UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

Towards a Short-Range Laboratory for Testing the Accuracy of Terrestrial 3D Laser Scanning (TLS) Technologies

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A research report submitted to the Faculty of Engineering and Built Environment, University of Witwatersrand, Johannesburg, in partial fulfilment of the requirement for the degree of Masters of Science in Engineering.

Johannesburg, 2019

DECLARATION

I declare that this research report is my own unaided work. It is being submitted for the degree of Master of Science in Engineering to the University of Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

PO Kolapo

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Signature of Candidate

27 September 2019

ABSTRACT

Laser Scanning is a 21st century surveying technique used to generate high density and point cloud data in 3D for surveying, mapping and monitoring purposes, for example rock mass movement in mining. For high precision and accurate work, the instrument must be used correctly and with regular calibration and checks to ensure that it constantly performs according to expectations and manufacturer specifications.

The aim of this research was to develop a short-range scanning laboratory for testing the accuracy of terrestrial laser scanning systems for rock engineering applications. This research was based on methods used by previous researchers in testing the accuracy of the instrument and the development of a suitable facility for such testing.

The procedure used in developing the short-range testing facility included selecting an appropriate venue of size and shape that suits the requirements for a short-range laser scanning laboratory. This was followed by the construction of the master control beacon and creation of additional scan set ups in order to capture all the points in the facility. Targets were strategically placed on the wall and roof of the laboratory in order to determine the centre point coordinate of each target.

A Leica Total Station TCR 1201+ and Trimble S6 Total Station were used to establish accurate coordinates for the control beacon and the targets respectively. Thereafter, the scanning of the targets was carried out using a FARO Focus XD 130 terrestrial laser scanner. Comparisons were performed using the coordinates from the terrestrial laser scanning and those of the Total Station to examine the point accuracy of the scans.

The results from the comparison between the scanner coordinates and the total station coordinates showed that the FARO Focus laser scanner performed within manufacturer specifications but not always. This implies the instrument is capable of generating accurate point and reliable cloud data that can be used for the purpose of monitoring underground rock mass movements. Errors regarded mistakes in the final analysis occurred as a result of target design (in terms of size and orientations) and oblique lines of sight.

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Lastly, my heartfelt thank you must be given to my family and my loving parents for their moral support, my brother, Engineer Emmanuel Kolapo for his financial support and encouragement throughout my study. My deepest gratitude goes to Babalola Titilope for her support and prayer during the entire research work. Above all, I give thanks to God almighty, the source of wisdom, knowledge, and understanding for guiding my path in completing this degree.

DEDICATION

This research work is dedicated to God Almighty, the Alpha and the Omega and to those who believe in themselves.

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CHAPTER ONE

1 Introduction

1.1 Background

Laser scanning is a recent innovation used for generating high density point cloud data. This type of measuring system potentially provides complete and detailed mapping for monitoring of rock mass movements in mining. It is therefore important to check the accuracy of these laser scanners to check if their point clouds are fit for the purpose of rock engineering analysis in mining. Randall & Philip (2013) reported that laser scanners were first introduced in the late 1980s and were commercially available in the market in the 1990s. Since then, there has been significant technological advancement in data collection, data storage, processing speed and mobile mapping techniques. This scanning system captures high density data by emitting light-pulse (laser beam) for the recording and reflecting of light to determine the distance of reflected objects. This process is known as LiDAR (Light Detection and Ranging).

Recent advancements in the technology include spot geo-referencing and electronic levelling of the laser scanners. The integration of GNSS (Global Navigation Satellite System) and camera systems as a common use for geo-referencing of the point cloud is another improvement. With all these elements, 3D laser scanning is becoming the generally accepted method for 3D point cloud generation. The advantages of this equipment over other surveying equipment are significant. The major benefit of the equipment include, quick, detailed, precise data capturing that reduces the field work time.

However, the current mining market is overwhelmed by technology vendors offering laser scanning systems as a solution for real time mapping and monitoring rock mass movement for mine safety purposes. It is therefore necessary to independently check the accuracy and precision of the laser scanner to prevent unnecessary expenditure and in making good safety decisions in mining. These checks will increase the level of confidence in the quality of the results as mines are faced with the problem that the accuracy of the technology is yet to be tested for mine safety accuracy and conditions. Fangi, *et al.*, (2001) indicated that factors affecting that the accuracy of a laser scanner include the following;

- small beam spot size;
- short laser wave length;
- strength of the laser pulse; and
- the narrow width of each laser pulse and detection sensitivity.

These factors are caused by environmental effects such as temperature, atmospheric pressure and in addition to the properties of the reflectivity of the target.

It is important to establish the accuracy of the laser scanner to increase integrity and confidence in the quality of the acquired point cloud data of the instrument used. The accuracy of the laser scanner can be determined by performing accuracy analysis using various means of control measurement and calibration testing. Prior to the commencement of testing a laser scanner, the target coordinates have to be determined accurately by Total Station surveys. In order to evaluate the accuracy of any 3D laser scanner, the distance and the coordinates measured between the instrument and the points (targets) must be compared to those obtained from a Total Station survey from an accurate survey control network. The difference between the scanned data and the measured coordinates will indicate the level of the accuracy of the laser scanner.

1.1.1 Problem Identification

Accuracy is an important parameter of any laser scanning system to consider. This would assist with making sound decisions on mine safety when the resulting point cloud data comparisons detect a potentially unstable rock mass. This would also assist in creating high quality and reliable point clouds for decisions to prevent loss of life, injury and equipment damage. Before mines integrate new solutions into their operations, there is a need for proper testing and calibration of the equipment in order to confirm that accuracy requirements are being met.

The request to scientifically test the accuracy of a laser scanning system initially came from Gold Fields that had bought a mobile laser scanning system. After mounting the scanner on the mobile platform, they detected underground rock mass movement over short periods of time. The questionable results brought about the request for the Wits Mining Institute (WMI) to further investigate the accuracy of their laser scanning system.

The accuracy and precision checks must be done on a stationary beacon before they can be conducted on a moving platform. This research provides the accuracy and precision checks from the stationary beacon.

Before checking the accuracy and precision from a moving platform, this must be done from a stationary beacon which this research covers. Then, this will be followed by accuracy testing on a moving platform once the accuracy from a terrestrial laser scanner is known.

In addressing this issue, a short-range scanning laboratory with a master point cloud was developed. Comparisons were done between the scanner value and the conventional survey value. The laser scanner value was also compared to the manufacturer specifications for that laser scanner. The results would decide if the scanner was performing according to manufacturer's specifications. Moreover, it would determine the quality of the measurement and highlight any accuracy deficiencies of the device.

The accuracy testing service that WMI would provide will improve confidence in the results produced by other laser scanners, as the technologies will be certified for a particular task.

1.1.2 Rationale and Motivation

The main goal of developing this laser scanning laboratory was to test the accuracy of terrestrial laser scanners and whether these are not fit for the purpose of rock engineering analysis. Testing is done by comparing point clouds to determine whether the instrument is performing within manufacturer specifications. The compared point clouds data will evaluate the quality of measurement by the scanner to decide the most suitable laser scanners for particular tasks. More importantly, it will help to decide if the equipment is generating high quality data points that can be used for good decision making on detecting rock mass movement. The potential benefits of the scanning laboratory include;

- Good decision-making for mine safety purposes;
- A better way to identify sources of errors and performance of the laser scanner;
- The best way to decide which laser scanner is best for which task;
- A better way to determine whether the device requires manufacturer calibration;
- Improving accuracy in mapping for monitoring rock mass movement;
- Increase the level of confidence in the quality of the results;
- Accurate volume calculations in mine planning; and
- Intelligent 3D Computer Aided Design (CAD) as-built models with integration of a camera system for effective monitoring.

In surveying, the ability of terrestrial laser scanners to work effectively and efficiently pose a significant opportunity in mining. This is why it is important to investigate the effectiveness and the quality of the results produced by the laser scanning system (Mechelke, *et al*., 2007). The assessment will highlight any issue pertaining to the performance of the laser scanner in providing quality point cloud data. In order to achieve this, research was proposed with the aim of developing a standard testing laboratory service that would certify a new laser scanner for particular tasks of spatial verification.

1.2 Research Objective

The objective of this research was to develop a short-range scanning laboratory for testing and analysing the accuracy of terrestrial laser scanners. To test the accuracy of the laser scanner, the point cloud data would be compared with the Total Station (true) value in order to determine the performance of the laser scanner. This would determine if the laser scanner is fit for the purpose of monitoring rock mass in underground mining environment. The result would be compared with manufacturer's specifications to establish the performance of the laser scanner.

1.2.1 The Scope of the Research

The research was aimed at the development of a laboratory for testing terrestrial laser scanning (TLS) systems, with targets fixed on the wall at different heights and on the roof of the testing laboratory. The short range facility with typical operating range of 10m was used for the scanning. The dimensions of the scanning laboratory are 14.2m x 8.2m x 4.4m with an approximate triangular shape. The research was strictly based on the use of angles and ranges to determine the point accuracy of a terrestrial laser scanner using high precision targets in the short range.

This research would be aimed at improving the confidence in the results produced by scanning equipment. The point cloud comparisons would decide if the laser scanner was performing within the manufacturers specifications and would assist in selecting the best laser scanner for the task. In addition to the comparisons of point cloud data, errors in the results would be identified and good decisions could be made on mine safety and operational efficiency matters.

1.3 Terrestrial Laser Scanning Techniques

Terrestrial laser scanners (TLS) produces a point cloud based on the flight time of the laser signal by emitting and detecting the reflected laser signal from the targets. The measured flight time for the emitted and reflected laser signal is used for calculating an accurate distance between the scanner and the object. The instrument records the object surface and its physical features. The ability to perform effectively and efficiently in data acquisition, makes the laser scanner superior to other land surveying instruments.

The point cloud is commonly used in analysing a detailed 3D representation of the surrounding area in the field of engineering, which includes 3D modelling, mapping and real-time monitoring of rock mass movement. To obtain point clouds, the terrestrial laser scanner was used to scan the location from different positions. The ideal set up for the scanning was done in a way that the position of the laser beam would be perpendicular to the surface of the targets.

The value of the laser scanner over other traditional surveying instruments in capturing millions of points in a single scan should increase the level of confidence in the result. This is why testing of the laser scanner is important to detect if there are any accuracy deficiencies in order to ensure that good and quality results are produced. Despite the accuracy and precision of the laser scanner, the point cloud may contain some errors caused by the mechanical properties of the laser scanner, scanning geometry and the properties of the targets (Ji Sang, *et al*., 2016). The incidence angle influences the quality of the point cloud produced, the lower the incidence angle the higher the reflected intensity and the higher accuracy of the distance measured (Soudarissanane, *et al*., 2007). In order to obtain accurate and precise data, regular testing and calibration of the terrestrial laser scanner must be conducted to confirm the accuracy requirements.

1.3.1 Working Principle of Terrestrial Laser Scanner

A terrestrial laser scanning system is a remote sensing instrument that works on the concept of transmitting light-pulse (laser beam) and receiving the returning signal at a known position. This generates a point cloud based on the time of flight of laser signals which are emitted from a laser scanner and reflected from targets. The laser scanner serves as the transmitter, receiver, and detector of the laser signal. An example of measurement of time taken by the laser signal to travel back to the source is shown in Figure 1.1. The emitted laser signal returned to the source after hitting the surface of an object to deliver the positioning (X, Y, Z), intensity and Red Green Blue (RGB) colours. The intensity of the returning signal depends on the factors such as the distance between the scanner and the targets, the incidence angle and the surface properties of the target.

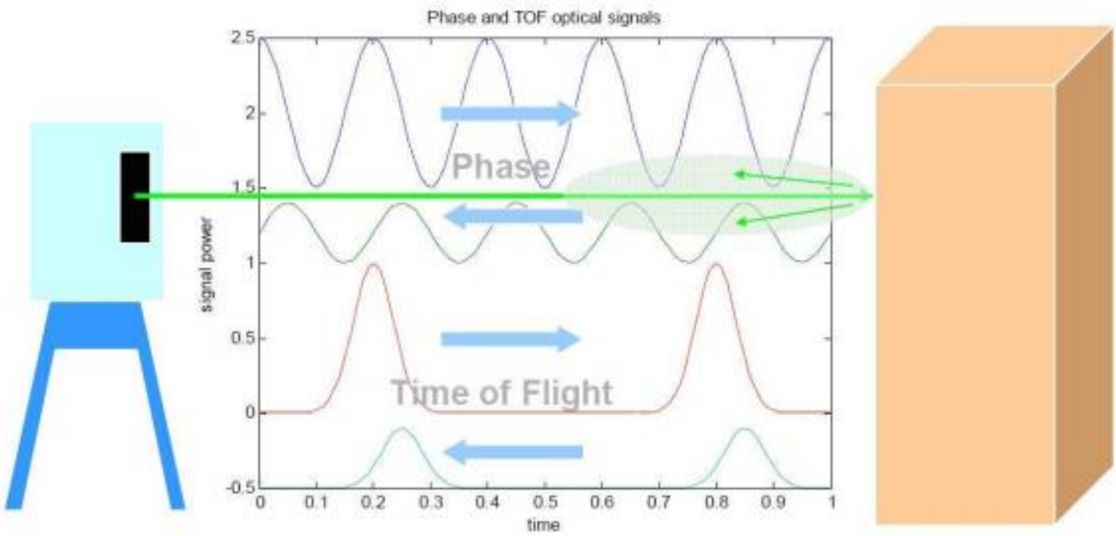


Figure 1.1: Laser Scanning Principle (Al-Neshawy, *et al*., 2009).

The reflected laser signal returns to the laser scanner with the calculated distance, coordinate and the intensity of the returning laser signal. The intensity of the returning signal might influence the quality of the point cloud along with errors from the terrestrial laser scanner. The instrument errors in laser scanning systems occurred as a result of instrument imperfections from the manufacturer. These errors are categorised into range error and angular error (Ji Sang, *et al*., 2016). The range error is the maximum error in the distance measured between the scanner and the target. Boehler & Marbs (2003) stated that the range error in measurement can only be determined when a known distances in range direction are measured with the laser scanner. The angular error occurred as a result of poor synchronisation between angular reading components of the laser scanning system (Abbas, *et al.*, 2013a). The misalignment of the rotating optical component of the laser scanner system will result in errors perpendicular to the propagation path. An example of this is the angular error caused through the deflection of laser pulse by a small rotating mirror (Boehler & Marbs, 2003).

1.3.2 Distance Measurement

Distance is measured by calculating the travel time between the emitting and returning signal. The travel time determines the travel distance which is twice the distance between the laser scanner and the target, that is, to the target and back to the laser scanner. The quality of a measured distance is a function of the scan angle, thus the lower the angle of incidence and the shorter the range, the higher the accuracy of the distance measurement.

The principle of distance measurement in terrestrial laser scanning technology can be categorised into pulse based and phase based. A pulse-based scanner is also known as a time-of-flight (TOF) scanner that measures at long distances with lower accuracy and scanning speeds. This scanner measures distance by timing the round-trip time of a pulse light. The phase-based laser scanner measures at a short distance with high speed and better accuracy. Distances are measured using the phase difference by taking the difference between the transmitted and the returning wave. A phase-based laser scanner has a higher measurement rate of up to millions of points per seconds with a wider field of view on both vertical and horizontal angles. Accuracy of a time-of-flight laser scanner depends on how precisely one can measure the travel time of the laser beam.

The accuracy testing identified the sources of systematic error in the scan which would be used in checking the performance of the scanner. Time of Flight (TOF) scanner sends a short laser pulse to the target, and the time difference between the emitted and received pulses is used to determine the range. The systematic errors in range measurement can be determined when the distance between the scanner and the target are known. When travel time *t* is recorded, the distance can be calculated as shown in equation (1.1) (Feng, 2012);

$$Distance = \frac{\text{Speed}*\text{Time of Flight}}{2} \quad (1.1)$$

The travel time *t* is the time taken for the emitted signal to capture the object and return to the sensor. At known speed of light, the round-trip time determines the total distance travelled which is the distance between the scanner and the surface. Figure 1.2 shows the measurement of the distance from a phase based laser scanner from the emitted laser signal and the received signal.

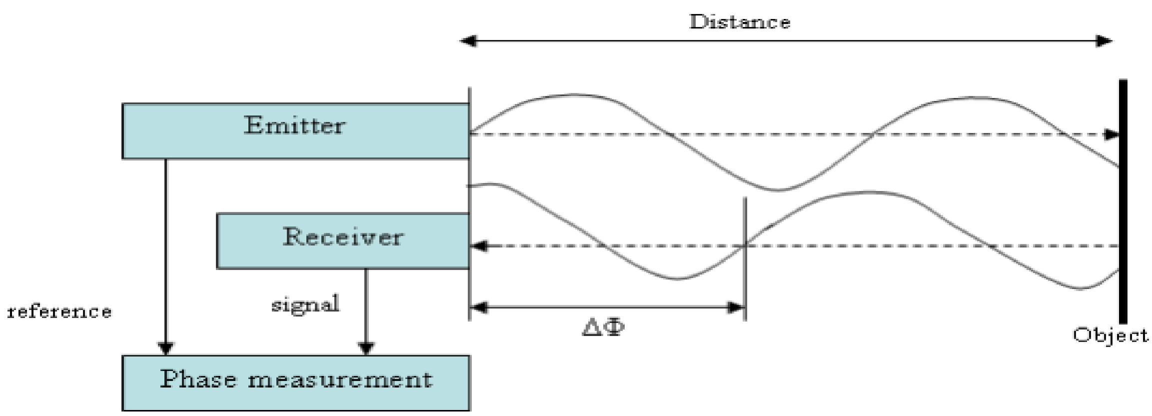


Figure 1.2: Phase Based Measurement Principle (Genechten, 2008)

1.3.3 Types of Scanning Systems

A laser scanner captures millions of points from a single scan with high speed and accuracy. Its ability to offer detailed analysis of the surroundings for digital modelling and visual effects attracts surveyors and engineers to the technology. These benefits make laser scanning a better option for point clouds acquisition compared to other surveying instruments. According to Liang, *et al*., (2014) laser scanning system can be classified into three systems;

- Airborne Laser Scanning system (ALS);
- Terrestrial Laser Scanning system (TLS); and
- Mobile Laser Scanning system (MLS).

Airborne Laser Scanning system (ALS)

Airborne Laser Scanning uses an aircraft or drone as a platform to capture three-dimensional point clouds. This scanner captures millions of point cloud data for large areas from the air within a short period of time. ALS was designed for data capturing and digital modelling because of its high penetration capacity and ability to reflect the laser beam while flying. The scanning instrument is often used to calculate the volume of landfill materials and earth masses (Lenda, *et al*., 2016). A particular attribute of ALS is the ability to capture information about inaccessible areas or conditions posing a threat to humans. This instrument can be flown at very low heights, and consequently the potential to obtain better precision and resolution. With a field of view of 60^o to 75^o, it is easier to acquire a complete set of data during a single flight.

The components of ALS as described by Balenović, *et al*., (2013) are shown in Figure 1.3:

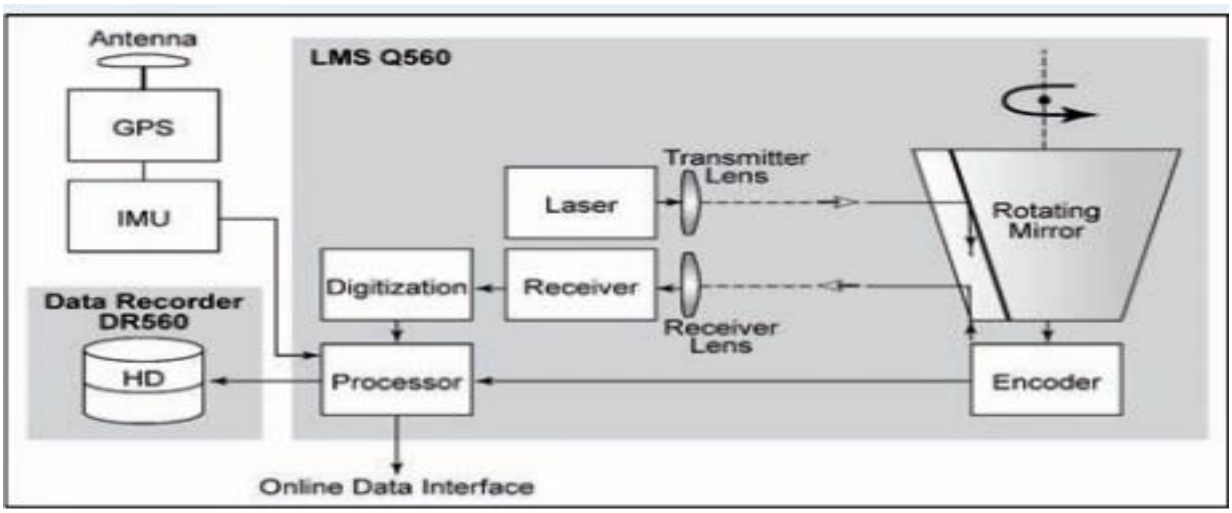


Figure 1.3: Diagram Showing Relationship Between the Components of ALS (Petrie, 2011)

These components

- a laser scanner;
- a GNSS receiver;
- Inertial Measurement Unit (IMU);
- Charge-Couple Device (CCD) camera; and
- a computer system for storage of collected data.

Moreover, it is possible to install an additional multispectral imager for specialised image analysis. This camera system improves the accuracies of the scanner by using accurate geo-referencing of the images captured.

ALS operates on aircrafts, drones and helicopters with different scanning heights depending on the type of flying platform used. ALS attains a height of about 200-300m for helicopters while between 500 to 1000m from an airplane. The range measurement is calculated based on the difference between the ALS and the target object. In order to determine the accuracy of the scanner, a comparison is done between the acquired coordinates and the coordinate of the control points. The accuracy of the results are mainly affected by the use of a single-frequency GNSS receiver and the synchronisation between the GNSS receiver and the IMU. The connectivity between each component of an ALS is presented in Figure 1.3.

The capturing and recording of data in ALS mapping can be categorised into discrete return (DR) and full wave (FW) (Petrie, 2011). The difference between these two recording principles is the recording strength of the reflected laser beam (energy) from the target. The FW records the entire reflected beam from the target while the DR only picks single or a few laser signals from the reflected object.

Terrestrial Laser Scanning System (TLS)

A terrestrial Laser Scanning system can be described as a static laser scanning equipment. It operates on a similar concept to that of a Total Station instrument by using signal properties to measure distance. The significant differences between the two are the rate of data acquisition, pre and post processing of data and the amount of data collected. Soudarissanane (2016) reported that the measurement rate depends on the user defined maximum distance. That is, the pulse travel time increases with increasing in distance to the object as shown in Figure 1.4.

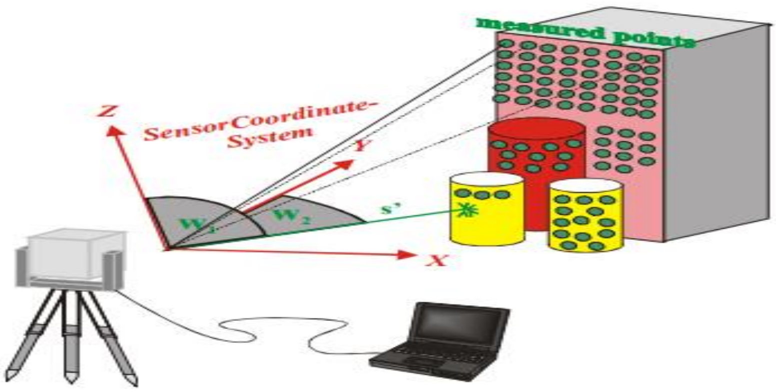


Figure 1.4: Principle of Terrestrial Laser Scanning (Staiger, 2003)

TLS produce accurate scan results with measurements that are perpendicular to the surface. The incidence angle is directly proportional to the error generated by the scanner. The larger the angle, the more the beam can elongate and the greater the error produced by the returning signals (California Department of Transport, 2018). The incidence angle therefore has direct influence on the quality of the scan. Furthermore, the distance between the scanner and the target must be considered. This is important for designing the size of the surface area of the target. Also, the returning signal will be weak if the scanner is far from the object, which also affects the density of data points on the target.

Mobile Laser Scanners (MLS)

Mobile Laser Scanners work on the same principle as with ALS. This is a ground-based laser scanning system that works on platforms such as utility vehicles, ships, trolleys and machines. Images in Figure 1.5 shows the various methods used in mounting the MLS on mobile platforms.

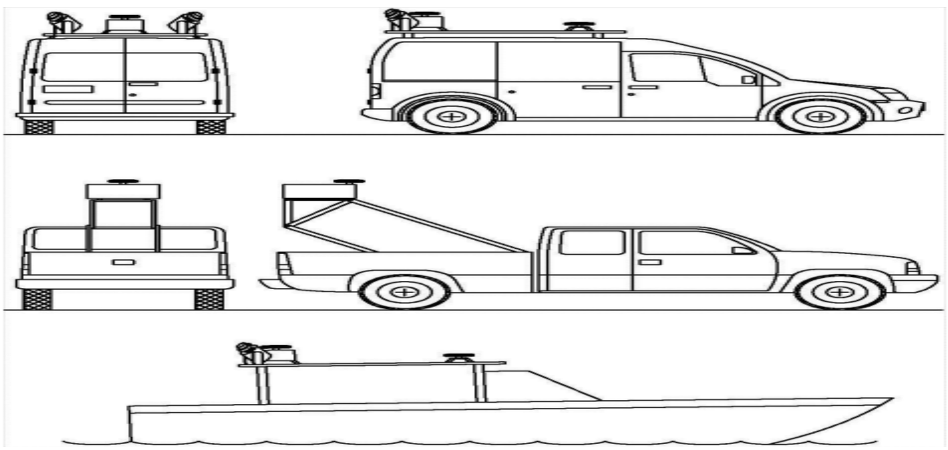


Figure 1.5: Images of Mobile Laser Scanning System (California Department of Transport, 2018)

The integration of Global Navigation Satellite System (GNSS), DMI (Distance Measurement Unit), laser range, scan angle and Inertia Measurement Unit (IMU) from a moving platform produce highly accurate geospatial data. The spatial coverage is carried out by the movement of the vehicle on which the scanner and all other components are mounted. The scanners are mounted at a height that will give good coverage and the scanning rate can be increased as the vehicle is moving. During scanning, the instrument makes use of the auxiliary sensor to maintain the accuracy. This is because the auxiliary sensors are designed to correct the orientation and position of the scanner to complete a geo-referenced point cloud automatically. The system utilizes accurate IMU, GNSS antennas and a DMI to generate high resolution 3D topographical data of the surrounding objects (Kukko, *et al*., 2012).

The noticeable flaw of this equipment during surveying is the obstruction of GNSS line of sight to the satellite from moving or static objects. This happens when structures such as tall buildings and trees obstruct the satellite visibility, which affects the navigation of IMUs that defines the achievable accuracy of the MLS. Thus, it is important to ensure visibility of the geospatial control from the moving platform.

The recorded data from the GNSS and IMU are used in determining the precise geospatial location and orientation of the instrument during the scanning process. California Department of Transport (2011) described the component and function of MLS as;

- the IMU defines the orientation of the laser scanner;
- accelerometer (motion sensor); and
- the gyroscope (rotation sensor) in calculating and recording of position, orientation and the speed of the moving object.

The weakest feature of the MLS is its dependency on GNSS for position reference (Botes, 2013); its accuracy is determined by the accuracy of the GNSS system. Figure 1.6 shows the connectivity between the GNSS component of the MLS and the satellite. The MLS requires adequate visibility from satellites for GNSS positioning accuracy.

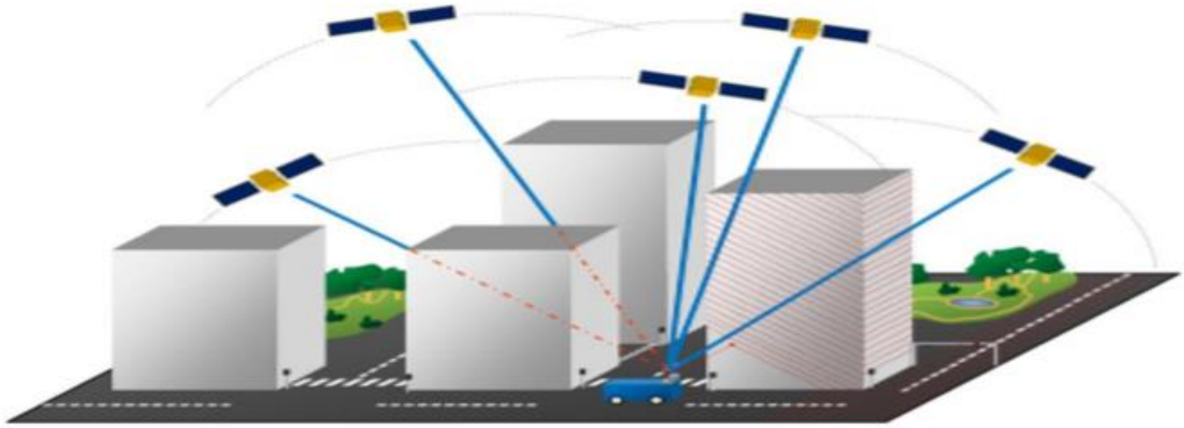


Figure 1.6: ***MLS Utilises GNSS-IMU Positioning for Geo-referencing (Kukko, et al., 2012)***

1.3.4 Errors in Surveying

Errors in surveying can occur with causes such as faulty instrumentation, unfavourable environment and improper measurement procedure. Cosarca, *et al*., (2009) listed laser scanners amongst measurement devices that suffer from factors such as;

- the environment conditions where the scan is taken;
- the incidence angle to the surface;
- the distances from the laser scanner to target; and
- the reflectivity of the targets.

Errors can be detected by different means, such as when a measurement is being performed repeatedly and by different equipments. The reiteration of measurements can lead to different results which might be equal to measurement error. Another method is by comparisons of results; this will highlight any discrepancies in the results. According to Fan (2010), error can be categorised into three sources;

- Mistake (Blunders);
- Systematic Error; and
- Random Error.

Mistake

A mistake is also known as a blunder. This type of error can arise by misuse of an instrument, incorrect measuring and computational error. Blunders occur when inappropriate procedures are used in taking the measurement or when surveying is carried out in a difficult working environment. Examples include, transcription errors, incorrect use of equipment and calculation mistakes.

Systematic Error

Systematic error is usually originated from the source such as mechanical defect. It occurs as a result of instrument malfunctions, errors in physical propagation and atmospheric parameters. The best way to minimise the effect of this error is modelling and analysing the results. An example of this error is the deflection of laser beam caused by misalignment of the rotating prism of the laser scanning system.

Random Error

A random error is known as a statistical error which is whatever error remains after the mistake has been removed and systematic error has been corrected. This error can be investigated using statistical analysis by estimating an average value from set of measurements (Kalla, 2009). To minimise the impact of this error, standard measurement procedures must be followed. Also, this can be mitigated through statistical analysis of the repeated measurements.

1.4 Possible Source of Errors in Terrestrial Laser Scanning System

The TLS uses the intensity of reflected signal from the target surface to obtain its range measurement. The presence of these errors affect the accuracy of the instrument and in order to identify these errors, an accuracy test must be carried out on the scanner. The accuracy of the measured distance depends on the factors such as;

- instrumental and atmospheric effects (ambient light, humidity, temperature, and atmosphere);
- the property of the targets (size, roughness, reflectivity, colour, and angle); and
- the measurement geometry (incidence angle and range differences) to the surface.

These factors must be carefully observed in order to obtain quality data. The possible reason for an instrument deviating from its accuracy depends on its age and its components. According to Cosarca, *et al*., (2009), the four (4) possible sources of error in TLS are;

- Instrument error;
- Error from nature of the target;
- Environmental error; and
- Methodological error.

- **Instrument Error**

This error is caused by instrument anomalies. This can impart the precision of both angular and distance measurement for pulse base scanning. Instrumental error can be classified under both random and systematic errors.

- **Errors from Nature of the Target**

The nature and the size of the target is very important in determining the intensity of the returning pulse. The target material and colour affects the intensity of the reflected light. The important properties to take note in designing the target are first the size and second the reflectivity. A shining surface is difficult to measure due to its high specular reflection characteristic of the material. This can be explained by surface reflectance and multipath reflection.

Surface Reflectance

This explains the determinant of surface reflectance of the laser beam. Laser scans can easily be affected by reflective substance materials such as glass or shiny objects. If these reflective substances can be avoided in the scan environment, it will improve the accuracy of the scan results. Targets with reflective material return few or no signals back to the laser scanner. This will lead to errors in the measured distance and will also facilitate the production of noise and beamwidth uncertainty in the result. If the colour of the surface is black, it will result in poor reflection by absorption of the light by the surface. In preventing the absorption of light, a white target surface should be used to enhance strong reflection of the laser beam. The illustrations for reflections of laser beam for both isotropic reflectance and multipath reflectance of target surface are shown in Figure 1.7 and Figure 1.8 respectively.

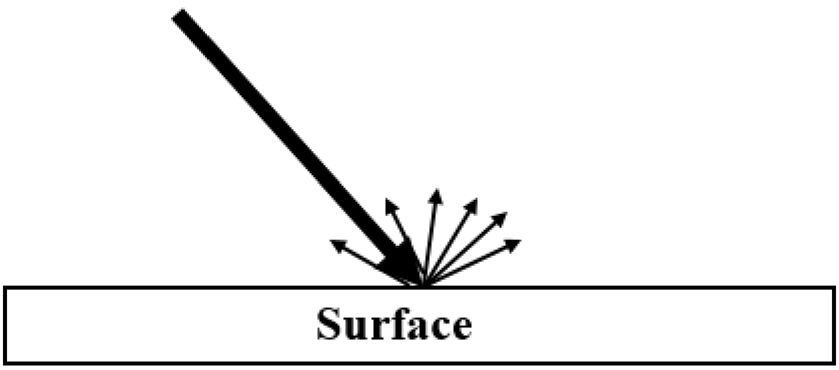


Figure 1.7: Reflection of an Isotropic Surface (Cosarca, et al, 2009)

Multipath Reflectance

This explains the nature of reflective coating of a target surface that permits the laser beam to refract and reflect which leads to the additional distance measure.

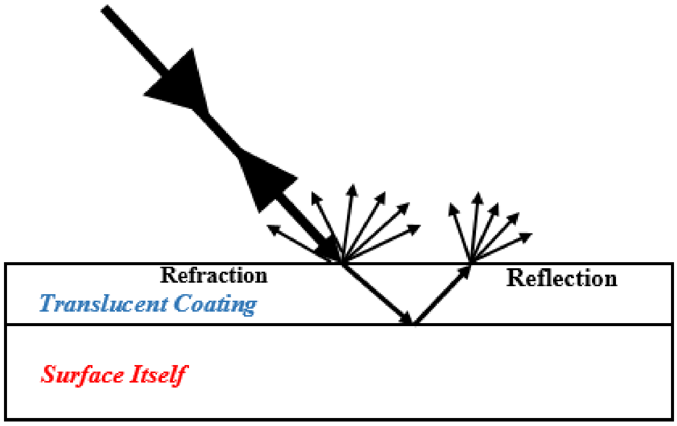


Figure 1.8: Effect of Refraction and Reflection on Translucent Coating Surface (Cosarca, et al., 2009)

- **Environmental Error**

These are errors caused by atmospheric effects such as temperature, interfering radiation, weather condition and wind. High temperature can cause internal heating of the equipment which influences the scan result. The scanner works at a particular temperature which will be specified in the system manual. Scanning under intense sunlight can lead to interference from external radiation that affects the result.

