reference targets. Terrestrial laser scanners can be considered an areal measurement method compared to a tacheometer, which is focused on single predefined points. The reference point, e.g., of a sphere-target, is derived by adjusting a sphere in the corresponding 3D-point cloud. The adjustment is based on the least-square method by minimizing the residuals. The diameters of the reference spheres used at ETH Zurich are 15 cm and 12 cm (verified by tacheometer). Hence, a sphere with a known diameter is fitted into the 3D-point cloud. The diameter is handled as a constraint for the adjustment.
[GAECHTER, 2006], for instance, presents an algorithm based on template matching in 2D-images for the detection of the centre points of spheres. Thus, the 3D-point cloud has to be projected into a 2D-frame. This algorithm for the centre point detection of spheres is applicable, in particular, for noisy scanning data.

In terms of the ZLS07, spheres are preferred as reference targets instead of flat targets. The adjustment of the centre point for flat targets is usually based on the intensity value of the reflected laser beam (cf. [VALANIS and TSAKIRI, 2004]). Because the ZLS07 acquires only the intensity values with a vertical resolution of 1° (cf. section 3.3.4), the sphere-targets are preferred. Furthermore, a sphere-target appears identical from different views. Thus, it is independent of the scanner stationing. In addition, the centre point is derived from the geometric information of the 3D-point cloud. Nevertheless, scanning a sphere-target is crucial for boundary points (Figure 5-13 and Figure 5-14). The angle of incidence of the laser beam highly diminishes towards the boundary of a sphere. The size of a reference sphere is also a crucial parameter. According to [HEISTER, 2006], the optimal size of a reference target $S_R$ is calculated as:

$$S_R = 0.01 \ldots 0.02 \cdot d$$

(5.8)

with $d$ as the optimal measurement range. For the ZLS07, the diameter of a reference sphere should be about 32 cm compared to the given diameter of the reference targets of 15 cm and 12 cm. An additional aspect to the optimal size of reference targets is the resolution of the TLS system. Low resolution requires a larger size of the reference targets. Thus, the number of points is a crucial factor for modelling the reference targets and should be considered as an additional parameter for choosing the size of the reference target.

![Figure 5-15 Front view of fitted sphere into 3D-point cloud (distance to scanner: 5.8 m).](image1)

![Figure 5-16 Side view of fitted sphere into 3D-point cloud (distance to scanner: 5.8 m).](image2)

The number of points that represent a sphere-target after scanning by a terrestrial laser scanner is highly correlated with the distance from the scanner to the reference target. Figure 5-15 and Figure 5-16 show the modelled sphere-targets with the corresponding 3D-point clouds in a range of about 5.8 m from the terrestrial laser scanner. However, the boundary points possess large distance-dependent residuals. Figure 5-17 represents the correlation between the number of points and the distance from the scanner. The sphere-targets were scanned by the ZLS07 with the resolution high (0.125° horizontal, 0.25° vertical). The standard deviations of the residuals $\sigma_{sphere}$ by adjusting a sphere with known diameter in the 3D-point cloud are described in Figure 5-18. The results show that the optimal range for the used sphere-target (diameter: 15 cm) is up to approximately 8 m. Furthermore, sphere-targets can be acquired up to
14 m. However, it should be noted that the standard deviation of the residuals (1σ) increases up to 18 mm.

Figure 5-17 Numbers of points defining sphere (diameter: 15 cm) versus range.

Figure 5-18 Standard deviation of residuals from sphere adjustment versus range.

Figure 5-19 shows the distance differences $\Delta_{distance}$ between a nominal value measured by an interferometer (cf. section 4.2.1) and the distance derived by the centre point modelled for the sphere-target. Even though the standard deviation of the residuals for the modelled sphere-target increases for longer distances, the distance differences $\Delta_{distance}$ lie within ±10 mm over the range of up to 14 m.

As mentioned previously, the optimal measurement range for sphere-targets is up to approximately 8 m. The test results show the longitudinal deviations. Beside the scanning resolution, the beam divergence and beam shape are main parameters for the modelling accuracy of the sphere-target. Especially, the measurements of the boundary region of the sphere-target depend on the beam divergence. According to the product specifications of the SICK LMS200-30106 [SICK, 2006] – the distance measurement unit for the ZLS07 (cf. section 3.2) – the beam divergence is about 0.32°. This divergence corresponds to the diameter of the laser beam footprint of about 8 cm at a range of about 14 m, influencing the distance measurement, in particular, for small angles of incidence. For sphere-targets in general, the angle of incidence of the laser beam gets smaller for the boundary parts of the sphere. However, it can be stated that the sphere-targets are well established reference targets for TLS in general and for the ZLS07 specifically.
5.3.2 Pyramid-Targets

5.3.2.1 Truncated Pyramid

TLS is susceptible to small angles of incidence. That is, the optimum of an angle of incidence is 90° for the laser beam on an object. When scanning sphere-targets, the boundary is difficult to acquire due to small angles of incidence, which cause an imprecision of the lateral position of the centre of the sphere. Therefore, a truncated pyramid was selected as a reference target (Figure 5-20). Each of the four corners of the cover patch builds a reference point. The size of the truncated pyramid was chosen according to [HEISTER, 2006]. Hence, the optimum size of a reference target $S_R$ was calculated according to (5.8). The size of the truncated pyramid was chosen as 0.3 m by 0.3 m for the cover patch and 0.8 m by 0.8 m for the ground patch. Considering the maximum measurement range of 32 m for the ZLS07, the size of the reference target corresponds approximately to 1.3% of the measurement range (cf. section 5.3.1).

![Figure 5-20 3D-model of truncated pyramid as a reference target.](image)

![Figure 5-21 Ground view of truncated pyramid with labelled patches and edges.](image)

To test the characteristics of the ZLS07 by scanning a reference object (scanning resolution high), the truncated pyramid was scanned from different distances to the laser scanner. Thus, the maximum distance was set to 14 m while the minimum distance was 2 m. This range corresponds to the range of application. The truncated pyramid itself was set up vertically in the horizon of the ZLS07 so that the laser beam of the ZLS07 approximately hit the cover patch perpendicularly. Generally, the truncated pyramid can be considered a test specimen. Test specimens are well known from coordinate-measuring machines (cf. [KUNZMANN and WAELDELE, 1983]).

5.3.2.2 Measurements Characteristics of the ZLS07 on Pyramid-Targets

The numbers of points that represent the scanned truncated pyramid depend on the distance from the scanner to the object. The farther away the scanner is from an object, the fewer points acquired. Figure 5-22 shows the relation between distance and number of points for each of the five patches that build the truncated pyramid. By doubling the range, the number of points is reduced four times. The four top vertices of the truncated pyramid are calculated by diluting the cover patch with two corresponding side patches. Each patch itself is fitted into the 3D-point cloud by an adjustment according to least-square method, although the residuals for each point are minimised. The standard deviations $\sigma_{\text{patch}}$ of the residuals are an indicator of the quality of the 3D-point cloud that represents the corresponding patch. Figure
5-23 illustrates the standard deviations $\sigma_{\text{patch}}$ for patches at different ranges from the scanner. The standard deviations describe a linear trend for the range between 2 m and 14 m.

In addition to the modelling of patches from the 3D-point cloud, the four top vertices are of main interest for further investigations. However, the top vertices depend on the quality of modelling of the patches. A comparison of the distances between the modelled vertices and the nominal value characterises the accuracy of the modelled truncated pyramid. Figure 5-24 shows the distance differences $\Delta_{\text{edge length}}$ for the lengths of the edges. The length of the edges can be considered a kind of reference distance. However, for ranges up to 10 m, the mean values of distance differences $\Delta_{\text{edge length}}$ are within ± 10 mm.

The mean absolute error of the length of edges can be calculated according to:

$$\overline{\Delta_{\text{edge length}}} = \frac{1}{n} \sum_{j=1}^{n} |\Delta_{\text{edge length}}|$$  \hspace{1cm} (5.9)

with $n$ measurements and within a measurement range of 2 m to 14 m. For the test series presented in Figure 5-24, the mean absolute error is estimated at approximately 7.4 mm.

In general, a truncated pyramid can be considered an appropriate target for investigation purposes of TLS systems according to the results of investigating the measurement behaviours of a truncated pyramid. Compared to sphere-targets, a truncated pyramid is generally not usable as a reference target for project-oriented tasks because it is preferable that the laser beam hit the cover patch perpendicularly, enabling a complete scanning of the whole truncated pyramid, including the slant patches. Otherwise, missing slant patches make detection of the edges and vertices impossible.
5.3.3 The ETH 3D-Reference Field

The ETH 3D-reference field was installed in a basement of the ETH Zurich. Its dimensions are approximately 15 m by 15 m by 5 m (Figure 5-26). In addition, an extension of up to 15 m by 30 m by 5 m is possible. Due to the maximum range of 32 m for the ZLS07 and its limited vertical resolution of 0.25°, the standard 3D-reference field was used for all the investigations with the ZLS07, as well as the scans with the Imager 5006. Spheres and truncated pyramids serve as reference objects. In total, seven spheres and eight truncated pyramids have been installed. Eight truncated pyramids correspond to 24 reference points. Depending on the angle of incidence of the laser beam on the truncated pyramid, the number of reference points can result in less than four. However, the reference objects in the 3D-reference field cover the terrestrial laser scanner’s field-of-view. Different distances, horizontal angles, and vertical angles are the consequence. The reference coordinates of the reference points have been determined with a Leica TCRP 1201 tacheometer. The standard deviations of the reference coordinates resulted in less than 0.9 mm.

**Figure 5-25 ETH 3D-reference field in a basement of ETH Zurich.**

**Figure 5-26 Dimension of ETH 3D-reference field with sphere- and pyramid-targets.**

In general, the terrestrial laser scanner was set up on a tripod in the centre of the 3D-reference field (Figure 5-25). This setup enabled the acquisition of all the reference objects. There was no need for levelling the terrestrial laser scanner because a least-square adjustment based on a 3D-Helmert transformation (cf. [LUHMANN, 2003]) was calculated afterwards. For the ZLS07, the scanning resolution high was used (cf. section 3.3.4).

The evaluation of the measurement data quality is based on a 3D-Helmert transformation. The transformation is specified by six to seven unknown parameters: transformation (three unknowns), rotation (three unknowns), and scale (one unknown). However, the residuals are used for characterizing the 3D-measurement quality of a TLS system by the accuracy of modeled objects (cf. section 2.2.3). Furthermore, the a posteriori standard deviations $s_o$ of one single observation is reported. $s_o$ (5.10) describes the accuracy of a single coordinate since coordinates are observations for the adjustment.

$$s_o = \sqrt{\frac{\nu P \nu}{n-u}}$$

(5.10)

$n$ number of observations

$u$ number of unknowns

$\nu$ residual

$P$ weighting
The a posteriori 3D-accuracy $3D-s_0$ of a modelled reference point from the 3D-point cloud is calculated as:

$$3D-s_0 = \sqrt{3} \cdot s_0 \quad (5.11)$$

The standard deviation in (5.11) describes the accuracy of a terrestrial 3D-laser scanning system and the accuracy of modelled objects. However, it should be noted that this accuracy consists of errors of distance and angle measurements and the algorithm of modelling the reference points based on the reference objects (cf. [MECHELKE et al., 2007]).

5.3.4 Results

5.3.4.1 ZLS07

As mentioned before, the 3D-reference field contains two different types of reference objects: sphere-targets and pyramid-targets. The transformation of the reference points is based, on the one hand, on sphere-targets and, on the other hand, on pyramid-targets. In addition, an overall transformation by using all the reference targets has been performed. It must be noted that the number of sphere-targets is significantly lower than the number of pyramid-target reference points. A pyramid-target corresponds to four reference points. Nevertheless, the residuals admit a conclusion about the accuracy and reliability of the different reference-targets.

![Figure 5-27 Residuals of sphere-targets after 3D-Helmert transformation.](image)

![Figure 5-28 Residuals of pyramid-targets after 3D-Helmert transformation.](image)

Figure 5-27 shows the residuals for the sphere-targets after a 3D-Helmert-transformation. The residuals of the pyramid-targets are presented in Figure 5-28. Both figures represent a ground view of the reference-field. Thus, the residuals correspond to errors in X- and Y-directions. The sphere-targets and pyramid-targets were installed with the same geometry configuration within the 3D-reference field. Thus, a direct comparison of the residuals is feasible. Targets close to the zenith of the ZLS07 feature the greatest residuals. This phenomenon is related to the wobbling of the vertical axis (cf. section 5.2) and the errors of the horizontal and vertical axes (cf. section 4.3). In addition, the distance measurement calibration, which was performed for the laser beam in the horizon of the ZLS07 (cf. section 4.2), influences measurements in the zenith of the ZLS07. The detected additive constant does not correspond to the additional constants of the distance measurements for laser beams with different vertical direction. An additional distance measurement calibration of the laser beams with different vertical directions would be required.
Apart from the residuals of the 3D-Helmert transformation, the standard deviation $s_0$ of the observations describes the quality of the reference points in the scanner system, cf. (5.10). A systematic error in the distance measurement can be detected by analyzing the scale of the 3D-Helmert-transformation. Because the distance measurement unit of the ZLS07 was calibrated on the calibration track of the IGP (cf. section 4.2), only a small scale was calculated by the 3D-Helmert transformation. Table 5-4 gives an overview of the parameters of main interest that resulted from the 3D-Helmert transformation. Two scans have been chosen to represent the test results.

<table>
<thead>
<tr>
<th>targets</th>
<th>mean absolute residual [mm]</th>
<th>$s_0$ [mm]</th>
<th>$3D-s_0$ [mm]</th>
<th>scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>all</td>
<td>14.5</td>
<td>6.5</td>
<td>11.3</td>
<td>0.9998</td>
</tr>
<tr>
<td>sphere</td>
<td>9.5</td>
<td>4.4</td>
<td>7.6</td>
<td>1.0001</td>
</tr>
<tr>
<td>truncated pyramid</td>
<td>15.0</td>
<td>6.6</td>
<td>11.4</td>
<td>0.9998</td>
</tr>
<tr>
<td>all</td>
<td>13.0</td>
<td>6.0</td>
<td>10.4</td>
<td>1.0003</td>
</tr>
<tr>
<td>sphere</td>
<td>9.9</td>
<td>4.6</td>
<td>8.0</td>
<td>1.0005</td>
</tr>
<tr>
<td>truncated pyramid</td>
<td>13.5</td>
<td>6.2</td>
<td>10.8</td>
<td>1.0003</td>
</tr>
</tbody>
</table>

Table 5-4 Overview of results for two data sets of ZLS07 after 3D-Helmert transformation.

A most significant difference is detected by using sphere-targets as reference objects. The $3D-s_0$ is approximately 70% better than that obtained by using pyramid-targets. The number of reference points could be a reason for this effect. However, tests confirm the sphere-targets as convenient targets for TLS because the reference objects look similar from different viewpoints. Further, the pyramid-targets, the truncated pyramids, depend on the alignment to the laser beam in contrast to sphere-targets. They feature the same geometry from all different view angles.