- **Methodological Error**

This error normally occurs based on the experience of the operator of the laser scanner. If the observer is inexperienced, it might affect the quality of the point cloud produced. Wrong application of the scanning system can affect the data during data registration and processing of the data. An example of this is using a phase-based (short range) laser scanning system to scan objects at a very long distance beyond the stated manufacturer's specifications.

1.5 Point Clouds

The end result of laser scanning is the point cloud data. This data shows a 3D representation of the scanned environment made up of single points that are densely populated. This data can be obtained within a short period of time at the push of a button with very little involvement from the user. The acquired point cloud can be transferred into different computer software packages to create a model of the laser scanner surrounding objects. After the processing of the raw data, the results can be exported into existing post-processing 3D software programs such as AutoCAD, ArcView and GIS software or other user-familiar systems. These softwares packages will not only handle the data volume but also improves display performance such as feature extraction and fusion with imagery data.

The point cloud data is in the form of X, Y, Z geo-referenced data that comes with RGB colours and intensity as shown in Figure 1.9. This can be converted into common file format (ASCII), which is convenient for use in computer software packages such as AutoCAD and GIS softwares.

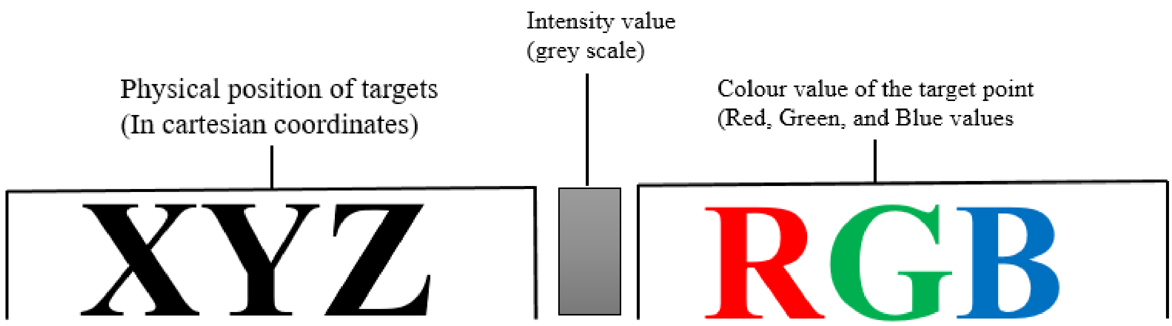


Figure 1.9: Point Cloud Data Representative (Randall & Philip, 2013)

There are different ways of generating 3D point cloud data but the quickest and most detail method is by laser scanning technology. Laser scanners can generate millions of points within a few minutes compared to conventional surveying methods. The point cloud data is however not suitable for immediate use and the data has to be processed before data representation. Each scan has its own local coordinate system, this coordinate system first has to be transformed into an appropriate coordinate system; this procedure is referred to as registration of Points. This data transformation process involves encoding which is the technique that involves data registration and filtering; these are the two major steps in data pre-processing, and conversion of measure data into the relevant cartesian coordinate system of the mine.

1.5.1 Registration of Point Clouds

The registration of point cloud data is the first and most important step of point cloud data processing. The problem of having target with many views need to be brought into a common coordinate system. This process of transforming these multiple views of point cloud data into a coordinate system is the registration of point clouds. The merging of the scans will provide a 3D representation of the scan area when the scans are registered together. The registered scan will be linked to a reference coordinate system, in order to compare with other survey data.

The major task here is the identification of the common points in each overlapping point cloud and transform them into a single coordinate system (Han, *et a*l., 2017). The workflow for processing laser scanning data into a registered point cloud for further processing is shown in Figure 1.10.

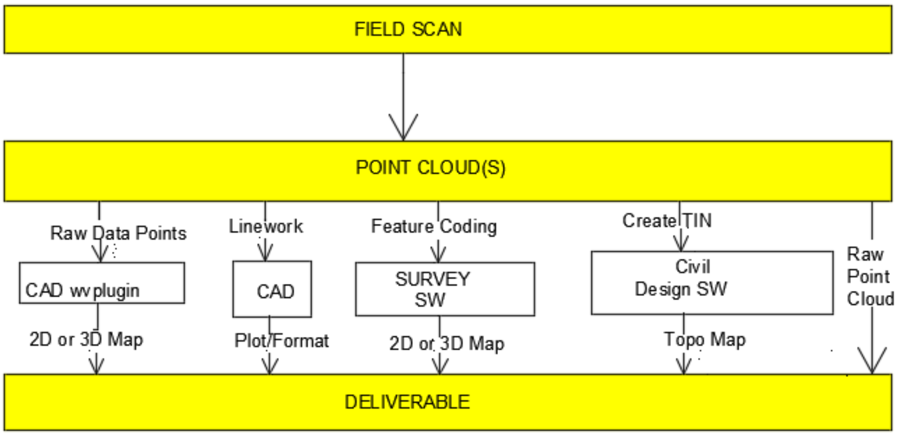


Figure 1.10: Work Flow and Deliverables (Bu & Zhang, 2008)

1.5.2 Filtering Point Clouds

Most scans experience some level of inherent noise which needs to be removed so as to improve the quality of the point cloud. This intrinsic noise occurs as result of the limitation of the acquisition device, the reflective or lighting nature of the scan area. Not all the points in the raw scanning data can be used because they come with some noise. Filtering of this data will remove noise from point cloud data. Also, it will reduce the file size of the point cloud data. This step is important to obtain an accurate set of data before applying further processing techniques. Due to advancement in point cloud processing software packages, it makes it easier for surveyors and engineers to eliminate this noise from the final point clouds.

1.6 Application of Terrestrial Laser Scanning in Rock Engineering

Laser Scanning has benefited the mining industry at large most especially in surveying and rock engineering. This benefit concerns both engineering surveying measurement tasks and geotechnical applications such as rock mass displacement. The laser scanner can digitise a rock face in 3D with a fast scanning speed and high resolution of up to millimetre accuracy. Laser scanning is now frequently undertaken at large open-pit and underground mines in diverse applications ranging from stope stability monitoring, detection of pillar sloughing, underground blast control optimisation, providing of information about unstable ground, detection and measuring of stope closure to list but a few applications. The stability of a particular stope or underground excavation is usually controlled by the presence and orientation of discontinuities in the rock mass and the presence of water under pressure in the area. The intersection of these geological discontinuities result in the formation of keyblocks that affects the stability of the slope. Thus, the terrestrial laser scanner can be used for discontinuity mapping in tunnels without limitation in terms of the tunnel position (wall or roof). Comparison of several sets of point cloud data will identify rock mass movement and rock deformation.

In deep mines where mine-induced seismicity is a challenge facing the mine, several scans can identify rock mass movement and deformation. These scans will assist in identifying areas that may have become unstable over time with detailed analysis of the support system which is geo-referenced to millimetre accuracy for every scan. In the design of ultra-deep mining shafts, the 3D scans data are used for computational fluid dynamics (CFD) to simulate an efficient airflow rate. This improves the flow pattern and recirculation of air from the surface to the underground and provision of adequate airflow within a mine.

In underground coal mining, the scan data can be used to evaluate coal pillar stability. This helps to estimate the performance of the reinforcement, rib bolt movement and its functionality. The comparisons of the scan data can be used to detect the cracks and fissures of areas with stability challenges, as appropriate measures can be taken to ensure stability. During the design and extraction of underground coal mining, the laser scanner has proven to be useful as the data acquired is transferred into computer - aided design (CAD) software for as excavated models and 3D documentation. The laser scanner is used for coal strata monitoring especially where scaling of pillars or severe pillar deformation may occur. This equipment has an immense contribution in ensuring safety and a safe working environment underground.

1.6.1 Practical Application of Terrestrial Laser Scanner in an Underground Excavation

In a typical underground excavation, such as tunnelling operations, shaft sinking and stope panel design, the terrestrial laser scanners are used for profile scanning to determine overbreak and underbreak. Estimation of shotcrete thickness, tunnel face change detection, and surface deformation of rock can also be defined. The laser scanner can generate data on the deviation of a tunnel profile design from actual tunnel shape and alignment. The deviation of the excavation surface is determined by comparing the point clouds obtained at different times. This helps in controlling the geometry of the tunnel and most applications focus on geometric information of the tunnel extracted from laser scanning data. These sets of scan data are mainly used in a tunnelling project for deformation measurement and feature extraction. Fakete, *et al*.,

(2010) also reported the application of laser scanning data for stability analysis of a tunnel in a "blocky" rock mass as illustrated in Figure 1.11.

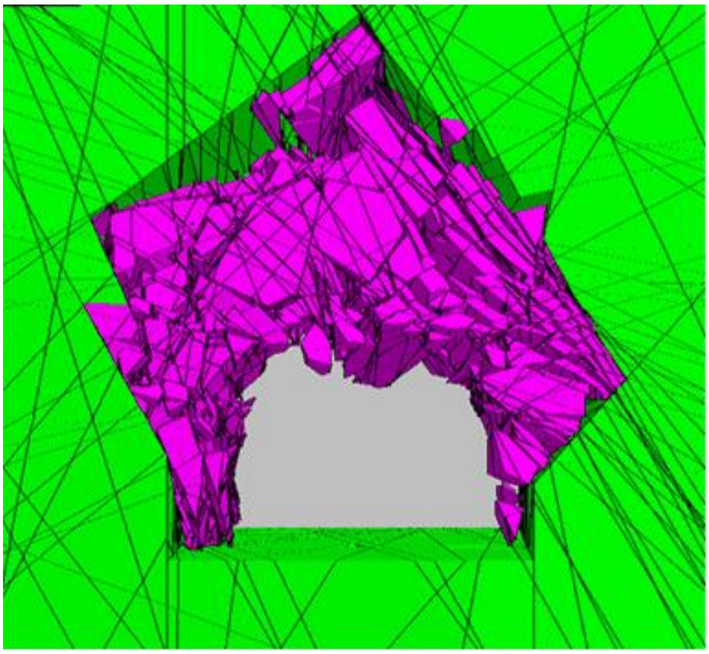


Figure 1.11: Block Model of Rock Mass Using 3D Point Cloud Data (Fekete & Diederichs, 2012)

The scan data was used to develop a block model of the rock mass which improve the tunnel by showing overbreak and underbreak. From this, a workflow was designed to assist geotechnical tunnel analyses. Gikas (2012) used a long-range terrestrial laser scanner with less point cloud resolution to examine the geometry of the tunnel and presented the application in geometric documentations of tunnels. These applications include;

- information at the excavation face;
- cross-section and volume calculation during support measure operations; and
- metal arch form work.

The potential application of terrestrial laser scanner in rock engineering projects was described by Feng (2012) as;

- Site characterisation of rock;
- Quality control of tunnel blasting;
- Deformation monitoring in underground excavation;
- Improved input data for numerical modelling; and
- Documentation and visualisation.

1.6.1.1 Site Characterisation of Rock

The complex nature of a rock mass is affected by geological structures such as joints, faults and foliations. Consequent to this, an important aspect concerning the evaluation of rock strength is the geometrical characterisation of discontinuities. The terrestrial laser scanner is mostly used for 3D site characterisation of the exposed rock mass. Currently, mapping of a rock surface is done by traditional methods of using a compass with an inclinometer to measure dip and strike, taking notes in a notebook and also taking some photographs for documentation purposes. With the integration of the laser scanner for rock surface mapping, there is a great potential to avoid the drawback of the traditional methods of rock surface mapping and characterisation. The use of laser scanners allows for effective management of time and access constraints encountered typically during rock engineering projects, since it provides a realistic and permanent representation of excavation surfaces. Moreover, it requires only a reduced number of physical targets to be installed for data referencing purposes.

According to Ulusay & Hudson (2007), the International Society for Rock Mechanics (ISRM) suggested ten features of exposed rock face that can be used to characterise rock mass, such as orientation, spacing, persistence, roughness, aperture, wall strength, fillings, seepage, number of fractures sets and block size. In most cases, a trace length (the intersection between a joint and rock face) is used where small areas of discontinuities are exposed in a rock face (Cacciari & Futai, 2016). Considering all the points in a point cloud are in a metric cartesian coordinate system, it is possible to measure the trace length using a measuring tape in a CAD environment as in conventional mapping. Photographs of measurement of fractures and identification of discountinuities are illustrated in Figure 1.11 and 1.12 respectively.

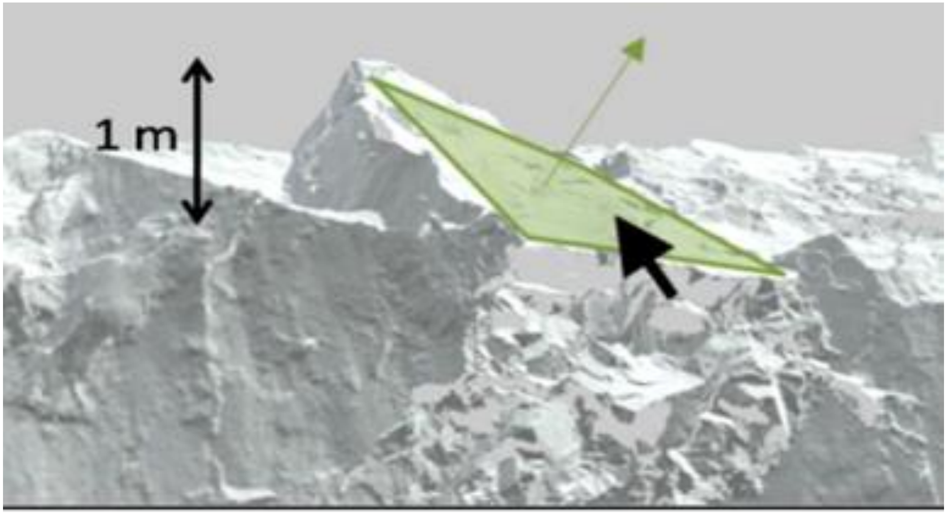


Figure 1.12: Measuring Fracture Length and Spacing in a 3D Laser Scanning Point Cloud (Fekete & Diederichs, 2012)

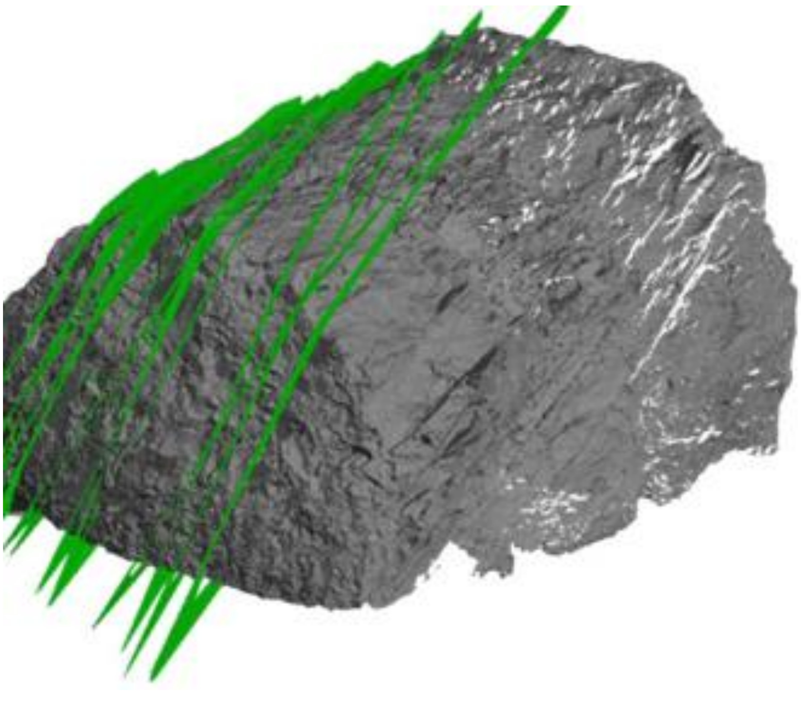


Figure 1.13: Identification of Discontinuities in Point Cloud and Orientation of the Plane (Fekete & Diederichs, 2012)

With a full laser scan, fracture data can be captured for the whole rock face in a short period of time. Human mapping errors or blunders can be prevented or eliminated with the use of a laser scanner, as the data will be captured automatically, as is.

1.6.1.2 Quality Control of Tunnel Blasting

During the mining or blasting of an underground excavation, it is important to control the over-break and under-break as compared to the design. According to Cacciari & Futai (2016), the orientation of the discontinuity, trace length and frequency were analysed in different regions of the tunnel to determine the most representative data. It was found that the representative data can be used to calculate the true spacing of the discontibuity plane. With full-coverage laser scanning data, the quality of blasting can be controlled through a 3D model of the radial fractures during the dynamic loading phase of an explosion.

Deformation Monitoring in Underground Excavation

Deformation occurs by both natural and artificial forces in tunnelling and mining operations, which may result in disaster for both personnel and infrastructure. Traditionally, the rock mass is monitored by measuring the displacement of several points at some defined positions, but there is a risk of missing some unstable parts with this technique. The terrestrial laser scanner at full-coverage with high-density scanning points to millimetre accuracy, can monitor the whole rock surface, and makes it possible to measure the deformation of the whole surface.

Improved Input Data for Numerical Modelling

The success of numerical modelling prediction of rock mass behaviour depends on the quality of input parameters that represents the the rock mass (Yassitli, 2016). Therefore, it is important to input quality parameters that closely describe the real condition of a rock mass. The terrestrial laser scanner improves the quality of the input boundary parameters and the results of the modelling can be closer to reality. Also, the laser scanner can be used to obtain some input parameters in rockfall analysis, such as;

- joint orientation;
- the slope;
- block geometry; and
- volume.

Documentation and Visualisation

Traditionally, a notebook with writing materials and drawings, together with a camera are commonly used in documentation and visualisation. With the recent advent of 3D laser scanning systems, documentation, visualisation, and high-resolution image can be recorded and visualised in 3D with its coordinates accurately measured.

1.6.2 Application of Terrestrial Laser Scanner for Slope Monitoring and Deformation

Slope monitoring is one of the key responsibilities of geotechnical and mining engineers in open pit mines. One of the major factors that determines the stability of a slope is the slope angle. For many years now, conventional survey instruments such as close-range photogrammetry, levelling, real-time kinematic global positioning system, satellite imagery, airborne laser scanner and a total station are used for slope monitoring activities. These methods take a longer time to complete the task of monitoring and can become monotonous in data acquisition.

Recently, the use of a terrestrial laser scanner (TLS) for monitoring of rock mass movement and deformation measurement has been increasing. This technique is based on reflectorless and contactless remote acquisition of a 3D point cloud of the topography using time of flight distance measurement of an infrared laser pulse (Wan Mohd Akib, *et al*., 2012). There is a growing interest in using the instrument for slope monitoring, as it provides a high data redundancy which allows good deformation measurement to be detected to millimetres accuracy. The laser scanner is capable of predicting slope failure with better confidence. The terrestrial laser scanner can scan full coverage of a rock face with high resolution in a shorter period of time compared to previously mentioned instruments. The advantages of TLS in deformation monitoring are the capability to provide fully 3D deformation measurements, including 3D displacement of rock mass prone to rockfall and the use of advanced Least Square (LS) 3D surface matching analysis tools for estimating deformation parameters. The rescale range analysis method and 3D laser image scanning system are used to obtain slope data. The rescale range approach is a statistical analysis that is used to investigate the apparent variability of a series of change with time-period being considered (Depeng, *et al.*, 2010). This method was used to monitor a large number of slopes over time in order to investigate the displacement over time through point comparisons. From this, the slope movement can be analysed. This surpasses the conventional prism method of monitoring a slope. Prism monitoring can measure a vector but laser scanning shows maximum displacement of rock mass towards or away from the instrument.

Miyazaki, *et al*., (2008) defined a slope movement phenomenon which was caused by rock mass movement at 0.01mm to 10mm. With a terrestrial laser scanner, the rock slope will be scanned to measure any surface movement and deformation with a minimum of 10 millimetre accuracy at a maximum measurement range of 350m. This will offer solutions for monitoring rock mass movement for mine safety purposes. Also, the equipment will assist to identify areas that may have become unstable overtime.

1.7 Research Questions

The research will provide answers to the following questions:

- Are terrestrial laser scanners performing within manufacturer specifications?
- Are terrestrial laser scanners generating accurate and precise point clouds that can be used for monitoring underground rock mass movement?

1.8 Methodology

The approach to the research looks at developing a short-range laboratory for testing terrestrial laser scanning systems. This will be achieved by the study of existing calibration and testing facilities, building and equipping the laboratory and establishing an accurate coordinate network for the control beacon with a Total Station. Targets were fixed on the wall at different heights and on the ceiling of the laboratory. Laser scanner was positioned on the force-centred beacon for scanning at a known X, Y, and Z position. Comparisons were done between the observed scanner values and the survey true values. The results will be compared with manufacturer specifications to establish the performance of the laser scanner. This indicated any accuracy deficiencies in the instrument and will determine whether the instrument is fit for the purpose of monitoring rock movements in the underground mining environment. Appropriate software by technology vendors of the scanner were used for further analysis on the point clouds.

1.8.1 Research Methodology

At the beginning of the research, a workshop was organised by the Wits Mining Institute (WMI) to guide and contribute to the scope of the research topic. During the workshop, a summary of the research points were highlighted and a research schedule was discussed in detail. The laboratory is at the reception area of Wits Mining Institute (WMI) in the basement of the Chambers of Mines building. The facility would indicate whether the laser scanner is performing within manufacturer's specifications and make sound decision on the laser scanner being fit for purpose.

The following was evaluated during the development of the laboratory;

- Monitoring of the laboratory's atmospheric conditions (temperature and humidity);
- The nature of the points (targets) surface will be examined to determine best reflective properties;
- Design, manufacturing and placement of control targets on walls and ceiling;
- The coordinate of the control beacon in the laboratory; and
- Process of scanning with different equipment and different techniques.

Deliverable: Development of a fit for purpose laboratory for testing 3D terrestrial laser scanners at the Wits Mining Institute (WMI).

1.8.2 Procedure for Testing Terrestrial Laser Scanners

The following activities were done in testing terrestrial laser scanners;

- Building of the control beacon;
- The co-ordinate of the referencing beacon using a Total Station;
- Manufacturing and placement of control targets;
- Point cloud data acquisition was done using terrestrial laser scanners;
- Data processing, computing and analysis of cloud results using appropriate software such as Cloud Compare software version 2.9; and
- Conclusion was made on whether the laser scanner was suitable and fit for the purpose of monitoring rock mass movement after comparing the two sets of results.

1.9 Research Outline

This research report is organised according to the following chapters;

Chapter 2: Literature Review

This chapter examines past approaches used in determining the accuracy of a terrestrial laser scanner. The establishment of the physical space facility and some features in the laboratory which have to be taken into account in investigating the accuracy of a terrestrial laser scanner was analysed.

Chapter 3: Mobile Laser Scanning Techniques and Sources of Errors in Terrestrial Laser Scanners.

This chapter discusses the principle of Mobile Laser Scanning Techniques and several approaches used to investigate the accuracy of mobile laser scanners. Also, investigation of errors in terrestrial laser scanner data is another branch of this research, the sources and types of errors will also be discussed.

Chapter 4: Surveying with a Total Station and Short Range Laboratory Preparation.

This chapter contains the main aspect of this research. It outlines the calculation of the coordinate of the control beacon using a Total Station from known control points. The short-range testing laboratory was developed, and relevant factors that were considered in setting up the testing laboratory are discussed. The overview of the laboratory is also explained.

Chapter 5: Scanning with Terrestrial Laser Scanner and Point Cloud Data Processing.

In this chapter, the terrestrial laser scanning method for point cloud data acquisition and data processing were explained. The main aspect of data processing was discussed, such as registration and filtering of point cloud data.

Chapter 6: Results and Analysis of Acquired 3D Point Cloud Data from a Terrestrial Laser Scanner.

In this chapter, the results of the scans from the laboratory were compared against the total station survey to determine the terrestrial laser scanner accuracy based of angle and distance measured. Also, the scans data were compared against the manufacturer’s specifications.

Chapter 7: Conclusions and Recommendations

This chapter summarises the findings of this research in view of research questions and aims that were initially discussed. Conclusions and recommendations were deduced based on these findings.

CHAPTER TWO

2 Literature Review

2.1 Study of Existing Testing and Calibration Facilities

The calibration and testing of Terrestrial Laser Scanners (TLS) have received notable attention recently. There have been several investigations on how to establish the accuracy of scanners. Much of the earlier works on the calibration of terrestrial laser scanners have been on the instrument's performance evaluation, which is done by comparing the observed values and the known (true) surveyed values. This test exercise is done to check the accuracy of the TLS and the quality of the data being produced. This means, there is need for regular testing and calibration of a TLS in order to confirm whether the accuracy requirement is being met. To achieve this, a test facility is needed with specific qualities to test the instruments, based on observable angles and distances. Prior to analysing the existing testing facilities and the required qualities that should be considered in the setting up of a short-range testing facility venue, it is essential to discuss some factors that hinder the accuracy of measurement. These factors would be analysed and understood in order to develop a standard testing facility to evaluate laser scanner accuracy. The sources of these errors and other factors that caused inaccuracy in the instrument are fully discussed later in the chapter.

Terrestrial laser scanners are not free from errors and these errors arise from different sources. Some of these errors occur as a result of instrument imperfections coming from internal misalignment of system components. Therefore, in order to achieve high-quality scans, the instrument needs to undertake an accuracy assessment process that will identify and correct errors that may be present. Fangi, *et al.*, (2001) stated some of the factors that influence the accuracy of laser scanners as;

- Small beam spot size;
- Short laser wavelength;
- High strength of each laser pulse ; and
- The narrow width of the laser pulse and detection sensitivity.

However, there are other factors that affect the performance of the measuring device such as the target (colour, nature, and size), the age of the scanner and how the coordinates are converted between different computer softwares. Similarly, Garcia-San-Miguel & Lerma, (2013) discussed other factors such as the angle of incidence, reflectivity of the target, the distance and the weather condition of the scanning environment. In order to achieve accurate and precise point cloud results, it is important to conduct regular testing and calibration of the laser scanner in a specially designed facility that will highlight any accuracy deficiencies. This will test for both precision and accuracy of both horizontal and angular measurements for scan points, so as to confirm if the acquired data conforms with the accuracy specifications stated in the manufacturer's manual. These and other factors will be fully analysed in order to establish a standard facility for testing the accuracy of the terrestrial laser scanner.

Prior to the scanning task, it is important that the laser scanner is in good condition so as to ensure quality data is produced by the instrument. In order to achieve this, a testing facility would be set up to determine the performance of the terrestrial laser scanner and to conclude whether the laser scanner would be suitable and fit for the task at hand. This approach has proven to be successful in estimating whether the instrument is performing within the specifications given by the manufacturer.

Ideally, it is expected that when a terrestrial laser scanner is newly acquired, it should be free from any form of systematic errors and comply with manufacturer specifications. To ascertain the accuracy level and if the system is fit for the purpose, further accuracy testing is required. Garcia-San-Miguel & Lerma, (2013) recommended that quality assurance is required to ensure that the instrument is suitable and fit for its purpose. The accuracy specifications quoted in the manufacturer's publications must be checked under different conditions, as these vary from instrument to instrument (Boehler & Marbs, 2003). In order to meet the required measurement accuracy stated in the manual, the systematic errors have to be properly addressed.

In testing the accuracy and calibration of terrestrial laser scanners, there are some factors that need to be considered in establishing a standard short-range testing laboratory. These include the size and shape of the testing facilities, the network geometry, target designs and placement, and types of calibration methods used to analyse the accuracy of laser scanners. This literature review discusses the various factors that deserve attention when considering establishing a short-range testing laboratory.

2.1.1 Size and Shape of the Facility

In setting up a laboratory for testing the accuracy of the terrestrial laser scanner, the first task is to identify the physical space in which to establish the laboratory. The choice of selecting a particular space depends on the range of the laser scanner to be used. The effect of range observation was discussed by Glennie & Lichti, (2010) as this can cause distance offset in measurement.

The range must be considered in selecting an appropriate size of the laboratory and the type of laser scanner to be used, as this can cause problems at the post-processing stage. An important benefit of using long range spacing in examining the accuracy of the scanner is because it will make the scale factor of the network more reliable. By doing this, the distance offset parameters will be separated from the scale factor which will assist in a least square calculation (Glennie & Lichti, 2010). Lichti (2010a) stated that the space required for the self-calibration approach was a room the size of a class room with an option of placing targets on the walls. The size of space used for the laboratory testing varies from large halls to small rooms with options of placing the targets at different angles and orientations.

In substantial space facilities, there are options for placing the targets at strategic positions around the room. The effect of target positioning was discussed by Lichti (2010b) for both symmetric and asymmetric targets design in the scan area. However, in a substantial facility, the symmetrical positioning of targets does not have much influence on the accuracy of the results, as this only counts in smaller facilities. The size of the test facility is crucial in determining the number of setup and range offset. According to Medic *et al.*, (2017), a bigger facility increases the quality of the testing process. The availability of long range and large space reduces the angular correlations between parameters, thereby causing an increase in reflected laser signal from the targets.

Most of the parameters used in testing the instrument are angular based variables which depend on the scanner orientation angle. The orthogonality of the emitted laser beam improves angular precision by reducing the effect of collimation axis error[1] and trunnion axis error between the laser scanner and the targeted object. According to Litchi (2010b), it was demonstrated that in panoramic laser scanner, self-calibration is possible from only two scan positions as long as orthogonal orientations can be achieved. The perpendicularity of the laser beam to the target mitigates the correlation between the collimation axis error and the laser scanner orientation

[1] Collimation axis error occurs when the axis of collimation (line of sight) from the optical axis is not perpendicular to the horizontal axis while Trunnion axis error is the deflection that occurs when the trunnion axis (line of sight) is not perpendicular to the vertical axis of the instrument (Neitzel, 2006).

angles, which is reported to be the cause of collimation axis error (Schneider & Schwalbe, 2008). The correlation coefficient between the orientation parameters and additional parameters for both panoramic and hybrid scanners depends on number of orthogonal scans (Lichti, 2009). Results from Lichti's test suggested that the collimation axis errors estimation rely on the instrument's rotation angle. This is an important factor to be considered in reducing the effect of collimation axis errors in measurements as it dictates the number of scan positions. Thus, the larger the size of the room, the better the end results when the target geometry is not considered. In short, a longer range facility is a requirement in testing the accuracy of the terrestrial laser scanner (Lichti, 2010b).

Another factor to consider before selecting a space facility for the test is to determine whether the scan positions can capture all the targets, while avoiding obstruction from features in the space facility. Features in the scan area such as pillars create a nuisance by blocking the targets from certain setup must be minimised. Similar study by Reshetyuk (2010) indicated that the selected space must be efficient enough to capture all the targets by increasing the number of setups.

2.1.2 Network Geometry (Number of Setups and Placement of Targets)

After selecting a suitable space for the testing facility, the next issue to be considered is a good network design. This is important for producing accurate and reliable 3D point cloud data. A good geometric configuration and strong network design will improve the quality of a laser scanner end-points by reducing dependent variables. Skaloud & Lichti, (2006) discussed the importance of strong geometry as not only in terms of presenting an accurate measurement but also robust in terms of points convergence. Lichti (2007) reported the importance of strong network design in estimating the collimation axis and trunnion axis errors. In an ideal network design, temporary setups are selected to allow the targets to be viewed at each setup and at the same time guarantee good network arrangement between setups.

Soudarissanane, *et al*., (2008) & Reshetyuk (2006, 2010) in their studies acknowledged the importance of establishing a good and high redundancy network design when testing the accuracy of a terrestrial laser scanner for high precision measurements. The network design has to be carefully considered in setting up a testing laboratory, as this will improve the quality of individual points being measured by minimising the correlation between some of these variables. These variables are the basic additional parameters which comprises of collimation axis error, trunnion axis error and the vertical index error[2] (Lichti, 2010b). Moreover, a good design will support the creation of high data redundancy in the measurements and improve scan quality for both horizontal and vertical angles.

In the laser scanner calibration, network geometry has to be considered in order to reduce further correlation between calibration parameters and to ensure sufficient returns of the laser signals from the targets. This brings about improvement in the estimation of dependable model variables and the creation of a high redundant set of measurements. Lichti (2010a) referred to these model variables as additional parameters (AP) which are systematic error coefficients, angular orientation elements, target parameters and scan positions. All these parameters need to be considered in order to obtain high accuracy in the data. Reshetyuk (2010) stated that having a strong geometry for the calibration of laser scanners increases the redundancy and improves precision in angular measurements. This includes a good distribution of targets, an angular orientation which involves rotating the scanner at an angle of 90 degrees at different scan positions and using a minimum of two scan positions. The significance of setting up a strong network configuration is to obtain an accurate result and to reach the best possible accuracy.

High redundancy is important as this will identify all systematic errors during point cloud statistical analysis. On the other hand, Schulz (2008) analysed the effect of poor geometry in the registration of a point cloud as this will create biased results when combining scans into a common adjustment. High redundancy is important in the identification of all the systematic errors in the adjustment method and other models with analytical correction functions.

However, since the terrestrial laser scanning is a line-of-sight instrument, the scan position must be selected in order to capture all the points in the laboratory. Thus, in generating highly accurate and dense point cloud data, the laser scanner must be positioned at an optimum place where all the targets will be viewed without any obstruction. Bae & Lichti (2007) concluded that in order to maximise visibility of all the targets and improving the additional parameters, an optimal scan position must be established. Similarly, Chow *et al.*, (2010) discussed the influence of the scan position on the precision of the collimation axis and trunnion axis errors

[2] Vertical index error is the deviation that occurs when the horizontal base line of angle from 0 to 180 degrees in the vertical circle does not coincide with the vertical axis of the instrument (Gisresources, 2014).

in a normal level scan network. Shen, *et al*., (2017) & Reshetyuk (2010) explained the influence of field-of-view (FOV) and a number of scans between parameters in point-based accuracy testing. In other words, terrestrial laser scanning accuracy can be affected by the obstruction of targets in the area which can lead to having many scan positions. The arrangement of these scan positions should ensure that the number of scans is minimised while avoiding an obstruction in order to ensure the full coverage of the area.

The positioning of the instrument is a critical aspect in testing the accuracy of the terrestrial laser scanners. For precision work, force-centering of the laser scanner is very important as this will restrict any form of movement of the static laser scanner that can affect the orientation of the instrument. The force-centering control beacon is usually constructed using a thick plastic pipe casing to house the concrete or using a concrete pillar to provide a control beacon. This will assist in creating high redundancy in the measurement in order to identify systematic errors at the analytical stage. However, some researchers made use of tripod stands in their experiment such as investigation conducted by Reshetyuk (2010) at the Kungliga Tekniska Högskolan (KTH) laboratory. Al-Manasir & Lichti (2015) mounted the instrument on a standard wooden surveying tripod in order to calibrate a Leica HDS7000 at Nottingham University affiliated research centre at Ningbo in China. Another test by Pareja *et al*., (2013) made use of both tripod and force-centering beacon in their investigation. Gielsdorf, *et al*., (2004) calibrated a terrestrial laser scanner at Technical University in Berlin setup on a tripod to acquire several point cloud data from different locations. Lichti (2010b) and Glennie & Lichti, (2010) also made use of a tripod for their investigations.

Additionally, the coordinate system of the laser scanner from its scanning position, has to be determined. The position of the laser scanner has to be known with a precision of about one millimeter in order to get reliable results with zero error (Reshetyuk, 2010). It is difficult to estimate the precise mechanical centre of the instrument, which must be checked as part of the pre-delivery testing procedure. In most cases, the centre point coordinate of the instrument is determined by external methods such as intersection and resection.

2.1.3 Target Design for the Testing Facility (Size and Shape of Target)

The design of a particular type of target depends on its purpose, which influences the size, the shape and considers the geometry of the testing facility. Some targets are specially designed for laser scanner calibration with specific properties in order to enable accurate registration and georeferencing of point clouds. These targets serve as high precision control points for referencing the full scan of the area. The issue when selecting a target for scanning is the ability to find the centre point. According to Ge & Wunderlich (2015), the accuracy of a terrestrial laser scanner to a considerable degree, is limited by the ability to locate the centre of the target.

The effectiveness of targets also depends on locating the centre point. Any doubt in locating the centre coordinate of the target will directly affect the resulting point cloud and the accuracy of the scan data. The higher the accuracy in locating the centre point of the target, the more effective and efficient the target will be. There are different methods used in estimating the coordinates of the centre point of the target. These include traditional surveying methods and mathematical least squares methods performed by software. The least squares method was employed during KTH experiment, where the coordinates of the targets were determined by Leica software called Cyclone and the coordinates of the target were calculated in Matrix Laboratory (MATLAB). In a test by Lichti (2007), it was found calculating that the centre point value of targets using an intersection approach. The intersection approach was achieved using a total station and a Leica scale bar shown in Figure 2.1.

Figure 2.1: Image of Leica Scale Bar 0.9m Length (Hexagon Manufacturing Intelligence, 2019)

Lichti (2010b) used an observation equation method to find the centre point coordinates, additional parameters and Exterior Orientation Parameters (EOP's). One source located the centres of the target using a total station and intersection from two setup locations. A 900mm Leica scale bar in the network was also used for scale definition. The experiment was supported by iQscene software and a free network adjustment in three separate scans using 45 different targets with known coordinates. At the end of the investigation, Lichti & Licht (2006) achieved an average of 0.5 millimetre accuracy in the horizontal and 0.1 millimetre in the height.

Most 3D laser scanners acquire measurements in a spherical coordinate system, as the acquired point cloud data resembles a spherical object that presents these spherical coordinates in values. These values are represented on the Cartesian coordinate system in order to determine the range, the horizontal and the vertical angle measurements. This shows that the testing approach permits both parameters and errors to be analysed at the same time, including the coordinates of the target used (Chow, *et al*., 2010).

Direct geo-referencing of raw measurement is another approach to find the centre of a target, where all the observed point clouds data from all scan positions are referenced to the same local coordinate frame. A constrained adjustment network with unknown scan positions and targets with unknown coordinates are then used to estimate the calibration parameters for a Velodyne HDL-64E S2 (Glennie & Lichti, 2010). This approach is similar to the bundle adjustment technique used in a camera calibration.

An additional point to take note of in establishing a laboratory for the testing the accuracy of a TLS is that the targets must remain constant at a fixed position throughout the course of testing. It is preferable for targets to remain at their setup positions throughout all scans to avoid uncertainty introduced by resetting of the targets (Olsen, *et al*., 2010). The target represents high precision control points in the laboratory, with or without known coordinates. These known coordinates of the control points in the laboratory are used for geo-referencing and also assist in generating a 3D CAD model of the laboratory. Some targets are particularly placed within a specified range for precise work. If the distance between the scanner and target exceed manufacturer's specifications, this can lead to range error. Moreover, some targets are designed in such a way that when the TLS moves about the target and the target still maintains its centre point. An example of this is a spherical target that is viewed the same from any angle. This is useful where the instrument settings are constant and the targets are designed to handle the laser scanner working at different resolutions. A majority of targets in the scan area are used for the registration process and creating the full scan of the scan area. One of the key considerations when selecting targets for a particular task is the visibility of the centre point.

Another crucial aspect of target design is the selection of the target size to be used. The size of the target varies in terms of the dimension, depending on the distance between the scanner and the position of the target (Davison, 2017). A rule of thumb is that for every one metre away from the scanning position, the target should increase by one centimetre in size. For instance, if a scanner is positioned 12 metres away from the target, the suitable dimension of the target will be 12 centimetres by 12 centimetres in length and breadth respectively.

The use of different types of targets are allowed during a scan, provided they are of good quality. In an attempt to examine the accuracy of a phased-based terrestrial laser scanner (FARO FOCUS 3D), Garcia-San-Miguel and Lerma (2013) used both checkerboard and spherical targets placed on the walls, ceiling and floor of the testing facility. The use of non-standard or a combination of non-standard targets can lead to offset measurements (Chow, *et al*., 2010).

As mentioned earlier, there are targets that can be used for testing or calibration depending on the specifications of the instrument. In an investigation by Lichti, *et al*., (2000), a low-cost acrylic reflector was attached to a standard surveying target to assess the range accuracy of an I-site Optical Laser Scanner, over a distance of 250m. One of the issues raised from the I-site laser scanner was generation of multiple laser scanner signals caused by the effects of sampling, beam divergence and reflector size. To test the accuracy of the laser scanner, a combination of conventional surveying method and Differential GPS (DGPS) were used to take measurement with an estimated accuracy of 5mm. From the test, it was observed that at a distance of about 600m there were multiple returns of laser pulse coming from the target which created a problem of locating the position of the target centre. The returning signal appeared as a cluster to a single central point (halo effect), which caused confusion in their identification. Lichti, *et al*., (2000) suggested that the problem can be solved by using two approaches to determine the centre of the target. That is, by maximum return method, which involves taking the highest value of the returns signal as the centre of the target or by taking the mean of the weighted intensities.

The positioning pattern and preferred orientations of targets in the laboratory are additional factors to be considered when setting up a testing facility. Lichti (2009) reported that the positioning of targets in relation to the size of the facility affects the design of a good network. The study further explained the influence of symmetrical and asymmetrical targets. The dimensions of the facility has a minor influence on the measurement when the target is symmetrically distributed but has significant effect on asymmetrical target field design. Lichti (2010a) also gave guidance on how to design a rigid network for self-calibration of TLS. These include:

- how to reduce correlation between target offsets and scanning positions using asymmetrical targets field pattern;
- using a larger and longer range facility to reduce the correlation between additive constants in order to give a better result;
- the scanning orientation must be in orthogonal direction; and
- the use of numerous targets with a minimum of 130 targets.

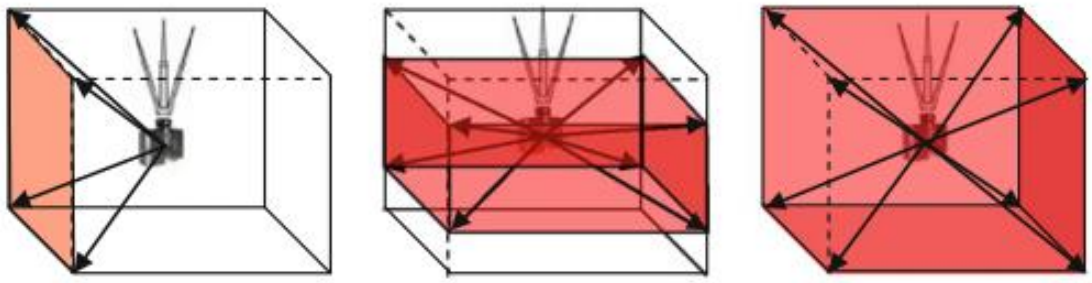
The determination of the number of targets to be used for testing the accuracy of TLS is another critical point that must be considered when designing the testing facility. An example of this was found in testing the range accuracy of a laser scanning system, where a single target was used to check the accuracy of the system. In a scenario where both angular accuracies are to be investigated, more targets are to be placed at different positions. Similarly, in an investigation to calibrate a 2D LMS 200 laser scanner, Ye & Borenstein (2002) used a total number of 13 targets. However, this number of targets was relatively low compared to the one recommended by Lichti (2010b) in his investigation.

Based on the investigations by several authors, there is no specific standard to follow on the number of targets to be used. Nevertheless, it is recommended to make use as many targets as possible. The higher the number of targets used, the higher the accuracy of the final registered scan (Gleason, 2013). Limiting the number of targets used can greatly affect the post-processing analysis which will lead to low-quality registration of data. Although in most cases, the number of targets to be used depends on the number of setup and network geometry. The more scans captured, the higher the precision and accuracy of the measurement. This provides more data for the analysis. Various authors have centered their recommendations on a minimum of two scans per setup, though this varies with the size of the facility (Lichti, 2007) and (Lichti, 2009). Therefore, smaller facilities will have less setups that can influence the correlation between additional calibration parameters.

2.2 Accuracy Testing of a Terrestrial Laser Scanner

Self-calibration or testing is important for precise work as it reduces the impact of systematic errors and dependencies between model variables in the observed measurements. The term self-calibration or testing is a common expression used to describe the process of finding only the parameters needed to adjust the instrument observation to acquire results closer to manufacturer specifications (Reshetyuk, 2010). Added to this interpretation, Boehler & Marbs (2003) defined calibration of a laser scanner as the process of checking the accuracy of the observed measurement and comparing it to the quoted manufacturer specifications. The calibration exercise will not only check the accuracy but also improve the accuracy of subsequently acquired point cloud data and reduce the functional dependence of model variables (Lichti, 2007).

Terrestrial laser scanners can be categorised into three major groups based on their mechanical components and design features. According to Lichti (2009), these are camera scanners, panoramic and hybrid laser scanners. Both panoramic and hybrid laser scanners have the same functionality but differ in terms of their method of scanning and vertical field of view (FOV). A panoramic laser scanner captures data through a horizontal range of 180^o, while a hybrid scanner generates points in a full 360^o horizontal with a vertical view that ranges between a minimum and maximum values of 50^o and 60^o respectively (Petrie & Toth, 2008). The vertical field of view for a panoramic scanner is nearly a complete circle except for the single-facet mirror directly below the equipment which covers only tens of degrees. The camera scanner has a low and narrow field of view of about 40^o x 40^o between the three types of terrestrial laser scanners based on FOV as shown in Figure 2.2.



(a) *(b)* *(c)*

Figure 2.2: Images showing Classification of TLSs Based on Field of View (a) Camera Scanner (b) Hybrid Scanner (c) Panoramic Scanner (Abbas, et al., 2013b)

The significance of the FOV as an internal architecture feature reduces the correlation of some additional parameters such as collimation axis error in hybrid and panoramic terrestrial laser scanners (Lichti (2007; 2009; 2010a) & Reshetyuk (2009)).

Recently, there have been substantive investigations and publications on how to independently calibrate and test the accuracy of terrestrial laser scanners. Many of these tests have been conducted on how to develop a model and procedures for calibrations of the laser scanner. In some experiments, the investigations were done by comparing point cloud data from different scanners using reference targets and objects. An example of this was the self-calibration technique employed at the Geodesy Division of the Royal Institute of Technology (KTH). In this experiment, MATLAB was used to determine the coordinate of the targets with the help of a software called Cyclone. The differences between the coordinates acquired by the laser scanner and the calculated coordinates by the software were the errors in the system.

The self-calibration of a laser scanner involves using a set of coordinate points with known accuracy to reduce the dependency variables in the model. Reshetyuk (2010) & Abbas *et al*., (2013a), defined calibration as a process of estimating the parameter required to bring the instrument observation closer to the manufacturer specifications or true values. This process can generate a model that can be used to identify and update error in the system. Though there is a slight difference between the calibration and self-calibration of a laser scanner; Chow, *et al*., (2010) and Al-Manasir & Lichti, (2015) explained the difference between calibration and self-calibration. The calibration process involves using special equipment or an EDM baseline and oscilloscope while self-calibration only requires targets of any form, positioned in the free space in order to identify systematic errors.

Two techniques used in examining the accuracy of a terrestrial laser scanner were discussed by Abbas *et al*., (2013) & Reshetyuk (2006) as component and system calibration methods. The component approach is based on modelling of systematic errors in the instrument that requires special facilities. The system calibration method makes use of statistical analysis to investigate the presence of systematic errors of a scanner with other system parameters. The following diagram in Figure 2.3 shows the self-calibration or accuracy testing procedures for a terrestrial laser scanner according to (Abbas, *et al.*, 2013a).

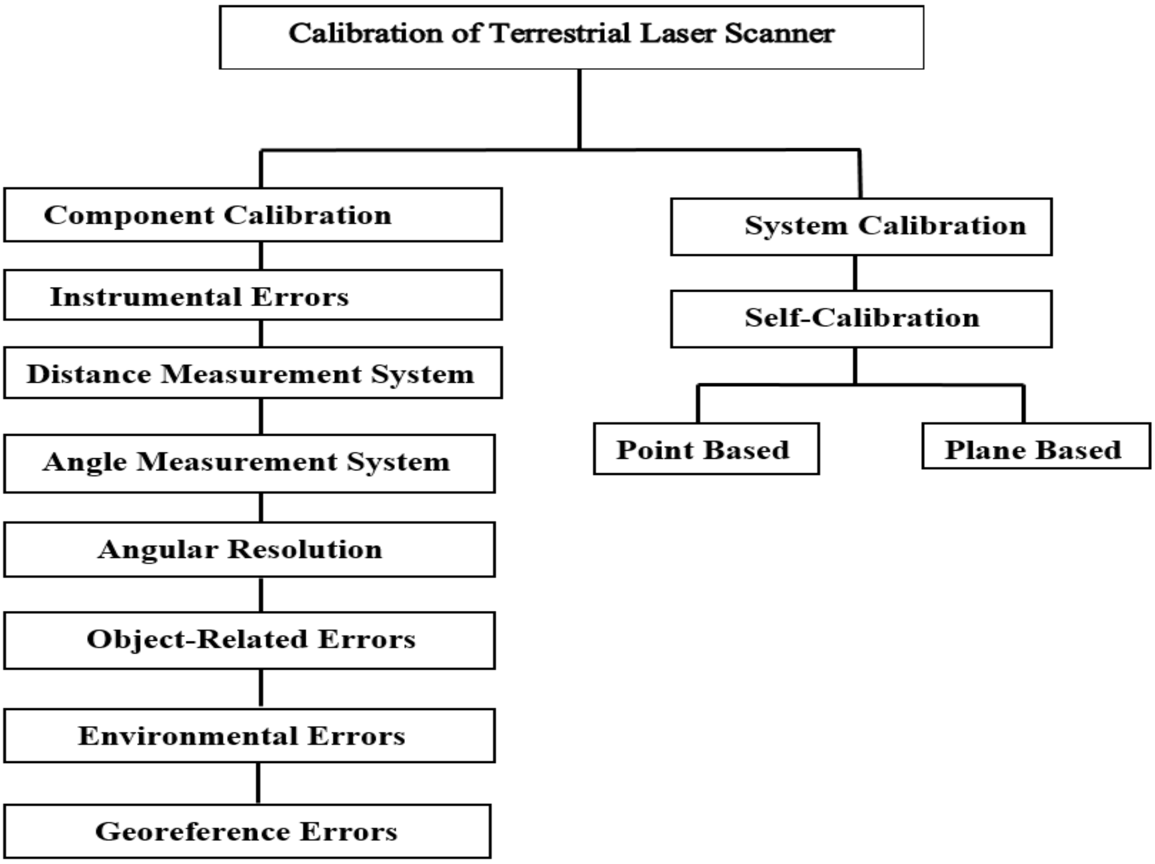


Figure 2.3: Calibration Procedure for Terrestrial Laser Scanner (Abbas, et al., 2013).

Significant work has been performed on accuracy testing and calibration of terrestrial laser scanners using different approaches to reduce the impact of systematic errors. The systematic errors limit the accuracy of the laser scanner and a good calibration approach will guarantee improvement in the quality and reliability of the acquired results. Many researchers have independently used these methods to identify systematic errors present in the data and to improve the quality of the results for precise work. Quality control is an important procedure in the field of laser scanning due to the ability of the instrument to capture a huge amount of data within a shorter period of time. The component and system calibration methods have been used in testing the accuracy of TLS and analyse the types and sources of errors in the instrument.

According to Davison (2017), there are two types of sources of TLS error; namely physical and empirical errors. The known factors such as rangefinder offset, cyclic error, trunnion axis error, vertical circle and collimation error that affect the accuracy of a scanner lead to a physical error. On the other hand, empirical sources are those errors that lack detailed explanation but show a high magnitude of substantial errors. The empirical source cannot be modelled, unless a thorough investigation is done. This is one of the reasons why most researchers use already developed parameters for the modelling of errors in a total station which is similar to that of TLS (Lichti & Licht, 2006). Using total station models in calibrating a TLS is challenging to certain extents as some of the sources of these errors in a TLS are more complex compared to that of a total station.

In testing the accuracy of the laser scanners, there are two major approaches adopted by a number researchers based on the types of target used. These are categorised into plane and point based target methods (Chow, *et al*., 2011). However, there are other types of targets with less accuracies such as spherical and cylindrical targets (Ge & Wunderlich, 2014). Nonetheless, a combination of these targets can be used, as was employed by Lichti &Licht (2006) in error modelling of the terrestrial laser scanner Faro 880. In testing or self-calibration of terrestrial laser scanners, either of the two techniques can be used to reduce functional dependency between the model variables. These methods are known for the collection of a high redundant set of data depending on the choice of the researcher.

Apart from the abovementioned methods used in calibrating laser scanners, one needs to look at the concepts used by Zhao, *et al*., (2007) in calibrating laser scanner and other sensor systems. In order to register the data from the mobile scanning platform (the laser scanner and the camera system), they used a calibration checkerboard at different angles and orientation which was visible by the scanner and camera. The coordinates of the checkerboard positions were used to compare the location of the laser scanner and the camera system. Though the method is commonly used in the self-calibration and accuracy testing of video cameras. This method can be adopted to laser scanners with the use of planar surface checkerboard. Zhao, *et al*., (2007) classified this approach into intrinsic and extrinsic methods. The intrinsic method involves defining parameters related to camera focal length, optical distortion, and principal point. On the other hand, the extrinsic calibration approach involves finding correlative rotation and translation between various sensor coordinate systems in order to generate calibration parameters. The benefits of this approach is that it requires no special facilities like self-calibration and it is very fast and cheap to perform (Zhao, *et al*., 2007).

2.2.1 Accuracy Testing Using Plane-Based Self-Calibration Method

The plane-based method of self-calibration is an approach of using planar templates that are printed and positioned at different angles and orientations in a test facility. This technique depends on the intensity of the returning laser beam from the surface of the planar target to extract some planar features. The extracted planar features are used for self-calibration of the laser scanner. Based on investigation by Gielsdorf, *et al*., (2004) in order to minimise the effect of instrumental errors, calibration parameters are estimated using planar targets placed at different angles and orientations. The concept behind this technique is to divide the acquired point clouds with its correspondent planar panel to estimate the variables such as the scanner position and orientation of the instrument (Lichti, 2010a). A least-squares normal equation is formed from the corresponding observable point cloud data that lie on the planar panel. The equation is used to estimate the scanner positions, some Exterior Orientation Parameters (EOPs), plane parameters and additional parameters for modelling of systematic errors. The application of this method for self-calibration of terrestrial laser scanners was discussed by Gielsdorf, *et al*., (2004), Bae & Lichti (2007), Dorninger *et al*., (2008), Glennie & Lichti (2010) & Lichti (2010a).

2.2.2 Accuracy Testing Using Point-Based Self-Calibration Method

For the point based method, various point cloud data are captured from different scan positions in a space where the planar targets are fixed to the wall, ceiling and floor. The equations generated from the scans are used to solve for the exterior orientation parameters, target centre coordinates and other additional parameters (Lichti, 2010a). The targets used for the calibration procedure must be of high-contrast components that are visible for the scanner to locate its centre coordinates. However, reflective targets are not recommended, as these can cause range errors in the measurements.

This approach has been successfully used by many researchers, but it requires a strong network configuration with a large number of targets. Moreover, this method can be used to improve the geometry quality of the captured 3D coordinates with the aid of a terrestrial laser scanner sensor. The observation equation for each of the target centre and the equation of the external orientation parameters are all solved concurrently.

The accuracy testing procedure of point based method requires a reference framework that defines the object space coordinate system. The system coordinates will be in a 3D coordinate system that directly defines the centre of the target. The measurement from the target captured by the TLS will be referenced to a local coordinate frame where all the calibration parameters are defined. There are calibration models developed for the positioning of a single point (i) which depends on errors from the three raw observation components. These components are range (ρ), horizontal angle (Θ) and the elevation (vertical) angle (α) in the horizontal plane. Lichti (2007) used the following self-calibration models to investigate the accuracy of TLS by deriving the three observation components.

$$P_{ij} + V_{\rho ij} = \sqrt{x_{ij}^2 + y_{ij}^2 + z_{ij}^2 + \Delta_P} \tag{2.1}$$

$$\theta_{ij} + V_{\theta ij} = \arctan(\frac{y_{ij}}{x_{ij}}) + \Delta_\theta \tag{2.2}$$

$$\alpha_{ij} + V_{\alpha ij} = \arctan\left(\frac{z_{ij}}{\sqrt{x_{ij}^2 + y_{ij}^2}}\right) + \Delta_\alpha \tag{2.3}$$

Equation (2.1), (2.2), (2.3) and (2.4) source: Lichti (2007).

From these equations, (*i*) represents the spherical object coordinate and (*j*) is the coordinate of the scanning systems. Thus, the cartesian coordinates of point *i* and scanner space *j* can be described as (X*ij* Y*ij* Z*ij*). In case of a panoramic scanner, 180^o must be added to the right hand side of the equation (2.2) which is the model for horizontal direction. On the other hand, 180^o must be subtracted from right hand side of equation (2.3), that is, the model for elevation angle (Lichti, 2010a). The unknown systematic error Δρ, ΔΘ and Δα denote interior orientation of the laser scanner which needs to be applied on the raw measurement for proper corrections.

The observation equation for both systems (the scanner space and object space) coordinates will be related by the 3D rigid body transformation that forms the six EOP's parameters for each scan station.

$$\begin{bmatrix} X_{ij} \\ Y_{ij} \\ Z_{ij} \end{bmatrix} = R_3(k_j) R_2(\varphi_j) R_1(w_j) \left\{ \begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix} - \begin{bmatrix} X_{si} \\ Y_{si} \\ Z_{si} \end{bmatrix} \right\} \tag{2.4}$$

Equation (2.4) source: Lichti (2007).

In equation (2.4), (X, Y, Z)i and (X*s*, Y*s*, Z*s*) denote the coordinates of the object point "*i*" and scanner position "*j*"; (ω, φ, κ) are the rotational angles from the object space to the scanner space; (X, Y, Z) are the object space coordinate of object point *i;* and R_1, R_2, R_3 are the matrices of rotation about X, Y and Z axes.

In order to use this technique, it is important to define the centre of each target, which centre coordinate is determined by conventional surveying methods. These include the use of total station and the application of mathematical least squares calculation approach performed by Leica software (Cyclone) and MATLAB. This method is suitable in an underground environment such as tunnels, where the instrument is used to generate as-built design verification and to collect a 3D dataset of the scan area as the excavation is advancing. This approach has been used by several researchers such as Reshetyuk (2006; 2009), Lichti (2007) & Schneider & Schwalbe (2008). The point base method is popular among researchers despite the plane based method having a higher level of redundancy.

As discussed earlier, the choice of selecting the method suitable for testing the accuracy of a terrestrial laser scanner depends on the user. One also needs to consider the features in the laboratory where one can easily fix the targets on an object. In a tunnel scanning task, point-based target techniques are mostly used due to the nature of a tunnels geometric shape, variation in the incidence angle, the range of the laser beam and influence of target obstruction that can affect the measurement quality (Pejic, 2013). All these can influence the modelling and profiling of the tunnel if the quality of the geometry point cloud data is not satisfied. Due to irregularity in tunnel face geometry, it will be difficult to fix the plane based target on the surface. For this reason, the point-based target method is adopted for a tunnelling project in order to determine the target centre for easy georeferencing of the registered point cloud.

Apart from these two abovementioned major techniques, there are other methods used by researchers in testing terrestrial laser scanners. An example of this was found in an investigation conducted by Alkan & Karsidag (2012) in testing the accuracy of a Z + F IMAGER 5006i terrestrial laser scanner using the difference in distance and scanning densities. In this approach, six stainless steel geometrically shaped objects were placed in the scan area instead of designing a good network configuration. Three of these six objects were a rectangular prism, a cube and a sectional pyramid with metallic colours. Also, five reflective targets were placed at the scan area in order register the scans. The shapes of the object in the scan area were scanned with the scanner settings at “high”, “superhigh” and “ultrahigh” mode. Afterwards, the true base length of the object was measured with a mechanical caliper and the value was compared with the laser scanner observations. The comparisons showed that there was a difference in the observed length at different distances using different instrument settings. According to Alkan & Karsidag (2012), the result of the test shows that the evaluated differences are inversely proportional to the scanning intensity and directly proportional to the scanning distance.

Another initiative adopted by Kaasalainen, *et al*., (2008) was the use of intensity value of the returning laser pulse to calibrate the laser scanner. Although this is commonly used in a moving scanning system such as a Mobile Laser Scanner (MLS) and Airborne Laser Scanner (ALS) to improve their data accuracy and change detection. The intensity value in a TLS is categorised as uncalibrated raw data but can be used in the registration of point cloud data with a high-quality image from the digital camera. In addition, the calibrated intensities are also useful in a point cloud processing algorithm such as the scaling of point cloud data. Notably, the major benefit of calibrated intensity is that there would be no need for geo-referencing of a dataset as this will create calibrated reflectance image and the coordinate.

2.3 Conclusion

The testing methods described in this chapter have been found to be suitable for investigating the accuracy of the terrestrial laser scanner. Some factors that need to be considered in developing a standard laboratory for testing the accuracy of terrestrial laser scanner have been discussed in this chapter. These include:

- Size and shape of the space facility for the test;
- The design of targets to be used (types and size considerations);
- The network geometry of the test area (number of set up and positioning of targets); and
- Selection of self-calibration or testing techniques (Plane and point methods).

These above-listed factors are essential in establishing a testing facility for examining the accuracy of a terrestrial scanner. The results of the test present information about the quality of the acquired point cloud data by the scanner. The testing techniques also provide a quantitative description of the accuracy that the scanner can achieve.

Chapter three discusses the system description of Mobile Laser Scanners (MLS) and several techniques used in investigating the accuracy of MLS. The possible sources and types of errors of a Terrestrial Laser Scanner will be fully discussed.

CHAPTER THREE

3 Mobile Laser Scanning Technique and Sources of Error in Terrestrial Laser Scanners

3.1 Mobile Laser Scanner (MLS) Description

A Mobile Laser Scanner (MLS) is a ground-based laser scanning technology mounted on moving platform to obtain detailed and precise 3D point cloud data. This scanning system consists of a laser range finder integrated with other multiple sensors mounted on the moving platform to measure range and angle from the surroundings. In general, the integrated sensors are digital frame cameras, Global Navigation Satellite Systems (GNSS), Inertial Navigation System (INS) for acceleration and orientation of the moving platform, and the Distance Measuring Indicator (DMI) for determining accurate vehicle velocity as shown in Figure 3.1. The MLS system acquires 3D point cloud data with respect to the trajectory of the moving platform (Hong, *et al.*, 2017).

Figure 3.1: Image Showing Mobile Laser Scanner and Components (Ma, *et al.*, 2018)

The MLS components are categorised into two major parts, the positioning and the mapping sensors (Puente, *et al.*, 2011). The position sensors are used in determining the exact location of MLS systems with regard to GNSS; these sensors are GNSS, INS and the DMI. During scanning, the orientation of the moving platform is recorded by GNSS and the IMU which are used in determining the precise geospatial location and orientation of the instrument during the scanning process. The precision of this measurement depends on the positioning accuracy of the vehicle, and the angle and range accuracy of the laser scanner.

The mapping sensors present information about the features of the scanning environment relative to the local coordinate system of the moving platform. Examples of these sensors are laser scanner, digital camera, and the positioning sensors such as GNSS, DMI and INS. The laser range-finder measures the distance between the laser scanner and the targeted object. The function of the high-quality multiple cameras in the system is to ensure a view of 360^o in the horizontal plane.

Similar to other types of laser scanners, systematic errors are also present in MLS. These errors are caused by manufacturer imperfections such as misalignment of sensors. Therefore, in order to achieve acceptable quality results for both range and angular measurements in MLS, the system needs to be calibrated. The calibration facility will geometrically align both positioning and mapping sensors together. However, the accuracy of the scanner depends on the positioning accuracy during navigation (Han, *et al*., 2017). That is, the precision and accuracy of the GNSS systems control the geospatial accuracy of the mobile laser scanner.

During the scanning task, the instrument makes use of the auxiliary sensors to maintain its accuracy. This is because the auxiliary sensors are designed to correct the orientation and position of the scanner to complete a geo-referenced point cloud, automatically. In general, one of the challenges facing MLS during mapping is the obstruction from structures and high rise objects which may restrict the visibility of satellites for the GNSS sensors. This can cause positioning error in the acquired results by the MLS. With the integration of Simultaneous Localisation and Mapping (SLAM) technique, highly accurate positioning can be achieved. Moreover, inaccuracies during the calibration process, to a certain extent, can be compensated with a SLAM algorithm. Another significant contribution of SLAM algorithm to mobile laser scanners are the registration of 3D point cloud data and the estimation of closed-loop trajectory (Bosse, *et al*., (2012).

In the mobile laser scanning system, the mounting of the laser scanner and other systems on the moving platform are important as these have great influence on the results. By mounting systems on a moving platform, the acceleration and vibration of the system will affect the speed of the platform, causing an increase in field of view outside the standard scanning plane. In an ideal case, the scanner should be mounted firmly on the moving platform so as to prevent system vibration in rough terrain and other unwanted disturbances. In preventing this, other support instruments such as a gimbal are used to stabilise the sensors on the platform.

3.2 Investigating the Accuracy of a Mobile Laser Scanner (MLS)

The precise position and orientation of all the sensors have to be known to obtain a high-quality measurement with a mobile laser scanner. The variations in measurement are caused by systematic errors. These systematic errors occur as a result of misalignment of sensors and sensor data time of recording. Ideally, all systems in a MLS need to synchronize to a common time frame. Timing accuracy, synchronization, and calibration have been recognised as a key factor in precision mapping (Bosse, *et al*., 2012). That is, measurement of data by a laser scanner, IMU, GNSS sensors and other systems have to be time-stamped in order to be able to combine laser scan data with other systems.

System integration errors in a MLS were discussed by Xu *et al*., (2015) as installation errors, time synchronisation errors and coordinate transformation errors. Installation errors arise from sensor deviation that causes systemic variations in the results. This type of error can be prevented by determining the three boresights angle and the lever arms prior to the MLS scanning as shown in Figure 3.2. The time synchronization errors occur when the reference time for each sensor is different. The sensors must synchronize at the same time to prevent time-delay error in results. Coordinate transformation errors occur when the when the sensor coordinates are limited by the transformation model.

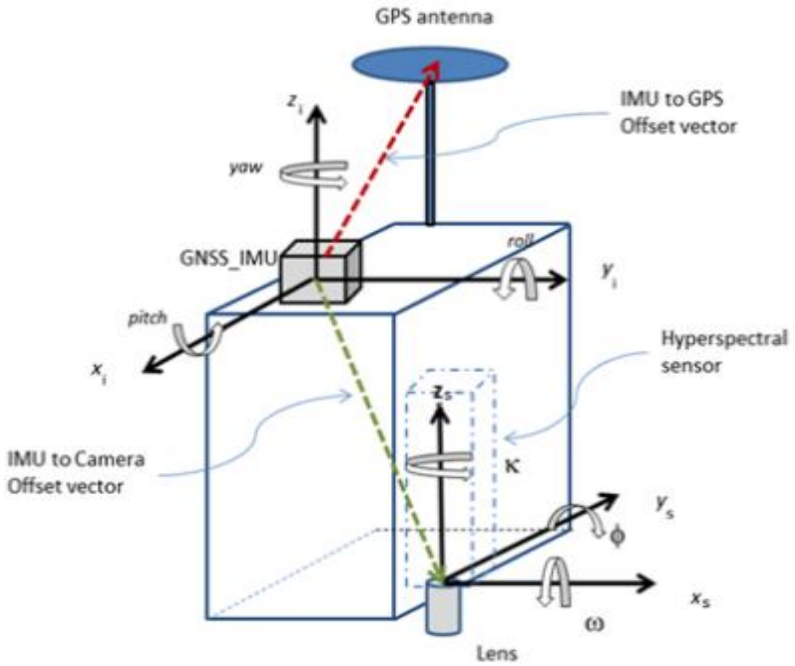


Figure 3.2*: Calibration Consideration using the Eccentricity distance between GPS and IMU Framework as well as Angular Boresight Angle (Elrahman, et al., 2016).*

It is unfortunate that the manufacturers of laser scanning systems do not make their calibration approach available for user reference. Likewise, laser scanners in the market lack a suitable description on how to efficiently carry out accuracy testing on the systems. In recent times, there have been several techniques suggested by various authors on how to examine the accuracy of mobile laser scanners and other components. Some of these methods rely on terrestrial laser scanner (TLS) to provide accurate coordinates for assessing the performance of a mobile laser scanner. The TLS is preferred because of its higher precision and accuracy in generating 3D point cloud data. According to Mao, *et al*., (2015), assessing and controlling the accuracy of technology can be classified into data-driven and model-driven. The data-driven technique applies ground control points to eliminate and reduce errors that are present in the measurement. While the model-driven makes use of analytical methods to reduce the impact of the errors.

Several investigations have proven to be successful in establishing the accuracy of a MLS. Botes (2013) compared the MLS results with other existing systems with proven accuracy and precision. The results from MLS are assessed against airborne laser scanning (ALS), photogrammetry and other conventional ground-based surveying instruments with better accuracies. The outcome of the investigation by Kaartineen, *et al*., (2012) showed that the accuracy of the MLS depends on the performance of the GNSS. This experiment was conducted in a permanent test field, where the point cloud data from different systems such as Optech, Riegl and Street Mapper were compared with one another. This was done in order to establish some point tests in the test field for examining the accuracy of laser scanners. Similarly, Barber *et al*., (2008) examined the accuracy of Street Mapper by comparing its result with that of Real-Time Kinematic (RTK) GNSS. The results of the comparison revealed that the data generated by the Street Mapper had an elevation difference of 3cm as compared to (RTK) GNSS. Hong, *et al*., (2017) calibrated the Mobile Mapping System (MMS) using control reference features to improve the system performance. This approach involves using point and plane features from the camera, mobile scanner and the terrestrial laser scanner to estimate the performance of the MMS. At a later stage, the least squares adjustment technique was used for both points and features based methods in estimating a calibration parameter for the MLS. The compared data serves as the control reference features for estimating the calibration parameters for MLS calibration.