5.3.4.2 Comparison ZLS07 with Imager 5006

To compare the ZLS07 with a commercial terrestrial laser scanner, the terrestrial laser scanner Imager 5006 was chosen. This terrestrial laser scanner represents the latest generation of TLS systems for close- to mid-range applications. But compared to the ZLS07, the main differences beside the initial costs are based on the distance measurement principle, the angular resolution, the laser spot size, and the better axes system of the Imager 5006. The distance measurement unit of the Imager 5006 operates according to the indirect time-of-flight principle (AMCW-principle) whereas the ZLS07 measures distances according to the pulsed time-of-flight principle (cf. section 3.2.1). Nevertheless, the measurement range and application areas of ZLS07 and Imager 5006 are established in similar regions.
The 3D-reference field was scanned by the ZLS07 and Imager 5006. The results of the 3D-Helmert transformation are presented in Figure 5-29 and Figure 5-30. For the adjustment, the sphere- and pyramid-targets were used. The residuals are significantly smaller for the reference points derived from scans by the Imager 5006 than those from the ZLS07. Furthermore, for the Imager 5006, the standard deviation $s_0$, cf. (5.10), corresponds to approximately 15% of the standard deviations for observations with the ZLS07. Table 5-5 gives an overview of the comparison of ZLS07 and Imager 5006. The 3D-Helmert transformation was performed with and without estimating a scale factor. It can be stated that there is a similar scale detectable for both scanners. Generally, it must be considered that the results depend on the adjustment of the reference targets for the detection of the reference points and the dimensions of the 3D-reference field. It is difficult to separate these errors.

<table>
<thead>
<tr>
<th>scan</th>
<th>mean absolute residual [mm]</th>
<th>$s_0$ [mm]</th>
<th>$3D-s_0$ [mm]</th>
<th>scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZLS07</td>
<td>13.3</td>
<td>6.1</td>
<td>10.6</td>
<td>---</td>
</tr>
<tr>
<td>ZLS07</td>
<td>13.0</td>
<td>6.0</td>
<td>10.4</td>
<td>1.0003</td>
</tr>
<tr>
<td>Imager 5006</td>
<td>2.1</td>
<td>0.9</td>
<td>1.6</td>
<td>---</td>
</tr>
<tr>
<td>Imager 5006</td>
<td>1.5</td>
<td>0.7</td>
<td>1.2</td>
<td>1.0002</td>
</tr>
</tbody>
</table>

Table 5-5 Comparison ZLS07 with Imager 5006.

The scanning resolution influences the modelling quality of a reference target (cf. section 5.3.1). The number of measurements representing an object increases with the smaller angular resolution of the terrestrial laser scanner. The Imager 5006 has a maximal horizontal and vertical resolution of 0.0018° whereas the ZLS07 has a limited vertical resolution of 0.25°. As expected, the scanning resolution of the terrestrial laser scanner influences the modelling accuracy and the determination of the reference points (cf. section 5.3.1 and section 5.3.2). Thus, it can be concluded that the modelling quality depends amongst others on the scanning resolution.
5.3.5 Discussion

The ETH 3D-reference field constitutes an appropriate infrastructure to perform an overall test for terrestrial laser scanners. The terrestrial laser scanner can be investigated and verified as a system. Because different reference objects are in use, the scanning behaviour on different objects can be evaluated as well. It can be demonstrated that the 3D-accuracy of the modelled reference objects strongly depends on the modelling quality of the reference targets. The 3D-accuracy corresponds to the residuals by comparing the reference points to a reference coordinate system by a 3D-Helmert transformation. However, for system investigations, it is difficult to distinguish between internal and external errors of the measurement system “Terrestrial Laser Scanner.” The system investigations consider the whole measurement system (cf. section 2.3).

The evaluation of adequate targets and reference objects are important for investigating TLS systems and, even more, for practical applications, e.g., on construction sites. The modelling of reference objects influences the 3D-accuracy of the derived reference points. By using either sphere-targets or pyramid-targets, the residuals show different results in comparing with a reference coordinate system. Sphere-targets show the better results than the pyramid-targets (Table 5-4). A main advantage of a sphere-target is that a sphere appears similar from different angles of view. In contrast to an axially symmetric sphere, the viewpoint is crucial for scanning a truncated pyramid. Thus, the target size affects the range between terrestrial laser scanner and target. For the terrestrial laser scanners in general and the ZLS07, specifically, the resolution is an additional crucial parameter for target acquisition. The dimensions of the ETH 3D-reference field and the dimensions of the targets have to be chosen accordingly.

In general, the ETH 3D-reference field allows an appropriate possible verification of the quality of a terrestrial laser scanner by considering the whole measurement system. The accomplished investigations for the ZLS07 show that the 3D-accuracy of modelled objects is around 11 mm by using all reference targets. On the other hand, the Imager 5006 performs a 3D-accuracy of modelled objects of about 2 mm. Differences are significantly detectable between these two TLS systems with respect to system accuracy.

5.4 Review

The investigations of the ZLS07 were largely intended to determine and verify the measurement quality of the measurement system as well as the characteristics of single components. In contrast to the calibration (cf. section 4), the investigations do not deliver a calibration function for implementation purposes. However, the investigations were focused on the angle measurement system, the wobbling of the vertical axis, and the 3D-accuracy of the measurement system. The specifications of the ZLS07 are based on the performed investigations (cf. section 3.3.4). In addition, determining the wobbling of the vertical axis has been chosen for verification of the angular contact ball bearing used in the rotation table.

The accuracy and precision of the angle measurement system of a terrestrial laser scanner were determined by comparing angle differences. For terrestrial laser scanners, the angle differences were derived from 3D-point clouds (Cartesian coordinates) and not directly measured. However, the accuracy of the angle measurement system corresponds to the mean absolute error of the angle differences. The precision of the angle measurement system is defined as the standard deviation of the angular offsets. For the ZLS07, the horizontal and vertical angular accuracy of 0.040° was detected with an angular precision of 0.045°. The investigations confirm that the angle measurement systems for horizontal and vertical angles correspond to each other in terms of angular measurement accuracy. A combination of these two components is reasonable. In general, it must be considered that the detection of the accuracy
and precision of the angle measurement system also contains errors due to modelling the reference targets and transforming the 3D-point clouds in the corresponding reference system. Thus, the results have to be considered as a range of the accuracy and precision of the angle measurement system.

A repeatable wobbling of the vertical axis could be detected by inclination measurements. Thus, an inclination sensor was mounted on the ZLS07 for the investigations. Test measurements identified a mean square wobbling error of 0.100 mrad along and across the laser axis. The wobbling influences the horizontal and vertical angle measurements. Nevertheless, there are no corrections of the measurements. With respect to the intended tasks, inclination sensors are implemented in the ZLS07.

A 3D-reference field was established to determine the 3D-accuracy for modelled objects. Spheres and truncated pyramids were used as reference targets. The pros and cons of both types of targets in the ETH 3D-reference field were discussed. The reference points were derived from the 3D-point cloud by modelling the reference targets according to least-square adjustments. For the ZLS07, a 3D-accuracy (1σ) for modelled objects (sphere- and pyramid-targets) of 12 mm at a range of 9 m was detected.

In general, the investigations of the ZLS07 show that the ZLS07 meets the requirements in terms of measurement accuracy. Nevertheless, the investigations have shown particular limitations of the ZLS07 in terms of the vertical resolution (0.25°) and the large footprint of the laser beam (footprint of 10 cm at a range of 20 m). In addition, it can be concluded that the sphere-targets are still better qualified as targets than truncated pyramids due to the spheres’ symmetrical properties. Sphere-targets are invariant in terms of orientation to the laser line.
6 Acquisition of Underground Utility Caverns

The main application of the terrestrial 3D-laser scanner ZLS07 is the acquisition of underground utility caverns in the field of water and sewage engineering. Therefore, the development of the ZLS07 is influenced by the requirements for the scanning of these technical buildings. The specific features of the ZLS07 with the elongated vertical axis are motivated by this application.

Following, the underground utility caverns, their functionalities, and the present measurement methods are introduced. Furthermore, TLS in terms of the acquisition of these caverns is presented, with focus on the ZLS07. Finally, difficulties related to the measurements are described, and possibilities for post-processing the 3D-point clouds of underground utility caverns are introduced.

6.1 Overview

6.1.1 Underground Utility Caverns

In urban areas, sewage and water systems are installed for hundreds of years and form part of the infrastructure. Proper sewage and water systems minimise the possibility of diseases in the population. The water system regulates the drinking water supplies while the sewage system conducts the sewage to sewage treatment facilities or into rivers or lakes. Nowadays, many sewage and water systems are in need of renovation. They either do not meet requirements anymore or do not perform sufficiently. Thus, actual geometric information is needed for planning purposes and the installation of GIS. For the following descriptions and investigations, the sewage system, in particular, is addressed.

Figure 6-1 Manhole cover plate on road surface.

Figure 6-2 Access into underground utility cavern through vertical manhole.

Underground utility caverns are part of the sewage system and occur at the intersections of the pipes. The access to these technical buildings is through a vertical manhole, the length of which is typically about 3 m to 4 m. Access is necessary for servicing the infrastructure. The underground utility caverns and the vertical manholes are usually located underneath roads or, at least, in the vicinity of roads (Figure 6-1). The manholes themselves are covered by manhole covers. A vertical ladder, which is permanently installed in the manhole, enables access
by workers (Figure 6-2). The dimensions of underground utility caverns can be up to 20 m or larger, but the standard dimensions are about 4 m by 4 m by 3 m. The design and dimensions of underground utility caverns vary depending on their requirements and functionalities.

Underground utility caverns connect and regulate inlet and outlet pipes. In addition, there are infrastructures as overflow buildings (Figure 6-3), gullies (Figure 6-4), slider plates (Figure 6-5), separators, pump stations, gratings (Figure 6-6), and catch basins. Storm sewer water, for instance, flows directly through vertical manholes into catch basins before flowing into the sewage treatment facility to avoid the flooding of roads. In addition, sensors can be installed as well as valves or apertures for the sewage. Today, the underground utility caverns are made of concrete. In the past, bricks were also a common building material for underground utility caverns. Pipes often are made of PVC, depending on the application. The environment is rather humid and often warm. Gases and mud, which is deposited on walls and hard shoulders, are the consequences of the sewage.

Today, the sewage systems are managed by GIS-systems or, more generally, by pipe cadastral systems. Due to the extensive size of the sewage infrastructures, it is important to know the position and geometry of the elements in the sewage system. In addition, the actual condition of the infrastructure has to be documented. This information is also meaningful for maintenance or for capacity calculations of the sewage system. The sewage system is differentiated between the pipe system and the underground utility caverns that connect the pipes. They are considered nodes of the system. The inspection of pipes requires different technologies (e.g.,
video) than those used for geometry detection and is performed by specialists for canalisation inspection (cf. [MOEKAH, 2008]). However, geometry detection of underground utility caverns and their infrastructure is a task for surveying engineers.

6.1.2 Acquisition of Underground Utility Caverns – State-of-the-Art

There are no national or international standards for the acquisition of underground utility caverns. Depending on the requirements of the customers, the surveying companies define the measurement process and the deliveries. Thus, the state-of-the-art and the requirements for the measurement of caverns have been adopted from the city of Zurich, specifically the surveying department of the city of Zurich GeoZ. The acquisition of geo-data with respect to sewage is a service provided by GeoZ for the ERZ (Entsorgung + Recycling Zürich), which is responsible for waste water collection and treatment of the city of Zurich.

Figure 6-7 Detailed 2D-plan of an underground utility cavern.

For the city of Zurich, the underground utility caverns and the whole sewage system with its pipes are measured and processed by GeoZ. In addition, GeoZ determined specifications regarding the acquisition process, accuracy, orientation, and level-of-detail for the underground utility caverns. The results have to achieve the following aspects (cf. [ZOGG et al., 2007]):

- Determination of absolute position and height of underground utility cavern: Height reference is the centre of the manhole cover. The orientation of the cavern is determined with reference to the pipe axes.
- Geometry and dimension of underground utility cavern: A relative accuracy of 3 cm (1σ) in position and an absolute accuracy of 3 cm (1σ) for the height must be achieved. The relative accuracy describes the quality of the geometry of the cavern. The absolute height accuracy is a crucial parameter due to its significance to the water flow. The sewage system of the city of Zurich has some small height differences.
• Acquisition of infrastructure inside of underground utility caverns: The infrastructure includes inlet and outlet pipes, slider plates, overflow buildings, catch basins, and sensors. In addition to the geometric data, the information about functionality and the current state have to be registered.

• Reports of material and condition of underground utility cavern: The conditions of underground utility caverns are important aspects for maintenance and renovation purposes.

• Results and documentation: A detailed plan has to be created for each underground utility cavern (Figure 6-7). Either an analogue plot or digital data are delivered to the customers.

Until now, the acquisitions of underground utility caverns have been carried out manually by operators with measuring tapes or laser distance meters. The operators have to climb down through the manhole into the underground utility caverns. The field work requires careful planning because security-relevant regulations and arrangements have to be respected. Furthermore, most manhole covers are on roads or in the vicinity of roads, thus requiring signaling and exclusion zones. Because of potential gases inside the underground utility caverns, aeration is indispensable, in particular, before an operator enters the underground utility caverns because of the danger of suffocation or explosion. Aeration is arranged by opening manhole covers close to the utility cavern to be measured. The operators have to wear special overalls and gas warning indicators. In addition, the operator who has to climb into the underground utility cavern has to be secured by a second operator due to slippery conditions inside the caverns. At least, a second operator must be outside of the cavern for security reasons. The measurement van of GeoZ is equipped with all the special equipment for the acquisition of underground utility caverns, a cable winch for saving persons, and oxygen masks in case of emergency. Apart from slippery conditions, a sudden rise of water makes an underground utility cavern a dangerous workplace.

In recent years, several measurement systems have been developed for detecting the geometry of underground utility caverns without an operator entering the cavern. The measurement systems can be controlled from outside. Hence, the risk to the operators is minimised. Nevertheless, the systems are not in widespread use due to either the prototyping character and com-
plex installation or the high cost of purchasing. Bodemann GmbH [BODEMANN, 2008] has developed and operates the CUS 3D-measurement system (Figure 6-8). The cavern is measured selectively by an electronic distance meter that is guided on a boom into the underground utility cavern (Figure 6-9). The operator controls the boom and the electronic distance meter. In addition to complex and numerous installations, the CUS system requires illumination of the underground utility cavern.

Based on tacheometry, [FUHRLAND, 2007] presents the measurement system ArgusTAT for measuring underground utility caverns. The line of sight of a tacheometer is guided into the cavern through an optical telescope with additional tilted mirrors and is directed through the manhole. A selective measurement of the cavern geometry is possible. However, the ArgusTAT system is used for the orientation transfer into a cavern. Moreover, the ArgusTAT system requires illumination of the cavern. Thus, the ArgusTAT system is not practical for an efficient measurement of underground utility caverns.

6.1.3 Terrestrial Laser Scanning for Underground Utility Caverns

Today, the demand for 3D-data for planning and constructing facilities is strongly increasing. The growing urban areas, which require, for example, extension of their sewage systems, and the renovation of aging sewage systems have caused a need for a fast, secure, and three-dimensional acquisition method for underground utility caverns. In collaboration with GeoZ, the concept for the application of TLS in the field of underground utility acquisition was developed. The main idea was to lower a terrestrial laser scanner through the manhole into the underground utility cavern. This approach would introduce a fast, three-dimensional acquisition of the geometry and minimise the necessity for operators to climb down into the building.

Although there are several TLS systems available on the market, the available terrestrial laser scanners are qualified to varying degrees for the acquisition of underground utility caverns. Beside the field-of-view, the distance measurement principle is a main characteristic for terrestrial laser scanners [SCHULZ and ZOGG, 2006]. For the acquisition of underground utilities, a terrestrial laser scanner must have a large field-of-view, high scanning speed, and the ability to scan head-down. In addition, the environmental conditions are often rough. Splash
water can occur or vapour can be caused by the high humidity and temperature differences between the inside and outside of the underground utility cavern.