Apart from features comparison method, the calibration of mobile scanners can also be done using calibration grids. This technique does not need any calibration object apart from the grid positioned at different angles and orientations. The method was used by Zhao, *et al*., (2007) in an attempt to calibrate MLS with multiple sensors on a vehicle. In their investigation, both the laser scanner and camera were considered in the process.

In another attempt to examine the accuracy of the mobile laser scanner by Scaramuzza, *et al*., (2007), a calibration grid technique was adopted in the experiment. The calibration grid was positioned at different angles and orientations in order to view the range information acquired by the laser scanner. This visual identification of points between the 3D laser range finder and the camera image becomes the connection for image pairing. The obtained corresponding image with Perspective and Point (PnP) algorithm was used to calibrate the laser scanner and the camera system. According to Scaramuzza, *et al*., (2007) this approach can be classified as a self-calibration technique, as calibration parameters for both systems are determined concurrently.

Analysing the accuracy of MLS using image alignment was achieved by Miled, *et al*., (2016). The study calibrated a mobile laser scanner using image alignment by Mutual Information (MI) between the image source and the points reflectance. In doing this, the acquired point cloud data with the image was transformed into a single coordinate system for georeferencing. The idea behind this method was to check if the image and point clouds acquired are aligned with the reference coordinate system.

3.3 Sources of Error in Terrestrial Laser Scanner

Similar to other conventional surveying instruments, Terrestrial Laser Scanners (TLS) are also affected by the presence of errors originating from different sources. These errors can be regarded as an instrumental error or non-instrumental error. The instrumental errors in TLS occur as a result of mechanical imperfections in the instrument which creates a discrepancy in the results. Non-instrumental errors are common to the surveying field when standard measurement procedures are not followed. These errors control the precision of the instrument by influencing the measurement process, hence they impair the accuracy of the point cloud data. Notably, human errors are minimised in TLS with recent development in the technology; the instrument performs many of its tasks by automation. For this reason, the most common errors from the TLS are caused by the instrument, observation method and the environmental factors.

Terrestrial laser scanning is a recent technique for generating 3D point cloud data, with this, there are sources of errors in the system that needs to be better understood. These errors in measurement occur through various means such as faulty instrumentation, unfavourable environment and an improper measurement process. The knowledge of the source of errors in terrestrial laser scanner is essential in generating reliable point cloud data. The earlier one is able to spot the occurrence of these errors in measurements, the better one is able to correct these errors. Also, knowing the possible source of errors in TLS will provide information about the quality of data generated and performance of the scanner. The scan results from TLS might contain some inherent errors, these can be either systematic or random errors. To identify these errors, an accuracy test must be carried out on the laser scanning system. This test will indicate if the laser scanner is performing according to manufacturer's specifications and specify if is fit for tasks at hand.

The terrestrial laser scanner works on the principle of using the intensity of the reflected signal from the target surface to obtain its range measurement. The accuracy of the measured distance depends on the following factors:

- Instrument and atmospheric effects (ambient light, humidity, temperature, and atmosphere);
- The property of the targets (size, roughness, reflectivity, colour and angle); and
- The measurement geometry (incidence angle and range differences) on the surface.

Reshetyuk (2006) reported that the following reflectivity factors affect the intensity of the returning laser signal:

- The material properties of the object (conductivity, permeability and the electric permittivity);
- The surface colour of the target;
- The surface roughness of the target which is a factor of the incidence angle and wavelength of the emitted laser beam;
- The temperature of the scanning environment. That is, an increase in temperature of the scanning environment causes reduction in the strength of the returning signal;
- The moisture on the object surface; and
- The polarisation of the laser beam.

The sources of error in any surveying instrument depends on its application. For instance, the accuracy of TLS depends on the type ranging principle employed in the measurement. The possible sources of error in TLS were classified into four groups according to (Reshetyuk, 2006) and Cosarca *et al*., (2009) as:

- Instrument error;
- Error arising from the nature of the target;
- Environmental error; and
- Methodological error.

Lichti & Gordon (2004) further summarised the above listed sources of errors into two groups as; internal errors and external errors. The internal errors are made up of errors coming from the instrument while external errors consist of georeferenced errors, methodological errors and environmental errors.

3.3.1 Instrumental Errors in Terrestrial Laser Scanning

These are errors caused by instrument anomalies. The imperfections of the instrument are influenced by deviation in the manufacturing and assembling of components which lead to errors in the measurement. It is possible to have both systematic and random errors in TLS measurements. The systematic error controls the total station by creating complex modelling issues between the accuracy parameters. The random error can influence the precision of the results of the distance and angular measurements when the time of flight principle is applied.

Reshetyuk (2006) grouped the instrumental errors in TLS into fundamental errors and errors attributed to the hardware design of the system. Examples of these errors in TLS are the rangefinder, beam deflection errors and axes errors.

Rangefinder Error

The rangefinder measures the phase difference between the transmitted and the returning laser pulse. To determine the 3D position of a single point, the laser signal needs to be redirected into two orthogonal directions, which can be achieved using a reflective surface target. The reflecting target is vital in estimating the speed of the returning laser pulse as this will direct the intensity-modulated laser beam back to the source (transmitter). Deviation of the laser signal caused by irregularities of air density leads to error in the range measurement. According to Reshetyuk (2009), the precision in range measurement depends on the signal to noise ratio (SNR). In order to produce reliable range measurement, the SNR must be a minimum of ten, while no range value can be measured when the SNR is equal to five. In Pedersen, *et al*., (2014) in the investigation, it was found that the best value of SNR for LiDAR was estimated by reducing the SNR value by a factor of $\sqrt{2}$ which is approximately -1.5 dB. This reduction in SNR will in most situations not limit the operation of the LiDAR, but under conditions with very clear air or very fast measurements it must be taken into consideration.

In addition, the accuracy of the rangefinder depends on the intensity of the propagation and linearity of the returning laser signal to the surface of the photodiode. It is obvious that linearity of the rangefinder is important for accurate measurement, as this will eliminate the effect of the cyclic error which causes divergence of the laser beam. Moreover, calibration and proper handling of the instrument will improve the ranging precision of the terrestrial laser scanner. In investigating the factors that affect the range measurement, the distance of the reference target must be known accurately in order to measure the range accuracy of the instrument. Primarily, the fluctuation in the refractive index of the air along the beam path of the optical components of the instrument is a major factor that controls the accuracy of the rangefinder. According to Reshetyuk (2006), the best way to test the range accuracy of a terrestrial laser scanner is to conduct a scan and model a planar surface. The standard deviation of the fitted plane will be compared to that of the single points to evaluate the ranging precision for the scanner. The sources of error that led to rangefinder error were categorised by Hashemi, *et al*., (1994) as; drift error, statistical error, alignment error, cyclic error and slope error. All the abovementioned sources were summarised into two categories by Reshetyuk (2006) as random error and systematic error.

Beam Deflection Errors

A beam deflection error in laser scanning technology is another source of systematic error. The deflection of the laser signal is the widening of the beam that occurs as a result of the distance travelled. That is, the beam divergence in a laser scanner is a function of distance travelled. It becomes relatively high in longer distances which cannot be neglected. The instrument imperfections also affect the precision of the angular measurements which occurs as a result of misalignment of rotating mirrors. Higher numbers of these errors take place as a result of the network design. Ideally, the emitted laser signal must return to the scanner aligned to the centre of the mirror after reflecting back from the inclined surface. If the returning laser signal cannot spot the centre position of the laser scanner that creates the digitised coordinate, this will lead to beam deflection error. The mechanical angular variations in the sensors also contribute to the propagation of this error. The orientation of the sensor for measuring both horizontal direction and vertical angles can also influence the quality of the acquired point cloud data.

The emittance of laser beam works on the principle of a rotating mirror in axis which is assumed to be orthogonal in deflecting the emitted laser beam. The deflected beam depends on the axes of the rotating mirror, that is, the vertical deflection that creates the vertical profiling of the scan surface while the horizontal deflection measures the following adjacent profile. The centre point of the scanner is located in the middle of the mirror. Thus, any deviations from this centroid position will lead to the emergence of beam deflection error in the acquired point cloud as shown in Figure 3.3.

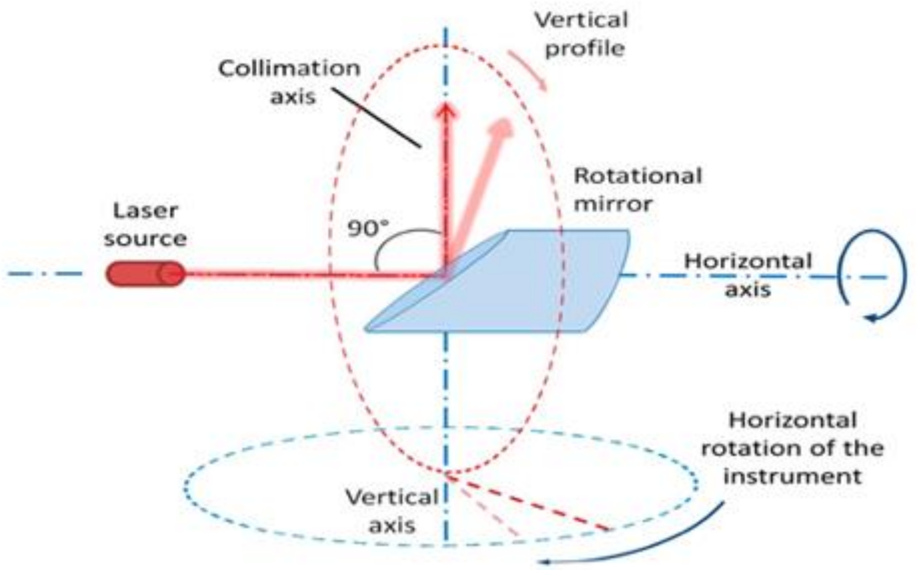


Figure 3.3: Illustration of Panoramic Terrestrial Laser Scanner Geometry (Medic, et al., 2017).

The laser scanner is an electro-optical device, the accuracy of the laser beam depends on the tangent of the scan angle and its position within the scan window (Xi, *et al.*, 2001). For this reason, the geometry of the scanned surface also influences the accuracy of the acquired point cloud data. This type of instrumental error is common among Airborne Laser Scanners (ALS) and Terrestrial Laser Scanner (TLS). The other sources of error in the beam deflection component was discussed by Reshetyuk as angular accuracy, zero error and scale error.

Axes Error in Terrestrial Laser Scanner

The source of the laser signal in TLS launches from the centre of two rotating mirrors that revolves in both primary (horizontal) and secondary (vertical) axes. The deviation of the laser beam from these axes leads to these axes errors which are majorly caused by mechanical imperfections of the components and misalignment of axes. Though, the upside about these errors is that they can be eliminated through modelling while the random error can be mitigated by following a standard procedure during measurement. The axes errors in TLS can be compared to that of the total station (to a certain extent. Although calibration procedures in TLS are more complex than that of the total station. This is as result of the ability of the laser system to measure multiple points from a single set up, as compared to a Total Station that sends light to a specific target to measure the actual distance and direction from a single set up.

Similar to total station instrument, TLS also has three axes errors which were reported by Reshetyuk (2006) and AbdulHussain, *et al*., (2017) as horizontal axis error, collimation axis error and vertical axis error. Most of these errors are caused by misinterpretation of horizontal circle readings.

- **Horizontal Axis Error**: This error exists when there is a deviation between the horizontal axes and vertical axes. In an ideal situation, the deflected laser signal must be perpendicular to the tilt axis of the instrument. That is, the horizontal axis must be perpendicular to the vertical axis (orthogonal). If these two axes are not at right angles to one another due to mechanical misalignment, the observed measurement will contain horizontal error.
- **Collimation Axis Error**: This type of axis error is also known as the "sight axis". That is, an error that originated from the scanner as a result of non-perpendicularity of the laser signal to the horizontal axis. This axis defines the line that passes through the centre of the mirror and extends in the direction of the reflected laser beam. The error occurs when the reflected laser signal is not perpendicular to the horizontal axis which brings about movement of the laser signal within a cone instead of a plane as the prism is rotating.
- **Vertical Axis Error**: This is the axis that is aligned in the vertical scanning plane, which is the rotational axis of the instrument's head. The vertical error occurs when the axis is not vertically upright leading to the deviation of the reflected laser beam. This

axis can be defined as the orthogonal axis that lies between the two mutual oscillating mirrors that are moving in vertical and horizontal axes.

3.3.2 Terrestrial Laser Scanning Errors Arising from the Nature of the Target

Another source of error in terrestrial laser scanning technology occurs as a result of the nature of the target in the scanning facility. TLS system data is collected by calculating the time difference measured between the emission of a laser signal and the return of a laser signal from the target surface. That is, the scanner is dependent on the reflected signal from the target surface to measure the distance. The intensity of the reflected laser beam also depends on the colour of the surface and other factors which determines the point accuracy of the scanner. A dark surface will absorb the laser signal and reflect few or no signals which lead to errors in the observed data. A highly reflective (white) surface will yield a strong reflection. However, an extremely highly reflective surface should be avoided as this will cause scattering of the reflected laser beam which results in the propagation of errors in range.

The variability in the surface of the target will bring about an offset in the measured distance. The offset caused in the distance measured corresponds to the wavelength of the scanner. That is, scanning at different surfaces and wavelength can introduce range error into the results. This is the reason why manufacturers of a laser scanner usually recommend the type of target to be used at a specific range.

The reflectivity is an important factor to consider for high precisions scanning work. Laser scanners are very sensitive to a reflective substance such as glass, water and shiny objects. A highly reflective surface will generate low returns of laser signal which leads to range error in the measurement. Actually, low return of signals are caused by the attenuated amplitude of the reflected laser beam due to the scattering effect of the reflected signal. If these reflective substances can be removed in a scan environment, it will improve the accuracy of the scan. Moreover, the reflectivity property of the scan surface also affects the intensity of the returning laser pulse. As the shiny surface is difficult to measure due to its high specular reflection characteristics. This can be explained by surface reflectance and multipath reflection.

Surface Reflectance

Targets with highly reflectivity material return few or no signal back to the laser scanner. This will lead to errors in the measured distance and also will facilitate the production of noise and beamwidth uncertainty in the results. If the colour of the surface is black, it will result in poor reflection by absorbing the light from the surface. In preventing the absorption of light, white targets were used which enhances a strong reflection of the laser beam.

Multipath Reflection

This explains the nature of the reflective coating of the target surface that permits the laser beam to refract and reflect which leads to the additional distance measurements. It has been proven by various investigations that the signal to noise ratio (SNR) increases significantly in longitudinal mode due to surface coating. Variations in the SNR have an influence on the accuracy of the laser scanner.

3.3.3 Environmental Error in Terrestrial Laser Scanning

These are errors caused by temperature, atmosphere, relative humidity, pressure, interfering radiation and distortion from motion. All these factors contribute to the presence of this error in TLS measurement.

Temperature

It is important to take note of the temperature of the instrument and compare it with that of the surroundings, as the scanner works at a particular range of temperature. The Riegl VZ - 6000 has a recommended temperature range of -10^{o} C to 50^{o} C, while the Faro Focus 3D X 130 is recommended to work best in a temperature range of 5^{o} C to - 40^{o}C. This recommended temperature range is usually stated in the manufacturer manual of the system. A high temperature can cause internal heating of the equipment which influences the scan results. The internal temperature of the laser scanner might be higher than that of the surroundings due to the heat generated by components in the system. This can cause reduction in the signal-to-noise ratio (SNR) and affect the precision of the distance measurement. Scanning under intense sunlight can lead to interference from external radiation that affects the measurement result.

Interfering Radiation

Interference of the laser signal occurs when the emitted laser signal operates at a very close frequency band to an external illuminating source. In this case, the accuracy of the results are affected by the interfering radiation from external lighting sources such as sunlight, lamps and other sources of illumination. The precision of the range measurement can be controlled by the interfering radiation when the power from these external sources are stronger than that of the transmitted laser signal. The interference in terrestrial laser scanning can be reduced by placing a narrow-band optical interference filter in front of the receiver lens (Reshetyuk, 2006).

Atmosphere

The atmosphere comprises of temperature, pressure, relative humidity and CO_2 content in the air. Variation in atmospheric conditions will affect the speed of the emitted laser signal especially in longer distance measurements. The difference in temperature, pressure and relative humidity affects the refractive index of the air, which leads to environmental error in the measurement results. The density of the air influences the speed of the emitted signal which also depends on the atmospheric condition. That is, the air density controls the speed of the laser signal which might have a great influence on the result of the scan distances. As mentioned above, unfavourable atmospheric conditions will result into a reduction in the intensity (attenuation) of the laser signal. Also, this depends on the distance to be measured. In the case of longer distances, the attenuation will be more prevalent compared to shorter distances. Though, in the case of short ranges, this effect is negligible. However, scanning in an environment where there is presence of dust, fog or steam can cause bending of the laser-scanning path (edge effect) which may reduce the point cloud data quality considerably. Therefore, atmospheric conditions must be taken into consideration for high precision scans as this can influence beam propagation in a long distance scan. The effect of the atmospheric conditions on the propagation of beam was discussed by Reshetyuk (2009) as:

- distortion of returning laser pulse; and
- intensity reduction (attenuation) of the laser pulse.

Distortion from Motion

During terrestrial laser scanning, vibration and disturbance can cause displacement of the laser scanning mirror to be out of phase which will generate errors in the measured angles. Also, the tripod on which the scanner is mounted must be stable so as to minimise the effect of small displacements from motion. Therefore, it is important to reduce the cause of the source of error during scanning. Part of the effort to keep the instrument stable during scanning is the use of an external stabilisation device known as isolators found in modern laser scanners. Another approach which employs detecting and correcting movement during scanning is the compensation (adjustment) techniques through a dual-axis compensator (tilt). The tilt compensator monitors and measures the tilt at the beginning and end of the scan. The information collected during this process is used to correct the tilt and also changes in the tilt.

3.3.4 Methodological Error in Terrestrial Laser Scanning

This types of error depends on the experience of the operator of the technology. That is, errors happen when the user is not familiar with the instrument or due to chosen survey techniques. An example of this can be found in the target design for scanning work. Other sources of methodological error in TLS is the selection of the wrong terrestrial laser scanner. For instance, when a short-range terrestrial laser scanner is used to measure a distance longer than the recommended manufacturer specifications, it can result in an inaccurate scan product. Another source of methodological error may occur during point cloud data processing. An example of this is error that during the registration process of point cloud data. This error depends on the types of technique used in registering the point cloud data. An example of this is the wrong application of the scanning system type which can affect the result during data registration and processing of the data.

3.4 Types of Errors in Terrestrial Laser Scanning Surveying

Errors are likely to occur in any task that involve data acquisition and measurement. The inexactness and the degree of variances in between values, regardless of the approach or types of scanner used, are known as errors. These variances exist as a result of the difference between a measured value and a true value. The true value is determined by taking the mean of all the repeated measurements. In laser scanning, repeated measurement of the same environment always lead to results that differ from the true values. These redundant measurements are used in providing quality control and to check the presence of an error in the measurement. With terrestrial laser scanning, it is important to study the mode and effect of error propagation in a scanning method. Errors can be introduced through many means in TLS, such as faulty instrumentation, an unfavourable environment and an improper measurement procedure. Errors in surveying can be detected by different methods, such as when the measurement is being done repeatedly and by different equipment. The reiteration of measurements can lead to different results which might be as a result of errors present in the results. Also, comparisons of results can also serve as another method of identifying errors in TLS. That is, the acquired values must be compared to a baseline set of values (true values) in order to establish the accuracy of the laser scanner. These types of errors can be categorised according to Fan (2010) as:

- Mistake;
- System Error; and
- Random Error.

3.4.1 Mistake

A mistake is also known as a blunder (gross error). This type of error is typically caused by human factors such as unfamiliarity with the instrument, carelessness, incorrect measurement and improper procedure. It also occurs when a survey is to be carried out in a difficult working environment or when inappropriate procedures are used. Examples of these improper procedures are:

- inaccurate positioning of an instrument over a control point;
- mistakenly changing of a number during calculation;
- incorrect recording of data;
- incorrect identification of setup position or targets
- improper levelling of the instrument; and
- incorrect use of the instrument.

For high precision work, the blunders need to be eliminated before the analysis stage. That is, before the data adjustment stage, as this assures the removal of errors from the data set. There must be an approach to check and identify this in any measurement.

One of the methods used in eliminating blunders in results is reiteration of measurement. In any measurement, there must be sufficient redundancy in order to identify the mistakes in the observed results. Notably, measurement with enough redundancy will impact the result by improving the quality of acquired data. Likewise, the large redundancy will filter out the inevitable noise that may be present in the acquired point cloud data and also eliminate errors in the observed point cloud data. It will be difficult to detect the presence of gross error in measurement with small redundancy.

According to Elgazooli & Ibrahim (2012), there are two major ways of identifying blunders in measurement. These are: pre-estimation and post-estimation gross error detection. Another method used in detecting blunders in measurement is hypothesis testing. The hypothesis method involves the use of statistical method in detecting gross error in measurement. This method has not gained much recognition in detecting gross errors due to its poor accuracy in predicting blunders. In most cases, this method gives a wrong alarm when detecting errors in measurement. For instance, hypothesis method presents error free results when blunders are found in the results. Alternatively, gross error can be detected and minimized in measurement by checking the reading on multiple occasions. As recommended by Elgazooli & Ibrahim

(2012), the most effective approach in detecting blunders is statistical quality control (SQC) method. The outcome of this method gives efficient and assured precise results.

3.4.2 Systematic Errors in Terrestrial Laser Scanner

Systematic errors are usually originated from the sources such as using non-calibrated instruments. In a terrestrial laser scanner, the imperfections of the system are caused by malfunction of the mechanical components and deviation in the electro-optical measurement. These two flaws can lead to polar beam deflection and rangefinder offset caused by inclination errors from the mirror. The accuracy of the scanner is hindered by the presence of systematic errors in the measurement. These errors in the system need to be properly modelled in order for the scanner to perform at its best. These models will be determined by the self-calibration approach that allows the scanner to achieve the required level of accuracy. The self-calibration procedures will determine if there is any systematic error (calibration parameters) present in the measurement, and also provides a model to reduce the impact of these errors.

Terrestrial laser scanners emit the laser signal from a sensor based on the principle of a rotating mirror in axes. These axes are orthogonal that intercept at a common point that serves as the source of the laser signal (sensor). Systematic errors occur as a result of a deviation of the laser signal from the centre point that leads to the rangefinder offset, the collimation axis error, and the vertical circle index error. Similarly, Isheil, *et al*., (2010) listed three parameters from mechanical parts of the TLS that can influence systematic error in laser scanning measurement. These are:

- the distance between the sensor and the object surface;
- the angle between the laser plane and normal axis of the surface (incidence angle); and
- the angle of ortho-incidence between the axis of laser plane and normal axis.

The above-listed parameters can be represented by parameters which can be derived from mathematical models through redundant measurement. The estimation of these mathematical parameters is generated by comparing measured values to the reference values (true values) in order to determine if there are any systematic errors present in the measurement. This method improves the quality of the acquired results by developing an empirical model for correcting the systematic error in the instrument. In most cases, the systematic errors in TLS are linked to mechanical flaws from the sensor and other components. For instance, the uncertainties of the laser point centre rely on the angle at which the laser beam is emitted from the optical sensor.

The discrepancy caused by the misalignment of the laser point will lead to angular deviation (angular error) in the TLS measurement. This optical angular error determines the angular displacement which directly causes frequency fluctuation of the laser beam (Tamada, *et al*., 2016). Other sources of systematic error, apart from instrument malfunctioning, are the measurement process, error in physical propagation and atmospheric parameters.

The best way to minimise the effect of systematic errors is by modelling and analysing the results. The establishment of the model from all the estimated parameters will assist in reducing the influence of systematic errors in the results. This will also improve the quality of the measured point by bringing the results, after measurement, closer to the reference value (true value). These errors are modelled using either the point or plane target approach in order to determine all model parameters that cause components misalignment error. Regardless of the method used, the estimated model for a TLS must be able to examine the distortion in collimation axis, non-orthogonality of axes and vertical circle index.

Finally, in order to ensure that quality point cloud data is captured, all the systematic errors present must be properly modelled before using the results. The scanner must be in good working order and follow accepted scanning procedures to eliminate or mitigate systematic errors in the measurement.

3.4.3 Random Errors in Terrestrial Laser Scanner

Random errors in terrestrial laser scanning come from sources that are difficult to control. These errors may occur as a result of measurement procedures, such as the speckle noise caused by the summation of light waves on the Charge-Couple Device (CCD) is one of the main sources of random error in triangulation-based laser scanning technique (Feng & Xi, 2001). Likewise, change of environment and measuring instrument can also bring about this error, as this causes variability in the acquired results. It is important to take note of the atmospheric conditions of the scanning environment, especially in long-range scanning. Variation in ambient temperature and atmospheric pressure will influence the propagation speed of the laser signal which can lead to a deviation from the true value.

Random errors are not predictable but can be compensated for by repeating measurements, as these errors will still remain in the measurement even after eliminating both systematic and gross errors. The occurrence and magnitude of these errors are beyond the observer’s control. A significant source contributing to random error in terrestrial laser scanner was mentioned by

Hartzell, *et al*., (2015) as a non-zero beamwidth of the laser beam. That is, an angular error originated from the sensor with reference to the beam centre line which assumed the centre of the reflecting target. This is an additional source of error induced by the uncertainty of the beamwidth which leads to angular and range error source during scan acquisition. The inconsistency in the value of the vertical and horizontal angles within acquired results have a large influence on the quality of data captured. The stability of the instrument during scanning can also propagate random errors as the inclination of sensor reading could be affected by tripod movement during scan acquisition (Hartzell, *et al*., 2015). In addition, the scattering of points around the target surface also produces noise (random error) in the point cloud data when determining the coordinate and the distance. Another example of random errors was found in a triangulation-based laser scanner, where the light waves on a CCD are the major factors causing the speckle effect which is a source of random error (Feng, 2012). This creates uncertainties to determine the centroid of the CCD laser image, which is used in calculating the coordinates of the scanned surfaces. In determining the precise centroid of the laser point, the presence of uncertainties in the acquired point cloud data will result in the creation of 'speckle noise which signifies the presence of random errors. The 'speckle' noise affects the precision of the acquired point cloud data by causing a blurring effect in the image captured by the scanner. This effect can however be controlled by parameters such as: accurate positioning of laser beam centre for point precision, standard beam diameter (spot size), resolution capacity of the scanner and the Effective Instantaneous Field Of View (EIOV) (Barbarella, *et al*., 2017).

A random error can be investigated using statistical analysis, by distributing the results around the mean measurement to lower and higher values. Since the random error is statistical, this can also be removed by statistical means such as determining the mean value of the measurement. In most cases, taking the mean value of the measurement can help in eliminating the effect of random errors in the results. Though random errors are difficult to detect, they can also be minimised by the least squares adjustment solution and through redundant measurements. The least squares adjustment method identifies the mistakes in the measurement and also evaluates the most likely adjusted value for precise results.

Finally, the best way to reduce the impact of random errors is to follow standard measurement procedures. Having a quality scan process will reduce the effect of the potential random errors that may be present in the acquired point cloud data.

3.5 Conclusion

Mobile Laser Scanner systems are a ground-based technology mounted on a moving platform to generate dense 3D point cloud data. A full description of the system components has been discussed along with various techniques used by different researchers. The methods used in examining the accuracy of mobile laser scanners have been duly analysed. Also, the possible sources and types of error in TLS systems have been examined.

Chapter four discusses the estimation of a master beacon coordinates from a Total Station survey method using established ground control points (reference points). The development of the short-range scanning laboratory will be examined and other relevant factors that were considered in setting up a laboratory will be fully discussed.

CHAPTER FOUR

4 Surveying with a Total Station and Short-Range Laboratory Preparation

The previous chapter discussed the various methods used in testing the accuracy of mobile laser scanners and the possible sources of error in terrestrial laser scanning techniques. The objective of this chapter is to determine the coordinates of the control beacon and the targets in the laboratory using a Leica T1201+ and Trimble S6 Total Station respectively. Also, the construction and the positioning of the control beacon, with other factors such as the design and placement of targets in the laboratory, were also discussed.

4.1 Overview of a Total Station Surveying Instrument

A total station is a surveying instrument that is used to determine the coordinate of a point based on the information from the set-up point and another known point with respect to distance and direction measured. This instrument is made up of a combination of electronic distance measurement (EDM) and the electronic transit theodolite (Afeni, 2012). The integration of these two components and some systems such as a microprocessor, an on-board storage system allow the instrument to measure both horizontal and vertical angles with the slope distance to the object and store in the instrument simultaneously. This provides a huge benefit to surveying in terms of speed, convenience, and accuracy compared to other traditional surveying instruments.

The EDM component measures the distance between the instrument and the object using electromagnetic waves. This object can be a reflective prism or other reflective surface. The ability of the instrument to measure a point using a reflective or non-reflective surface is one of the factors considered in categorising the instrument into two groups; these are the reflector and reflectorless types. When prisms are used as target objects, the method is known as a direct reflection which requires constants such as temperature and pressure to be applied during surveying (Hope & Dawe, 2015). Most total stations use a purpose made glass prism as the reflector for the EDM signal, and can measure distances up to a 1500 metres, but some instruments are "reflectorless", and can measure distances to any object that is reasonably light in colour and the reflectivity of the object, up to a hundred of metres (Afeni, 2012).

The advancement in technology has brought about the integration of a wireless system and the instrument is referred to as a ‘robotic total station’. This allows the user to operate the instrument remotely without the help of a survey assistant to hold the prism at the point to be measured. The robotic total station will track the prism as it moves around for the sequence measurement of points. Another improvement in the technology is the integration of a Total Station and GNSS, this integration is refered to as a '*smart station*'. With these improvements, human tasks are being minimised, hence reducing human errors in measurement.

4.1.1 Reflector and Reflectorless Total Station

The reflector method calculates the distance between the instrument and the target using a prism placed at the point to be measured. The distance is based on the time to travel to the prism and back to the instrument. The accuracy of the measurement using this technique can be influenced by the atmospheric condition of the environment in which the distance measurement are taken.

The reflectorless method does not use prisms or reflective targets to measure the distance between the instruments and object. This approach is adopted when taking measurement to inaccessible points where it is impossible to position a prism or target due to risk. The effect of this approach is that its accuracy can easily be influenced by the atmospheric conditions. The surface of the object being measured must be smooth must be smooth with a clear line of sight (Hope & Dawe, 2015).

4.1.2 Total Station Components Description and Mode of Operation

The total station works on the principle of sending an infrared light on a reflective target to simultaneously measure the slope distance and horizontal distance. The EDM calculates the distance from the phase shift between the emitted radiated light and reflected light from the reflector or prism which is positioned at the measurement point as shown in Figure 4.1.

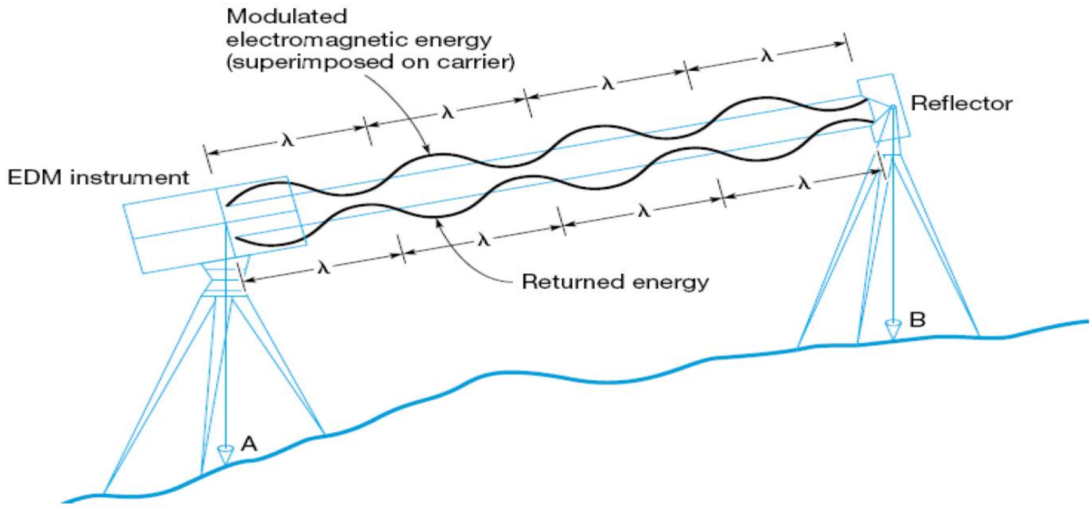
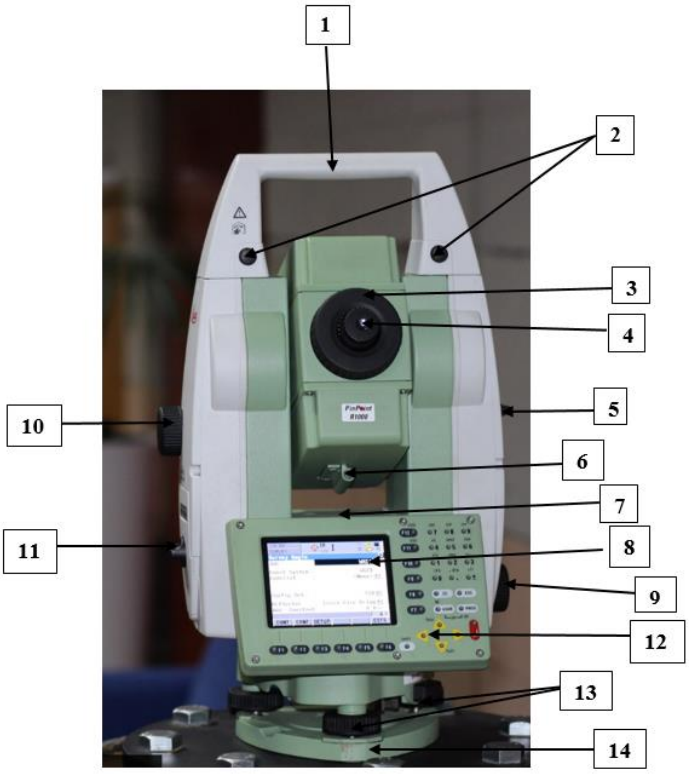


Figure 4.1: Working Principle of Total Station Distance Measurement Using Reflector Prism (Afeni, 2012)

The total station measures the distance using the time taken for the electromagnetic waves from the instrument travel to the prism and return to the instrument. Each measurement is recorded in the instrument storage device which can later be transferred to a computer for software based-applications. When the reflected light returns to the transmitter (receiver), the transmitter directs the light to the appropriate optics (demodulator and phase comparator) to analyse the data considering the type of target (prism constant or reflectorless constant) used before displaying the result on the total station display screen. The demodulator and phase comparator measure the signal wave and compare the reflected light to the signal received from the modulator respectively. The difference in the comparison is then sent to the resolve ambiguity section of the phase measurement and displays the result on the screen.

A Leica Total Station TCR 1201+ and a robotic Trimble S6 Total Station were used to measure the coordinates of the beacon and all the control points in the laboratory. Figure 4.2 shows the components of a Leica Total Station TCR 1201+.



1 – Removable Handle
2 – Point Guide
3 - Telescope Focusing Knob
4 - Telescope Eyepiece
5 - Battery Space
6 - Sighting Colimator
7 - Optical Plummet Eyepiece
8 - Digital Screen
9 - Vertical Image Adjuster
10 - Horizontal Image Adjuster
11 - USB A and Mini Connector
12 - Keyboard
13 – Tribrach Leveling Screws
14 - Tribrach

Figure 4.2: Description of a Leica Total Station TCR 1201+ (Afeni, 2012)

When prisms are not used for measurement in total station surveying, the instrument is set at reflectorless mode which is also known as Direct Reflection Mode. In this approach, the intensity of the reflected infrared light depends on the properties of the object surface and the colour of the object. The intensity of the reflected light from the object surface and the geometry of the target object are the factors used in calculating the range. This makes it possible to measure a long distance without searching for the prism to take a measurement. In fact, it is tedious to search for a prism when the instrument is set at reflector mode especially in a difficult working environment.

The effect of using different colours for the targeted object was investigated by Mazalová *et al.*, (2009). They concluded that black targets were difficult to sight as they caused dispersion of the returning infrared light. Contrarily, the white target met with the accuracy specification while other colours do not have a notable influence on the results.

The introduction of reflectorless measurements eliminates the need for prisms. This attribute of the instrument is a preferred solution to the challenges of working in an environment where it is dangerous to install prisms due to inaccessibility. This makes it possible to take readings and collect data but under the right conditions. Presently, reflectorless EDM technology has become a standard surveying technique where it is either not practical to place a prism because of access or it is unsafe to place prisms (Hope & Dawe, 2015).

Currently, EDM technology can be categorised based on these two methods which are:

- Time of Flight (TOF); and
- Phase-based.

Time of Flight Reflectorless Measurement

As the name implies, the time of flight EDM technology uses the time the light travels to determine the total distance covered. This method transmits the infrared light from the telescope to the reflector target. The total time for the light pulse to travel and return along the parallel path to the transmitter is used to determine the distance travelled. If the distance covered between the instrument and target is known, one can easily determine the speed of the light along the travel time. Time of flight emits more powerful energy compared to the phase-based method. This is the reason it is able to measure much longer distances without a prism than the phased based method (Rada & Bedada, 2012).

Phase-Based Reflectorless Measurement

The phase-based observation method makes use of the phase difference between the transmitted and reflected light to determine the total distance covered. The instrument transmits a visible modulated red laser beam to the target point in order to determine the distance between the transmitted and received light. The Leica TCR 1201+ Total Station used in measurements of the coordinate of the control beacon made use of phase based measurement for prisms as shown in Figure 4.3.

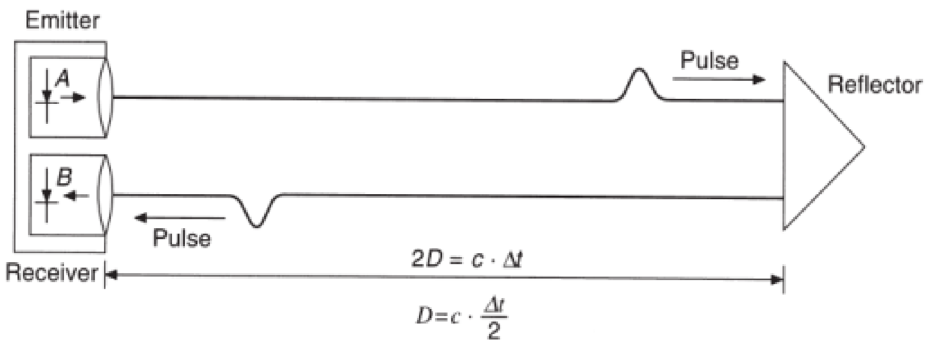


Figure 4.3: Principles of Phase Based Distance Measurement (Rada & Bedada, 2012)

4.1.3 Measurement with a Total Station (Leica TCR 1201+)

The Leica TCR 1201+ Total Station is a modern EDM system that can measure up to 3km with an accuracy specifications of ±2 mm + 2 ppm as stated in the manufacturer's manual. The stated accuracy by the manufacturers can be affected by a change in temperature, pressure and relative humidity of the environment. Although, the instrument can correct these factors for atmospheric effect by inputting the measurements of temperature, pressure, and humidity for the environment for each setup (Solomon, 2014). The parts per million (ppm) is a correction factor that can be applied when temperature and pressure are known. This compensates for the effect of temperature and pressure when taking measurements in changing weather conditions or altitude. This is important in order to keep the measurement within the stated manufacturer's specifications. The temperature and pressure are measured regularly and the recorded values of temperature and pressure are entered into the Total Station so that the ppm is changed accordingly.

The instrument has the ability to take a measurement whenever the line of sight is visible with the centre of the target. In measuring the coordinate of an unknown point, the total station needs direct line of sight for observation from a known point and two more unknown points. That is, the instrument must establish a line of sight in between the known and the unknown points to measure the subtended angles. The measured angles and distances from the instrument and data from the known point are used to compute the coordinates of the unknown points.

The Leica TCR 1201+ Total Station can work in reflectorless mode to measure the slope distance to the object and calculate the point coordinates from the measured horizontal and vertical angles (Beshr & Elnaga, 2012). The instrument measures the horizontal distance, the slope distance and both vertical and horizontal angles between the instrument and the prism. The instrument is capable of performing many tasks such as data processing, elevation difference measurement, distance and angular measurements. For this research, the instrument was set at reflector mode in order to take a measurement to the prism positioned at the measurement points. For this reason, the temperature and pressure were considered in order to get accurate and adjusted results from the instrument.

4.1.4 The Circular Prism

Most surveying tasks that require high precision measurement are done using circular prisms. This is recommended for both long and short range measurement of distance and angles. The reason in using the circular prism is its ability to reflect the emitted signal from the total station back to the total station for processing. This is why it is essential to study the properties of the prism before selecting it for a particular surveying task as this ensures proper reflection of light back to the instrument. Mao & Nindl (2009) listed factors that influence signal reflecting properties as: the centring accuracy of the prism, beam deviation caused by the reflector, reflex coating and anti-reflex coating for particular wavelength, glass quality and alignment to the instruments line of sight. Thus, for high precision survey, genuine manufacturer's prisms are recommended.

In this research, prisms were used for the surveying task to determine the coordinate of the control beacon in the scanning laboratory. The prism used was Leica GeoSystems standard circular prism and holder (GPR1 and GPH1) model as shown in Figure 4.4.

Figure 4.4: Standard Leica GPR1 Circular Prism

It has a diameter of 62 millimeters with 2 millimetres centre accuracy and zero millimetre reflector constant. These abovementioned properties are suitable for proper signal reflection and to ensure accurate measurements when that the prism is aligned with the instruments line of sight.

These circular prisms are mounted on tripod stands with the instrument positioned at a point between the two tripods. The prisms were used for measurement of the backsight and the foresight of points to determine the horizontal angle, vertical angle and slope distance between the prisms.

4.1.5 Establishment of a Control Beacon Coordinate by Traverse Surveying

There are two types of traverse surveying, namely open and closed traverse surveys. The closed traverse survey method was used in calculating the coordinates of the control beacon in the laboratory. In this method, the traversing must close back to its starting point or a known point. The first step in a traverse is to carry out a reconnaissance by locating all the positions of the control points. This is very important to ensure that adequate control points are available at the site. The closed traverse surveying principle was used in determining the distance and subtended angles of points that have been identified in the field. From this approach, the exact coordinates of all the unknown points will be determined from an established control point. The angular misclosure for the all the internal angles was determined by taking the difference between the sum of the angle measured and the sum of angles in the polygon. Sum of the internal angles in a polygon is expressed as,

$$\sum = (2n - 4) \times 90 \qquad (4.1)$$

The summation of all the internal angles as stated in equation 4.1 must be equal to the sum of the geometrical value for accurate measurement. The difference between the two values signifies the presence of angular errors in traversing. The result of subtended angle measurement for the control beacon is presented in Table 4.1, while other results and the photographs for the survey of the control beacon are attached in the Appendix A (Table A1 to A6 and Figure A1 to A3) of this research report.

Table 4.1: Measurement of Internal Angles for Control Beacon Survey

STATION	CLOCKWISE ANGLES	INTERNAL ANGLES	ADJUSTED INT. ANGLES
A1			
A9	-- -- --	-- -- --	-- -- --
T001	270^0 42'30"	89^0 17' 30"	89^0 17' 25.8"
T002	223^0 21'36"	136^0 38' 24"	136^0 38' 19.8"
BEACON	237^0 29'19"	122^0 30'41"	122^0 30' 36.8"
T003	80^0 32' 12"	279^0 27' 48"	279^0 27' 43.8"
T004	261^0 24'56"	98^0 35' 04"	98^0 34' 59.8"
B3	216^0 07'08"	143^0 52' 52"	143^0 52' 47.8"
B21	241^0 24'04"	118^0 35'56"	118^0 35' 51.8"
A1	216^0 28'54"	143^0 31' 06"	143^0 31'1.8"
A9	232^0 28'42"	127^0 31' 17"	127^0 31' 12.8"
		1260^0 00' 38"	**1260^0 00' 00.2'**

From Figure 4.5, the control points A1, A9, B3 and B21 have known coordinates.

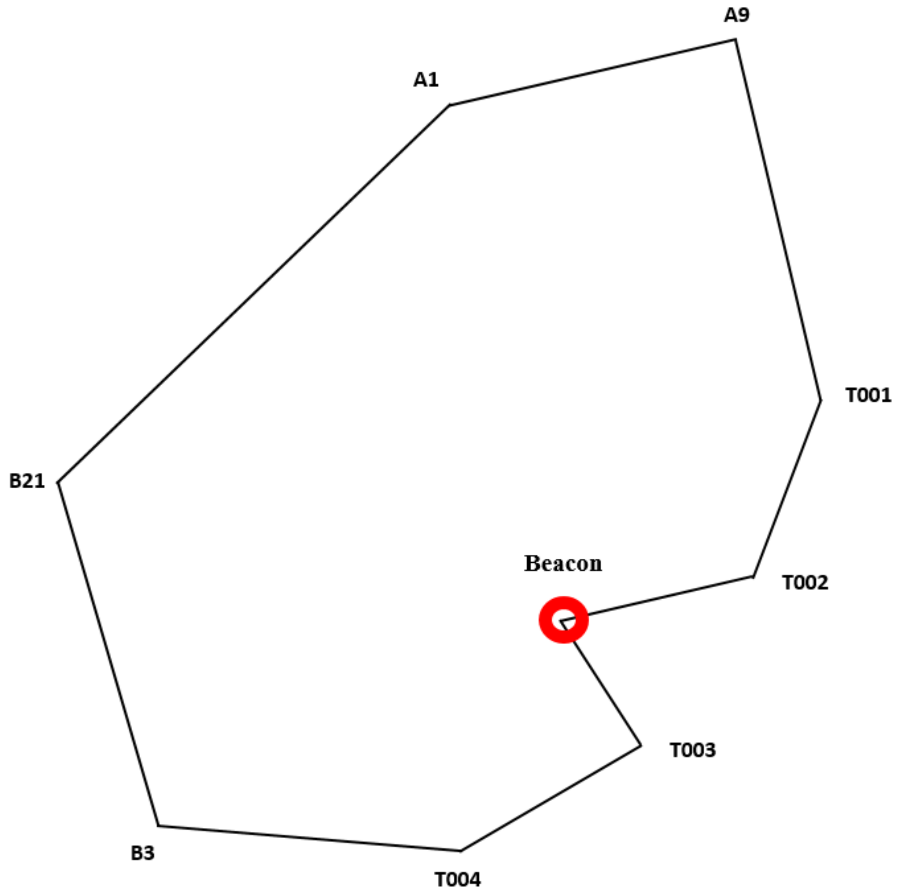


Figure 4.5: Closed Traverse Route to Calculate the Coordinate of the Control Beacon

From Table 4.1, the difference between the sum of observed angles and required values is 38 seconds and this is known as the angular misclosure. Adjustment of the angles was applied to reduce the errors in angular measurement by equal distribution of the angular error. This method was used to adjust the horizontal angles since there was an error in the measured angles. The results of the distribution reduced the angular misclosure value to an acceptable value of 0.02 seconds. The interior angles correction was made by either adding or subtracting from all measured angles depending on the magnitude of the measured internal angle. The outcome of this correction on the measurement produced precise 2D (Northing, Easting) coordinate of the control beacon. For this study, a 3D coordinate of the control beacon was needed for the scanning laboratory. The difference in height between points are measured by taking the difference between the backsight and foresight of points using a level, which is also known as the elevation in order to make a complete 3D point cloud data (X, Y, Z).

Levelling is achieved by using the height plane of collimation to determine the height differences between points. The height difference is measured using an automatic level to sight a levelling staff in order to take the difference in height measurement between the two points.

This is done by mounting an automatic level on a tripod to measure the height difference between the backsight and foresight using levelling staves as shown in Figure 4.6. The backsight readings always carry positive sign (+) while the foresight is negative (-).

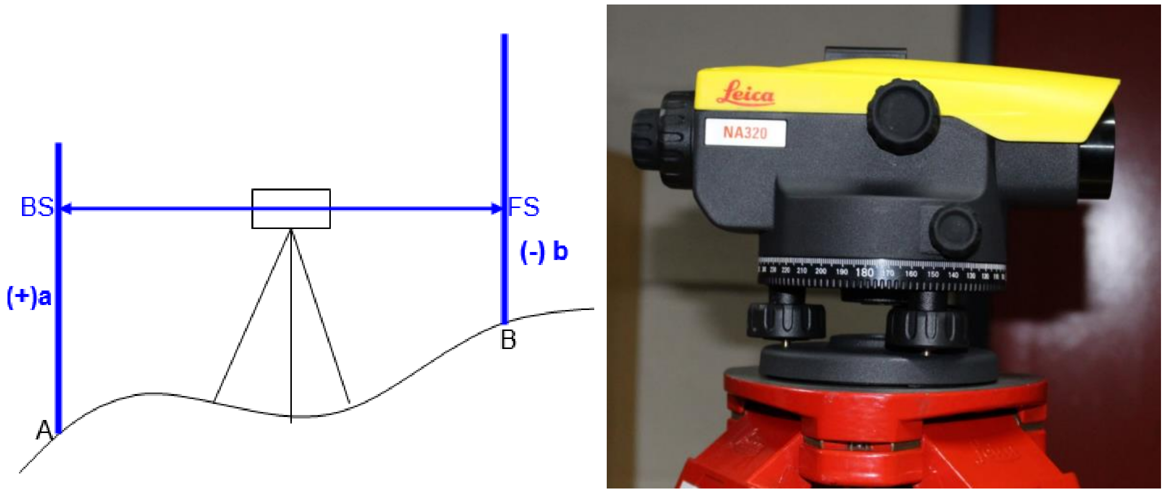


Figure 4.6: Principle of Levelling and an Automatic Level

In calculating the height difference between points, a positive value indicates a rise and a negative value denotes a fall from point A to B as shown in Figure 4.6. This approach is carried out repeatedly to determine the height difference between points in a levelling run. The result of the levelling is presented in Table 4.2 showing the elevation of each control point. The levelling recording sheet and the photograph for the measurement of the control points can be seen in Appendix B and Figure B1 respectively.

The check for the Rise and Fall Levelling Method is:

$$\sum BS - \sum FS = \sum Rises - \sum Falls = \text{Last Initial RL} - \text{First RL} \quad (4.2)$$

Equation (4.1) and (4.2) source: Uren & Price (2010).

Table 4.2: Presentation of the Levelling Results

POINT	B.S	I.S	F.S	Rise	Fall	Reduced Level	Adjustment	Final Elevation
A1	1.561					1758.7350		1758.7350
A9	2.972		1.060	0.501		1759.2360	0.0003	1759.2363
T001	1.312		1.333	1.639		1760.8750	0.0007	1760.8757
T002	1.338		1.305	0.007		1760.8820	0.0009	1760.8829
BEACON	0.242		0.215	1.123		1762.0050	0.0010	**1762.0060**
T003	1.384		1.368		1.126	1760.8790	0.0015	1760.8805
T004	1.780		1.381	0.003		1760.8820	0.0020	1760.8840
B3	0.757		0.987	0.793		1761.6750	0.0021	1761.6771
B21	1.205		2.020		1.263	1760.4120	0.0024	1760.4144
A1			2.885		1.680	1758.7320	0.0030	1758.7350
CHECK	**+12.551**		**-12.554**	**+4.066**	**-4.069**			
		-0.003		**-0.003**				

The elevation of the control beacon in the scanning laboratory was levelled to an accuracy requirement as shown in Table 4.2 to make a complete 3D coordinate system.

4.2 Short-Range Scanning Laboratory Site Preparation

The venue selected for the establishment of the scanning laboratory is located at the reception area of the Wits Mining Institute (WMI) in the basement of The Chambers of Mines building. The space also serves as kitchen and dining area for the institute with two entrances. The facility would be perfect for testing the accuracy of short-range laser scanners as there are few objects in the space that are not at obstructing the view of the laser scanner. An additional benefit of this venue is the option of positioning the targets on the walls and on the roof that ensures orthogonality of laser scans.

Prior to the establishment of a short-range scanning laboratory for testing the accuracy of terrestrial laser scanners, there is preliminary planning that deserves attention in order to obtain the best accuracy as possible. There are no standard rules that have been established in developing a testing facility. However, to recreate such testing laboratory, there are factors that need consideration. The facility is expected to have regular activities such as movement of postgraduate students and guests visiting the institute. This makes it difficult to set up a permanent tripod at the venue due to nature of the activities at the venue.

In ensuring accurate and precise scans, a 1.2m height force-centred control beacon with a 5/8” British Standard Whitworth (BSW) thread was constructed for the positioning of the scanners. This was designed to prevent the movement of the instrument and keep it stable during scanning. The control beacon was positioned in such a way that the mounted scanner can view 360 degrees around the selected point. An additional two setups were positioned in the space with the idea of designing a strong network geometry. The benefit of these additional scan positions in the area was to ensure that both angular and range accuracy were fully analysed. These additional positions were setup to allow a maximum number of targets to be captured at each location.

The use of the force-centring control beacon will add value to the quality of the scans by preventing errors that may occur due to the movement of the tripod and tribrach. The 5/8’’ BSW thread is a standard dimension that works with all kinds of surveying instruments. The beacon design will allow the terrestrial laser scanners to be mounted comfortably regardless of the vibration from the instrument and other environmental factors. The control beacon was bolted to the floor to ensure that the force-centring beacon is firmly attached to the concrete floor as shown in Figure 4.7.

Figure 4.7: Image of the Control Beacon in the Laboratory

The design and construction of the force-centring beacon is similar to that of foundation in civil engineering in terms of specifications as shown in Figure 4.8.

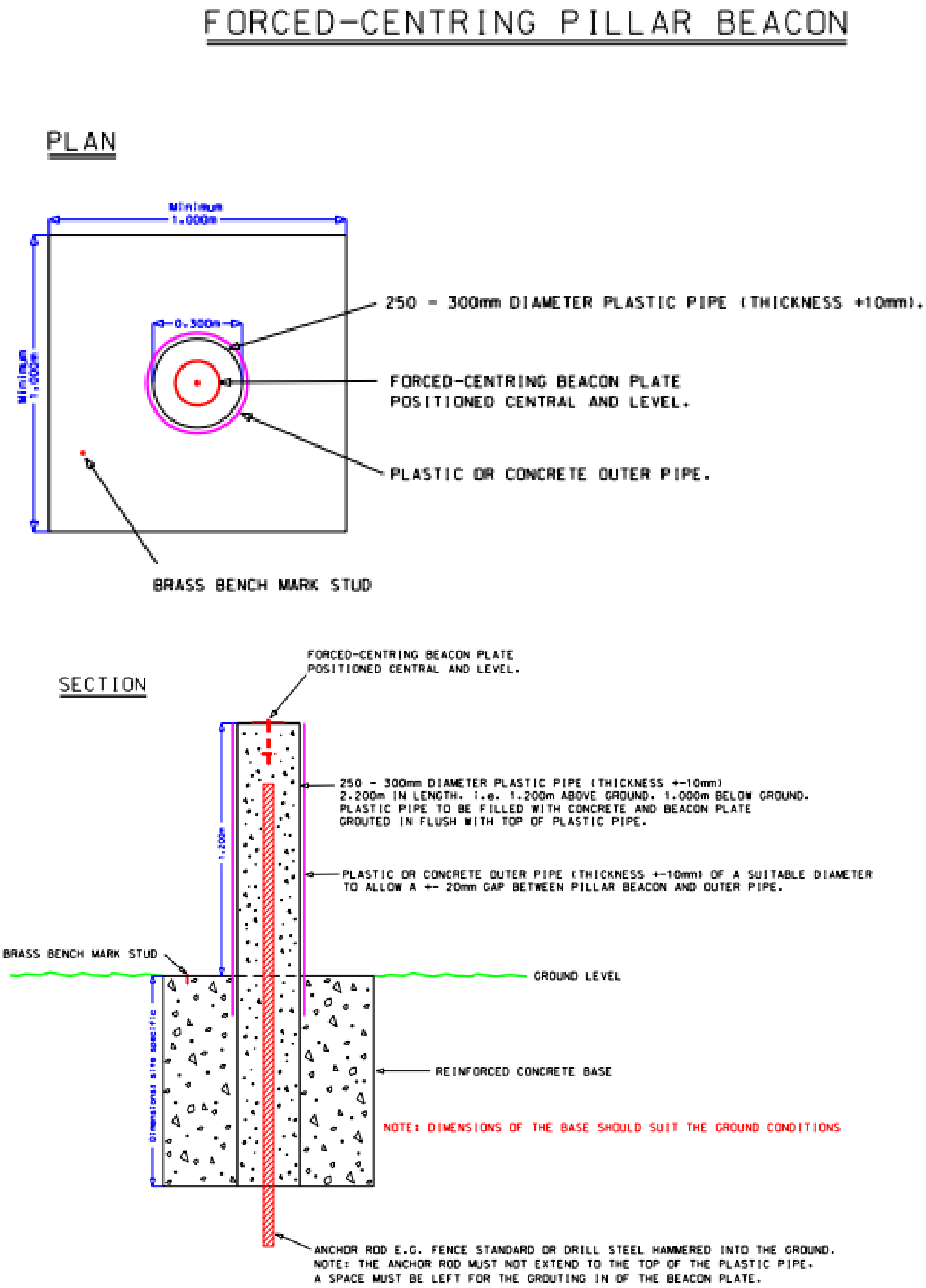


Figure 4.8: Illustration of Force Centring Beacon Design (Thomas, 2011)

The materials used for the construction of the control beacon are sand, stone, cement, anchor rod, force-centring plate, and a 250 to 300mm diameter thick plastic pipe. The curing period for the construction of the beacon should be at least 28 days. The photographs of the construction of the control beacon are attached in the Appendix C of this research report.

The concrete mix proportions for the construction of force centring beacons are presented below: as per specifications given by Cement and Concrete Institute of South Africa.

Material for a two bag batch of concrete, using 26.5mm or 19mm stone:

	Cement 50 kg bags	Sand		Stone		Yield
		Litres	Wheelbarrows	Litres	Wheelbarrows	m^3
Medium strength: 25 MPa	2	160	2.5	160	2.5	0.26
High strength: 30 MPa	2	130	2	130	2	0.22

Material for a two bag batch of concrete, using 13.2mm stone:

	Cement 50 kg bags	Sand		Stone		Yield
		Litres	Wheelbarrows	Litres	Wheelbarrows	m^3
Medium strength: 25 MPa	2	160	2.5	160	2	0.24
High strength: 30 MPa	2	130	2	130	1.5	0.20

One cubic metre of concrete, using 26.5mm or 19mm stone:

	Cement 50 kg bags	Sand m^3	Stone m^3
Medium strength: 25 MPa	7.7	0.62	0.62
High strength: 30 MPa	9.2	0.60	0.60

One cubic metre of concrete, using 13.2mm stone:

	Cement 50 kg bags	Sand m^3	Stone m^3
Medium strength: 25 MPa	8.4	0.68	0.54
High strength: 30 MPa	10.0	0.65	0.50

4.2.1 Venue Selection and Accessibility to the Venue

Prior to the selection of the venue for a scanning laboratory, proper planning and measurement was done in order to enable the visibility of all the targets in the facility. According to Davison (2017), two key aspects to consider in selecting a venue for a testing facility are the shape and dimension of the area. If these two features are met, then the area can be selected as a testing facility.

The range and angular measurement observation possibilities were considered for the short-range testing facility. The maximum observable range for the area was approximately 15m. At this distance, the laser scanner can acquire point cloud data at high scanning speeds and a wide field of view that can rotate in both the vertical and horizontal range.

One of the major challenges in facility selection is finding an appropriate venue with correct dimensions, shape, availability and lack of obstacles such as pillars and structures that can obstruct to the view of the laser scanners. The shape of the selected venue must allow for a full scan of the wall. Also, the distance between the walls and scanner must be in the operating range of the terrestrial laser scanner in order to prevent range error (Boehler & Marbs, 2003). The structure of the venue comprises of a combination of steel and concrete walls with smooth surfaces. The concrete walls are planar while the steel wall is cylindrical in shape.

Another key factor to take note of is that there are no reflective materials in the facility. Laser signals can easily be affected by reflective materials such as a mirror, water or other shiny surfaces. Boehler & Marbs (2003) reported that shiny surfaces are not easy to scan with a terrestrial laser scanner. Shiny surfaces have different reflectivity that can result in range error.

Additionally, the presence of a steel wall at the venue poses a threat as the temperature of the facility needs to be constantly checked in order to monitor expansion and contraction of the steel wall. The thermal property of the steel wall needs to be considered during the scanning of the laboratory. These changes in temperature are not only in the winter and summer months but even in the course of the day with low evening temperatures and higher daytime temperatures. Therefore, the surrounding temperatures of the space facility need to be taken into account during scanning to minimise the impact of the thermal movement of the steel wall. The location of the venue for the scanning facilities can be seen in Figure F1 in Appendix F with a map of the University of the Witwatersrand.

4.2.2 Dimension and Size of the Scanning Laboratory

The Wits Mining Institute reception area has a perfect shape for a short-range testing facility with it dimensions in terms of range and angular view. The space has an irregular shape with the dimension of 14.2m x 8.2m x 4.4m. The distance from the floor to the roof is approximately measured to be 4.4m. Due to the irregular shape of the facility, it is difficult to have a full 360-degree field of view from some scan positions based on the asymmetric pattern of the facility. In fact, a proper plan was done prior to the placement of the targets in order to have a suitable geometry that enables visibility of all the targets in the facility as shown in Figure 4.9.

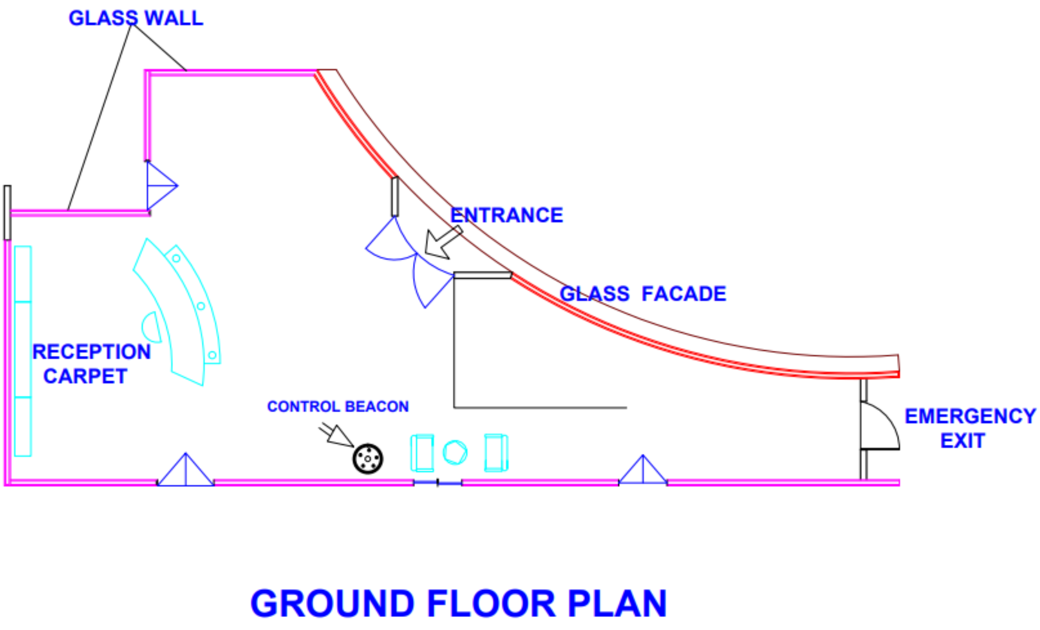


Figure 4.9: Plan View of the Scanning Laboratory

The reconnaissance is important in order to generate redundancy in the results produced. This asymmetric plan is presented in Figure 4.10.

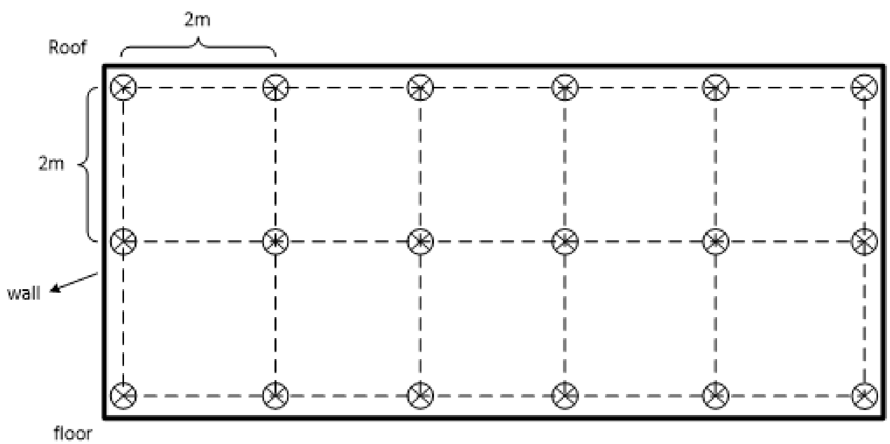


Figure 4.10: Description of Asymmetric Target Placement Plan

The shape of the steel wall of the scanning laboratory makes it difficult to measure. The concrete walls are planar in shape, while the steel wall is curved in shape. The long concrete wall has a maximum range of approximately 14.2m from end to end with an average height from floor to ceiling of approximately 4.4m.

The venue was large enough to contain numerous targets due to the surfaces available for the placement of targets. The texture of the walls were checked to ascertain if they were capable of holding the target firmly on the wall without applying additional adhesive. From the plan view of the facility in Figure 4.10, the shape of the laboratory is not square which made it difficult to obtain a regular geometric pattern at some certain scan positions. Hence, in order to achieve a full field of view, at least three additional setup positions in the laboratory had to be established as they give a good network geometry.

4.2.3 Target Design and Placement

The design of the target used depends on its purpose, such as the testing of the laser scanner. The target used for the scanning laboratory was black and white alternating four squares with edges touching one another at the centre. Targets were placed strategically in the laboratory with known coordinates in order to compare the observed results with the calculated results.

A Trimble laser scanning checkerboard target was used for the scanning laboratory as shown in Figure 4.11.

Figure 4.11: ***Photograph Showing Placement of Trimble Checkerboard Targets in the Laboratory***

This lightweight 3D target has adhesive material for easier placement on a smooth surface without drilling holes or using any messy adhesive. The black and white surface target was selected because it is easy to be identified by the laser scanner. Moreover, the target has little reflection properties that works for perfect geo-referencing and recognition of point cloud data. According to Hiremagalur, *et al.*, (2009), identification of targets in the facility is more important than individual point accuracy as poor target recognition leads to poor-georeferencing.

The dimension of the target used was based on the distance between the instrument and the position of the control targets. That is, for every metre of range measurement, the target requires one centimetre in dimension (Davison, 2017). The venue has a range of approximately 15m from end to end. The target dimension of 15cm x 15cm would be a good design for the scanning laboratory. The target was large enough to be able to survey its centre points and to be clearly seen from each of the scan positions. At a maximum range of 15m, it was possible to view the targets except for some at a particular angle due to the shape of the venue which lead to the creation of additional scan positions in order to be able to view all the targets. The advantage of the venue is that many targets could be placed with good coverage and spacing for angular readings. The structure of the laboratory also allowed targets to be placed on the walls and ceiling except for the floor due to regular movement of people.

The targets were positioned on the walls and the ceiling to ensure visibility from the control beacon. A total number of 45 targets were used, with 13 targets on the steel wall, 27 on the concrete wall and the remaining 5 targets were placed on the ceiling. Targets were not placed on the floor of scanning venue due to the frequent activities taking place at the venue. All the targets were placed for sufficient coverage in order to avoid an incidence where the scanner could not see all the targets. These targets were named according to the placement in the room. The concrete wall was labelled “Cn”, the steel with “Sn” and the ceiling was named “Rn”. A majority of these targets are used for 3D point cloud processing (registration) and creating a full scan of the facility.

The venue has a height of 4.4m from ground level at regular intervals around the venue. The uniformity between the floor and the ceiling allowed for a good vertical angle range from the control beacon with few obstruction. There were some targets placed at a very low angle below the height of the terrestrial laser scanner. Similarly, five targets were placed on the ceiling in order to add the vertical measurement. There are objects and materials in the laboratory that can cause obstruction during the scanning such as sofas, metallic rectangular shaped vent duct and chairs. These targets were placed in such a way that obstruction of targets is avoided. The positioning of the targets can be seen in Figure 4.12 with targets placed on the walls and ceiling of the scanning laboratory.

Figure 4.12: An Image Showing the Placement of Targets on the Concrete Wall and the Ceiling of the Scanning Laboratory

The presence of reflective materials such as metals or mirror surfaces were avoided in the laboratory due to their specular nature. Materials of this nature reflects few or no signal back to the laser scanner which causes deviation in the range measurement.

4.2.4 Potential Range and Angular Capacity

The maximum range of the laboratory is 15m. At this observable distance, the scanner can acquire points at a high scanning speed and wide field of view that can rotate in both the vertical and horizontal range. At a maximum range of 15m, the facilty will have a perfect span for a short-range scanning laboratory with high accuracy and precision. As the distance becomes longer the lesser the accuracy of the scan produced (Feng, 2012). The positioning of the control beacon is important in order to ensure full visibility of all the targets. The range and angular observations depend on the position of the beacon to prevent poor visibility and obstructions of the scan. It is obvious that the position of the scanner has an influence on the angle of incidence. The larger this angle of incidence the lower the density of the resulting points cloud. Also, the increase in the incidence angle leads to a reduction in the intensity of the reflected beam. All of these factors were considered in the positioning of the control beacon. At the maximum range of 15m, there will be redundancy in the measurement in order to improve the overall precision. Although, at this observable distance, the control beacon cannot guarantee visibility to view all the targets in the facility leading to the creation of additional scan positions to make sure all the targets can be captured with high accuracy. The control beacon would have been positioned in the middle of the selected space but the irregularity in the shape of the space was considered in placing the beacon for better sighting of the targets in the facility.