At the end of 2005, the most convenient terrestrial laser scanner for the scanning of underground utility caverns with high precision and medium range was the Imager 5003. Other terrestrial laser scanners, for example the HDS 3000, were not able to scan in an unlevelled horizontal position. First test results with the Imager 5003 (Figure 6-10) showed that TLS was generally an appropriate method for the acquisition of underground utility caverns. However, the measurement problems were particularly located in the asymmetric weight arrangement around the vertical rotation axis of the terrestrial laser scanner, causing a strong wobbling of the vertical telescope pole on which the terrestrial laser scanner was guided headfirst into the underground utility cavern (Figure 6-11).

The wobbling and oscillating of the vertical pole seriously affected the measurements and the results. The 3D-point cloud (Figure 6-12) resulting from a scan showed significant waves caused by the wobbling (Figure 6-13). The amplitude could not be detected because each test scan showed different wave characteristics. Thus, the amplitude depended on the length of the telescope pole. Further investigations were not carried out because it was decided to develop a new system based on the non-compliance of the specifications for the acquisition of underground utility caverns by the Imager 5003.

Based on the encouraging results of the test scans with the Imager 5003, the ZLS07, a convenient measurement configuration for scanning of underground utility caverns was developed at the ETH Zurich (cf. section 6.2). In addition to accuracy, cost efficiency, robustness, and splash water resistance were primary advantages of the ZLS07. In addition, loss of or damage to the ZLS07 while measuring underground utility caverns would not have serious financial consequences.

### 6.2 ZLS07 for Acquisition of Underground Utility Caverns

#### 6.2.1 Measurement Configuration

For the acquisition purposes of underground utility caverns, a measurement system was developed at ETH Zurich. It is based on the ZLS07 and a telescope tripod (cf. [ZOGG et al., 2007]). Investigations of the ZLS07 regarding its measurement accuracy (cf. section 5.3) confirmed the achievement of the specifications for the acquisition of underground utility caverns (cf. section 6.1.2). The ZLS07 is mounted to the telescope tripod and guided through the manhole into the underground utility cavern (Figure 6-14). A tackle on the tripod enables
the convenient lowering and lifting of the ZLS07 into the object to be measured. The laser scanner is ready to measure as soon as it arrives at the correct vertical position. By means of 360°-scans, the whole object is three-dimensionally acquired.

![Configuration of ZLS07](image1.png)  ![View from aboveground into the underground utility cavern](image2.png)

Figure 6-14 Configuration of ZLS07 for acquisition of underground utility caverns.  Figure 6-15 View from aboveground into the underground utility cavern.

The actual configuration of the telescope pole enables measurements through manholes with a depth of up to 4 m. A further extension of the telescope pole is possible but requires more elements for the telescope pole while the setup loses stability. Compared to the setup with the Imager 5003 (cf. section 6.1.3), the ZLS07 is constructed in a way that the centre of the mass is located in the rotation axis of the ZLS07. The rotation axis itself lies in the direction of the telescope pole. This configuration minimises the oscillating movements of the telescope pole (cf. section 6.2.4.1) and results in usable measurements.

![3D-point cloud](image3.png)  ![Inside view of 3D-point cloud](image4.png)

Figure 6-16 3D-point cloud of underground utility cavern acquired by ZLS07.  Figure 6-17 Inside view of 3D-point cloud of underground utility cavern.

The ZLS07 is controlled by a computer system (e.g., a laptop) from above ground. Hence, an inspection by an operator is no longer required but still reasonable for certain circumstances. For example, underground utility caverns with large dimensions and special infrastructure are also observed by an operator. The connection between the laser scanner and the laptop is realised by a cable which is independent from the telescope tripod. In addition, the electrical power is provided by 24 V batteries that are installed above ground.
The results of the scans are 3D-point clouds of the objects (Figure 6-16). The data from an underground utility cavern largely consist of one scan from one stationing. The geometry and the infrastructure are measured. Furthermore, the direction and diameter of the inlet and outlet pipes can be derived from the 3D-point clouds. Through point-to-point measurements, the dimensions and geometry of the utility caverns are well detectable. The geo-referencing of the 3D-point clouds into the superior coordinate system and the construction of 3D-models need additional extensive post-processing (cf. section 6.3.1).

6.2.2 Measurement Workflow

![Figure 6-18 Measuring the height reference underneath the manhole cover.](image)

The telescope tripod and the ZLS07 are set up above the manhole, which provides the access into an underground utility cavern. The cable winch of the telescope tripod allows convenient guidance of the ZLS07 into the caverns. The process of measuring an underground utility cavern takes about 20 minutes, including the setup of the measurement system, the actual scan by the ZLS07, and the additional measurement of the height reference by a measuring tape, graduated measuring rod (Figure 6-18), or electro-optical distance meter. The height of an underground utility cavern is determined by the centre of the manhole cover. It is measured from the manhole cover to a point close to the entrance ladder on the hard shoulder of the utility cavern. The height is a crucial parameter for the sewage system because the sewage flow is defined by height differences. In addition, the underground utility cavern can be captured by a digital video camera that is installed on top of the ZLS07. These data are just for documentation purposes. Because the light conditions inside the utility caverns are rather poor, the value of the video data is limited. In the future, an illumination flashlight is planned.

For the orientation of the acquired 3D-point clouds, no additional measurements are required (cf. section 6.3.2). The orientation is realised by the directions of inlet and outlet pipes, which are known from the pipe cadastral systems. These directions are known from measurements taken during the construction process of the pipe system. Not having to measure reference points makes the acquisition by TLS much faster. Furthermore, no additional measurements by tacheometer or GNSS are needed for referencing into a better coordinate system.

The calculation of the 3D-point clouds from the raw measurements and the determination of geometric information are the main tasks during the post-processing (cf. section 3.5 and section 6.3). Depending on the level of detail to be modelled and the geometry information requested, the time for post-processing and the post-processing method vary.
6.2.3 On-Site Evaluation

The collaboration with GeoZ allowed the on-site tests of the measurement system, testing under real environmental conditions, which facilitated the interaction between development and application and the comparison with the conventional measurement method. Apart from the practicability and flexibility of the measurement system, the limits and potential for improvements can be identified. The limits refer to the dimensions and geometry of the underground utility caverns to be acquired, and the measurement system can reach its limits due to the environmental conditions, for example, heavy splash water.

Figure 6-19 On-site evaluation in collaboration with GeoZ.

Figure 6-20 Acquisition of underground utility cavern by ZLS07.

For the on-site tests, the measurement van owned by GeoZ was equipped with the ZLS07 and the telescope tripod. The battery supply and computer system also were placed inside the van, allowing a flexible and time-saving measurement setup for each object to be scanned (Figure 6-19 and Figure 6-20).

In general, each underground utility cavern is unique with respect to its geometry. There are largely standard utility caverns, but even they differ in size and geometry. For large underground utility caverns, there are two or more manholes, enabling the acquisition from several setups of the terrestrial laser scanner. In addition, some underground utility caverns cannot be fully acquired by TLS. This may be the case for large utility caverns where columns restrict the field-of-view of the terrestrial laser scanner. The background behind the columns is not visible to the terrestrial laser scanner, so the acquisition of these objects according to the convenient method is indispensable. Figure 6-21 shows 3D-point clouds of different types of underground utility caverns measured by the ZLS07. However, the lower-right 3D-point cloud in Figure 6-21 represents the general standard underground utility cavern. The specifications of standard objects are the simple geometry, the possibility of being measured by a single scan, and a minimal infrastructure of an inlet and outlet pipe.
6.2.4 First Results and Experiences

The on-site evaluation revealed limitations and difficulties of the measurement system with respect to the acquisition of underground utility caverns, in particular, oscillating movements of the telescope tripod and pole, rough environmental conditions, and measurement of the water surface with the penetration of the laser beam. These limitations are described and discussed in the sections below.

6.2.4.1 Oscillating Movements

For the measurement of an underground utility cavern, the ZLS07 is fixed to the telescope pole and guided headfirst through the manhole into the utility cavern. The ZLS07 is simply screwed onto the pole of the telescope tripod without any additional anchorage. The setup is similar to a pendulum with the terrestrial laser scanner as a weight. Even though the centre of mass of the ZLS07 is approximately in the centre of rotation, the measurement setup performs small movements during the scanning of an underground utility cavern. The oscillating movements of the pole are caused by the horizontal rotation of the terrestrial laser scanner. These oscillating movements influence the measurements of the ZLS07 by varying the horizontal position of the terrestrial laser scanner. Furthermore, there must be a recovery time period after lowering the measurement system into the underground utility cavern and before starting the measurements.

For the detection and verification of oscillating movements, investigations were performed at the IGP [ZOGG, 2007]. The test setup was realised in the staircase (Figure 6-22) to determine the oscillations behaviours. An inclination sensor by Pewatron [PEWATRON, 2008] was mounted on top of the ZLS07 (Figure 6-23) for the detection of inclination variations of the
scanner horizon. The analogue single-axis inclination sensor performed with a resolution of 0.001°, an accuracy ($1\sigma$) of 15.4" for the inclination variation ($\Delta$-inclination), and a measurement frequency of 10 Hz. The axis of the inclination sensor was aligned along the laser beam direction of the terrestrial laser scanner. This test setup allowed the real-time registration of inclination variations during a scan with the ZLS07.

Figure 6-22 Test setup for the detection of oscillating movements.

Figure 6-23 ZLS07 with additional inclination sensor (by Pewatron).

As mentioned previously, the oscillating movements were investigated between lowering the system into the underground utility cavern and starting the measurements as well as during the scanning procedure. First investigations were intended to define the recovery time for the measurement system. The influence of movements due to the installation process of the scanning procedure should be minimised. For this purpose, the telescope pole with the ZLS07 was lowered to the appropriate vertical position. Afterwards, the inclination values were registered for a period of about 400 s. The second investigations were designed to detect the movements of the telescope pole and the ZLS07 during the measurements. This investigation was conducted by registering the inclination variations and the corresponding actual horizontal position of the ZLS07 while scanning. However, the dynamic registration of inclination variations also included components resulting from acceleration that could not be differentiated by the inclination sensor. Nevertheless, the inclination variations were used to detect the temporal oscillation behaviour. In addition, the absolute inclinations were not determined.

The results of the investigations demonstrate that there are movements of the telescope pole after installing the measurement system and during a scan. Thus, it is essential to delay the beginning of the measurement after setup and lowering the terrestrial laser scanner. Figure 6-24 describes the inclination values along the laser beam direction relative to the time. The telescope pole featured a length of about 4 m. The results show that the inclination values were smaller than 60" after about 5 min. Further results of the investigations show that the waiting time was between 2 min and 5 min for horizontal inclination variations smaller than 60" to be reached. In addition, the most significant diminishing of the oscillating movements was within the first minute.
During the scanning process, the oscillating movements of the telescope pole induced by the motions of the terrestrial laser scanner are more crucial in terms of measurement accuracy than the movements after lowering the measurement system. Nevertheless, tests indicated that the time between setup and start of a scan influences the measurement accuracy as well. Figure 6-25 shows the inclination values during a 360° scan. It must be noted that these inclination values describe the inclination values reduced by the errors of the vertical axis of the ZLS07 (cf. section 4.3). The investigations showed that the system for mounting the ZLS07 to the telescope pole caused a misalignment of the vertical axis of about 0.8°. The misalignment was repeatable and based on the leaning screw thread due to mechanical construction. Nevertheless, for the duration of a measurement period of 360°, the horizontal inclination variations along the measurement direction of the ZLS07 were detected within ±40″.

The oscillating movements influence the measurements of the ZLS07. On the one hand, the centre point of the terrestrial laser scanner is dislocated while, on the other hand, the vertical angle measurements of the ZLS07 are affected. However, the dislocation of the centre point is about 0.5 mm in horizon which was not further investigated nor implemented as a calibration function. The influence on the vertical angle measurement results corresponds to the inclinations variation along the laser axis. Thus, an inclination variation of 40″ corresponds to a vertical displacement of about 2 mm at a range of 10 m. While this influence is also ignored for the measurements with the ZLS07, it must be considered in the analysis of the measurement accuracy for the acquisition of underground utility cavern. An implementation of an inclination sensor on the ZLS07 would enable corrections of the measurements due to oscillating movements. Additional stabilisation of the vertical pole by using, for example, small tubes instead of poles would minimise the oscillations.
6.2.4.2 Specific Environmental Conditions

The environmental conditions inside underground utility caverns are rough and not very convenient for terrestrial laser scanners with their sensitive optical parts and electronics, e.g., the Imager 5006. Most terrestrial laser scanners are not specified for splash water and high humidity (Figure 6-26), which occur quite often in sewage systems. In contrast, the conditions in water systems or storm water systems are more favourable. The temperature and humidity are significantly lower, resulting in less fog. The consequences of foggy conditions are small water drops that cover the body and optical parts of the terrestrial laser scanner. This effect also happens with the ZLS07, but there are no damages as a consequence. The main components of the ZLS07, the SICK LMS200-30106 and the rotation table, proved to be splash-water resistant and, therefore, were reliable components for rough environmental conditions. The rotation table was originally constructed at the IGP for a microwave water vapour radiometer. However, the water drops affect the measurements of the ZLS07 so that the laser beam is deflected, resulting in false distances.

![Figure 6-26 Foggy conditions due to high humidity and temperature differences.](image)

Splash water in underground utility caverns occurs independently of the environment conditions outside the utility cavern. However, foggy conditions depend on the temperature and humidity differences between the inside and the outside. Especially in winter and for chilly weather conditions, the accumulation of fog is intensified inside the underground utility caverns. An approach to solving this problem is the aeration of those underground utility caverns that have to be measured by opening other manhole covers nearby. Furthermore, an acclimation of the laser scanner inside the cavern is indispensable.

6.2.4.3 Measuring Water Surface

Gullies, pipes, or collecting basins of underground utility caverns are often partially or completely covered by water or waste water, but for geometry detection, the technical construction without any water is of interest. Nevertheless, draining is not possible largely because it is too complicated or a permanent operation cannot be ensured. However, scans have to be performed under different conditions. Thus, investigations into the interactions between the laser beam and water surface were performed at the IGP. The primary objective was to observe whether a terrestrial laser scanner, specifically the ZLS07, actually measured water surfaces and what was measured. [VOGEL, 2008] gives a detailed description of the investigations and the results. In addition, a comparison between the ZLS07, which measures distances
according to the pulsed time-of-flight principle, and the Imager 5006, which determines distances according to the indirect time-of-flight principle (phase difference), was achieved.

In general, it can be stated that water surfaces and the depths of water highly influence measurements by a terrestrial laser scanner. There are two cases in terms of laser beam reflection: partial deflection on the water surface and total deflection. The laser beam is deflected by the water surface, which results in distance measurements that are too long. Moreover, the measurements depend on the angle of incidence of the laser beam on the water surface and the water depth. The investigations under laboratory conditions (with clean water) resulted in an accuracy decline of 15 mm per 10 cm water depth for the pulsed time-of-flight measurement system. A significant difference could be detected between distance measurements according to the pulsed time-of-flight principle and the detection of phase differences. Thus, water depths of more than 4 cm could hardly be penetrated for measurement according to the phase difference whereas measurement by pulsed time-of-flight could measure through water depths of more than 10 cm.

The investigations showed difficulties in scanning objects through a layer of water with a thickness of several centimetres. In addition, polluted water (waste water) disables the penetration of the laser beam entirely. Instead, the waste water surface is scanned or a total absorption of the laser beam is realised. Nevertheless, gullies, pipes, or collecting basins with low water level (below 10 cm) could be measured by the ZLS07 with resulting lower measurement accuracy. For the Imager 5006, water depths of more than 4 cm could hardly be penetrated. Thus, it can be concluded that the ZLS07 is more convenient for measurements of objects covered by water than the Imager 5006.

6.3 Data Post-Processing Workflow

TLS produces a huge amount of data in a short period of time. Even though the performance and data storage of computers have increased over recent years, data reduction and modelling of the 3D-point clouds are still important and crucial aspects in terms of scanning data post-processing (e.g., [BORNAZ and RINAUDO, 2004] and [MILEV, 2005]). For TLS in general, the post-processing workflow can be organised into three main steps (cf. Figure 6-27): 1. pre-processing (noise reduction, detection of outliers, and so on), 2. geo-referencing or registration of the 3D-point clouds, and 3. data modelling. Registration usually refers to the transformation of TLS data into a common coordinate system. Geo-referencing means, specifically, the transformation of TLS data into an established coordinate system, e.g., the state plane coordinate system.

For post-processing scans of underground utility caverns, the workflow is defined differently to the normal TLS post-processing workflow. It is more efficient to model the 3D-point cloud first and afterwards perform the geo-referencing. Because the centre lines of inlet and outlet pipes have to be detected for geo-referencing the data of underground utility caverns, the centre line directions of the pipe are used for the orientation of the 3D-point cloud or 3D-model. In addition, the centre point of the manhole cover is used for the positioning of the object. Reference targets, which are normally used for TLS data registration and geo-referencing, cannot be used for underground utility caverns. Reference targets have to be installed in the caverns and measured by a tacheometer or GNSS, which is difficult or even impossible to achieve.

In the following sections, the feasibilities for the modelling of 3D-point clouds of underground utility caverns and the geo-referencing of the objects are discussed. In addition, the problems, difficulties, and solutions in post-processing data from underground utility caverns are discussed.
6.3.1 Modelling

Modelling of a 3D-point cloud refers to the deduction of geometric information and data reduction. Furthermore, it is an important process in terms of transferring the data into GIS (e.g., pipe cadastral systems) or CAD-systems. However, the post-processing, in particular, the modelling of 3D-point clouds is a time consuming process depending on the modelling method and the level-of-detail. However, the time restrictions for an efficient modelling of underground utility caverns are set by GeoZ to one hour or a ratio of 1:3 of scanning and modelling. This time corresponds to the actual time for post-processing the manual measurements. The requirements with respect to the time for post-processing demand an efficient post-processing method for 3D-point clouds. Furthermore, semi-automatic or automatic geometry detections are preferred (cf. section 7). However, the deduction of pipe centre lines, pipe diameters, and the geometry information of the cavern and its infrastructure are realised by modelling a 3D-point cloud of an underground utility cavern.

For the modelling of 3D-point clouds of underground utility caverns, the following four post-processing methods are most adequate: determining geometric primitives, triangulation, digitising, and automatic geometry detection (Figure 6-28). All the modelling processes, except the automatic geometry detection, were performed by commercial software packages (e.g., Cyclone by Leica Geosystems [LEICA GEOSYSTEMS, 2008] or Geomagic Studio/Qualify by Geomagic Inc. [GEOMAGIC, 2008]). Prototype software for the automatic geometry detection of underground utility caverns was developed at the IGP in conjunction with this project (cf. section 7).
**Geometric Primitives:** The 3D-point cloud is modelled by matching geometric primitives into the 3D-point cloud according to the least-square method. Geometric primitives are simple geometric shapes, such as patch, sphere, cylinder, cube, cone, pyramid, and torus. This method is rather time consuming even though the geometry of underground utility caverns is rather simple. The modelling of 3D-point clouds with geometric primitives generally requires manual input as a starting point for each geometric object. In [SCHNABEL et al., 2007], an approach to the automatic detection and modelling of geometric primitives from 3D-point clouds is described.

**Triangulation:** The triangulation establishes a topological relation between the points of the 3D-point cloud. The amount of data is not diminished unless an edged sensitive filter algorithm is applied to the triangulated 3D-point cloud. The reduction of triangles often depends on the curvature of the surface. A next step after triangulating a 3D-point cloud is the parameterisation of the surface, e.g., by NURBS (cf. [PIEGL and TILLER, 1997] and [TEUTSCH et al., 2004]). Parameterisation results in significant data reduction.

**Digitising:** The digitising of a 3D-point cloud is the manual vectorisation by point-to-point measurements. Single points are selected from the 3D-point cloud. Digitising is performed in either a 2D- or a 3D-approach.

**Automatic Geometry Detection:** Automatic geometry detection enables the automatic modelling of a 3D-point cloud by using adjustment algorithms. Automatic or, at least, semi-automatic approaches are indispensable for an efficient modelling of 3D-point clouds. For underground utility caverns, the automatic geometry detection algorithms must be able to recognise the required geometric information. The output has to be 3D-vector data with information about the geometry of the cavern as well as the centre lines of the inlet and outlet pipes and their diameters.

Investigations of the different modelling methods resulted in determining the manual digitising of a 3D-point cloud as the most efficient method besides the automatic geometry detection. The digitising can be performed in any CAD-software that is well known to operators, but its limits mainly lie in precise edge and corner detection. Edges and corners are digitised by point-to-point measurements, even though TLS is an areal measurement method (cf. section 2.1.2) and, therefore, the corners and edges are not measured in particular. Thus, the quality of a digitised model depends on the scanning resolution.
Modelling according to geometric primitives allows an accurate edge and corner detection by intersecting the modelled patches. However, this modelling method is extensive and time consuming (three to ten times more than digitising). Furthermore, underground utility caverns feature free-form shaped objects (e.g., gullies or special half-pipes) which cannot be modelled by geometric primitives. However, triangulation with additional NURBS parameterisation allows the modelling of free-form shaped objects. The limitations of triangulation lie in the detection of edges and corners, which are important elements in conjunction with underground utility caverns. Due to limited resolution of the scans, the edges and corners are not directly represented by 3D-points. Thus, the modelling of edges and corners of an underground utility cavern by triangulation is not ideal or even possible.

Underground utility caverns often feature similar geometries. Thus, the detection of geometric elements can be automated. Algorithms that focus on the automatic geometry detection of underground utility caverns with similar geometry were developed and tested in conjunction with this thesis at ETH Zurich (cf. section 7).

6.3.2 Geo-Referencing

Geo-referencing implies the transformation of a 3D-point cloud or a 3D-model into a superior coordinate system. The transformation is usually performed according to a 3D-Helmert transformation based on reference targets [NIEMEIER, 2002]. As mentioned before, the use of reference targets in underground utility caverns is impractical. Thus, geo-referencing according to a 3D-Helmert transformation by using reference targets is unfeasible for scan data of underground utility caverns. Instead, a four-parameter transformation is applied for geo-referencing the 3D-point cloud or 3D-model. In an ideal case, three translations and one rotation describe the transformation. The elongated vertical axis of the ZLS07 allows the acquisition of the manhole or, at least, allows the deduction of the manhole centre point from the 3D-point cloud. Thus, the horizontal translation parameters $\Delta x$ and $\Delta y$ are derived by comparing the manhole centre point coordinates with the relative coordinates in the state plane system. Furthermore, the height offset $\Delta h$ is defined by measuring a height reference underneath the manhole cover (Figure 6-18). The height reference point is positioned close to the entrance ladder on the hard shoulder of the utility cavern. In addition, the reference point must be detectable in the 3D-point cloud.

![Image](image_url)

*Figure 6-29 Process of geo-referencing scan data of underground utility caverns.*

In addition to the three translations, a rotation is performed around the vertical axis (Z-axis, yaw) for the orientation of the 3D-point cloud. The horizontal angular offset $\Delta \kappa$ is derived from the direction of the inlet and outlet pipes. The direction of the pipe centre lines can be modelled by adjusting a cylinder with an unknown diameter in the 3D-point cloud. Additionally, the directions and orientations of the pipes with reference to the global coordinate system are known from pipe cadastral systems. Figure 6-29 illustrates the process of the 3D-point
cloud translation. The 3D-point cloud and 3D-model of an underground utility cavern is geo-referenced by three translations (Δx, Δy, and Δh) and one rotation (Δκ).

The presented orientation and transformation routine assumes that the vertical axis of the ZLS07 is aligned along the plumb-line during the measurements. This assumption allows a reduction of the similarity transformation to one rotation and three translations. Additional rotations around the X-axis and Y-axis (roll, pitch) are not required for this ideal case. However, investigations of the verticality of the telescope pole and the vertical axis of the ZLS07 identified a misalignment of the scanner horizon to the nominal horizon of about 0.8° (1σ) for the actual measurement configuration. This misalignment is caused by the leaning screw thread that connects the ZLS07 and telescope pole (cf. section 6.2.4.1). This problem has to be solved in the future for proper orientation of the 3D-point cloud according to the transformation by four parameters described. A misalignment of 0.8° does not meet the requirements (cf. section 6.1.2). Instead, the roll and pitch have to be derived from the inclinations of the modelled pipe axes. The horizontal orientation is derived from the direction of the pipe axis. The pipe direction accuracy can be assumed at about 0.2° (1σ), and the height offset and the horizontal translation parameters can be defined with an accuracy of about 0.01 m (1σ).

6.3.3 Remarks

The post-processing of 3D-point clouds of underground utility caverns operates well according to the described workflow. Even though the caverns often feature different geometries and infrastructures, similarities can be detected and used for further processing. Similar geometry elements of underground utility caverns allow knowledge-based data modelling. The pipe diameter, for instance, is known from pipe cadastral systems and can be integrated into the modelling procedure either for verification of the modelling or as additional information for the modelling. The development of a database containing the typical elements of underground utility caverns would be a next step for increasing the modelling efficiency.

Figure 6-30 Scanned waste water surface and scan shadow caused by hard shoulder. Figure 6-31 Scan shadow behind over flow construction.

Depending on the dimensions of the underground utility caverns and its infrastructures, geometric information may be missing in a scan due to the scan shadows of objects in front (e.g., columns, pipes, walls). Depending on the location of the manhole entrance into the underground utility cavern and the vertical position of the ZLS07 for the measurements, the shadowing effects vary. Figure 6-30 shows a scan shadow caused by the hard shoulder underneath the manhole. In Figure 6-31, the wall of the overflow construction makes the measurements for the ZLS07 behind the wall impossible. Geometric information is missing in the regions of the scan shadows. This additional information can be either detected by an additional manual inspection or reconstructed based on geometry knowledge of other similar underground utility
caverns. In addition, the CCD-camera on top of the ZLS07 delivers additional information based on digital images (with illumination of the underground utility cavern assumed) allowing the visual inspection and geometry detection of the cavern.

In addition to shadow effects from interfering objects, the scanning of the waste water surface disables the acquisition of the full geometric information of a gully or half pipe. In Figure 6-30, the waste water surface is visible instead of the basement of the gully. However, the diameters of inlet and outlet pipes are detectable even though the lower parts of the pipes or half pipes are covered by waste water. The diameters and pipe centre lines are adjusted into the 3D-point clouds of the upper parts of the pipes and half pipes. Moreover, additional information from the pipe cadastral system focusing on pipe diameters is used as well.

6.4 Review

The acquisition of underground utility caverns is becoming increasingly important because the water and sewage systems of populated areas, cities in particular, are more than a hundred years old and renovation work is necessary. Basic plans concerning the geometry are often missing. Thus, measurements of the underground utility caverns are indispensable. In addition, the caverns have to be measured after renovation work for the implementation geometric data into a GIS.

The adoption of TLS for acquisition of underground utility caverns was largely driven by safety and economic reasons. In addition, the increasing demand for 3D-data and the need for geometric information as a planning base for renovation of the water and sewage systems required fast 3D-data acquisition. The ZLS07 features an adequate measurement system. Special features, such as the elongated vertical axis, the fast scanning speed, or the balanced weight allocation, characterise the ZLS07. Additionally, the measurements require a robust, reliable, and fast terrestrial laser scanner. For the acquisition of underground utility caverns, the ZLS07 is guided headfirst through the vertical manhole into the caverns. A telescope tripod with an additional cable winch enables a fast and convenient measurement setup.

The limitations of TLS in terms of the measurements of underground utility caverns are largely due to the reflectorless electro-optical distance measurements. The object surfaces influence the distance measurements and are often crucial factors in the success or failure of obtaining measurements. The presence of too much splash water or fog inside the cavern disables the distance measurement and, therefore, the scan. However, in contrast to traditional measurement systems such as tacheometry or photogrammetry, TLS does not require any illumination of the environment and delivers area-wide 3D-data within a few minutes.

On-site evaluations of the measurement system based on the ZLS07 returned satisfactory results. The focus was on the handling and the practicability of the instrument. Thus, the measurement setup and scanning procedure for an underground utility cavern took less than 20 min. Furthermore, investigations on the measurement accuracy were performed under laboratory conditions. Nevertheless, it can be concluded, based on the results of the investigations, that the measurement configuration with the ZLS07 meets the accuracy requirements of 3 cm in position and 3 cm in height for acquisition of underground utility caverns.

Apart from scanning the underground utility caverns, the post-processing of the 3D-point clouds is an important process. Post-processing refers to the modelling and geo-referencing of 3D-point clouds. Moreover, the post-processing strongly depends on having the required results. However, different modelling methods were introduced. For projects in conjunction with GeoZ, the digitising of the 3D-point cloud proved to be the most efficient and satisfying post-processing method. However, semi-automatic or automatic geometry detection is also worthwhile.
7 Automatic Geometry Modelling

The post-processing of TLS data is often the most time consuming part in the workflow from surveying an object to delivery of the requested results. In addition, the post-processing usually requires intense interactions by operators, with largely semi-automatic processes implemented. In general, post-processing can be considered the crucial criterion for an efficient and successful project. In addition to the registration of the 3D-point clouds and the data filtering (e.g., noise reduction and elimination of outliers), the modelling and geometry detection of the scanned objects are the core elements in the post-processing. The modelling process is the reconstruction of objects from 3D-point clouds. The modelling process generally includes the data reduction of the 3D-point clouds by means of vectorisation and derivation of vector data. Depending on the application, the required data models and data accuracy may vary.

In the field of 3D-reconstruction, polygons are usually the ideal way to represent the results of the measurements by TLS (cf. [REMONDINO, 2003]). The polygons are derived by triangulating the 3D-point clouds. The modelling of 3D-point clouds by geometric primitives is also in widespread use. However, all the methods of modelling the 3D-point clouds require a great deal of interaction by operators. In addition, they are very time consuming, and the main focus often lies more on visualization purposes than on the geometric quality of the results. Nevertheless, for applications in the field of engineering geodesy, the geometric quality of the results is more important than the visualization aspect.

Commercial post-processing software supports only a few semi-automatic or automatic modelling tools (e.g., fitting of geometric primitives into 3D-point cloud, automatic edge detection, or triangulation) and are often focused on universal applications. In addition, the automation is often limited due to the complexity and individuality of the scanned objects. In terms of underground utility caverns, complexity and individuality of the objects is also a consideration. However, underground utility caverns have similar features. Most caverns (approximately 80%) consist of a single room that can be scanned from one scanner station. In addition, the geometry of the room is quite simple, apart from the infrastructure geometry (e.g., pipes, slider plates, or overflow buildings). The relatively simple geometry of the underground utility caverns allows an automatic extraction of geometric information.

The main objective in terms of modelling underground utility caverns is the derivation of a wireframe model from the 3D-point cloud. The boundaries should represent the edges and corners of the cavern.

Below, the requirements for the data modelling of underground utility caverns are described with focus on automatic geometry detection. In addition, previous works in the field of automatic geometry detection in general and a prototype of a software tool for automatic geometry detection developed at the IGP in conjunction with this thesis are presented.

### 7.1 Data Modelling Requirements

The requirements for the acquisition of underground utility caverns and for the results to be delivered from scanning data are posted by GeoZ. Section 6.1.2 describes the requirements with respect to accuracy and subject of content. In summary, the following requirements are stated by GeoZ:
• Determination of absolute position and height of underground utility caverns
• Geometry and dimension of underground utility caverns with an accuracy of 3 cm (1σ) in position and an accuracy of 3 cm (1σ) for the height
• Acquisition of infrastructure of underground utility caverns
• Reports of material and condition of underground utility caverns
• Results and documentation: a detailed plan has to be created for each underground utility cavern. Either an analogue plot or digital data are delivered to the customers.