Other scan positions were achieved by mounting the terrestrial laser scanner on tripods with a foot-chain to prevent movement of the tripod due to the nature of the floor; the floor of the laboratory is a concrete floor with a slippery surface. These additional scan positions were to ensure a good network geometry between the terrestrial laser scanner and the targets fixed on the wall. In an ideal setup, the geometry must be between 45 and 90 degrees (orthogonal), avoiding small angles or larger angles between the instrument and the scanner. The terrestrial laser scanner must be positioned in such a way that the laser beam is perpendicular to the targets. By having an orthogonal geometry, a spatial coverage of good geometry is ensured. This arrangement will support strong geometry and produce redundancy in the measurement to ensure precision and accuracy in the acquired 3D point clouds data. The image of the additional scan positions and scanning from the control beacon are shown in Figure 4.13.

Figure 4.13: Photograph of the Terrestrial Laser Scanner Placed on the Control Beacon and Tripod Stand

Initially, the shape of the venue was a bit challenging in terms of establishing new scan positions as only a few targets could be seen from this location. Although the requirements were to ensure visibility of all the targets at the beacon position and having a good geometry between the scanner and the targets. The initial setup of the control beacon could not guarantee the visibility of all the targets in the scan area.

4.3 Problems Encountered in Developing the Scanning Laboratory

The requirements to be considered in establishing a test facility to investigate the accuracy of a terrestrial laser scanner are the shape and dimension of the venue to be used. The shape of the selected space poses a challenge in terms of its irregularity, as a regular geometric pattern could not be attained. An open space with a square shape would have been a perfect structure with no objects or features that can cause obstruction in the facility. Despite creating these temporary scan positions, the target C6 and C22 on the wall could not be measured because the targets were out of the line of sight for the Trimble S6 Total Station and the FARO Focus3D X3130. Thus, the scan position has to be a control beacon and other additional scan positions placed in such a way to allow a full field of view for the terrestrial laser scanner to capture the data at a specified operating range.

Another challenge in the course of establishing a scanning laboratory was the distance between the floor and the ceiling of the venue. The ceiling of the venue is very high which makes it difficult to place targets on the surface. Only five targets were able to be placed on the ceiling. Similarly, due to regular activities at the venue, no target was placed on the floor of the laboratory in order to prevent rearrangement of targets. If sufficient targets were positioned on the ceiling and floor, this would give a strong network geometry that will result in quality scan. In addition, this could be used to investigate the accuracy of a TLS focusing on the observations of angle with the hope that the results would give an indication on the performance of the laser scanner.

Moreover, the presence of the large metallic ventilating ducts in the venue was another issue encountered during the placement of targets causing obstruction to targets during laser scanning. This requires proper planning to ensure that the metallic vent does not cause obstruction to the targets placed in the area.

4.4 Conclusion

The development of a testing laboratory to investigate the accuracy of terrestrial laser scanners has been fully discussed in this chapter. The factors that deserve attention towards establishing a test facility have been discussed extensively. The Total Station surveying technique was adopted in determining coordinates for the control beacon and other control points in the facility. The method used in measuring the coordinate of the control beacon with a Total Station (Leica TCR1201+) from known points to form a closed traverse was described. The coordinates of the targets in the facility were determined using the Trimble S6 Total Station survey instrument. The construction and the positioning of the control beacon with other additional scan positions in the laboratory were also described.

The factors influencing the establishment of a short-range scanning laboratory for testing the accuracy of terrestrial laser scanners were discussed. It was found that these factors require careful attention when developing a laboratory for testing the accuracy of laser scanners.

In chapter five, scanning with terrestrial laser scanners and point cloud data processing will be discussed. Terrestrial laser scanning principles and the operating mechanism in acquiring 3D point cloud data will be fully discussed. The transformation of an acquired 3D point cloud data into a common coordinate system and filtering of point cloud data will also be examined.

CHAPTER FIVE

5 Scanning with Terrestrial Laser Scanners and Point Cloud Data Processing

This chapter explains how the FARO Focus 3D X130 laser scanner is being used to generate 3D point cloud data of the laboratory. Also, the processing of the 3D point cloud data will be discussed, that is, the registration of spatial coordinates for the point cloud data and the removal of unwanted points from the point cloud data.

5.1 Surveying of Trimble Checkerboard Targets

After the development of a short-range testing facility, the next step was to commence with the investigative process. This process involve the surveying of targets in the facility to determine the targets centre coordinate values. The survey was done using a Trimble S6 Robotic Total Station. The Trimble S6 Total Station offers an automatic precise pointing system in order to take measurements at high speed, with accuracy and with confidence. The instrument is integrated with a servo-motor device that automatically controls the rotation of the instrument in both the vertical and horizontal axes and also tracks the prism with the aid of an Advance Tracking Sensor (ATS). The benefit of using the instrument is that the operator does not need to search for the target through the telescope. At the press of the button to start the measurement, the instrument locates the centre of the prism.

Prior to the survey of the targets, two additional positions were set up apart from the control beacon in order to ensure a maximum number of targets are measured. The Trimble S6 Total Station was mounted on the tripod with foot chains to hold the tripod legs in place.

The measurement was carried out with the instrument set at direct reflex (DR) mode to locate the centre of the target point by the visible laser beam from the machine. This method was used to measure all the targets in the facility from the control beacon and the other temporary additional setup positions. The coordinates of the new setup positions were calculated using the resection surveying method. In this method, the coordinate of the master control beacon was used to compute the coordinate of other temporary setup positions.

The instrument stores the measured points in the onboard memory card which was downloaded for further analysis. The survey data can also be viewed in drafting software such as Microsoft XL and Terramodel.

Proper planning was done prior to the surveying in order to select appropriate additional scan positions that will enable visibility of all the targets. The benefit of creating additional scan positions was to strengthen the network geometry in order to satisfy preset precision, reliability and accurate measurement. Apart from creating a robust network configuration, it also allows more checks to be done on all the measurements in order to ensure results with better accuracy.

The Trimble S6 Total Station was mounted on a tripod with a foot chain. This was done to ensure that accurate and reliable measurements are captured. After setting up and levelling the instrument, the instrument was triggered which enabled the Total Station to measure the centre of the Trimble checkboard target with a red visible laser beam. Care was taken before recording the data to ensure that there was no obstructions in the measurement path that could led to incorrect measurement. The traverse survey principle was adopted with a known coordinate of the control beacon and to a known point to establish the location of the additional setup positions. This approach was used to calculate the coordinate of the successive setup positions in the laboratory. These temporary setups were created to allow a maximum number of targets to be observed at each setup position to create a closed traverse survey.

Another important factor to take note of during surveying is the change in temperature and atmospheric pressure of the environment. During the surveying period, the temperature was monitored and measured at 18 degree Celsius throughout the survey period. For high precision work, the temperature and pressure of the surrounding should be measured regularly in order to prevent error in the measurement. The temperature and pressure of the surrounding were entered into the Total Station which then corrects their effect on the measurement for that station. Any change in atmospheric condition of 1ºC can cause about 1pmm error in the measurement (Afeni, 2012). Atmospheric conditions are important on distance measurement which can lead to error in distance measurement. The temperature and pressure were recorded at intervals and these readings were entered into the Total Station so that the ppm change accordingly. Moreover, the steel wall of the laboratory can also be affected by change in atmospheric conditions of the environment. This change in temperature can cause expansion and contraction.

The surveying was done using the principle of resection setting up on a temporary point which was a few metres away from the control beacon to be able to view all the targets in the facility. The process was adopted from the first setup position to determine the coordinate of the new setup position and its orientation. Although the shape of the laboratory was a challenge, this was solved by having additional scan positions to ensure the visibility of all the targets. The survey of the targets was obtained based on the distance and angular measurements from the control beacon and other three temporary setups. Targets C6, C22, S1, S7 and S11 were not captured as they were out of the line of sight of the instrument. The survey and scanning of the laboratory lasted for 2hours and 15minutes and that was carried out by Eugene Pretorius and Associates (EPA) Ltd South Africa. The result of this laser scanning and the survey are attached in the Table D1 and Table D2 in Appendix D of this research report.

5.2 Scanning of the Laboratory

The scanning of the laboratory was done using a FARO® Laser Scanner Focus3D X130 to acquire a detailed 3D master point cloud data as shown in Figure 5.1.

Figure 5.1: Faro Focus 3D, Picture Courtesy of Faro

This is a ground-based laser scanner that measures short distances at a maximum range of 130m. The Terrestrial Laser Scanner is classified as a panoramic laser scanner. At this range, the instrument is suitable for measuring short distance and documenting the complex environment and geometry in three-dimensions of the laboratory. The scanning was conducted by Eugene Pretorius and Associates (EPA) Ltd. A total number of three (3) different scans were carried out in order to have a complete 3D scan of the laboratory.

The laser scanner was mounted on the control beacon with the aim of capturing all the objects in the facility. The FARO Focus3D X130 scanner works on the principle of emitting a laser pulse from the centre of a continuously rotating mirror about 360 degrees in horizontal to measure the distance together with both vertical and horizontal angles in order to determine the coordinates in space.

The scanning of the laboratory started immediately after completing the total station survey of all the targets in the laboratory. The instrument was set at normal resolution and high quality in order to capture enough data and to ensure maximum area was being covered. These two parameters define the file size and the scanning time. High resolution and high quality scan setting were selected which takes time to complete the scanning task. In some cases, the computer processor was unable to open the file due to the size of the file.

Despite having high quality instrument settings and additional scan positions, the targets C6, C22 and S1 were not captured in the scan and could not be used. This happened as the targets were out of the line of sight. Placement of targets requires a good angle of incident between the laser scanner and the targets. Apart from these uncaptured targets, the point cloud was registered based on 40 targets which were coordinated with the total station. The acquired master point cloud consisted of more than 27 million points, which was visualised in Cloud Compare software. The picture of the visualised point will be presented later in the chapter.

After completing all the necessary settings such as scan range, scan size, sensor selection, resolution and quality on the laser scanner, the scanning of the laboratory commenced by pressing the start scan command shown on the digital screen. During the scanning task, Light Emitting Diode (LED) laser light measured the distances and the digital screen displayed the scan progression. The base of the instrument rotated 180 degrees during the scan to capture all the targets in the scan area and continued to turn saving the image using the in-built high definition (HD) camera. The scanner registered a spherical image of its surroundings except for a spherical cone which was directly below the instrument with an angle of 55 degrees (FARO Technologies, 2013). The instrument extends its rotation beyond the required scan area in order to calibrate the inclinometer.

The scanning of the laboratory from the main control beacon was completed in eight minutes, while the other temporary positions were completed in seven minutes at each scan position. The height of the scanner for these temporary scan positions was measured to be 1.3m for the field of view to cover as many target as possible in the laboratory. At this height, many targets were captured from all the necessary orientations.

The instrument gave an indication that it had completed the scan by beeping a tone. The result of the scanned laboratory was shown on the digital screen of the instrument. The image of the scanned laboratory was zoomed in to check if all the targets and other features in the laboratory were captured. The acquired point cloud data was stored on an SD card which was removed from the device after completing the scan.

In addition to the acquired 3D point cloud data, the scanner was also integrated with a high definition (HD) camera system up to 70 megapixels that delivers high quality colour overlays for scanned point clouds. Also, the camera system on the terrestrial laser scanner takes photo colour scans. This improves the visualisation and enables the instrument to capture 360 degree horizontal imagery of the scanned environment. The camera on the system makes it easier to recognise objects in the laboratory by providing results that contain orthophotos and point clouds. With this captured imagery, the outcome can be informed of an image (RGB) and point cloud (x, y, z) which depict a true 3D colour environment of the captured data that can be used to link the scans. Another benefit of the imagery produced by the laser scanner is, it enables the registration of individual point clouds. That is, for real colour RGB the relationship between the imagery and the 3D point cloud needs to be established as shown in Figure 5.2. The spherical image of the laser scans generated with full colour image of the instrument environment can be seen in the Appendix E (Figure E1 and E2) of this research report.

Figure 5.2: High Resolution Spherical Image of the Scanning Laboratory with full Colour Image

The temporary scan positions were marked 2 metres away from the control beacon. This was created in order to have a full 3D scan of the facility. Moreover, it is necessary to have numerous scan positions, in order to generate redundancy in the result and ensure precision of the point cloud data. Also, several scans are needed in order to avoid incomplete point clouds due to the restricted line of sight from the laser scanner.

5.2.1 Overview of FARO® Laser Scanner Focus 3D X130

The FARO® Laser Scanner Focus3D X130 laser scanner is a powerful high-speed scanner delivering realistic and detail 3D point cloud data. The instrument uses a high-speed three-dimensional Light Detection and Ranging (LiDAR) to capture 976,000 of points per second in a single scan (IQservice, 2018).

The instrument is designed in such a way that the emitted laser light has sufficient power to measure a maximum amount of data in accordance to the manufacturer's specifications. This consists of an emitter, a receiver and a detector see Figure 5.3.

Figure 5.3: Theoretical Image of Time of Flight (Kaldén & Sternå, 2015)

Each of these components has a specific function. The detector is a device in the scanner that determines the information of the scanned object and determines the total time taken for the laser LED from the emitter to return back to the receiver. High powerful laser components (chips) known as diodes are used in detecting the return laser beam.

The initiation of the laser LED starts from the micro controller by sending out two carefully timed pulses which are the control pulse of the laser driver and a start pulse to the Time Digital Converter (TDC). The laser driver is responsible for the control laser source which starts by emitting an LED light. The emitted light might not be perfect depending on the type of the laser scanner, for this reason, some optics are needed to shape the light and send it to the targeted object. The weak reflected light from the target surface hits the lens and sends the light to a detector. Signal amplifying and conditioning current are needed to boost and convert the weak signal from the photo-detector into a logic signal that will be sent to the TDC which stops the measurement. Another function of the TDC is to read the acquired data and performs some post-processing techniques such as filtering of the point clouds data.

The instrument has two aspects of acquiring 3D point cloud data that need to be considered; these are the angular and distance measurement techniques. According to Schulz (2008), the laser range finder is a part of the scanner that is responsible for the distance measurement and the repeatability of precise measurements. The system makes use of the time at which the laser light emanates from the emitter and returned back to the receiver. The clock starts reading when the instrument emits the signal and stops when it returns back to the instrument. Equation (5.1) is a mathematical model for calculating the distance covered by the laser light obtained from the speed of light formula which depends on the distance covered and time taken between the instrument and the targeted objects. According to Soudarissanane (2016), this equation is used to calculate the distance for both time-of-flight (pulse based) and phase based laser scanners.

$$S = \mathrm{c}\frac{\Delta T}{2} \tag{5.1}$$

The ΔT is the change in time taken for the signal to return back to the instrument from the targeted objects, while the constant C is the speed of light and S is the total distance travelled by the laser signal. The reflected signal from the target surface is used in calculating the total distance between the scanner and the object by comparing the reference output to signal measured which gives the phase difference (Yoon, *et al*., 2011). The deflected laser beam from the target takes two forms, this can either be rotating or oscillating mirrors.

With a maximum range of 130m, the instrument is suitable for measuring short distances such as the indoors of a building and mapping of urban areas where the measurement of short distances and high vertical angles are needed. The laser scanner can capture 976, 000 points per second. A set of points with RGB colours is referred to as point cloud data which represents the x, y, z coordinates. In addition to coordinates, for each point in the point cloud an intensity (*I*) value is provided. The intensity value of the signal depends on the reflectivity of the object and the frequency of the laser scanner. The settings of the frequency value can either be 1 kHz or 30 kHz in order to obtain an accurate range measurement (Davison, 2017).

5.3 Point Cloud Data

The end result of laser scanning task is the 3D point cloud data. This represents the surrounding area of the instrument which is made up of multiple points. The point cloud data explains a set of data in a given space that can be represented by XYZ georeferenced data that comes with RGB position and intensity. The XYZ coordinate denotes the (Northing, Easting, and Elevation) of a collection of multi-dimensional points or the object surface in the area.

Commonly, a laser scanner is a suitable technology for generating point cloud data from the real world to an image. Terrestrial laser scanners use the emitted laser pulse to collect information about the exact 3D location of points. The intensity of the returned laser signals is important in determining the accurate coordinates of points. The higher the intensity of the emitted and received laser signals, the denser the acquired point cloud will be. The point cloud data obtained within a short period of time and with less involvement from the operator of the laser scanner. The acquired point cloud data consists of either Cartesian or Spherical coordinates relative to the scanner positions (Rex & Stoli, 2014).

There are other different ways of generating 3D point cloud data but the quickest and most detailed approach is by the laser scanning method. This generates high-density point cloud data from a single scan position in a short period of time compared to other conventional surveying methods. Erroneous and invalid points are likely to be found in any point cloud generated by 3D laser scanners. This occurs as a result of several factors such as a reflectivity issue, refraction from the target surface. This is one of the reasons why the point cloud data is not suitable for immediate use and the data has to be processed before point cloud data can be utilised.

There are software packages made available for converting point cloud data from one format to another depending on the task at hand. The point cloud data can be converted into LAS LiDAR Aerial Survey (LAS), Polygon File Format (PLY) or generic format (ASCII) which is convenient for post-processing. The ASCII format works with different computer software packages such as AutoCAD, ArcView, and GIS software. The LAS format serves as the favourite amongst users because it has colour information together with the file format that supports the exchange of any 3D XYZ point. Meanwhile, the neutral ASCII format has two major challenges with file interchange. The first problem is that the file is always large in size which makes the process very slow. The second problem is that all the information related to LiDAR can be lost. Data loss in ASCII format occurs when all the information contained in the original data can be reconstructed from the compressed data (Houshiar & Nuchter, 2015). Loss of LiDAR data is common during transmission and archiving of point cloud.

However, the point cloud data has its own local coordinates system, this coordinate system first has to be transformed into the appropriate coordinate system. This transformation process involves encoding which is the technique required in data processing. The encoding can be categorised into two major steps; namely registration and filtering.

5.4 Point Cloud Data Processing

Terrestrial Laser Scanner systems generate a very large number of points of the surroundings in a short period of time. The acquired results may contain noise and other unwanted measurements within the point cloud. The basic task of aligning the acquired data into a common coordinate system and separating these unwanted measurements from the data is known as point cloud data processing.

Processing of point cloud data involves removing unwanted measurement or erroneous objects from the acquired 3D point cloud data. The unwanted measurements in the scan can be characterised as outliers, noise or gross errors. This intrinsic noise occurs as a result of the reflective issues and the lighting nature of the surroundings. The process of removing the errors from the point cloud data is time-consuming. Although this depends on the number and size of the scans, it can take a few minutes or up to several hours. The final deliverable of the processed point cloud data can be further applied for modelling of the scanner environment.

The modelling is referred to as the process of meshing the point into a single solid surface to better represent the features in the test area.

The processing of point cloud data involves two major steps which are;

- Registration of point data; and
- Filtering of point cloud data.

5.5 Registration of Point Cloud Data

The registration of point cloud data is the first and most important step in point cloud data processing. The first task associated with 3D models from the laser scanner is the transformation of the local XYZ coordinate system into a geographical common reference system. The identification of these common points in each overlapping point cloud and then transform them into a single coordinate system. That is, the alignment of various individual scans positions into a single coordinate system. In terrestrial laser scanning, the object scan position is recorded by means of range measurements which represent a dense surface model of the scanned object. These individual scan positions must be transformed from their respective internal systems to a defined national coordinate system which denotes the object space, in other words, the object space is the Cartesian system.

Moreover, computer software such as Autodesk Recap and Faro Scene can also be used in the registration of point cloud data, although the two softwares have similar functions. The Autodesk Recap software has five major functions, these include registration of points, selection of base scan, identification of common reference features, rough estimation and validation of registration results. In order to perform all of these functions, the software uses a target-free method for the registration process. This method eliminates the use of targets for registration and makes use of features that are common to both scans which can be in form of a flat surface and a clear-cut corner for registering the point cloud data (Rex & Stoli, 2014).

The main objective of the point cloud data registration is to obtain a spatial transformation parameter that can align sets of point cloud data into a common coordinate system (Pomerleau, *et al*., 2015). Point cloud registration between two different scan positions is essential for producing a complete test area description of the instruments surroundings. This is vital in point cloud data processing as the discrepancies in the data should be properly manipulated for a precise transformation. For instance, having two scans in the form of Scan A (X_1, Y_1, Z_1) and the second scan coordinate to be Scan B (X_2, Y_2, Z_2). The mathematical relationship that exists between the two scan positions that transforms the coordinates of the two scan points into a common coordinate system represents the transformation.

According to Al-Manasir & Fraser (2006), the registration algorithm between the two scan positions with six variables that define the transformation can be rewritten using a Helmert transformation. Three of the six variables represent translation, while the other three represent the rotational property. A scale factor can be introduced which increases the number of the unknowns to seven parameters. Theoretically, the observation models for a transformation parameter estimation are expressed in terms of Cartesian coordinates. In order to achieve a balanced transformation model, at least three common points are required to have redundancy in the measurement. The mathematical relationship between the six variables can be revised using the Helmert Transformation equation for two datasets on a point-to-point correlation:

$$\begin{pmatrix} X_1 \\ Y_1 \\ Y_1 \end{pmatrix} = \lambda \mathrm{R} \begin{pmatrix} X_1 & -X^C \\ Y_1 & -Y^C \\ Z_1 & -Z^C \end{pmatrix} \qquad (5.2)$$

Equation (5.2) source: Al-Manasir and Fraser (2006).

The position of Scan A and Scan B coordinate reference frame in the Equation (5.2) is represented by X^C, Y^C, and Z^C. Where R is the rotation matrix from three-axial rotation angles, while λ represent the scale factor in the case of laser range data absolute scale. As soon as all the seven variables or (six if the scale factor remains constant) are calculated between the overlapping point clouds, thus the transformation into a common coordinate system takes place.

Another equations were derived by Chuang & Jaw (2017) from the spatial transformation of point cloud for corresponding conjugate points such as for line and plane based transformation. These can be represented by the equations (5.3), (5.4) and (5.5)

$$FPi = \begin{bmatrix} X_{(2)i} \\ Y_{(2)i} \\ Z_{(2)i} \end{bmatrix} - sR \begin{bmatrix} X_{(1)i} \\ Y_{(1)i} \\ Z_{(1)i} \end{bmatrix} - \begin{bmatrix} t_X \\ t_Y \\ t_Z \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \quad (5.3)$$

Where,

$$R = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} \quad (5.4)$$

=

$$\begin{bmatrix} \cos(k)\cos(\varphi) & \sin(k)\cos(\mathrm{w}) + \cos(k)\sin(\varphi)\sin(w) & \sin(k)\sin(w) - \cos(k)\sin(\varphi)\cos(w) \\ -\sin(k)\cos(\varphi) & \cos(k)\cos(w) - \sin(k)\sin(\varphi)\sin(w) & \cos(k)\sin(w) + \sin(k)\sin(\varphi)\cos(w) \\ \sin(\varphi) & -\cos(\varphi)\sin(w) & \cos(\varphi)\cos(w) \end{bmatrix} \quad (5.5)$$

Equation (5.3), (5.4) and (5.5) source: Chuang & Jaw (2007).

Where ($X_{(1)}i,j$, $Y_{(1)}i,j$, $Z_{(1)}i,j$) and ($X_{(2)}i,j$, $Y_{(2)}i,j$, $Z_{(2)}i,j$) denote the coordinates of the conjugate point in system 1 and 2, *s* is the scale parameter; *R* is the rotation matrix; *φ, w* and *k* are rotation angles; and $[tx\ ty\ tz]$ is translation vector.

In registering the point cloud data, features such as the corner points or distinctive points in the laser scanning surroundings can also be used as reference points in the scan data. That is, in successful alignment or the registration of scan data, some common geometric features that appear in the same position in two or more scans are fitted together in order to develop an accurate relationship between each of the scan positions. The merging of the scans will produce a complete shape when the scans are registered together.

There are several techniques used in registering scan data from the terrestrial laser scanner. These can be artificial or natural targets depending on the level of the overlapping point clouds.

Irrespective of the method used, the common goal of registration of a point cloud is to bring several local coordinate systems into a common global coordinate system. In achieving this, the coordinates of all the reference points in the facility must be known.

5.5.1 Target-based Registration of Point Cloud Data

The registration of point cloud data based on targets in the facility requires two major features, these include the placement of targets in the area and type of target used for the scanning task. Targets in the facility can be both natural and artificial targets. The manufacturer of the laser scanner provides suitable targets that can be used as control points. Some of these targets are manufactured for a particular surveying instrument. The major features between the target and the instrument are the intensity value between the instrument and the target which allows for determination of the centre point of the targets with a high level of accuracy. Traditional surveying instruments such as GNSS or a Total Station are used to determine the centre point of the target. This will assist in geo-referencing the measured centre point of targets to a referencing system, for example the Universal Transverse Mercator (UTM).

Usually, there is a dedicated software that automatically assembles the individual scans. For instance, the Faro Laser Scanner uses a software called Faro Scene to process the point cloud data from the scanner. The artificial targets used for the scanning laboratory are the Trimble checkerboard targets which are designed according to the specification of the laser scanner. The colour reflective property of the target is considered in order to enable the accurate localisation of the geometrical centre point of the target which is used as the reference point. The checkerboard target used consists of black and white alternating four squares with edges touching one another at the centre. The software used the point of intersection as the reference point for the registration of points. In order to achieve a good scan result, proper planning was done in fixing the target to allow for the assembly of individual scans during registration.

Natural targets are used for point registration especially in a location where artificial targets can be rarely used such as unsafe or an inaccessible environment. In terms of accuracy, artificial targets have high accuracy compared to natural targets (Cox, 2015). This is the reason targets are recommended for high precision work such as stabilisation of points during registration for calibration of terrestrial laser scanners.

There are different methods used in the registration of point cloud data. Altuntas & Yildiz (2008) listed different approaches used for registration of an overlap area between point cloud data into a common coordinate system as;

- Iterative Closest Point (ICP);
- Least squares 3D (LS3D); and
- Conformal transformation approach.

Iterative Closest Point (ICP) Method

This is the most commonly used method for aligning two or more points collected from different scans into a suitable reference coordinate system. The approach is an algorithm based registration technique used to transform point-to-point correspondence by establishing the best rotation and translation that reduces error based on the distance between the corresponding points. The method entails using conjugate point coordinates to determine transformation parameters by repeating the Euclidean distance between the two datasets until the lowest distance is attained. The Euclidean distance refers to the distance between two points. In a point cloud data analysis, the Euclidean distance is the nearest neighbour distance. An example of this is shown in Figure 5.4, the Euclidean distance between is the length of a segment connecting the master and the slave.

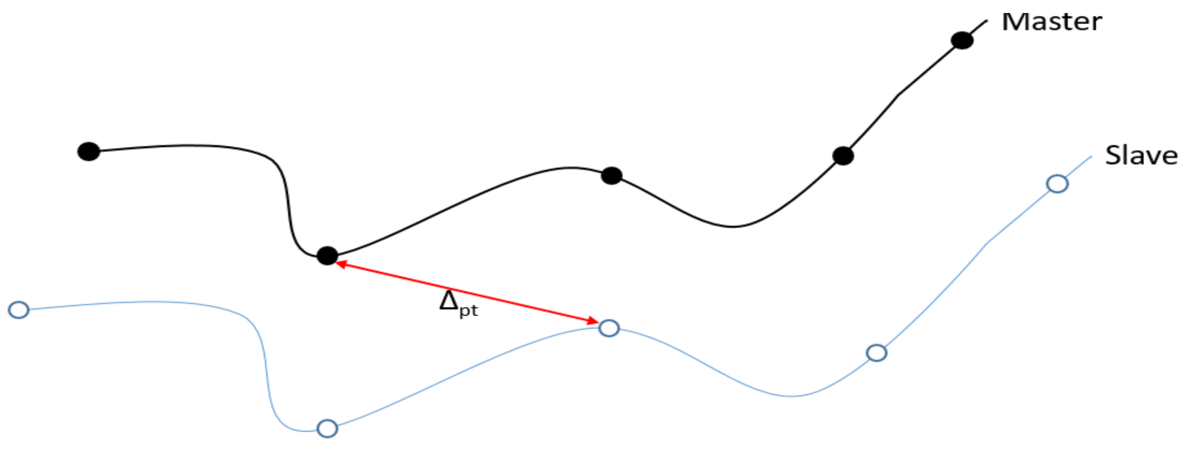


Figure 5.4: Illustration of ICP Distance Calculation for Conjugate Points (Vosselman & Mass, 2010).

The main objective is to reduce the sum of squares of Euclidean distance between the conjugate points, that is, the slave points and the master point cloud surface (Vosselman & Mass, 2010). The distance between the model and point cloud data is the sum of the distance between the point pairs (conjugate points).

The ICP algorithm will estimate the six parameters for the transformation with a scale factor of 1. The algorithm computes the transformation that minimises the residual distances between the model and the transform data. In order to determine the validity of the estimated value of transformation parameters, if the first estimated value is good, then the new values must have a minimum of 5 to 6 iterations (Altuntas & Yildiz, 2008).

Least Squares 3D (LS3D) Method

This is another approach used in registering 3D point cloud data and matching of a digitised 3D object surface method. After acquiring point cloud data from the laser scanner or other surfaces measuring techniques, the method treats the registration problem of overlapping surface by the mathematical method based on Least Squares Matching (LSM).

The method was developed by Gruen & Akca (2005), using the least square and other statistical tools approach for 3D surface matching correspondence problems. This involves matching one or two surfaces with a 3D search surface in order to minimise the sum of Euclidean distances between the surfaces. The approach allows one or more conjugate (slave) surfaces to be matched with a master surface. The goal of this technique is to minimise the square distance between the surfaces by using the least-square model to incorporate shaping parameters and outliers detection in between the point clouds.

For instance, two partially digitised surfaces $f(x,y,z)$ and $g(x,y,z)$ are conjugate regions of discrete 3D representations of surfaces. In calculating the geometric relationship between these two conjugate surfaces, the orientation and shape of the surface must satisfy the minimum condition of the Least Square Matching (Gruen & Akca, 2005). That is, the functional Least Square Matching model for these two partial surfaces is

$$f(x,y,z) = g(x,y,z) \tag{5.6}$$

According to Gruen and Akca (2005), in order to avoid discrepancies and bias caused by random errors in the least square matching model, a true vector $e(x,y,z)$ was integrated into Equation (5.6).

$$f(x,y,z) - e(x,y,z) = g(x,y,z) \tag{5.7}$$

The purpose of using Least Squares matching is to reduce the sum of squares of the Euclidean distance between the template and the surface element using generalised Gauss-Markoff model. This can be represented by:

$$\sum \|\vec{d}\|^2 = \min \tag{5.8}$$

Where *d* denotes the Euclidean distance between the two partial surfaces of the same object. The partial surface can be related to the features representation in a point cloud. These features include points, curves or a surface model of a structure (Boda, 2009). Partial surfaces are utilised in the matching technique where local structure information is used for registration of an area. Potmesil (1979) proposed a surface matching algorithm which utilises the transformation that maximises shape similarities in the registration of two objects; examples are surface control points and points of maximum curvature.

Conformal Transformation Method

Similar to other point cloud data registration techniques, registration of overlap point cloud data can be done by conformal transformation techniques. After obtaining dense and accurate point cloud data from the scanning system, the data needs to be transformed from its intrinsic nature to a common coordinate system. To transform points from the intrinsic reference system to the ground reference system, a 3D roto-translation has to be computed in order to transform it into a common coordinate system (Scaioni, 2005).

For proper transformation, a minimum of three points are needed for the establishment of registration between two scanned overlap areas. In practice, there must be an increase in the ground control points in order to increase the redundancy. These points have to be a control point with known coordinates. Likewise, a scan can be considered as a reference for co-registering all other overlap points in the ground reference system. The calculation of conformal parameters will compute the transformation parameters needed to transform on the basis of common control points. The number of points in the adjacent overlap scan has an influence on the accuracy of calculated orientation parameters.

5.5.2 Feature-based Registration of Point Cloud Data

The feature-based point cloud data registration method involves using the geometry of natural features in the scan area such as sphere, cylindrical image, planes or man-made structures for feature matching and transformation parameter calculations. Similar to the point-based registration approach, this also makes use of transformation variables that allows easy transformation of two or more conjugate 3D line features with high accuracy and flexibility. These transformation parameters describe a complete scan area of the instrument and takes control of the discrepancies between the data for accurate transformation calculation.

The feature-based registration technique is made up of the integration of three spatial 3D transformation models to tackle LiDAR point cloud registrations. These include point-based, line-based and plane-based 3D transformation techniques. The transformation has seven parameters, these include the scale factor(s), the translation vector ($[tx\ ty\ tz]^T$), and the three angular rotation matrices. According to Chuang & Jaw (2017), in order to effectively determine the influence of feature observation derived from the point cloud data, variance-covariance matrix observation techniques are considered. Therefore the transformation parameters are concurrently determined from these different datasets through weighted least-squares adjusted methods.

A flowchart for registering LiDAR clouds data from a featured-based was proposed by Jaw & Chuang (2008) as shown in Fig 5.5.

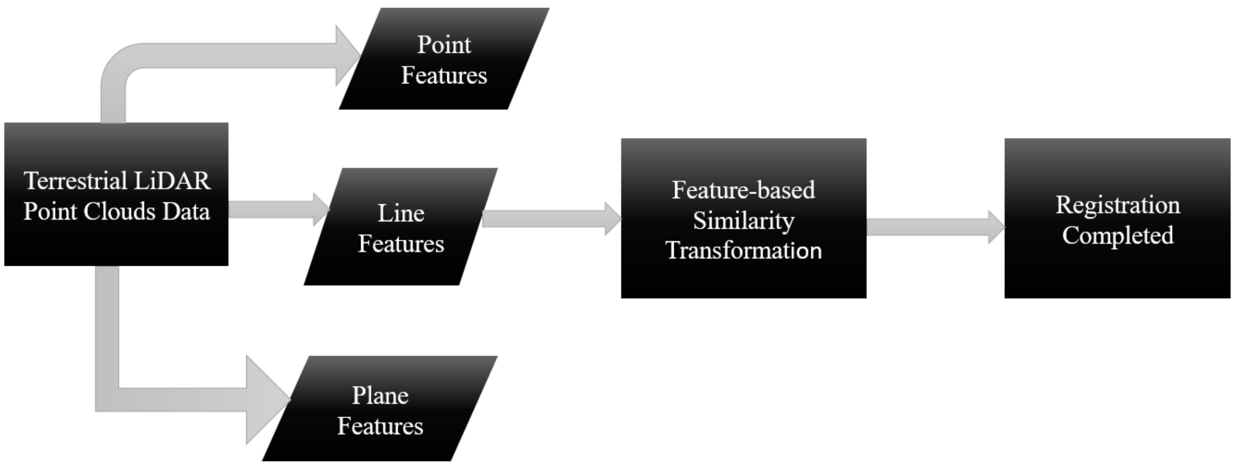


Figure 5.5: Illustration Showing the Integration of Point, Line, and Plane Features for Registering LiDAR Point Cloud Data (Jaw & Chuang, 2008).