The documentsations of underground utility caverns are not clearly specified by GeoZ. Until now, a 2D-drawing has been designed from the manual measurements and delivered to the customers. Due to limited knowledge about TLS and its possibilities with respect to post-processing, the deliveries from terrestrial laser scanning data are not used by GeoZ. Ideal data documentation can be proposed. However, the results by TLS must be delivered in a generally readable format for commercial GIS or CAD-systems (preferably *.dxf or *.dwg), and further data processing must be possible. Generally, the minimal result to be delivered corresponds to the actual result derived from manual measurements (cf. section 6.1.2).

For geometry detection and modelling of the 3D-point clouds of underground utility caverns, additional requirements have been elaborated. The main focus lies in the geometry detection of the underground utility cavern and the inlet and outlet pipes. The list below summarises the minimum in terms of geometric elements to be derived from the 3D-point cloud:

- Horizontal cross-section of underground utility cavern
- Centre lines of inlet and outlet pipes
- Diameters of inlet and outlet pipes
- Height information: height differences between the ceiling and the bottom points of the inlet and outlet pipes where they enter into the underground utility cavern. Furthermore, height differences between ceiling and surrounding platform, which is used for maintenance work, are of interest.

These requirements are effective for most of the underground utility caverns that are part of the sewage system of the city of Zurich. Depending on special types of underground utility caverns, the requirements have to be adjusted, and an individual processing of the laser scanning data has to be developed. However, a semi-automatic or automatic processing of the laser scanning data is desired due to a more efficient post-processing of the 3D-point clouds.

### 7.2 Previous Work

Modelling scan data is a challenging process. Even today, the development of modelling and interpretation processes of 3D-point clouds is ongoing and incomplete. A more effective post-processing has to be achieved. [RABBANI, 2008] states that the state-of-the-art for 3D-point cloud processing is far behind the state-of-the-art for the data acquisition. This statement is fully supported by the experiences encountered during this thesis. The various fields of application for terrestrial laser scanners (cf. section 2.4) require different results and, therefore, various post-processing methods. Thus, different post-processing algorithms have to be developed. An overview of the modelling and interpretation of TLS data is given in [BRENNER, 2007].

The development of post-processing methods has to cover a wide range of specific applications. The use of particular software or software tools often limits the post-processing possi-
bilities for users to a specific range of applications. For modelling 3D-point clouds of underground utility caverns, for instance, boundary models based on nodes and edges are needed for further processing in CAD-systems or GIS. Depending on the modelling method (cf. section 6.3.1) and the expected results, the effort varies. A complete automation of the 3D-modelling process is not realised yet and is still subject to further investigations. Rather, semi-automatic post-processing is in widespread use, but it requires additional information input by operators. Further, 2D-modelling is often preferred to 3D-modelling by generating cross-sections.

The post-processing of 3D-point clouds has been investigated by various research institutes for different fields of application. In terms of engineering geodesy, the International Society for Photogrammetry and Remote Sensing (ISPRS) [ISPRS, 2008], specifically the working group WG III/3, deals with the post-processing of 3D-point clouds from terrestrial laser scanners and other sensors. With respect to the modelling of underground utility caverns, three different approaches for the post-processing of 3D-point clouds are presented. The automatic generation of cross-sections, a semi-automatic detection of boundaries such as nodes and edges, and the automatic matching of geometric primitives are focused on.

The detection of cross-sections is a common process in the field of technical construction surveying. Cross-sections represent the geometric 2D-structure of an object parallel to a predefined plane. Horizontal cross-sections are very common and often used in construction engineering. Cross-sections can be derived from 3D-point clouds either by manual digitising or by automatic or semi-automatic processes. [KERN, 2003], for instance, presents a method for generating cross-sections by intersecting a patch with the triangulated 3D-point cloud. Thus, it requires a triangulation of the 3D-point cloud. This method can be described as semi-automatic due to required manual improvements of the derived cross-sections. The approach of automatic detection of cross-sections is further investigated in conjunction with this thesis (cf. section 7.3).

[DORINGER and BRIESE, 2005] describe an effective 2.5D-approach for the generation of a consistent topological network of structure lines, called boundary representation. The semi-automatic process requires a digitising of 2D-approximations in the 3D-point cloud, which is projected into a 2D-image frame coded by intensity values of the reflected laser beam or distance dependent. The digitising of the boundaries serves as 2D-approximations for the 2.5D-calculations of the structure lines. Moreover, based on the structure lines, final corner points can be defined.

For automatic approaches in reconstruction of objects by geometric primitives, [RABBANI, 2006], for instance, groups the workflow in segmentation of the 3D-point cloud, surface fitting, registration (if several 3D-point clouds available), and object recognition. Moreover, he presents an automatic reconstruction of industrial installations. However, the segmentation of 3D-point clouds is a crucial task in terms of automatic object reconstruction. Segmentation is a process that is also performed for 3D-data from airborne laser scanning, e.g., [VOSSELMA et al., 2004]. [SCHNABEL et al., 2007] describe an algorithm for a fast 3D-point cloud segmentation based on the RANSAC-algorithm (RANdom Sample Consensus) by [FISCHLER and BOLLES, 1981]. An alternative to an automatic segmentation is a semi-automatic segmentation by manually selecting initial points, so-called seed points.

In terms of 3D-point cloud segmentation, [SCHLEINKOFER et al., 2006] present an approach for vertical patch detection in 3D-point clouds. The algorithm is based on digital image processing and enables the detection of 2D-drawings or 3D-models. Vertical patch detection is of great interest for indoor surveying of buildings. However, the development of individual algorithms and methods enables an effective post-processing of 3D-point clouds.
7.3 Development of an Approach for Automatic Cavern Detection

Until now, no commercial software has been available for a fully automatic post-processing of 3D-point clouds from the field of underground utility caverns. However, automation would reduce time primarily for the post-processing. Thus, a prototype software tool was developed in Matlab® by The MathWorks Inc. [MATHWORKS, 2008] at the IGP (cf. [VOGEL, 2008]). Algorithms were implemented particularly for a convenient post-processing of underground utility cavern data. Furthermore, the adjustment of geometric elements into the 3D-point cloud according to least-square methods enables the derivation of selective information for a wireframe model of underground utility caverns with simple geometry.

The prototype software processes 3D-point clouds exclusively. The processing of additional image data is not implemented yet. However, the terrestrial 3D-laser scanner ZLS07 features an extra CCD-camera for image data acquisition primarily for documentation purposes (cf. section 3.2.3). Image information could also be used for geometry detection of corners and edges or simultaneous calibration of the involved terrestrial laser scanner and CCD-camera (cf. [SCHNEIDER and MAAS, 2007]). Furthermore, images allow the distinction of different coloured surfaces. For this purpose, the 3D-point cloud can be coloured by the RGB-values that are acquired by the CCD-camera (Figure 7-1). In any case, photogrammetry complements well the areal TLS measurement technology. For the acquisition of underground utility caverns, in near future, an additional light source will be implemented in the ZLS07 for the illumination of the caverns, enabling the acquisition of additional image information.

![Figure 7-1 3D-point cloud with additional image data from CCD-camera.](image)

The 3D-point clouds of underground utility caverns are processed by the prototype software with a 2.5D-approach. That is, a horizontal cross-section is derived from the 3D-point cloud. In addition, the height information is selectively extracted. The position and direction of the inlet and outlet pipes are defined, as is the diameter. The 2.5D-approach has an advantage compared to 3D-modelling because the geometry extraction can be performed according to well-known algorithms from vectorisation of 2D-raster data. The vectorisation of 2D-raster data is a topic from the field of cartography and image processing. [DOUGLAS and PEUCKER, 1973] describe an algorithm to reduce the number of points required to represent a line. This approach is implemented in the post-processing software for the detection of topological connections between single points.
By using the Douglas-Peucker algorithm, the corner points of a horizontal cross-section of the 3D-point cloud can be detected. Based on the corner points, straight lines are adjusted into the points between the corner points of the underground utility cavern. Depending on the number of points, the adjustment is performed according to either least-square method or robust adjustment methods. The robust adjustment enables the elimination of outliers or interfering objects, for example, the vertical ladder for accessing the underground utility cavern through the manhole. By intersecting the straight lines, new corner points are calculated and replace the previous.

The horizontal cross-section, the centre lines, and the diameters of inlet and outlet pipes are derived from the 3D-point cloud along with the vertical dimensions. Thus, the developed software meets the requirements listed in section 7.1. Up to now, the approach developed works only for caverns with simple geometric structures. The approach for automatic geometry detection is described in more detail in the sections below.

### 7.3.1 Cross-Section

For the deduction of a horizontal cross-section from a 3D-point cloud, a horizontal band of the 3D-point cloud is selected with a corresponding band width. Furthermore, the vertical height of the cross-section in relation to the terrestrial laser scanner can be adjusted to allow cross-sections of the object in different vertical positions. The selected band of the 3D-point cloud is treated as 2D-raster data for further processing thus allowing the implementation of known algorithms for 2D-vectorisation purposes. In contrast to approaches that derive cross-sections from a modelled or triangulated 3D-point cloud (cf. [KERN, 2003]), the presented algorithm deduces the cross-sections from a two dimensional approach.

![Figure 7-2 Outliers ignored by Douglas-Peucker algorithm.](image1)

![Figure 7-3 Outliers influences the edge detection depending on sensitivity of algorithm.](image2)

The points of 3D- and 2D-point clouds generally do not have any topological correlations to each other. For scans by the ZLS07, the 3D-point cloud is sorted so that the scanning profiles are listed in the order in which they were measured. Thus, the topological correlations exist already for the selected horizontal 3D-point cloud cross-section. In a first step of modelling the horizontal cross-section, the significant corners of the underground utility cavern have to be detected. Therefore, the Douglas-Peucker algorithm [DOUGLAS and PEUCKER, 1973] was implemented to find a first approximation of the corner points by selecting representative points from the 3D-point cloud cross-section. Depending on the parameters that control the sensitivity of the Douglas-Peucker algorithm, corner points can be detected. Outliers of the 3D-point cloud influence the algorithm. Adjusting the parameters can be indispensable, de-
pending on the geometry and outliers of a 3D-point cloud. Figure 7-2 shows a selection of the 3D-point cloud cross-section with outliers that were ignored by the Douglas-Peucker algorithm. However, Figure 7-3 presents the same section with the outliers detected by the Douglas-Peucker algorithm as corner approximations of the underground utility cavern.

In a second step towards the modelling of a cross-section, the points representing the 3D-point cloud cross-section (Figure 7-4) are segmented into sections limited by the approximated corners. Finally, the corners of the underground utility cavern are calculated as intersections between straight lines that have been adjusted into the relative point cloud segments (Figure 7-5). The adjustment of straight lines into the point cloud segments is performed either according to a normal least-square adjustment or according to a robust adjustment. The selection of the adjustment method depends on the number of points of the relevant segments. It must be noted that only line elements can be adjusted into the point segments because no curve fitting tool has been implemented yet.

### 7.3.2 Pipe Centre Line

The detection of the centre lines of inlet and outlet pipes is based on analysing a horizontal cross-section of the 3D-point cloud. The cross-section has to be realised in a vertical position that enables the mapping of the pipes in the cross-section. Similar to the deduction of the line elements for the horizontal cross-section, the adjustment of the centre line is performed in a 2D-approach by using the Douglas-Peucker algorithm for the reduction of points. Furthermore, a segmentation of the points is enabled. For each segment of points, a line adjustment is performed according to a least-square method or a robust method.

The centre line of a pipe is calculated as the mean value of two corresponding pipe border lines. A corresponding pair of border lines is evaluated by comparing the gradients of the adjusted lines. Figure 7-6 shows the 3D-point cloud cross-section with all adjusted border lines of the pipes. However, Figure 7-7 presents the resulting pipe centre lines. The vertical position of the centre lines is provided by the centre points of the pipe diameters, which are calculated by a least-square adjustment (cf. section 0).
A crucial parameter for the automatic pipe centre line detection is the inclination of the pipes with respect to the horizon. Thus, the inclination influences the parallelism of the border lines in the 3D-point cloud cross-section. Empiric tests with different types of underground utility caverns resulted in determining that automatic centre line detection according to the developed algorithm is not appropriate for pipes with an inclination of more than two degrees (cf. section 7.4).

### 7.3.3 Pipe Diameter

The diameter of an inlet or outlet pipe is calculated by adjusting a circle into the 3D-point cloud of a vertical cross-section of the pipe. Assuming that the centre lines of pipes are perpendicular to the corresponding surfaces, where they enter the underground utility cavern, a virtual buffer with a width of maximal 5 cm is built around the cavern for the selection of the 3D-point clouds (Figure 7-8). The selected 3D-point clouds represent the pipe dimensions. Due to the scanning configuration, the pipes are often partially scanned. Thus, the 3D-point clouds of the cross-sections usually represent only parts of the pipes. However, a least-square adjustment provides the diameter and centre point of the corresponding pipe by adjusting a circle into the cross-section of the 3D-point cloud with a 3D-approach. Thus, the buffer width has to be kept as thin as possible.

The detection of the pipe diameters is a challenging task. Diameters of pipes that are inside the underground utility cavern cannot be detected with the developed algorithm at all. Furthermore, the centre lines of the pipes have to be perpendicular to the corresponding surfaces of underground utility caverns. Additionally, the adjustment of a circle into the 3D-point cloud cross-section of a pipe depends on the buffer width. Finally, the algorithm supports only pipes with small inclination similar to the extraction of the pipe centre line (cf. section 7.3.2).
7.3.4 Vertical Dimension

The vertical dimensions of an underground utility cavern have to be extracted in an additional task due to the 2D-approach of the geometry detection. Based on the horizontal cross-section, the vertical extensions are detected for the corners and for the locations where the pipes enter or leave the caverns. The vertical dimensions are detected as the differences between the minimum and maximum vertical position (Z values) of the points below and above the location of interest. A buffer with horizontal and vertical extension selects a column of points for each location (Figure 7-9). Thus, the minimum and maximum of each column is calculated as the mean value of the lowest and highest points. These points are selected by another buffer with a vertical extension, analogous to the measurement noise of the terrestrial laser scanner used. For the ZLS07, the vertical buffer is set to 20 mm.

Figure 7-8 Buffer around underground utility cavern for pipe diameter detection.

Figure 7-9 3D-view of 3D-point cloud sections for geometry detection.
7.4 Results

The result of post-processing the 3D-point cloud by the developed algorithm is a wireframe model that represents an underground utility cavern (Figure 7-10). The output is a *.dxf file that can be further processed in any GIS or CAD-software. The geometric information addresses the horizontal cross-section, the directions of the pipe centre lines, the pipe diameters, and the vertical dimensions of specific areas, such as corner sections and inlet and outlet pipes. However, it must be noted that the introduced algorithms perform satisfactory only for underground utility caverns with a simple geometry structure as the example described above. Complex caverns with various pipes and infrastructures like slider plates are difficult to process or even not processible by the developed algorithm.

![3D-point cloud](image1)

![wireframe model (DXF)](image2)

*Figure 7-10 3D-point cloud with corresponding 3D-wireframe model.*

The geometry of the underground utility cavern is derived by a 2.5D-approach. Based on the detection of the horizontal cross-section, the third dimension is defined for selected areas, such as for the corners of the cavern and for the lowest area of inlet and outlet pipes. However, variations in the ceilings or height in the middle of the caverns cannot be located with the described approach. The volume model of the cavern corresponds to the horizontal cross-section with the relative vertical extensions. The resulting wireframe model must be considered a geometric simplification of the underground utility cavern.