The flowchart in Figure 5.5 is employed for simultaneous adjustment of two or more scans in which one of the datasets is chosen as the datum in which other datasets are registered using features. In an illustration by Jaw & Chuang (2008), the quality control for the registration of point cloud data can be checked via visual inspection by zooming in the overlapping feature to check the registration standard.

The integration of a camera system on the terrestrial laser scanner helps in generating full-colour photographs in addition to 3D spatial data of the scanning environment. The acquired colour information or intensity allows the full recognition of features between the overlapping scans through visual features.

One of the major issues encountered in registering 3D point cloud data using features in the scan area is the presence of noise in the range measurement, a limited field of view, an ambiguous range and the occurrence scan area dynamics which can cause notable errors. Likewise, the obstruction of targets during the scanning task results to low point density which requires scanning to be done at a different location to have a full coverage of the scan area. Since the feature-based approach depends on the visual structure in the scan area to align all the captured point clouds data to be transferred into a common coordinate system or through scan matching. The existence of these errors can cause misalignment despite having a corresponding feature. In order to solve the issue of errors that are present in the feature-based registration, Huhle *et al*., (2008) proposed a method that uses an energy function to reduce the impact of noise range data in scans.

$$E = \alpha E_{NDT} + (1-\alpha)\, \mathrm{E_F} \qquad (5.9)$$

Equation (5.9) source: Huhle *et al*., (2008)

Where the $\mathrm{E_{NDT}}$ in Equation (5.9) represents the Normal Distribution Transformation (NDT) scope function, $\mathrm{E_F}$ denotes energy function and α is the weight calculated as a result of preceding rough alignment using the same feature correspondences. The Normal Distribution Transformation (NDT) algorithm is a registration algorithm that uses standard optimisation techniques applied to statistical models of 3D point cloud in order to determine the most probable registration between two point clouds. The purpose of applying NDT for point cloud data registration is to provide the transformation that would allow individual points of the scan to be aligned with the reference scan surface. This method mitigates errors that causes misalignment during registration through numerical analysis such as a voxelized data structure and More-Thuente line search. Apart from reducing errors during registration, NDT is both faster and more reliable (Magnusson, 2013).

5.6 Filtering of Point Cloud Data

The next step in 3D point cloud data processing after registration is the filtering of point cloud data. Most of the point cloud data obtained from the laser scanners come with some level of inherent noise which needs to be removed in order to improve the quality of the point cloud. The purpose of filtering the 3D point cloud data is to remove intrinsic noise from the point cloud data while maintaining the geometry features. This inherent noise in point cloud data occurs as a result of surface reflectivity issues, presence of a lighting nature in the scan area and atmospheric environmental condition.

Filtering of the raw point cloud data is done by an internal software provided by the manufacturer of the laser scanner. For instance, Faro Scene and Autodesk Recap can perform filtering of 3D point cloud data.

The Faro Scene software is specially designed for processing of point cloud data. The software has four filters that are designed to perform different functions. These include the stray, distance, dark scan points and a smoothing filter. The stray filter is used for removing noise from the point cloud caused as a result of the laser beam not hitting the centre of the targets. The distance filter removes the point that does not lie within the stated distance by the scanner, while the dark filter removes the points that fall below the stated threshold and the smoothing filter is used to replace errors in the points in order to treat the presence of noise in the point clouds (Rex & Stoli, 2014).

The Autodesk Recap only has three filters that are used for noise cancellation and filtering the basic point's properties such as the distance and the intensity. The software is specifically designed to process the point distance from the scanner and remove the points that do not fall within the designated boundary. Another advantage of the filters in Autodesk Recap software is that they can also be used for registering point cloud data before scan integration.

According to Han, *et al*., (2017), the main techniques used in the filtering of 3D point cloud data can be categorised into four groups. These include:

- Statistical-based filtering method;
- Neighbourhood-based filtering method;
- Projection-based filtering method; and
- Partial Differential Equations (PDE's) based filtering method.

Statistical-Based Filtering Approach

The statistical approach used in removing unwanted measurements, noise and outliers from the point cloud data employs the statistical theory that is suitable for a particular point cloud data. There are several statistical frameworks designed in filtering the point cloud data. These include the Bayesian statistic for denoising the point cloud data using probability distribution of estimated point cloud S agreeing with measured data D, the Kernel-based clustering approach, an Iterative Least Squares (IRLS) method, an eigen-analysis of the matrix which is a fitting plane, the maximised a posteriori $P\ (S|D)$ to remove noise while preserving features and L1-sparsity pattern used in de-noising the point cloud data. In filtering the point cloud data, the first thing to do is to accumulate the local likelihoods Li and compute it on every point pi to define the likelihood function L modeling the probability for the noisy point cloud. This follows by moving the points to positions of high probability utilising an iterative scheme motivated by mean shift technique to smooth the point cloud. These are series of statistical approaches that can filter the unwanted measurement in 3D point clouds data. With these techniques, filtering can be achieved effectively with the objective of improving the quality of the point clouds and preserving the geometric features. This method achieves effectiveness in filtering and robustness in outlier detection

Neighbourhood-Based Filtering Approach

This method is basically used in the denoising and filtering of point cloud data by determining the filtered position based on the measured similarity between a point and its neighbour. This measured similarity between point and its neighbour has an impact on effective denoising of the point cloud data and the image generated. The rationale behind de-noising is to separate the real shape from the noise component in point cloud data. This can be achieved by using numerical approaches to find a subset of points in the local neighbourhood that may represent the local surface of an interest point. In the case of neighbourhood based point cloud processing, it can be assumed that within a local neighbourhood of appropriate size, data points can be assumed to be sampled from a locally planar surface. Therefore, we need to find a local region (surface) for an interest point *pi* by searching its local neighbourhood. The two well-known neighbourhood searching methods in point cloud analysis are the Fixed Distance Neighbourhood (FDN) and the k-Nearest Neighbourhood (k-NN). The FDN method selects all points within a fixed radius *r* around *pi*, whereas k-NN finds the k points having the least distance from *pi*. We prefer k-NN, because it can avoid the problem of point density variation and lack of adequate number of redundant observations.

The denoising issue is a common challenge in data and image processing. Part of the effort used in treating this problem is a bilateral filtering which uses identical neighbours to filter points which later become the shape properties of the features. The bilateral filter is applied directly on the point cloud data based on the point position and the intensity. From this approach, several techniques are generated with modification from initial bilateral filter methods. These include: trilateral filtering, colour information and intra-patch technique, an extended non-local means and mean shift procedure. All these approaches are designed for filtering, noise smoothing, and removal of sparse outliers of point clouds using the local neighbourhood and average local neighbourhood.

Projection-Based Filtering Approach

This method makes use of adjustment of the position of a point in point cloud data through projection plans to the filter point clouds data. The idea behind this approach is to iteratively project a subset of an input point cloud onto point cloud to reduce noise and outliers (Han, *et al.*, 2017). The Locally Optimal Projection (LOP) operator is a pre-processing algorithm that preserves unwanted shape features and used in normal shape estimation. This algorithm works on raw point cloud data by filtering the noise and the outliers in order to produce a new set of point cloud data that will be outlier free. According to Yang, *et al*., (2015), this is a set of algorithms developed to reduce noise, outliers and non-uniformity from raw point cloud data without relying on framework from their local points or orientation. LOP operator works well in creating evenly redistribution of a point cloud.

Other methods make use of the LOP to produce an evenly distributed set of points to filter the point cloud data. For instance, Weighted Locally Optimal Projection (WLOP) incorporated LOP and density weight of each point to obtain smoothness and preservation of geometric feature which also separates the outlier points. This improved LOP operator works effectively using a robust normal estimation method to perform consolidation of unorganised 3D point clouds data with better immunity against noise and outliers of raw scanned data (Yang, *et al*., 2015). Although, both LOP and WLOP have limitations of over-smoothing the point clouds data due to the improvement in local operators which generate extra features caused by noise (Cheng, *et al*., 2018). In another approach, LOP was redefined to obtain the Continuous LOP (CLOP) which was applied to the Gaussians mixture model in order to achieve high computing speed of LOP algorithm. Other techniques used in projection-based techniques include the Moving Least Square (MLS) which is used for surface construction of an unorganised point cloud through application of statistical techniques such as regression in learning theory and sensitivity analysis (Zhang, *et al*., 2015). This approach is regarded as a data fitting method that makes use of mathematical functions in calculating the weighted least squares measure for the construction of a surface from a set of points. The mathematical weighted function provides a convenient adjustment for MLS to perform fitting and smoothing of the point cloud.

PDE’s-Based Filtering Approach

The PDE (Partial Differential Equations) is commonly used in image processing and de-noising. The rationale behind this method is based on using a partial differential equation to filter point cloud data. This is done by assembling local finite matrices into a single matrix to form a processing structure to process point cloud through PDEs. This is used to separate and solve an anisotropic equation for filtering and smoothing the noise in point cloud data and also preserving them. Other related approaches that incorporate PDEs in filtering point cloud data are: *P*-Laplacian and Partial Differential Equations (PDEs) morphological operator. *P*-Laplacian operator and PDE morphological operator are graphical techniques where second-order partial differential equation is applied on graph for image processing and denoising of point cloud data. This is done by creating a weighted graph from the raw point cloud data and introducing PDEs to perform graph-based morphological processing of point cloud. The PDEs graph is constructed from the geometry of the scan area which allows processing of 3D surfaces and 3D point clouds from the raw point cloud data. Elmoataz, *et al*., (2016) pointed out the application this of method in the area such as de-noising, restoration, in-painting, feature extraction or estimation of shortest path on raw point cloud data of a scan area. In addition, one robust benefit of this approach is that it enables the processing of both geometry and colour associated with raw 3D point clouds.

According to Han, *et al*., (2017), there are other techniques used in filtering point cloud data and feature preservation. These include the hybrid filtering technique, signal processing filtering method, the Voxel Grid (VG) filtering method, the Quadtree-based filtering method, and the similarity-based filtering method. All the abovementioned techniques are used for noise and outliers removal.

5.7 Establishment of Accurate 3D Point Cloud Data

The final deliverable of the short-range testing laboratory is an accurate 3D master point cloud. Before the point cloud can be generated, there are several steps that must be completed. If we zoom out and look at the several steps that have been taken, one can develop a flowchart that can be used in testing the accuracy of Terrestrial Laser Scanners. The following flowchart shown in figure 5.6 is an example of the testing procedure taken in examining the accuracy of terrestrial laser scanners.

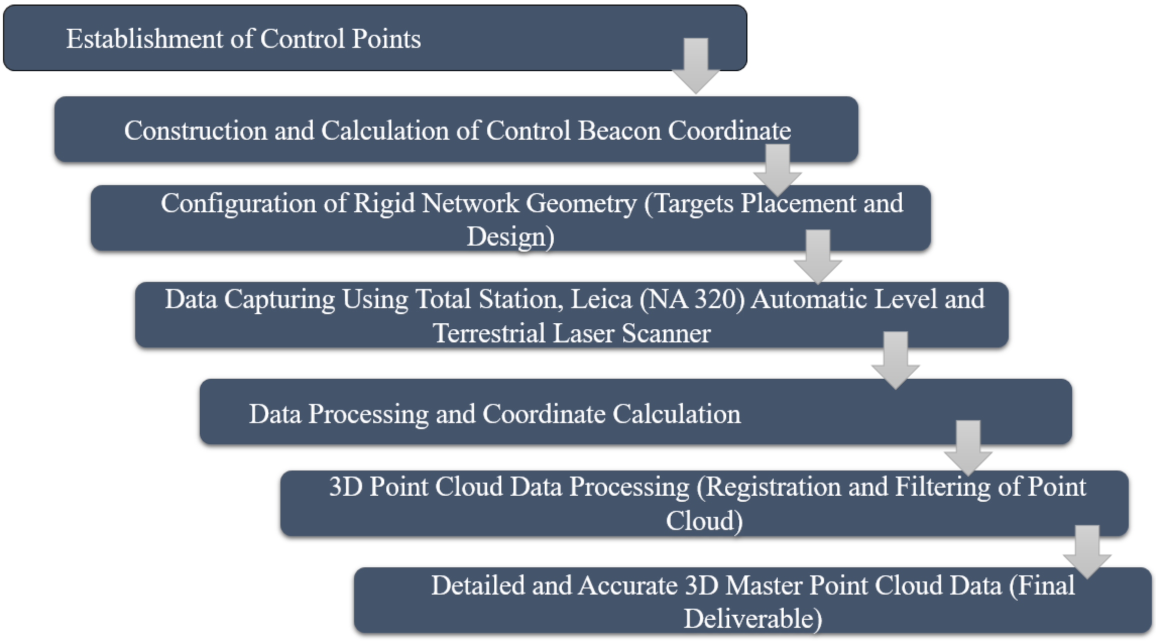


Figure 5.6: Illustration Showing a Flow Diagram from Ground Control Point's Development to Achieving an Accurate 3D Point Cloud Data.

Based on the flowchart depicted above, the user is guided throughout the process of testing the accuracy of terrestrial laser scanners. There are several of these flowcharts created by other users to simplify the process. Some include a step for the removal of any form of outliers or errors present in the data.

5.8 Conclusion

The scanning of the laboratory was achieved by using a FARO Focus 3D X130 laser scanner. Prior to the scanning task, all the targets in the scan facility were measured with a robotic total station surveying instrument (Trimble S6). The chapter has analysed the working principle of the FARO Focus 3D X130 and the steps taken in processing the acquired 3D point cloud data. Different techniques are used in registering spatial coordinates of each point cloud data and various filtering process of 3D point cloud data were fully examined. FARO SCENE software was used in processing the raw 3D point cloud data. Notably, a proposed workflow that summarised all the necessary steps has been developed to guide users in generating a master 3D point cloud data for testing the accuracy of terrestrial laser scanner.

The result and analysis of the acquired 3D point cloud data of the research are discussed in chapter six. This will show comparisons between the acquired point clouds data and the surveyed true value to deduce if the scanner is performing according to the manufacturer specifications.

CHAPTER SIX

6 Results and Analysis of Acquired 3D Point Cloud Data from a Terrestrial Laser Scanner

The previous chapter described the scanning of the laboratory using a FARO Focus 3D X130 laser scanner to generate the 3D point cloud data. Before scanning of the laboratory, all the targets were surveyed using a robotic total station (Trimble S6). This chapter discusses the comparisons between the acquired 3D point cloud data from the laser scanner and the surveyed true value obtained from the robotic total station instrument. The result of the comparison was used to evaluate the accuracy and performance of the FARO Focus 3D X130 laser scanner.

6.1 Short Range Testing Facility Results and Analysis

The acquired 3D point cloud data was used to evaluate the accuracy of FARO Focus3D X130 Terrestrial Laser Scanning system based on the coordinates that were calculated from the scanning measurements. This was done by comparing the acquired point cloud data to the survey (true) values from the Trimble Robotic S6 Total Station. The results from the comparison between these two survey instruments were used to analyse the performance of the Terrestrial Laser Scanner.

The specifications of the FARO Focus3D X130 are suitable for short-range accuracy testing. The instrument is a high-speed laser scanner with a maximum scan speed of 5,820 revolutions per minute (rpm) or 97Hz with both horizontal and vertical field of view of 360 and 300 degree respectively (FARO, 2014).

Prior to the scanning of the laboratory, some settings to correct for systematic errors were made on the instrument in order to fully capture the scan area. The scanner was set at normal resolution and high quality which resulted in eight (8) minutes scanning time from the control beacon. The same settings were maintained for the other two temporary scan positions resulting in seven (7) minutes scan time from each position with a 3D colour image of the scan surroundings.

The terrestrial laser scanner setting parameters such as resolution, quality and the scanning orientations are the parameters used by the instrument for recording the data with a high-quality image scan from the instrument. The higher the scanner parameters setting, the better the calculation of coordinates of the targets from the scanner and the better the results for comparative analysis of data (Davison, 2017).

When the instrument is set at high quality and resolution, it reduces the noise in the scan data and increases the scanning time (FARO, 2014). The resulting data from the scanning of the laboratory from the control beacon and other two temporary scan positions is presented in Table D1 in Appendix D of this research report.

From the results of the acquired laser scanning data in Appendix D, targets C6, C22, S1, S7, and S11 were not captured in the scan and could not be used. Target C11 was partially obstructed by the ventilation duct as shown in Figure 6.1

Figure 6.1: Showing Target C11 Being Partially Blocked by the Ventilating Duct

The room temperature and barometric pressure readings were considered for the Total Station measurement with an Oregon scientific weather instrument. This weather instrument makes use of wireless sensors to transmit weather information from its surrounding and is displayed on the screen of the device. The room temperature and pressure of the scan surroundings were measured at interval throughout the surveying task. The temperature and pressure were recorded as 18 degree Celsius and 829mbar respectively. Both systematic and atmospheric conditions were taken into account during the laser scanning task despite scanning at a short range. The scan facility has overhead fluorescent tubes that provide lighting.

The result of the scanning of the laboratory presented in Table 6.1 shows a reasonably good comparison between the FARO Focus3D X130 terrestrial laser scanner and the Trimble S6 RTS. In a precise and accurate scan, there should be no difference between the true (survey) value and the observed laser scanner value. The difference that exists between these two values is presented in Table 6.1. This difference between the two values shows that there is potentially a problem with the accuracy of the terrestrial laser scanner.

6.2 Accuracy Testing for the Short Range Facility

The approach used in testing the accuracy of the FARO Focus3D X130 laser scanner was done by comparing the values between the Trimble S6 RTS and the FARO Focus3D X130 laser scanner. The estimated differences between these two values was used in evaluating the accuracy of the laser scanner. Also, the evaluated difference was compared to the quoted manufacturer specifications in order to determine the performance of the laser scanner.

Table 6.1: Difference in Value Between the Laser Scanner and the Total Station Coordinates.

POINTS	**ΔY (m)**	**ΔX (m)**	**ΔZ (m)**	**REMARKS**
C1	-0.003	0.004	0.001	
C2	0.002	0.004	-0.002	
C3	0.008	0.011	-0.005	Oblique
C4	0.004	0.008	-0.002	Steep Upwards Inclination
C5	0.003	0.008	-0.004	
C7	0.009	0.014	0.002	Oblique
C8	0.009	0.009	0.004	Oblique
C9	0.007	0.022	-0.002	Oblique
C10	0.008	0.012	-0.004	Oblique
C11	0.006	0.013	-0.001	Full Target not visible
C12	0.002	0.012	0.001	Oblique
C13	0.011	-0.008	0.000	Steep Downwards Inclination
C14	0.004	0.002	0.006	Steep Upwards Inclination
C15	0.000	0.011	0.002	Oblique
C16	0.002	0.007	0.003	Oblique
C17	0.006	0.005	-0.002	Oblique
C18	0.004	0.006	0.009	Oblique
C19	-0.005	0.011	-0.001	Oblique
C20	-0.006	0.004	0.001	Oblique
C21	0.006	0.009	-0.002	Oblique
C23	-0.002	0.003	0.002	
C24	0.010	0.007	-0.003	Steep Upwards Inclination
C25	0.005	0.006	-0.003	
C26	0.002	-0.010	0.003	Steep Upwards Inclination
C27	0.000	-0.006	0.003	
R1	0.001	0.022	0.009	Steep Upwards Inclination
R2	-0.007	0.013	0.003	Steep Upwards Inclination
R3	0.000	0.007	-0.005	Steep Upwards Inclination
R4	-0.001	-0.003	0.008	Steep Upwards Inclination
R5	-0.005	0.004	0.005	Steep Upwards Inclination
S2	0.007	0.008	0.000	Oblique
S3	0.005	0.008	0.000	Steep Upwards Inclination
S4	0.001	0.005	-0.004	
S5	-0.000	0.009	0.000	Steep Upwards Inclination
S6	0.011	0.006	-0.001	Oblique
S8	-0.001	0.010	0.001	Oblique
S9	-0.001	0.014	0.003	Oblique
S10	0.001	0.006	0.004	
S12	-0.002	0.007	0.002	
S13	-0.002	0.010	0.003	
SUM	**0.097**	**0.316**	**0.031**	
MEAN	**0.002**	**0.008**	**0.001**	
σ (m)	**0.005**	**0.006**	**0.004**	
RMSE=0.008	**σ (m)= 0.005**			

Targets with obliqueness, non-visibility, and steep upward and downward inclination were regarded as errors which can be eliminated with better target design. For this research, investigation of the performance of the laser scanner for rock engineering applications was done by excluding all targets with errors from the dataset. Table 6.2 shows the difference between the Total Station coordinates and laser scanner coordinates after removing the errors from the dataset. The exclusion of these erroneous targets from the dataset significantly improved the RMSE value from 8mm to 4mm as shown in Table 6.2.

Table 6.2: Difference Between the Coordinate of Total Station and Laser Scanner After Removing the Errors From the Dataset

POINTS	ΔY (m)	ΔX (m)	ΔZ (m)
C1	-0.003	0.004	0.001
C2	0.002	0.004	-0.002
C4	0.004	0.008	-0.002
C23	-0.002	0.003	0.002
C25	0.005	0.006	0.003
C27	0.000	-0.006	0.003
S3	0.005	0.008	0.000
S4	0.001	0.005	-0.003
S10	0.001	0.006	0.004
S12	-0.002	0.007	0.002
SUM	**0.011**	**0.045**	**0.002**
MEAN	**0.001**	**0.005**	**0.000**
σ (m)	**0.003**	**0.004**	**0.003**
RMSE = 0.004	**σ (m) = 0.003**		

This shows more work has to be done on the design of targets in order to obtain a full view of all the targets in the laboratory. Spherical targets can also be used in order to improve the visibility of targets in the laboratory and also to minimise the occurrence of steep angle inclination as they can be viewed from any angle. Moreover, the spherical targets can also provide homogeneous reference surface from which the centre coordinates of the sphere can be calculated.

6.3 Analysis

The error of each control point is defined as the difference between the surveyed data (true data) and the corresponding terrestrial laser scanner data. Errors in the point cloud data are vectors with three Cartesian components (X, Y, and Z) which are represented by ΔX, ΔY, and ΔZ respectively**.** The difference allows the estimation of the Root Mean Square Error (RMSE) and the Standard Deviation (σ) value. RMSE is calculated as the square root of the average of the deviation from an independent source of higher accuracy for identical or same points. The standard deviation is the square root of the variance that measures the spread or dispersion of a set of data. The standard deviation is the common method used in measuring the degree at which dataset is spread out around the mean value. A low dispersion in measurement signifies the measurement has high, precision while RMSE is a good measure of accuracy. According to Trimble Navigation (2013), the instrument has an accuracy (RMSE) of 2 mm + 2 ppm for both prism and Direct Reflex (DR) standard mode. This stated accuracy by the manufacturer is suitable for monitoring rock movement in the underground mining environment. That is, with 2 mm accuracy (RMSE) value, the Trimble S6 Total Station is fit for the purpose of monitoring surfaces for rock engineering use. Leica - Geomatics stated that an instrument with an accuracy of ±2mm would be suitable for monitoring rock mass movements in an underground mining environment (Bornman, 2019). Hence, the measurement from the Trimble S6 Total Station can be regarded as an acceptable accuracy for the purpose of monitoring the movement of rock underground.

Table 6.1 shows the estimated value of the RMSE and the standard deviation. The results from the table show the differences in (X, Y and Z directions) between the Total Station surveyed (true) values and the measured value from the Terrestrial Laser Scanner. The RMSE and the standard deviation (σ) for all the forty (40) points were used to estimate the point accuracy and the precision of the laser scanner measurement, according to (Miyazaki, *et al.*, 2008). The exclusion of erroneous targets was done so as to avoid biased judgement on the performance of the laser scanner. The equation (6.1), (6.2) and (6.3) were used to calculate the RMSE, the standard deviation and the mean values of the point cloud data generated by the laser scanner.

$$\text{RMSE} = \sqrt{\frac{\sum(\Delta x)^2+(\Delta y)^2+(\Delta z)^2}{N}} \tag{6.1}$$

$$\text{Standard Deviation } (\sigma) = \sqrt{\frac{\sum(x-\bar{x})^2}{N-1}} \tag{6.2}$$

$$\text{Mean } (\bar{x}) = \frac{\sum_{i=1}^{n} x_i}{N} \tag{6.3}$$

Where N is the number of targets in the laboratory, ($\bar{x}$ - x) is the difference between the TLS coordinate and Total Station coordinate for all the points which are denoted by ΔY, ΔX and ΔZ.

The RMSE for all the registered points in the scan area is 0.008m (8mm), that is, the point accuracy for the points Y (Northing), X (Easting) and Z (Elevation). According to Cuartero, *et al*., (2010), the standard deviation value shows how the point cloud data is close to the true value in term of its precision and the RMSE value indicates the accuracy of the instrument. The outcome of this statistical analysis would indicate the accuracy of the instrument and ascertain if is fit for the task.

A total number of forty (40) targets (control points) were considered for the comparisons between the surveyed (true) value and the laser scanner value with their calculated RMSE, standard deviation, and mean value. Ten (10) of these target coordinates were used to determine if the laser scanner was generating accurate point cloud data.

Table 6.2 shows that the mean of the standard deviation is 0.003m (3mm) and an average RMSE of 0.004m (4mm) for the measurement. From the latter measurement, it appears that the FARO Focus3D X130 laser scanner can produce accurate and precise point cloud data at the range of 15m which can be used for underground rock engineering deformation analysis (Bals, 2018). This implies that the laser scanner is fit for the purpose of monitoring rock mass movements in underground mining. Although, this depends on the elastic properties of the rock such as the uniaxial compressive strength (UCS) and the young modulus of the rockmass. That is, the resulting point cloud data can be used in managing rock engineering risks depends on the elastic parameters of the rock mass, as different rock types have different elastic limits.

For the continuation of the testing, the second level of the comparisons is to compare the difference between the two values with the manufacturer specifications in order to assess the precision of the FARO Focus 3D X130 Terrestrial Laser Scanner. The manual issued with the instrument states its full technical specifications. Table 6.3 shows the quoted manufacturer's ranging error[3] of the FARO Focus 3D X130 laser scanner to be ±2mm with the range of 0.6 to 130m (FARO, 2014). This range suits the test facility provided for testing laser scanners accuracy because the laboratory range of 15m is within the instrument range.

[3] Ranging error is the maximum error in the distance measured between the laser scanner and the target. This is caused by systematic effect such as the colour, the incidence angle and the surface property of the target (Boehler & Marbs, 2003).

Table 6.3: Basic Technical Specifications of FARO Focus 3D X130 Terrestrial Laser Scanner (FARO, 2014).

Measurement principle	Phase-based
Range	0.6-130m
Measurement speed	976,000 points/second
Ranging error	±2mm
Ranging noise	@10m - raw data: 0.3mm @90% refl. @25m - raw data: 0.3mm @90% refl. @25m - raw data: 0.3mm @91% refl. @25m – raw data: 0.3mm @92% refl.
Integrated colour camera	70 Megapixel
Laser class	1st Class Laser
Weight	5.2kg
Built-in- Sensor	GNSS, Compass, Height Sensor, Dual Axis Compensator
Size	$240 \times 200 \times 100$mm
Maximum vertical scan speed	5.820rpm or 97Hz
Field of view(Vert/Horiz)	300°/360°
Step size	0.009° (40,960 3D-Pixel on 360°) / 0.009° (40,960 3D-Pixel on 360°)
Max. vertical scan speed	5,820rpm or 97Hz

The result from the Excel spreadsheet shows the standard deviation of the difference between the total station values and the laser scanner values as ΔY, ΔX and ΔZ. The calculated value of the standard deviation gives an overall indication of how the laser scanner value varies from the surveyed true value. The result of the comparisons between the two sets of values showed that the mean standard deviation is equal to 3mm and RMSE value of 4mm.

The mean standard deviation of 3mm described the degree of closeness of the measurement in terms of imprecision. This value represents the amount by which the scan data varied from from the survey (true) value.

From this evaluation, although it appears that the laser scanner did not generate the accuracy expected, the results are adequate for the purpose of monitoring rock mass movement depending on the rock mass behaviour. Although the instrument is capable of both the accuracy and precision, these can only be achieved with correct use and target design. More research has to be done on target orientation and placement in the scan area in order to improve the results. This is significant as it impacts the quality of the point cloud data produced by the instrument.

6.3.1 Analysis of Outliers in the Result

The results from Table 6.1 shows some discrepancies in the coordinates which implies that something was not correct with the acquisition of the point cloud data. The initial thought was that perhaps the measurements from the Total Station might have been incorrect leading to outliers in the data. After checking the point cloud data, one can easily identify the magnitude of X coordinate error which is directly related to the presence of systematic error in the observed data. This could be as a result of scattering of the returned laser pulse which has a significant influence in the calculation of the distance travelled by the laser pulse. From the results, the comparative difference between the measurements for individual points results in high values of the root mean square and standard deviation which signifies the presence of errors in the point cloud data.

The targets on the concrete wall (C3, C7 to C11, C13 to C14, C16 to C21 and C24) recorded the highest magnitude of outliers as shown in Table 6.1. This occurred as a result of the obliqueness between the targets and the laser scanner leading to poor scanning accuracy. The slanting of the laser beam was caused by poor network configuration as orthogonal scans could not be achieved between the laser beam and the centre of the target. The obliqueness between the control beacon and targets C9 and C7 can be seen in Figure 6.2. The laser beam was slanted from the centre point of the target with respect to the laser scanner orientation. In order to correct this effect, the angle between the targets and the scanner must be as close to perpendicular as possible.

Figure 6.2*: Illustration of Obliqueness of Targets C9 and C7.*

The orthogonality of the emitted laser beam improves the angular precision by reducing the angular error in the measurement. The emitted laser beams are slanted from the centre of the target due to poor geometry that exists between the scanner and the target.

Also, the irregularities in the shape of the laboratory added to the challenges encountered as the setups do not have a regular geometric pattern which would have been preferred. This also added to the challenge in locating the centre points of each target. Good scanning geometry influences the quality of the acquired point cloud data.

The position of the control beacon also affected the accuracy and precision of targets C13 and C14. The position of the control beacon prevents the laser scanner from utilising its angular view in measuring the targets with steep incline angles. The vertical angle between the instrument and the targets affected the accuracy of the point cloud. Target C13 has a lower angle of inclination as shown in Figure 6.3 while the accuracy of target C14 was influenced by a steep upward incline angle from the scanner.

Figure 6.3: Illustration of Lower Vertical Angle between the Control Beacon and Target C13.

The scanner cannot measure the target right underneath as the head motor and tripod are always blocking the view of the surface located below the scanner.

The outliers for targets placed on the ceiling (R1 to R5) is an indication that the instrument performed poorly in its vertical observation. This effect can be analysed based on the field of view (FOV) between the laser scanner and the targets. The laser scanner was affected by the high steep incline angle between the instrument and targets placed on the ceiling. The scan quality deteriorates with an increase in vertical angle and range (Davison, 2017).

The outliers are significantly high in the values of elevation (ΔZ) compared to any other set of control points in the laboratory. This shows a steep incline angle for targets is not a good idea especially where targets were placed out of the scanner's FOV. This takes effect in a circular measurement, especially when sighting a steep target (Rada & Bedada, 2012). The steep incline angle can be attributed to an increase in incidence angle which reduced the quality of the signal to noise ratio, which in turn causes low precision in measurement (Soudarissanane & Roderik, 2011). According to Rada and Bedada (2012), the noise increases with an increase in the angle of incidence. This may have been the cause of an increase in error of the target placed on the ceiling for vertical observations. The poor signal alignment between the instrument and the target would lead to obliqueness, as the signal could not locate the centre of the target which could introduce the sighting error in measurements. This occurs when the emitted laser signals on the surface are slanted with respect to the laser scanner. This can be seen in Figure 6.4 and Figure 6.5 when sighting a steep target.

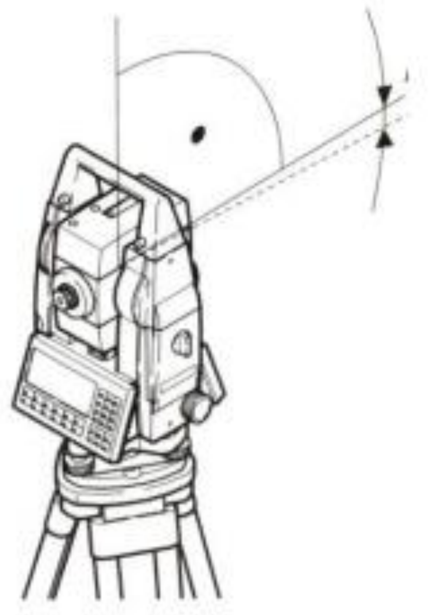


Figure 6.4: Image Showing Vertical Collimation Error in the Total Station (Rada & Bedada, 2012)

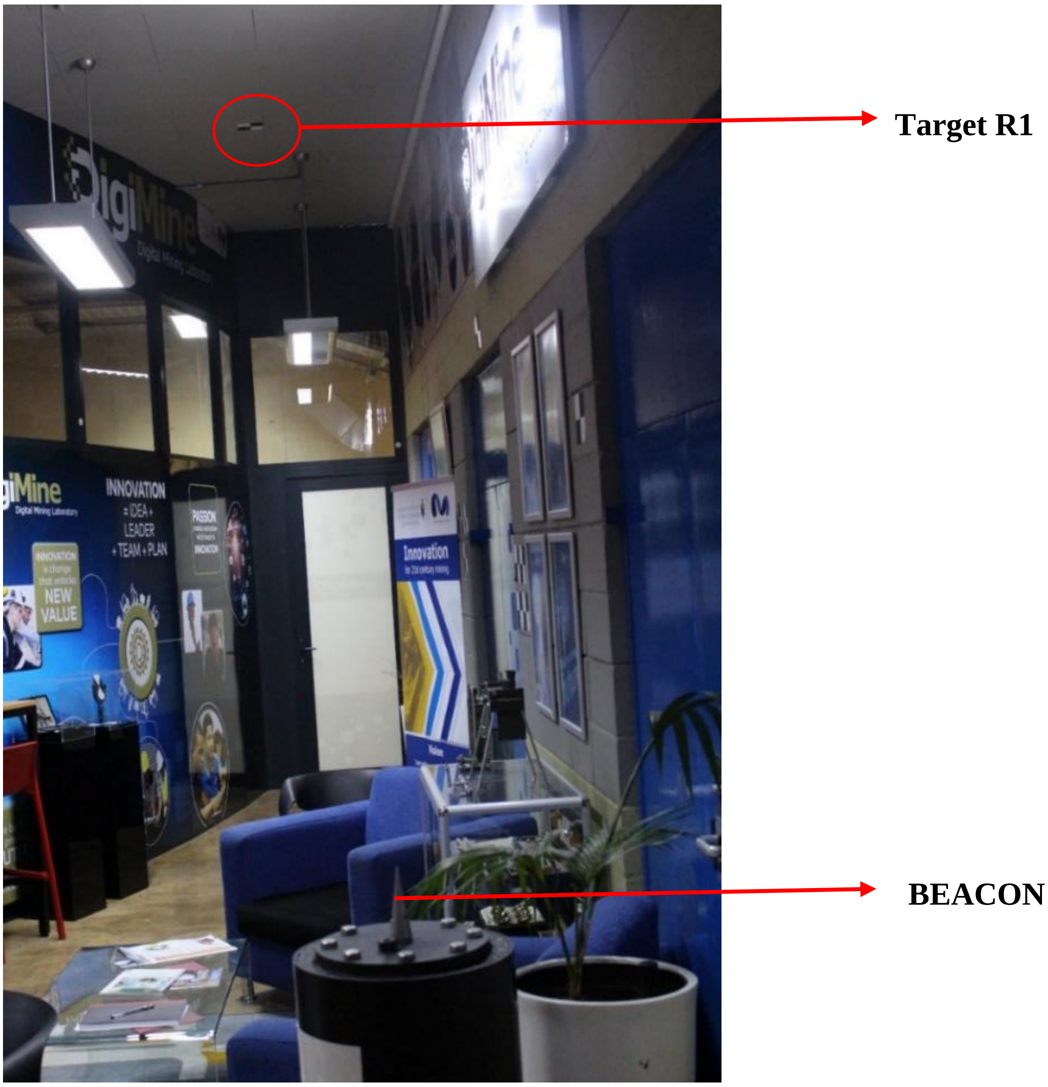


Figure 6.5: Diagram Showing the Beacon and the Target

The targets placed on the steel wall have better accuracy compared to the ceiling and the concrete wall. A total of ten (10) targets (S2 to S5, S6, S8 to S10 and S12 to S13) were considered in the scan. Targets on the steel wall are directly opposite to the control beacon which makes it possible to achieve orthogonal scan from the control beacon as shown in Figure 6.6. Figure 6.7 shows the effect of orientation between targets S6 and S9 resulting to high magnitude of outliers. This occurs as a result of the orientation between the targets (S6 and S9) and the instrument which resulted in obliqueness as the orthogonal scans could not be measured. The quality of the measurements from these two targets was poor due to poor sighting accuracy resulting in the tilting of the laser beam from the centre point of the targets.