As mentioned above, the developed algorithm is sensitive to the geometry of the underground utility caverns with respect to the success of the automatic geometry recognition. Beside complex geometry structures or interfering scanning shadows, which can be caused by columns of large underground utility caverns, the inclination of the inlet and outlet pipes is a crucial parameter for the pipe centre line detection. The centre line detection is based on a 2D-analysis as well. However, the centre line of a pipe is calculated as the mean value of two border lines that are derived from the cross-section of the 3D-point cloud and feature a parallelism with each other. Pipe inclinations of more than two degrees disable successful automatic centre line detection.
Figure 7-11 presents an underground utility cavern with a single inlet and outlet pipe. The cavern was scanned in the city of Zurich. The inclination of the inlet pipe is about 14.78° and the inclination of the outlet pipe around 6.83°. The horizontal cross-section and the adjacent adjusted border lines do not enable clear centre line detection. Furthermore, no parallel pair of border lines can be detected. Therefore, the implemented algorithm does not properly work for the described underground utility cavern. Manual centre line detection is indispensable.

In addition to the geometry of the underground utility caverns, the parameters for the adjustment strongly influence automatic geometry detection. The following primary controlling parameters have to be manually adjusted by the operators before performing an automatic geometry detection:

- Vertical position of horizontal cross-section of cavern as well as for the pipe centre line detection
- Band width of 3D-point cloud selection for cross-section
- Sensitivity of Douglas-Peucker algorithm
- Number of points that determine whether a least-square or robust adjustment for line adjustment is used
- Buffer size for selection of 3D-point cloud for pipe diameter adjustment
- Buffer size for detection of vertical dimension of underground utility cavern

It must be noted that the parameters are not adjusted automatically, but the parameters can be the same for underground utility caverns of similar geometry. Due to the 2D-approach for post-processing the 3D-point clouds, the selection of the vertical position of the horizontal cross-section is a crucial parameter for geometry detection. Hence, the cross-section has to be representative of the whole cavern. Whether the 3D-point cloud is registered or not, the verti-
cal position varies for every underground utility cavern, depending on the size of inlet and outlet pipes, functionality, infrastructure, size of surrounding platforms, and length of the vertical manhole. Figure 7-12 shows two horizontal cross-sections of a complex underground utility cavern with a rack in the northern part of the cavern for filtering driftwood from creek water. However, the vertical position of the two horizontal cross-sections varies about 6 cm. The resulting modelled cross-sections feature significant differences in the northern part as well as in the southern part, which presents a maintenance gallery.

Figure 7-12 Differences of edge detection for cross-sections at different vertical positions.

In general, the choice of the parameters influences the success or failure of the data modelling. But, a knowledge based parameter evaluation allows the use of the same parameters for underground utility caverns with similar geometric properties. Thus, the creation of a database with information about the modelling parameters for underground utility caverns with similar geometries would be worthwhile. Nevertheless, an accurate parameter evaluation is indispensable for underground utility caverns with complex and unique geometries. The manual selection of the parameters can be regarded as an iterative process subject to particular evaluation of the results by the operators.

7.5 Review

A 2.5D-approach for the automatic geometry detection of underground utility caverns was developed at the IGP. The approach is referred to 2.5-dimensions because the detection of the horizontal and vertical dimensions is separated in contrast to a real 3D-geometry modelling. In addition, the geometry information is derived from 3D-point clouds by an automatic vectorisation of 2D-raster data based on the Douglas-Peucker algorithm. The 2D-raster data are projections of cross-sections of the 3D-point clouds into corresponding parallel planes. Thus, procedures from image processing can be applied to the geometry detection.

However, the following geometric elements are automatically extracted from the 3D-point clouds of underground utility caverns: horizontal cross-sections, pipe centre lines, pipe diameters, and vertical dimensions. Nevertheless, numerous parameters – the vertical positions for the cross-sections or the sensitivity of the Douglas-Peucker algorithm, for instance – have to be chosen by operators manually for the 3D-point cloud processing. The parameters can be the same for underground utility caverns with similar geometric specifications. However, the selection of parameters has to be considered a very sensitive part of automatic geometry de-
tection. Furthermore, the selection of parameters is correlated to the post-processing experiences of the operators. The creation of a database with geometry information about the underground utility caverns and the corresponding modelling parameters would be a worthwhile future development.

Apart from the selection of parameters, the 2.5D-approach is limited by the detection of only straight line elements for the cross-sections because the detection of curvature has not been treated and implemented yet. However, the big advantage of automatic geometry detection compared to manual digitising is the adjustment of the geometric elements into the 3D-point clouds according to the least-square methods. Thus, the straight lines, for instance, are defined by several hundreds of points instead of two points that have been selected and digitalised manually by an operator.

The introduced 2.5D-approach for the modelling of 3D-point clouds from underground utility caverns has to be considered a step towards full three-dimensional geometry detection. For future work, a database or catalogue of geometric elements of underground utility caverns has to be designed and implemented. This database would enable knowledge-based post-processing and support the automatic geometry detection. In addition, the image data from the CCD-camera of the ZLS07 have to be implemented in the post-processing software as additional information to the 3D-point clouds for edge and corner detection in particular. Moreover, image data will support the detection of thematic data in terms of the conditions of the infrastructure and the building.
8 Various Applications for Terrestrial Laser Scanner ZLS07

The terrestrial 3D-laser scanner ZLS07 is applicable as a regular terrestrial laser scanner for close-range applications in the field of engineering geodesy beside the main application of the acquisition of underground utility caverns (cf. section 6). However, the measurement range, precision, and accuracy of the ZLS07 (cf. section 5) have to be considered in choosing appropriate applications. Nevertheless, there are applications for TLS and specifically for the ZLS07 (e.g., surveying of technical constructions) for which accuracy and precision are less important parameters compared to scanning time, costs, and robustness of the scanning system or difficult accessibility to the objects to be scanned.

In the following sections, two applications of the ZLS07 are presented from the field of damage detection and reverse engineering of technical buildings. Damage or deformation monitoring is a field of application for TLS with high potential. The described application deals with the damage detection of an incinerator. In addition, the Imager 5006 was compared to the ZLS07. Reverse engineering is well known from industrial applications [RAJA and FERNANDES, 2008]. It also plays an increasingly important role in the field of engineering geodesy, specifically in conjunction with extension constructions of technical buildings. The application presented describes the acquisition of the overflow building of Nalps dam in Switzerland. The overflow building is an object with restricted access for operators and for measurement equipment due to safety reasons. Thus, the ZLS07 is the appropriate measurement instrument due to its capabilities of performing measurements headfirst as in the application for underground utility acquisition (cf. section 6).

8.1 Damage Detection of an Incinerator

8.1.1 Introduction

An incinerator is usually part of an incineration facility and burns different kinds of waste under high temperatures. A burner in the lower part of the incinerator produces a fire and high temperatures usually by burning fuel or gas. The inner part of an incinerator often consists of firebricks that are fire resistant and provide insulation. Depending on the application of an incinerator, size and geometry vary. In the following discussion, the incinerator refers to a furnace that burns waste from the chemical industry. The scans were performed in a chemical plant in the southwest of Switzerland.

The cylindrical design of the incinerator to be scanned had a height of approximately 12 m and a nominal diameter of 3.50 m. The access into the furnace for maintenance purposes was enabled by a 0.9 m x 0.9 m entrance (Figure 8-1). In addition, a trestle was installed about 2 m above ground for servicing the furnace. Approximately every fourth year, the incinerator and the firebricks have to be renovated due to abrasion caused by the burners. The main task for survey engineers was detecting the areas of the firebricks with the most abrasion. A visual inspection by an operator was difficult because the firebricks were black and the light conditions were difficult inside the incinerator. Former experiences in conjunction with renovations showed that incorrect areas of abrasion were detected by visual inspection. Thus, TLS was an appropriate measurement method for the damage detection. Moreover, due to time being a
crucial parameter for the renovation of the furnace, a terrestrial laser scanner could scan the whole object within a few minutes.

![Figure 8-1 Entrance into incinerator.](image1)

![Figure 8-2 Setup of ZLS07 on tripod in incinerator.](image2)

Damage detection or deformation monitoring by TLS are well known from applications in the field of tunnelling (cf. [HEINIGER, 2006], [VAN GOSLIGA et al., 2006]). The 3D-point cloud as the result of a scan is compared with a nominal model of the tunnel geometry. Distance differences result from the analysis. The distance differences are calculated for each point of the 3D-point cloud as the closest distance to the nominal model. The damage detection of a melting furnace is similar to the application in the field of tunnelling. The nominal diameter of the furnace is known and can be compared with the measured geometry.

The main objective of the damage detection by the ZLS07 was the verification of the ZLS07 in this specific field of engineering geodesy. Additionally, the applications should show whether the ZLS07 was a viable alternative to commercial terrestrial laser scanners for this kind of applications, especially with respect to measurement accuracy and precision. A comparison of the ZLS07 and the Imager 5006 was also performed.

### 8.1.2 Method

The terrestrial laser scanners, ZLS07 and Imager 5006, were set up on a tripod in the centre of the incinerator on the trestle that had been installed for maintenance purposes (Figure 8-2). Controlling of the laser scanners was performed from outside the incinerator. The minimum distances from the terrestrial laser scanner to the wall of the furnace were approximately 1.7 m whereas the maximum distance was up to 10 m for the top of the furnace. In general, the conditions inside the incinerator were difficult and challenging for measurements by TLS. Apart from the black surface, which absorbed laser light and limited the backscatter, the angles of incidence of the laser beam on the surface of the furnace were a crucial parameter for the measurement accuracy. The black surfaces and the small angles of incidence aﬀected the intensity of the backscattered laser light, which influences the distance measurement accuracy. Angles of incidence strongly decreased for measurements in the zenith of the terrestrial laser scanner. Small angles of incidence of the laser beam on the object surface of the incinerator were similar to measurements in tunnels (cf. [VAN GOSLIGA et al., 2006]).
The inside of the incinerator was acquired by a 360° scan. Reference targets were not installed because a geo-referencing of the 3D-point cloud into a reference coordinate system was not required. The furnace was measured from one scanner position. Registration of two or more 3D-point clouds was not required.

8.1.3 Results

The incinerator was scanned with different resolutions from one scanner station. As mentioned above, neither a registration nor a geo-referencing of the 3D-point clouds was performed. For post-processing the data, points of the 3D-point cloud, which clearly did not belong to the surface of the incinerator, were removed manually as were such interfering objects as the trestle or illumination infrastructure. An additional filtering for smoothing of the 3D-point cloud was not realised. Rather, the 3D-point cloud, without further post-processing, provided already valuable information about the conditions of the incinerator. Figure 8-3 shows the 3D-point cloud of the incinerator scanned by the ZLS07 and a selected area with damage to the firebricks. The structure and conditions of the firebricks were detectable. The damaged areas were visually inspected in a first step of the post-processing by analysing the 3D-point cloud. The localisation of the areas of interest was recorded as a relative position to the entrance.

However, the 3D-point cloud, in general, contains information that can be derived without a time-consuming post-processing. For the incinerator for instance, the 3D-point cloud already indicated, besides the detection of damage, that the measurements in the zenith of the terrestrial laser scanner were crucial with respect to accuracy and reliability. Further analysis of the 3D-point cloud would confirm this assumption.

For the damage detection of the incinerator and the firebricks, the measured 3D-point cloud was compared with the nominal model (Figure 8-4), which is a cylinder with a diameter of 3.50 m. The cylinder with fixed diameter was adjusted into the vertical part of the 3D-point cloud of the incinerator according to the least-square adjustment, which was realised by the post-processing software Cyclone by Leica Geosystems [LEICA GEOSYSTEMS, 2008]. Thus, region-growing functionalities were used to identify and select the best number of points for adjusting a cylinder into the 3D-point cloud. Six seed points were identified manually in the 3D-point cloud. Afterwards, the post-processing software automatically selected points that met the affiliation criteria for the cylinder (diameter: 3.50 m; fitting tolerance:
0.024 m). The selected points built the seeding area. For the adjustment, surrounding points of the seeding areas were included as well.

![3D-point cloud compared with the nominal model.](image)

**Figure 8-4 3D-point cloud compared with the nominal model.**

Due to the rough surface and damage to the incinerator, the mean absolute error of the cylinder adjustment to the 3D-point cloud measured by ZLS07 was about 2.7 cm, and the standard deviation (1σ) of the errors was calculated at 1.5 cm. It must be noted that the adjustment depended on the manual selection of the seed points, which belonged to the furnace surface. However, different seed point selections showed results in the same range for mean absolute error and standard deviation. Additionally, it should be noted that the standard deviation of the errors approximately corresponds to the 3D-single point precision of the ZLS07 (cf. section 3.3.4).

The comparison of the 3D-point cloud with the nominal model was performed by using the software Geomagic Qualify by Geomagic Inc. [GEOMAGIC, 2008]. Hence, the 3D-comparison was carried out by looking for the shortest distance to the reference surface. A so-called 3D-compare algorithm was implemented in Geomagic Qualify. The distance differences were calculated for each point of the 3D-point cloud to the nominal model. Thus, a corresponding colouring of the nominal model resulted, and the size and the relative position of the deviations between the 3D-point cloud and the nominal model could be detected.

Figure 8-5 shows the results of the 3D-comparison between the 3D-point cloud and the nominal model. Deviations from the nominal model larger than 10 mm could clearly be detected, but it should be noted that, due to the geometry of the incinerator, small angles of incidence of the laser beam on the incinerator surface occurred for measurements with small vertical angles. The small angles of incidence influenced the distance measurements by the ZLS07 (Figure 8-5). Based on the calculated distance differences, it can be stated that the distances for vertical angles smaller than 30° were significantly shortened, hampering reliable damage detection. With respect to the incinerator with a diameter of 3.5 m, the damage detection could be reliably performed up to a height of 6 m above the scanner, corresponding to a height of about 9 m above the ground of the incinerator compared to its total height of 12 m.

Considering the whole 3D-point cloud measured by the ZLS07, the positive mean error of the deviations between the 3D-point cloud and the nominal model is 6.5 cm. These deviations were calculated by using only the 3D-points that were outside of the nominal model. Deviations caused by 3D-points inside the nominal model, due to small angles of incidence of the laser beam on the object surface, were rejected for the calculations.
In addition to the scans with the ZLS07, scans were performed by the terrestrial laser scanner Imager 5006. By comparing the 3D-point clouds measured by Imager 5006 with the nominal model, deformations of and damage to the incinerator were detected in the post-processing of the measurements by the ZLS07. Figure 8-6 presents damages detected by the ZLS07 and by the Imager 5006. The most significant damages were observed and located by both terrestrial laser scanners. Furthermore, distances measured with small vertical angles were shortened due to small angles of incidence. The positive mean error of the deviations between the 3D-point cloud and the nominal model is 6.0 cm for the measurements by the Imager 5006 compared to 6.5 cm for measurements by the ZLS07. The deviations were calculated by using only the 3D-points that were outside of the nominal model.

In addition to comparing the 3D-point clouds with the nominal model of the incinerator, the 3D-point clouds measured by the ZLS07 and Imager 5006 were compared to each other. However, the 3D-point clouds were registered into the same coordinate system by using an ICP-based algorithm that was implemented in the software Geomagic. The registration of the two 3D-point clouds was difficult to realise. On the one hand, the cylindrical geometry of the incinerator was not ideal for a point-to-point registration due to less significant geometric identifications. On the other hand, the measurement accuracies of the two terrestrial laser scanners...
Rather varied. Nevertheless, the registration performed by Geomagic resulted in an average distance of 18.3 mm and a standard deviation (1σ) of 9.3 mm for corresponding points in both 3D-point clouds.

After registering the two 3D-point clouds, the distance differences were calculated as the shortest distances between points of the 3D-point cloud by the ZLS07 to the triangulated 3D-point cloud of the Imager 5006. Figure 8-7 presents a visualisation of the distance differences for the lower part of the incinerator. The positive mean error is 19.2 mm and the negative mean error is reported as -14.2 mm. The standard deviation (1σ) of the errors is 36.3 mm. The upper part of the incinerator was not analysed due to larger deviations caused by small angles of incidence of the laser beam on the surface.

Table 8-1 summarises the analysis of the 3D-point clouds measured by the terrestrial laser scanners ZLS07 and Imager 5006. In addition to the larger scanning noise of the ZLS07 compared to the Imager 5006, the ZLS07 is, in general, more sensitive to small angles of incidence of the laser beam.

<table>
<thead>
<tr>
<th></th>
<th>ZLS07</th>
<th>Imager 5006</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of points (resolution middle)</td>
<td>1.1 million</td>
<td>10.6 million</td>
</tr>
<tr>
<td>adjusting nominal model (region-growing)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>number of points</td>
<td>45’879</td>
<td>1’011’802</td>
</tr>
<tr>
<td>mean absolute error</td>
<td>27.4 mm</td>
<td>6.7 mm</td>
</tr>
<tr>
<td>standard deviation (1σ)</td>
<td>14.5 mm</td>
<td>5.7 mm</td>
</tr>
<tr>
<td>3D-comparison to nominal model: positive mean error (3D-point cloud to nominal model; only points outside of the nominal model included)</td>
<td>64.6 mm</td>
<td>59.9 mm</td>
</tr>
</tbody>
</table>

Table 8-1 Comparison of ZLS07 and Imager 5006 related to scanning the incinerator.

8.1.4 Conclusion

Damage to the firebricks inside the incinerator could be detected inside the incinerator by the ZLS07. Furthermore, the application shows the potential and problems of the ZLS07 and its application range in the field of deformation and damage detection. In general, it can be stated that reliable damage detection with respect to the incinerator can be performed for measurements with vertical angles larger than 30°. For small vertical angles, the angles of incidence
of the laser beam on the incinerator surface were small, which resulted in errors of the distance measurements.

The angle of incidence is a crucial parameter for damage detection with the ZLS07 as well for the high-class terrestrial laser scanner Imager 5006. Compared to the ZLS07, the Imager 5006 has lower scanning noise and the measurement accuracy is in the mm-range. However, both terrestrial laser scanners could detect the main damage to the firebricks inside the incinerator. For the ZLS07, the damages with a depth larger than 20 mm could be clearly identified. An important aspect of damage detection is the location of the damages rather than their actual size.

In general, TLS is an appropriate measurement method for damage detection provided that both the original model and the geometry are known. In the case of the incinerator, a manual inspection and detection of damage are complex due to difficult light conditions and the dark surfaces of the firebricks.

8.2 Reverse Engineering at the Overflow Construction of Nalps Dam (CH)

8.2.1 Introduction

Reverse engineering is well known from industrial applications (cf. [FU, 2004]). Reverse engineering is the process and method for creating 3D-models of existing objects. According to [RAJA and FERNANDES, 2008], reverse engineering is the process of duplicating an existing object or product without using any drawings or documentations. In the field of engineering geodesy, as-built documentation is often used in the meaning of reverse engineering. Additionally, reverse engineering implies the modelling of an object after measuring, whereas as-built documentation may only assist with the acquisition of an object. As-built documentations of objects are widespread in the field of TLS in architectural and archaeological applications (cf. [STERNBERG et al., 2004]) as well as in facility management or acquisition of industrial plants. Alternative measurement methods to TLS are terrestrial photogrammetry and tacheometry. The following discussion refers exclusively to terrestrial laser scanning as an appropriate measurement method.

For TLS, reverse engineering refers to the recognition and extraction of objects from 3D-point clouds (cf. [MILEV and GRUENDIG, 2005]). The geometric data are derived from the 3D-point clouds by parameterisation. [BISKUP et al., 2007], for instance, present reverse engineering for TLS in the field of shipbuilding. A 3D-model was obtained for further analysis and verifications of the ship’s geometry. However, a project dealing with reverse engineering at the overflow construction of Nalps dam in Switzerland was performed at the IGP. The ZLS07 was launched for the measurements in this field of application.

The Nalps concrete arch dam (Figure 8-8) is located in the upper reaches of the Rhine in Switzerland, south of Sedrun in the Nalps valley of the Alps. Although the dam has a maximum height of approximately 127 m above the foundation, only about 100 m are visible, and the crest has a length of 478 m. Nalps has a water storage capacity of 44.5 million m³. It is operated by Hydro Surselva [HYDRO SURSELVA, 2008] and is closely monitored due to excavation of the Gotthard Base tunnel, 1350 m below the dam. The Gotthard base tunnel will be the world’s longest railway tunnel, with a length of 57 km, connecting northern and southern Switzerland through the Alps. Settlements of rock mass above the tunnel due to this excavation work are expected. Significant settlements may, therefore, damage the dam and cause it to fail in a worst-case scenario. An additional continuously observed deformation survey system was installed. It primarily monitors the deformations of the valley and, additionally,
the movements of the dam wall. A brief description of the monitoring systems is described in [BRAEKER, 2006].

Nalps dam, in particular, is monitored due to excavation of the Gotthard base tunnel. Until now, traditional surveying methods, such as levelling, GNSS, and tacheometry, have been adopted for the monitoring. Lately, investigations on TLS with a focus on dam monitoring were performed. In addition to deformation monitoring and damage detection of the dam, the geometry acquisition of the Nalps dam was of primary interest. In [ZOGG and SCHULZ, 2007], the acquisition of the Nalps dam by TLS and the analysis of the laser scanning data are described in more detail. In addition to the geometry acquisition of the dam, measurements of special constructions, such as the overflow construction (Figure 8-9) for the Nalps dam, were performed by TLS. With respect to the overflow construction, the ZLS07 was introduced.

![Figure 8-8 The 127 m high Nalps Dam south of Sedrun (CH).](image1)

![Figure 8-9 Overflow construction of Nalps dam.](image2)

The overflow construction prevents the dam from overflowing in case of a high water level. An almost vertical pipe with a diameter of up to 5 m controls the water down to the base of the dam. Hence, for safety reasons, people are not allowed to stay inside the overflow construction close to the vertical pipe. Access is possible only by securing an operator. Due to the difficult access, the measurement by TLS is challenging as well. However, the ZLS07 allows a practicable setup for scanning the upper part of the overflow construction. The ZLS07 was guided headfirst down into the overflow construction similar to manner in which it was set up for the acquisition of underground utility caverns (cf. section 6).

The main objective of the acquisition of the Nalps dam overflow construction by TLS was to test the operation of and possibilities of the ZLS07 for reverse engineering. The ZLS07 would enable the measurement of constructions and buildings with difficult access. Moreover, the project intended to investigate the quality of the measurement data taken by the ZLS07 for reverse engineering of technical constructions.

8.2.2 Method

The measurement campaign was performed by the ZLS07 and took about one day for the acquisition of the overflow construction. For the measurements, the overflow construction was divided into two sections: a lower and an upper section. The lower part could not be scanned with a conventional setup of a geodetic instrument on a tripod due largely to safety reasons. However, the ZLS07 was guided down headfirst into the overflow construction by a telescope tripod (Figure 8-10). The setup was similar to the setup for acquisition of underground utility caverns (cf. section 6). Four scans with “high” resolution were captured with the headfirst
configuration, one in each corner of the overflow construction. For scanning the upper part of the overflow construction, the conventional setup on a tripod was used (Figure 8-11). Ten scans with resolution “high” were obtained on both sides on top of the overflow construction. Additionally, for registration of the 3D-point clouds, spheres with a diameter of 15 cm were scanned as reference targets. At least four reference targets were measured for each scanner setup. The centre points of the reference targets were measured by a tacheometer. All the reference targets were determined to be in the same coordinate system. The 3D-point clouds of the upper part of the overflow construction were registered using the software Cyclone by Leica Geosystems [LEICA GEOSYSTEMS, 2008]. For the lower part of the overflow construction, no reference targets were scanned and used for the registration of the 3D-point clouds. The 3D-point cloud registration was performed by an ICP-based algorithm implemented in the software Geomagic by Geomagic Inc. [GEOMAGIC, 2008].

8.2.3 Results

The registration of the 3D-point clouds for the upper part of the overflow construction resulted in a mean absolute error of 9.0 mm and a RMS of 10.0 mm for the reference points by using the software Cyclone. The mean absolute error and the RMS refer to 3D-coordinates. At least four reference targets were used for each scan. The reference points were derived from the reference targets as the centre points of the reference spheres. A reference sphere with known diameter was adjusted into the 3D-point cloud of the reference targets by minimizing errors according to the least-square method (cf. section 5.3.1).

For the 3D-point clouds of the lower part of the overflow construction, which were scanned by setting up the ZLS07 headfirst, the registration of the 3D-point clouds was performed in the software Geomagic with an ICP-based algorithm. In a first step, pairs of corresponding points in overlapping regions of two scans had to be selected manually as starting points for the registration. In a second step, a so-called global registration automatically fine-tuned the registration of the 3D-point clouds by minimizing the distance differences between corresponding areas of the 3D-point clouds. As mentioned above, the lower part of the overflow construction was scanned by four scanner setups: two scans in the north and two scans in the south. For processing the scans, the two scans in the north and the two scans in the south were registered together. Figure 8-12 shows the registration of the two northern 3D-point clouds as well as the
result. Afterwards, the two pairs of scans were registered with the 3D-point cloud of the upper part of the overflow construction.

![Figure 8-12 3D-point cloud registration performed according to an ICP-based algorithm.](image)

The results of registrations in the software Geomagic are described and evaluated by an average distance and standard deviation of the distance differences between the points in the overlapping regions of the corresponding scans. Table 8-2 gives an overview of the statistics for the 3D-point cloud registrations of scans in the north and south of the overflow construction. Hence, an obvious difference is detectable in the standard deviations for the two registrations.

<table>
<thead>
<tr>
<th></th>
<th>scans north</th>
<th>scans south</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of iterations</td>
<td>17</td>
<td>20</td>
</tr>
<tr>
<td>total number of points</td>
<td>1.96 million</td>
<td>1.31 million</td>
</tr>
<tr>
<td>average distance [mm]</td>
<td>14.7</td>
<td>13.1</td>
</tr>
<tr>
<td>standard deviation [mm]</td>
<td>15.7</td>
<td>9.5</td>
</tr>
</tbody>
</table>

*Table 8-2 Statistics of 3D-point cloud registration performed in the software Geomagic.*

Before modelling the 3D-point cloud of the overflow construction (Figure 8-13), the scanning noise was reduced. For this purpose, a filter algorithm by Geomagic was used. According to the software specifications, the scanning noise was compensated for by moving points to the statistically correct locations. The 3D-point cloud was filtered depending on adjustable parameters of the software (type of noise reduction, smoothness level, iterations, deviation limit). For the overflow construction, standard parameters were used (type: free-form shape; smoothness level: 2; deviation limits: 0.1 m) and the results show an average distance of 9.2 mm and a standard deviation of 8.7 mm for the points that were moved during the noise reduction. However, the noise reduction performed by Geomagic is a sort of “black-box” in which it is difficult for users to interpret and reconstruct the results.

In addition to the noise reduction, 5% of the data were used for further processing. A regular point-to-point spacing of 50 mm was established. The 3D-point cloud of the overflow construction contains about 10.3 million points without data reduction. The primary reason for the data reduction was the processing capacity and handling of the 3D-point cloud by the
computer system. Separation of the 3D-point cloud would be an alternative solution instead of reducing the data.

![Figure 8-13 3D-point cloud of overflow construction.](image)

![Figure 8-14 Triangulated 3D-point cloud.](image)

Modelling the 3D-point cloud with respect to the overflow construction was largely focused on triangulation (Figure 8-14). The triangulated model contained about $915'000$ triangles. Data holes on the triangulated surface were interactively filled in by using the corresponding tools of Geomagic. Figure 8-15 shows the triangulated and shaded model of the overflow construction. Details of the triangulation can be seen in Figure 8-16. However, a triangulated 3D-point cloud enables, for instance, the calculation of cross-sections and the import into CAD-systems as well as the parameterisation of the 3D-surface according to NURBS. Modelling and parameterisation of surfaces by NURBS are well known specifically from industrial applications. In addition, surface modelling has been performed in the field of heritage recording and documentation (cf. [BRIESE et al., 2003], [TEUTSCH et al., 2004]), or [RESSL, 2004]).

![Figure 8-15 Triangulated and shaded 3D-point cloud.](image)

![Figure 8-16 Detail view of overflow construction with outlet.](image)

### 8.2.4 Conclusion

The acquisition of the Nalps dam overflow construction by the ZLS07 shows, on the one hand, the application of the 3D-laser scanner in the field of reverse engineering and, on the other hand, its capabilities for acquisition of objects with difficult access. The different configuration and setup possibilities of the ZLS07 enable new application areas for TLS in general. In any case, it should be noted that the measurement accuracy and scanning resolution of the ZLS07 are limited (cf. section 3.3.4). The registration accuracy and scanning noise of the performed scans lie in a range that could be expected.

The registration of the 3D-point clouds by point-to-point registration, according to the ICP-based algorithm, was crucial due to small overlapping areas of the corresponding 3D-point
clouds. The overlapping area of the 3D-point clouds was less than 30%. However, the registration could be performed with average distances of corresponding points of about 14 mm and standard deviations of up to 16 mm according to the statistics given by the software Geomagic. The rather large standard deviations were caused by the measurement configuration and the geometric specifications of the overflow construction. Small angles of incidence of the laser beam on the object surface were the consequence, and the angles of incidence influence the distance measurement accuracy (cf. section 4.2).

In general, it can be concluded that the ZLS07 is an adequate measurement system for applications in the field of reverse engineering. The main advantages are in the flexible measurement configurations and the robustness of the measurement system. In addition, a levelled measurement setup is not required for the scans, but the limitations are the measurement accuracy and range of the ZLS07 compared to commercial terrestrial laser scanners, such as the Imager 5006 (cf. section 5.3.4.2).

8.3 Review

The primary intended application of the ZLS07 is the acquisition of underground utility caverns (cf. section 6). Thus, the development of the ZLS07 was focused on this specific application. Nevertheless, the ZLS07 can also be used in other fields of application like reverse engineering or damage detection. In an incinerator from a chemical industry plant, damages to the firebricks inside the incinerator were detected by the ZLS07. Furthermore, a comparison with the Imager 5006 showed a high sensitivity on the part of the ZLS07 in terms of angle of incidence of the laser beam on the object surface. However, the same damage to the firebricks could be detected and located by the ZLS07 as well as by the Imager 5006.

Reverse engineering, which originated in the field of industrial surveying [RAJA and FERNANDES, 2008], corresponds to the well-known as-built documentation in the field of engineering geodesy. TLS is a convenient measurement method for reverse engineering due to the areal approach. Thus, the overflow construction of the Nalps dam south of Sedrun (CH) was measured by the ZLS07. For this purpose, the ZLS07 was set up by being lowered headfirst into the overflow construction because a setup inside the overflow construction was not possible due to safety reasons. This project revealed the flexibility of the ZLS07 in terms of measurement setup.

The range of applications for the ZLS07 is broad. Thus, it can be stated that the ZLS07 is a flexible applicable terrestrial laser scanner. Moreover, the setup of the ZLS07 does not influence the measurements. The instrument does not need to be levelled for measuring, enabling the scanning of objects that are difficult to access. Nevertheless, the weak points that limit the range of applications of the ZLS07 are largely the accuracy within a cm-range, the limited vertical angular resolution of 0.25°, and the limited range of 32 m for mm-resolution. In addition, the limited vertical angular resolution affects the level of detail for a scan.
9 Summary

9.1 Conclusions

High precision TLS is a very fast measurement method which allows contactless and area-wide surveying of objects. TLS can be considered a newer measurement technique in the field of engineering geodesy, so terrestrial laser scanners are not yet commonly in use, not at least due to the high initial costs of a TLS system (two to three times that of a high-end tacheometer) and the usually extensive post-processing. In addition, users are still unfamiliar with the measurement workflow and the laser scanner characteristics. Thus, the potential of new applications for TLS is often disregarded. Hence, this thesis intended to address both the low-cost aspect and the development of new applications along with the development of a robust close-range terrestrial 3D-laser scanner.

The described development of a robust close-range 3D-laser scanner was strongly focused on the acquisition of underground utility caverns. Until now, underground utility caverns have usually been measured manually by operators who had to climb through a manhole down into the caverns. Thus, TLS enables the measurement of underground utility caverns without manual inspection. Moreover, the sewage and water systems in most cities are in need of renovation. Therefore, the request for 3D-data of underground utility caverns will increase in the near future.

This thesis deals with the development of the terrestrial 3D-laser scanner ZLS07, its calibration and investigations, the acquisition of underground utility caverns, and the automatic post-processing of 3D-point clouds. In addition, it reveals further applications for TLS with a focus on the ZLS07. The thesis shows the adoption of low-cost components, specifically the 2D-laser scanner SICK LMS200-30106 by Sick AG [SICK, 2008], in engineering geodesy and presents calibration routines with a focus on the ZLS07. Although the implemented distance measurement unit originated in the fields of industrial applications and robotics, additional calibration routines enable the adoption for applications in the field of engineering geodesy. Based on test measurements, it can be stated that the ZLS07 meets the specific requirements in terms of measurement accuracy, operational handling, and robustness. Moreover, the ZLS07 has been established as a new measurement method in the workflow for the acquisition of underground utility caverns in the city of Zurich by GeoZ.

The calibration and investigations of the ZLS07 distinguished between component and system calibration and investigation. For system investigations of terrestrial laser scanners in general, a 3D-reference field is established. Measurements by terrestrial laser scanners are compared to measurements by tacheometers. For calibration purposes of the ZLS07, the component calibration is preferred to the system calibration due to the exact error determination of a particular component in the measurement system. In addition, new calibration routines are developed, for example, for the calibration of the data synchronisation between the rotation table and distance measurement unit of the ZLS07. Furthermore, well-established calibration routines for TLS are adopted for the ZLS07.

In addition to the development, calibration, and investigation of the ZLS07, this thesis introduces additional applications of the ZLS07 for the acquisition of underground utility caverns and deals with the post-processing of the 3D-point cloud with a focus on automatic geometry detection for underground utility caverns. Furthermore, the ZLS07 can be applied to applica-
tions other than the acquisition of underground utility caverns. However, for all applications of the ZLS07, the accuracy is secondary to overcoming difficult accessibility of the objects. Scanning the overflow construction of Nalps dam, for instance, also requires a headfirst measurement setup.

This thesis presents a fully operable measurement system. However, the limitations are identified largely in the post-processing of 3D-point clouds. As mentioned, post-processing is another crucial factor in terms of efficiency and success of a laser scanning project. As a matter of fact, the presented automation approach operates only under ideal conditions with a standard underground utility cavern. The geometry detection still needs interaction from the operator. Moreover, the described automation is based on a 2.5D-approach. Horizontal and vertical extensions of the caverns are separately deduced. For the hardware – the ZLS07 –, the main limitations are specified in the measurement range, the measurement accuracy, the vertical angular resolution, and the interfaces used. These limitations affect the range of applications of the ZLS07.

In conclusion, the developed ZLS07 is an operable area-wide measurement system that meets the above requirements. In addition, it enables new applications for TLS in engineering geodesy, specifically in the field of underground utility cavern acquisition.

9.2 Outlook

As mentioned above, the developed measurement system meets the predefined requirements. It works well and reliably. It achieves the expectations in terms of a new measurement system for the acquisition of underground utility caverns. However, there is still need for further development and improvement in the field of TLS in general and for the ZLS07, specifically. Improvements are possible for the hardware and software. In terms of hardware improvements, new sensors and measurement techniques, for instance, RIM-technology, will enter into the field and probably replace close-range 3D-laser scanning. The fusion of the different measurement techniques will lead to an all-in-one solution for engineering geodesy. For software related improvements, the post-processing of the resulting 3D-point clouds should be further automated. Data from additional sensors, such as CCD-cameras, have to be integrated into TLS post-processing software. Moreover, knowledge-based processing should be implemented. In addition, software tools with a strong focus on engineering geodesy should be designed instead of the particular and extensive data modelling. Deformation analysis and area-wide permanent monitoring are just a few specific subjects for software development.

In addition to hardware and software improvements in the field of TLS, a standardisation is strongly needed for the terminology and definition of the measurement accuracy and precision of a terrestrial laser scanner. Furthermore, standard calibration and investigation procedures should be developed, thus allowing a standardised comparison of different TLS systems and enabling users to understand and investigate these “black-boxes.” Moreover, users should be able to investigate their TLS system in the field with a standardised procedure similar to probing levelling instruments.

For the ZLS07 specifically, the focus of further research lies in the adoption of other applications and in the improvement of new sensor technologies. In terms of new applications, the focus should be centred on applications in the field of tunnelling. Rough environmental conditions need robust measurement instruments. In addition, highly dense 3D-data are being increasingly requested. Thus, the scanning and volume detection of the excavation could be an interesting application for a robust close-range 3D-laser scanning system. First tests were carried out in the Mont Terri tunnel (CH), where the dusty conditions turned out to be one of the greatest problems for electro-optical geodetic instruments. However, the first tests focusing on
the operation of the ZLS07 under conditions in tunnels were auspicious (Figure 9-1 and Figure 9-2).

Over the last years, new sensor technologies for measurement purposes have been developed, such as the RIM-technology. Compared to TLS, RIM-cameras acquire a distance map of all objects within the field-of-view of the camera. The field-of-view depends on the number of pixels of the CMOS-sensor. Figure 9-3 shows the SwissRanger SR-3000 by Mesa Imaging AG [MESA IMAGING, 2008] with a resolution of 176 x 144 pixels, a measurement range of 7.5 m, and an accuracy within dm-range. The resulting image, which contains distance and intensity information, can be visualised as a 3D-point cloud (Figure 9-4). In addition, the post-processing of the RIM-data is similar to the post-processing of TLS data. Thus, analysis and modelling algorithms and routines can be adopted. However, future research should deal with the implementation of this technology in the field of engineering geodesy and its appropriate applications. Further improvements of the RIM-technology should be achieved in terms of accuracy and measurement range for proper use in engineering geodesy.
In the near future, sensor fusion will become an increasingly discussed topic for research and commercial purposes. It will unify the different measurement technologies of TLS, tacheometry, GNSS, photogrammetry, and RIM and provide very flexible applicable measurement systems. TLS will contribute its part with regard to the fast, contactless, and area-wide 3D-measurements. Thus, the understanding of this measurement technology and the knowledge of its applications are indispensable for future developments.
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## Abbreviations

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<tr>
<td>AMCW</td>
<td>Amplitude-Modulated Continuous Wave</td>
</tr>
<tr>
<td>ANSI</td>
<td>American National Standards Institute</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society of Testing and Materials (ASTM International)</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge-Coupled Device</td>
</tr>
<tr>
<td>CHF</td>
<td>Swiss Franc</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary Metal-Oxide-Semiconductor</td>
</tr>
<tr>
<td>ERZ</td>
<td>Entsorgung + Recycling Zürich</td>
</tr>
<tr>
<td>GeoZ</td>
<td>Geomatik + Vermessung Stadt Zürich</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic Information Systems</td>
</tr>
<tr>
<td>GNSS</td>
<td>Global Navigation Satellite System</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphic User Interface</td>
</tr>
<tr>
<td>ICP</td>
<td>Iterative Closest Point</td>
</tr>
<tr>
<td>IGP</td>
<td>Institute of Geodesy and Photogrammetry at ETH Zurich</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organisation for Standardisation</td>
</tr>
<tr>
<td>ISPRS</td>
<td>International Society for Photogrammetry and Remote Sensing</td>
</tr>
<tr>
<td>LADAR</td>
<td>Laser Detection And Ranging</td>
</tr>
<tr>
<td>LASER</td>
<td>Light Amplification by Stimulated Emission of Radiation</td>
</tr>
<tr>
<td>LIDAR</td>
<td>Light Detection and Ranging</td>
</tr>
<tr>
<td>METAS</td>
<td>Swiss Federal Office of Metrology</td>
</tr>
<tr>
<td>NIST</td>
<td>National Institute of Standards and Technology, USA</td>
</tr>
<tr>
<td>NURBS</td>
<td>Non-Uniform Rational B-Spline</td>
</tr>
<tr>
<td>PVC</td>
<td>Polyvinyl Chloride</td>
</tr>
<tr>
<td>RADAR</td>
<td>Radio Detection and Ranging</td>
</tr>
<tr>
<td>RGB</td>
<td>Red-Green-Blue</td>
</tr>
<tr>
<td>RIM</td>
<td>Range Imaging</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>RTSP</td>
<td>Real Time Streaming Protocol</td>
</tr>
<tr>
<td>TLS</td>
<td>Terrestrial Laser Scanning</td>
</tr>
<tr>
<td>VIM</td>
<td>International Vocabulary of Basic and General Terms in Metrology (published by ISO)</td>
</tr>
</tbody>
</table>
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References


References


A Appendix

A.1 Rotation Table ETH Zurich

Figure A-1 shows the gear ratio of the rotation table for the terrestrial 3D-laser scanner ZLS07. The rotation table detects the actual horizontal angles of the ZLS07. The angles are defined by multiplying the actual number of motor axis rotations and the gear ratio. No encoder is directly implemented on the axis of the rotation table. In addition, the angular resolution depends on the gear ratio between the motor axis and rotation axis of the rotation table.

Figure A-1 Gear ratio schema of rotation table.
A.2 Software

Two software tools were developed for controlling the terrestrial 3D-laser scanner ZLS07 and for post-processing the raw measurements:

- **KMS-controller**
- **KMS-processor**

Figure A-2 presents the GUI of the KMS-controller. A real-time viewer that shows the actual vertical profile of the ZLS07 is implemented. In addition, the scanning resolution, working directory, interfaces, measurement modes (mm- or cm-resolution), and so on can be chosen.
A Appendix

Figure A-3 shows the GUI of the *KMS-processor*. The *KMS-processor* calculates the 3D-point cloud from the raw measurements (horizontal and vertical angles, distances) depending on the configuration of the ZLS07 (normal, yawing; headfirst, yawing-top). In addition, calibration parameters are implemented. They are added to the measurements by calculating the 3D-point clouds. Additional filters allow the data reduction, e.g., a distance dependent reduction.

Figure A-3 KMS-processor for processing the measurements of the ZLS07.
A.3 Fourier-Series

A periodic function can be represented by a sum of harmonic functions. This sum is called a Fourier-series. The Fourier-series models any periodical function by simple sine and cosine functions.

A simple sine oscillation, for instance, can be described as:

\[ y = f(x) = A \cdot \sin (\nu \cdot x + \varphi) \]  \hspace{1cm} (A.1)

with an amplitude \( A \), a frequency \( \nu \), and a phase shift \( \varphi \) (cf. [BRONSTEIN and SEMENDJA- JEW, 1999]).

The periodic function \( f(x) \) can be expressed as a sum of sine and cosine functions (Fourier-series):

\[ f(x) = \frac{a_0}{2} + \sum_{j=1}^{\infty} \left( a_j \cdot \cos (j \cdot x) + b_j \cdot \sin (j \cdot x) \right) \]  \hspace{1cm} (A.2)

The determination of the coefficients \( a_j \) and \( b_j \) is subject to a harmonic analysis, the Fourier-analysis.

For analysing a series of data, the Fourier-analysis enables the detection of periodicities and amplitudes of existing sine and cosine functions. An equidistant series of data (within the interval \( 0 \leq x < L \)) is required to detect harmonic oscillations. The coefficients \( a_k \) and \( b_k \) are called Fourier-coefficients and can be approximately derived by a numerical integration (cf. [BRONSTEIN and SEMENDJA- JEW, 1999]):

\[ a_0 = \frac{2}{N} \sum_{i=0}^{N-1} y_i \]  \hspace{1cm} (A.3)

\[ a_k = \frac{2}{N} \sum_{i=0}^{N-1} y_i \cdot \cos \left( \frac{2\pi \cdot i \cdot k}{N} \right) \]  \hspace{1cm} (A.4)

\[ b_k = \frac{2}{N} \sum_{i=0}^{N-1} y_i \cdot \sin \left( \frac{2\pi \cdot i \cdot k}{N} \right) \]  \hspace{1cm} (A.5)

\( N \)  \hspace{1cm} number of measurements

\( n \)  \hspace{1cm} half number of measurements. If \( N \) is odd-numbered: \( n = \frac{1}{2} \cdot (N + 1) \)

\( k \)  \hspace{1cm} 0, 1, 2, …, \( n \)

Finally, the Fourier-series \( g(x) \) is calculated as:

\[ g(x) = \frac{a_0}{2} + \sum_{k=0}^{n} \left( a_k \cdot \cos \left( \frac{2\pi \cdot k \cdot x}{L} \right) + b_k \cdot \sin \left( \frac{2\pi \cdot k \cdot x}{L} \right) \right) + \frac{a_{\infty}}{2} \cos \left( \frac{2\pi \cdot n \cdot x}{L} \right) \]  \hspace{1cm} (A.6)

The last element of the Fourier-series \( g(x) \) in (A.6) only results if \( N \) is even. The amplitude \( A_k \) and the phase shift \( \varphi_k \) of the harmonic oscillation at a specific frequency are calculated from the Fourier coefficients \( a_k \) and \( b_k \):
\[ A_k = \sqrt{a_k^2 + b_k^2} \]  \hspace{1cm} (A.7)

\[ \phi_k = \arctan \left( \frac{a_k}{b_k} \right) \]  \hspace{1cm} (A.8)

**Nyquist Frequency**: The Nyquist frequency \( \nu_N \) is the maximum frequency that can be detected. The period of the Nyquist frequency \( \nu_N \) is twice the measurement spacing \( \Delta D \).

\[ \nu_N = \frac{1}{2 \cdot \Delta D} \]  \hspace{1cm} (A.9)

The result of a Fourier-analysis is a frequency spectrum with corresponding amplitudes. For a Fourier-analysis, frequencies that accomplish at least a single oscillation within the measurement range are detectable. By reducing the measurement range, oscillations with accordingly smaller periods can be detected.

**Aliasing**: Aliasing is based on the fact that a series of data only contains discrete values and not a continuous data set. The measurement spacing \( \Delta D \) is responsible for the failure to detect a unique frequency of the data series. A sine oscillation of high frequency cannot be distinguished anymore by a lower frequency, although the lowest frequency \( \nu \) is called the principal alias. In general, the following frequencies are aliases of the principal alias [MAUTZ, 2001]:

\[ 2 \cdot \nu_N \cdot z \pm \nu \]  \hspace{1cm} (A.10)

\( z \in \mathbb{Z} \) (set of integers)
\( \nu \in [0, \ldots, \nu_N] \)
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This dissertation was carried out at the Institute of Geodesy and Photogrammetry ETH Zürich. I would like to thank all the people who contributed to the successful completion of this work. In particular, I would like to give many thanks to:

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Spanish         basics (spoken and written)