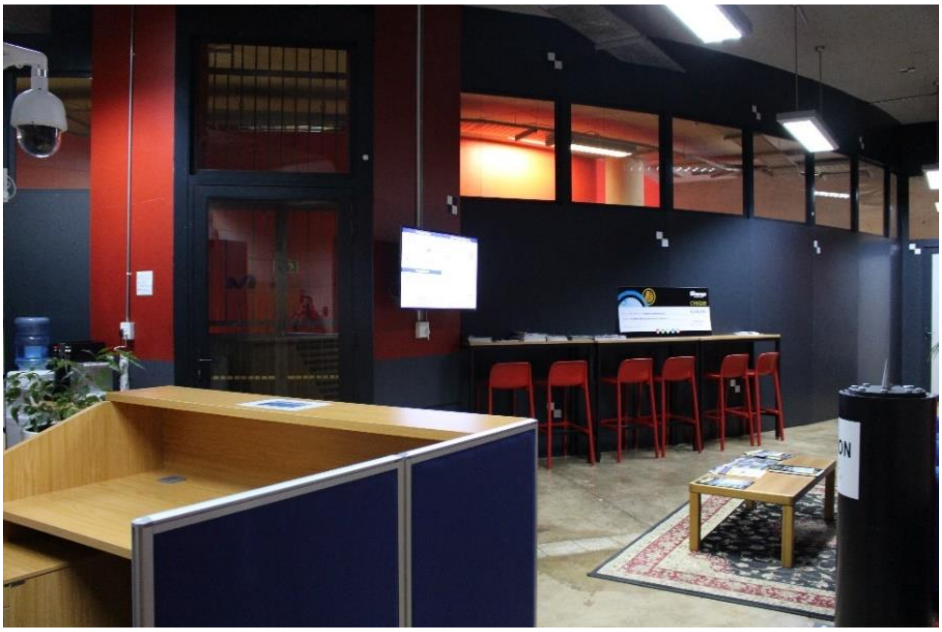


Figure 6.6: Image Showing Perpendicularity Between "S" Targets and the Control Beacon

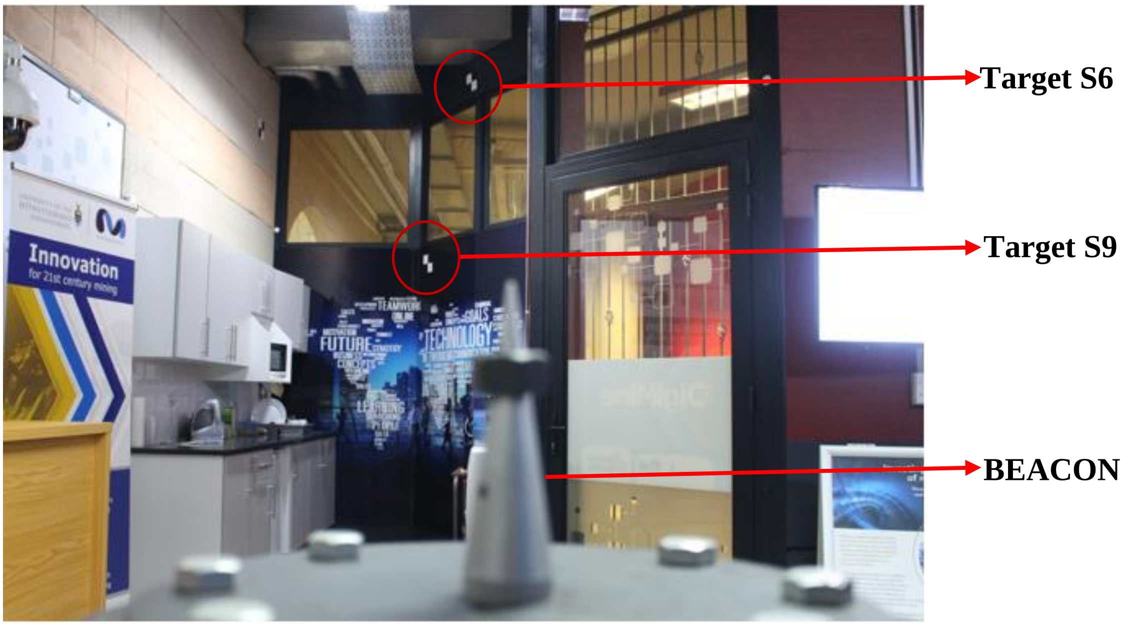


Figure 6.7: Diagram Showing Tilting of the Laser Beam from the Control Beacon

The effect of atmospheric conditions were taken into consideration during laser scanning. A change in atmospheric condition can cause reduction in the signal-to-noise ratio (SNR) and this affects precision of the measurement. The laser beam can be distorted or drifted from its original propagation direction due to atmospheric conditions that might be present in the scanning environment (Soudarissanane, 2016). In most cases, these errors have very little impact over a short distance. For high precision work, the atmospheric conditions, especially the air temperature, in particular, must be monitored throughout the scanning process in order to eliminate errors that are likely to influence the measurement, irrespective of the distance. In underground mining environment, this might be a different case as various atmospheric conditions such as high ambient temperature, humidity, ambient light, vibration due to turbulences and pureness of the air might cause scattering of laser signals. Moreover, temperature, humidity, and dust in underground mine can cause weak signal intensity (attenuation) of the returning laser signals. This can cause deviation in laser signal from its original propagation direction due to atmospheric disturbances. Thus, harsh atmospheric conditions in underground mining environment have to be considered when using the laser scanner compared to scanning in the laboratory, as this can influence the performance of the instrument.

6.3.2 Estimation of Precision in the Measurement.

The precision defines the closeness between the Laser Scanner value and the Total Station (true) value as shown in Figure 6.8.

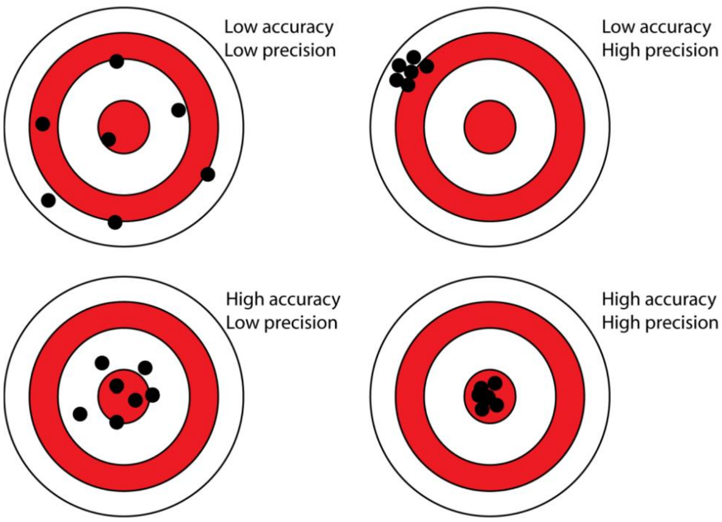


Figure 6.8: Image Showing the Difference Between Accuracy and Precision (Ruotsala, 2016)

This parameter examines the reliability in the measurement from the instrument. The precision was determined from the standard deviation and the mean value of the comparative difference between the Total Station and Laser Scanner. These two sets of results were used in plotting Gaussian normal distribution to estimate the closeness of the data to the true value or the precision of the scans obtained. The difference between the measurements in Table 6.1 on (page 111) shows a variability which indicates the presence of errors in the point cloud data. A quality measurement with high precision contains less systematic and random error in the required levels of accuracy.

The Gaussian normal distribution was used to express the precision in the difference between the Total Station measurement and the Laser Scanner measurement as shown in Figure 6.9.

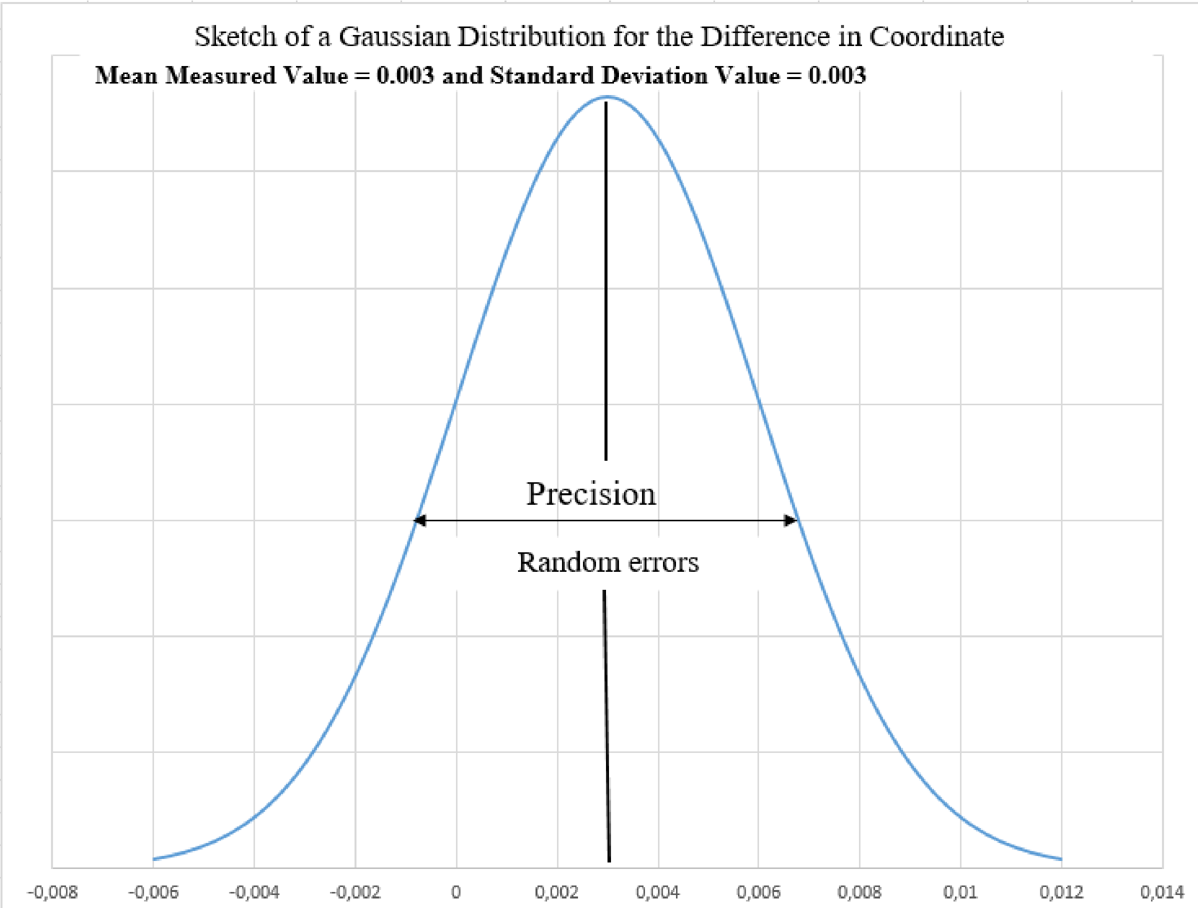


Figure 6.9: Gaussian Normal Distribution for the Difference in Point Cloud Data.

The dispersion shown in Figure 6.9 is measured by the value of the standard deviations that range from -0.008 to 0.0014 in Table 6.1. The highest point on the curve is where the mean is located and the standard deviation determines the spread in the measurement. The higher the standard deviation, the more the spread out of the curve (Courtney, 2018). The narrow shaped curve signifies high precision in the measurement while the wider curve describes the high spread of the data. Besides, the relative variability of the difference in point cloud data was calculated to characterise the variability in the measurement. Measurement with small variability shows a good repeatability and consistency in the obtained data. According to Rossi

& Deutsch (2014), the coefficient of variation (CV) is the value of the standard deviation divided by the mean value. That is,

$$\text{The Coefficient of Variation (CV)} = \frac{\sigma}{m} \qquad (6.3)$$

The CV = 0.003/0.003 = 1 (100%)

The lower the value of CV, the better the level of dispersion or variability in the data. As an approximate guide, when the estimated value of CV is less than 0.5, this indicates a fairly close data, while a CV greater than 0.5 indicates significant variability in the data (Rossi & Deutsch, 2014). From Equation (6.3), the value of CV is 1(100%) which signifies that there is notable spread in the data.

In Figure 6.9, the curve indicates the precision of the data which shows the distribution of random errors. The shape of the curve signifies how the data varies from the measured mean value of 0.003. This indicates the presence of random errors caused by obliqueness and steep angle observations which lead to low precision in the results.

6.4 Cloud Compare Software for Point Cloud Representations

Cloud Compare software version 2.9 Beta was used in generating the virtual representation of the scanning laboratory from the acquired point cloud data. Cloud Compare software was selected for its ability to provide various point cloud editing tools such as registration, sampling, automatic segmentation, statistics computation as well as integrated enhancement tools (custom colour ramps, colour & normal handling, calibrated picture handling, OpenGL shaders, plugins etc.) (Cawood, *et al*., 2018). The advantage of this computer package is that it is open-source software and available at no cost.

The acquired point cloud data contains large number of points in space with each point having an X, Y and Z coordinate. These acquired points come with colour information that represents the laser scanner environment in the form of RGB values. Figure 6.10 shows a disorder point cloud which gives a virtual representation of the scan environment but requires a point cloud processing algorithm as the structures are opaque. Generally, complex structures are handled by a triangulation meshing algorithm in Cloud Compare software by transforming all the points into surfaces through small triangles.

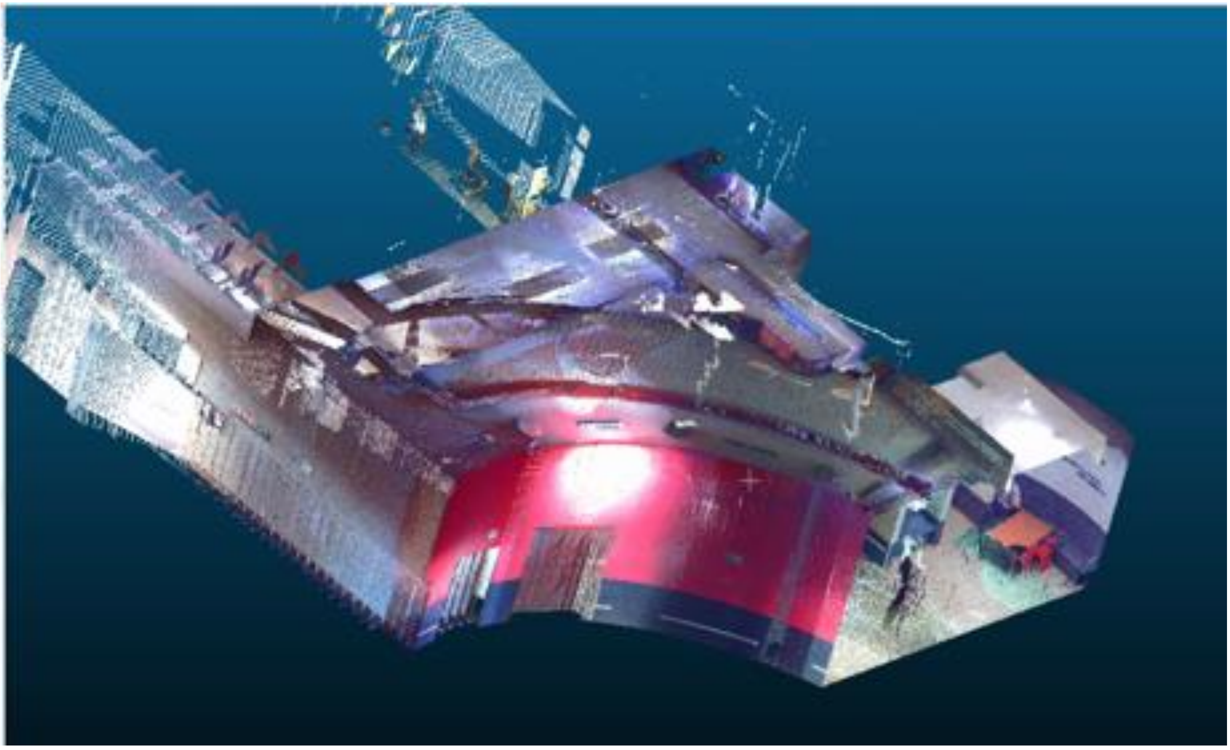


Figure 6.10: Screenshot of a Disorder Point Cloud from Cloud Compare Software.

Cloud Compare software is a point cloud data processing software that also performs other functions such as visualisation and direct comparison of 3D point cloud data. Also, the software can compare point cloud to point cloud and mesh to point cloud data. In this research, the software was used in transferring the acquired point cloud data to a virtual representation of the scanning laboratory. This is achieved by removing the excessive overlaying scans which cause irregular point density in the acquired point cloud. This process improves the accuracy of the point cloud data as quality analyses such as smoothing, thinning and segmentation are done to acquire a 3D point cloud.

The software makes use of a spatial structure called an Octree structure to perform its task, especially data generated from terrestrial laser scanners. An Octree is a processing algorithm used in managing 3D point cloud data. An Octree has a tree-like structure with eight branches which are referred to as nodes. The space at each node represents another eight octants. An octree algorithm performs functions such as restructuring, portioning, compressing and finds the nearest neighbour in point cloud data. Examples of nearest neighbour search in an octree structure are K-Nearest Neighbour Search and Neighbour within Radius Search.

Cloud Compare has the capacity to handle large point cloud data on a standard computer, that is, up to several millions of point cloud data. The resulting point cloud image was generated from five different scans with a total number of 27,943,726 points which were processed by the Cloud Compare software. The image of the 3D point cloud of the scanning laboratory can be seen in Figure 6.11.

Figure 6.11: 3D Point Cloud of the Scanning Laboratory Imported to Cloud Compare with 27 Million Points.

6.5 Terrestrial Laser Scanners Accuracy Testing in Wits Mining Institute (WMI) Digital Mining Project Line

Accuracy testing is essential in order to check if the instrument is performing according to manufacturer's specifications. The testing enables the users to determine the accuracy of the system in question and if it is fit for purpose. If an instrument is needed for precise and accurate work, the accuracy needs to be checked with that of manufacturer's claims (Boehler & Marbs, 2003). This serves as part of Quality Assurance (QA) in ensuring that the laser scanner is performing at the required level of accuracy.

At the Digital Mining Laboratory (DigiMine), there are four project lines which are also referred to as theme. These are:

- Wireless Communication Systems;
- Surveying, Mapping, and Navigation; which is the theme under which the scanning laboratory is resort;
- Health, Safety and Security; and
- System Integration for Smart Mining.

6.5.1 Surveying, Mapping, and Navigation

The project under this theme systematically progressed in the following order:

- Roof to sidewall networks;
- Indoor to underground navigation; and
- Using point-cloud data for automation.

This theme discusses how we can extend satellite signals from the surface to the underground mine to assist in determining real-time positioning. This will also enable technology systems to generate spatial information with pseudo signals for navigation purposes in an underground mine complex.

The aim of testing the point cloud data is to ensure precision and accuracy in the acquired point cloud data. This is important in getting laser scanners to perform reliably and effectively for real-time mapping and monitoring of rock mass movement for mine safety purpose. When the scanner is mounted on a moving platform, such as vehicle, it generates three-dimensional point clouds from the surrounding objects as illustrated in Figure 6.12. The comparisons of the point cloud data with Total Station survey value will assist with making sound decisions by indicating a potentially unstable rock mass.

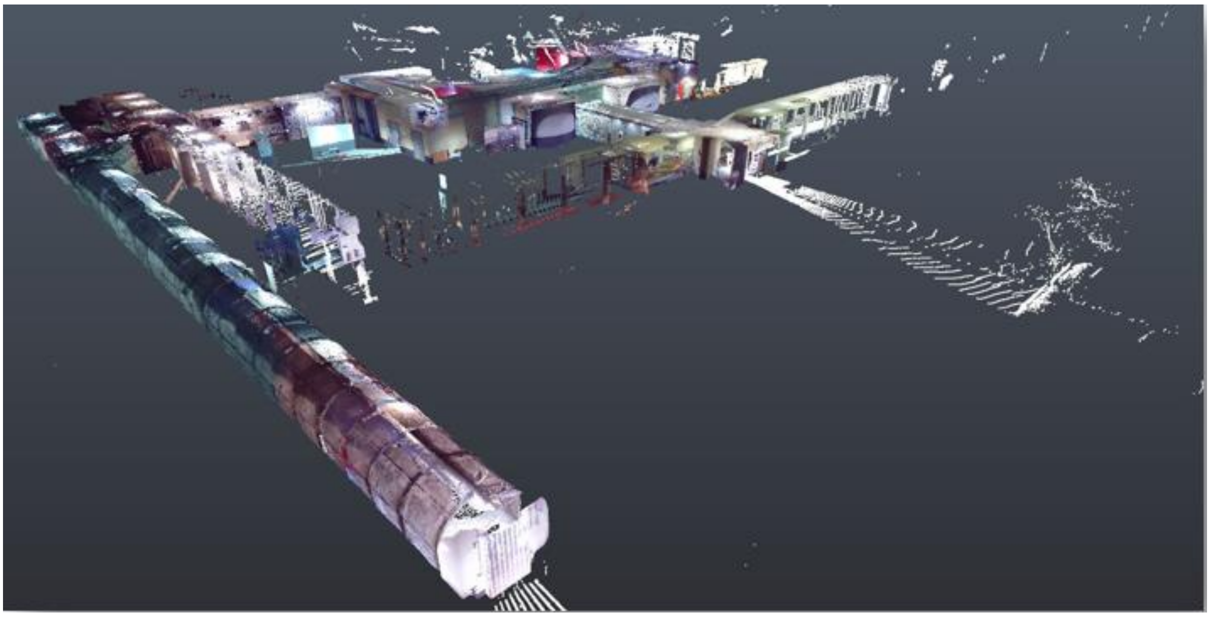


Figure 6.12: Showing Point Cloud Data View of the Chamber of Mines Building at the University of Witwatersrand.

6.6 Data Comparison Between the Trimble S6 RTS and the FARO Focus3D X130 Laser Scanner

The value of this research lies in the comparison that exists between the two measured values, that is, the difference between the values analysed is used to check if the laser scanner is performing according to the manufacturer specifications and is not generating inaccurate data. The aim of this research project was to find a way of comparing the surveyed coordinates to the 3D point cloud data from the laser scanner in order to examine the performance of the laser scanner. The observable difference from the comparisons indicates the laser scanner did not generate accurate point cloud data and also ascertains if the instrument is fit for the purpose. The comparisons between these two datasets were based on the coordinates derived from both the observed angle and range.

The data acquisition for both the Total Station survey and laser scanner measurement was done on the same day. The Total Station survey was done before collecting the 3D point cloud data by the static laser scanner. The true coordinates of all the targets in the scan area was analysed using Excel spreadsheets. Targets C6, C22, S1, S7 and S11 were not recorded as the centre points of the targets were not visible by the laser scanner. However, only ten (10) of these target coordinates were used for the final analysis. These represent the targets centre in the master point cloud data. From the Excel spreadsheet, calculations were done by comparing the targets centre coordinates with the true value (surveying coordinates). The coordinates of the targets from the true value were estimated from the horizontal distance, horizontal and vertical angles measured by the Robotic Total station. The difference between the master point cloud data and the true survey values is presented in Table 6.1.

6.7 Conclusion

This chapter has shown the use of statistical tools to analyse the performance of the terrestrial laser scanner, based on the comparison between the scanner and total station surveyed coordinates. From the results, a total number of forty (40) target points were placed in the laboratory, however, ten (10) target points were used to determine the level of accuracy of FARO Focus 3D X130 laser scanner. A standard deviation of 3mm and a root-mean-square error of 4mm for all the registered points in the scan area were obtained at a distance of 15m. From this result, it appears that the instrument produced an adequate point cloud data at a range of 15m. Hence, the instrument is fit for the purpose of monitoring underground rock engineering deformation analysis depending on the rockmass behaviour when the instrument is placed on a stationary beacon. The inaccuracy in the measurement might be as a result of irregularity in the size and shape of the selected facility and the target design in terms of orientations and placement. The orientations of the target must be perpendicular to the emitted laser beam and the instrument must be operated correctly.

After close analysis of the results, the following factors were highlighted as possible cause of outliers in the measurements:

- Non-visibility of targets, oblique sighting, and steep upward and downward inclination between targets and instruments;
- The laser scanner and Total Station instruments must be calibrated before measurement;
- The targets on the concrete wall are not perpendicular to the control beacon which resulted in oblique measurements;
- Poor targets design in terms of orientation during placement;
- Difficult scanning geometry between the scanner positions and the targets; and
- Irregularity in the shape and dimensions of the laboratory.

Chapter seven draws conclusions and gives recommendations based on the knowledge gained from this research. The acquired knowledge will assist in real-time mapping and monitoring rock mass movement for mine safety purposes.

CHAPTER SEVEN

7 Conclusion and Recommendations

The aim of this research was to establish a short-range laboratory which could be used for testing the accuracy of Terrestrial 3D laser scanners. The development of the testing facility was important as this would test the reliability and accuracy of 3D point clouds that are generated for real-time mapping, navigation, and rock mass monitoring in an underground mining environment. In order to develop this laboratory, some factors that deserve attention when setting up the testing laboratory were considered. These factors include the size and shape of the selected facility, the network geometry of survey control, target design and placement.

The established facility was able to generate a 3D point cloud data using a terrestrial laser scanner that was comparable to the surveyed observations so as to give an indication of the performance of the laser scanner. The result of the comparisons between the Total Station and Terrestrial Laser Scanner were analysed using statistical tools to test the accuracy of the FARO Focus3D X130 terrestrial laser scanning system. Another comparison was to establish if the laser scanner was performing according to the quoted manufacturer specifications when the result was compared with the manufacturer stated accuracy.

7.1 Findings of this Research

The following were the outcomes of this research;

- A short-range testing laboratory was established at the reception area of the WMI for testing the accuracy of Terrestrial Laser Scanners;
- Root-mean-square error (RMSE) of 4mm and a standard deviation of 3mm were obtained from the comparative difference between the measurements for individual points; and
- The manufacturer stated range error value of ±2mm could be achieved when the instrument was placed on a stationary beacon. Inaccuracies in the measurement are attributed to target design and orientation, instrument not calibrated before use, irregular shape of the laboratory, weak scanning geometry and the effect of human errors during measurements.

7.2 Conclusion

The established testing facility serves as an important feature in performing quality assurance (QA) task on the acquired 3D point cloud data. Quality assurance (QA) entails checking the discrepancies between the true and measured value to ensure that the equipment is performing to the specifications claimed in the manufacturer's manual. This has to be confirmed before embarking on the task at hand. The laboratory has shown that the instrument can handle the task at hand that is, fit for the purpose, for use based on the acquired 3D point cloud data.

The result of the comparison can be seen in Table 6.1 in previous chapter six of this report. The comparison shows the difference between the laser scanner value and the survey (true) value. Targets with obliqueness, non-visibility, and steep upward or downward inclination were considered as mistakes, as this can be eliminated from the dataset with better target design. Therefore, for this research, the targets that were considered as errors were removed from the dataset so as to avoid biased judgment on the performance of the laser scanner. It is important to have robust target design in terms of placement and orientation in order to prevent mistakes due to steep upward and downward inclination between the targets and the instruments. The arrangement of the targets in an almost vertical position below and above the instrument is significant as it assists to investigate the performance of the laser scanner in terms of its vertical measurements. The vertical measurement of targets in underground mining is important in order to identify continuous movement and change in the shape of the hangingwall and footwall.

The accuracy investigation was established using statistical analysis such as the standard deviation and RMSE to determine the overall performance of the laser scanner. In terms of the overall performance of the FARO Focus3D X130 laser scanner system, the instrument generated an accurate and high quality point cloud data in the short-range facility. The analysis was based on the statistical analysis of the comparative difference between the data with an average RMSE and standard deviation value of 4mm and 3mm respectively. This value represents the accuracy and precision of the laser scanner at a distance of ±15m. That is, the RMSE value represents the accuracy, while the standard deviation measures the precision of the laser scanner for all the targets in the laboratory. Therefore, the result generated by the FARO Focus3D X130 laser scanner is suitable for monitoring underground rock mass movement in mining depending on the elastic parameters of the rock mass, as different rock types have different elastic limits.

Another important application of point cloud data comparison in the mining environment is the extent to which the point cloud data can be compared to detect change over time. Numerous scans need to be performed with the space of time in order to establish rock movement and rock engineering deformation analysis over time. That is, the difference in scans shows instability of rock mass of the underground mining environment. The difference that exists between these measurements was used to detect any movement within the scan area captured by the laser scanner. Notably, this is vital in making decisions on mine evacuation when the resulting point cloud data comparisons show an early warning of rock mass movement. With such rock mass movement, this requires immediate mine evacuation to prevent loss of lives and damage of equipment. The change in point cloud data over time is very useful in making mine safety decisions and also identifying the risk-prone areas in an underground mine in order to maintain zero harm in a mining operation.

7.3 Recommendations for Future Research

This research has highlighted some key factors that deserve attention in establishing a short-range laboratory for testing the accuracy of terrestrial laser scanners. One of the major contributing factors that ensures accurate and reliable point cloud data are produced is the design of the target. This includes the placement, size and orientation of targets in the scan area. More work needs to be done on target design in order to prevent obliqueness and steep angle in measurements. Target such as sphere can also be used in order to improve scanning efficiency from various directions. The benefit of using sphere targets in a scanning task, is that, it can be viewed from different directions.

From the findings in this research report, the following recommendations are made for future research in order to produce reliable and quality point cloud data that will be used in establishing a short-range laboratory for testing the accuracy of terrestrial laser scanner:

- **Calibration**: The laser scanner and the total station must be subjected to calibration prior to measurements of targets in the laboratory. This is important so as to ensure reliability and trust in the results. For the total station, baseline calibration will be required, while the laser scanner can be calibrated using reference objects such as reference target or coated surface.

- **Target Design**: Robust target configurations need to be done in terms of placement and orientation when planning the laboratory. Care must be taken when placing targets in a vertical position during the design of the laboratory to prevent oblique sighting, steep upward and downward inclination of targets.
- **Scanning Geometry**: A good network design is essential in order to improve the accuracy in the measurement. Targets placed diagonally (tetrahedral shape) are more likely to have better accuracy in determining the centre of the targets. Other targets such as sphere can also be used in order to improve scanning efficiency from various directions.
- **Target Visibility:** Full targets must be visible from all the scan positions. If the target is not visible from these scan positions, then its coordinate must be excluded from the dataset.
- **Systematic and Atmospheric Corrections**: Systematic and atmospheric corrections must be applied correctly during scanning of the laboratory. The main effects of an atmospheric condition such as the air temperature, humidity, ambient light and turbulence in the air must be properly monitored so as to ensure that the temperature is kept constant throughout the scanning period. For precise work, it will be suggested to always record the atmospheric values due to some errors inherent by the instrument that can influence the measurements irrespective of the distance. Although, this might be different in underground mining environment as the atmospheric conditions are different from the surface.
- **Laser Scanner Field of View (FOV**): The laser scanner FOV for both vertical and horizontal should be checked before placing the targets and positioning of the control beacon as this will prevent targets not being captured from every setup. Targets placed outside the instrument field of view might not be captured and can also result in obliqueness in the measurement. One of the main challenges experience in this research was a poor sighting of targets in the ceiling (vertical observations).

This research has proven the accuracy of the FARO Focus3D X130 laser scanner. It confirmed that the instrument is fit for the purpose of monitoring rock mass movement in underground mining environments when placed on a stationary beacon at a short-range. For further research on laser scanner systems, accuracy investigation must be carried out on a moving platform, other types of laser scanners such as pulse-based and over longer distances.

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Appendix A Calculation of Control Beacon Coordinate from Leica TCR +1201 Total Station.

Table A1: Horizontal Angle Measurement Data from Leica Total Station

STATION	12TH SEPT, 2017	15TH SEPT, 2017	18TH SEPT, 2017	21ST SEPT, 2017	28TH SEPT, 2017
A9	-- -- --	-- -- --	-- -- --	-- -- --	-- -- --
T001	-- -- --	270^0 42'32"	270^0 42' 42"	270^0 42' 16''	-- -- --
T002	223^0 20' 44''	223^0 22'34"	223^0 22' 08"	223^0 20' 53''	223^0 21' 42"
BEACON	237^0 28' 50"	237^0 28' 45"	237^0 30' 00"	237^0 29' 32"	237^0 29' 28"
T003	80^0 32' 14"	80^0 32' 02"	80^0 32' 34"	80^0 31' 58"	-- -- --
T004	261^0 24' 32"	261^0 24' 57"	261^0 25' 24"	261^0 24' 52"	-- -- --
B3	-- -- --	216^0 07' 00"	216^0 06' 38"	216^0 07' 10"	216^0 07' 42"
B21	241^0 23' 44"	241^0 24' 28"	241^0 23' 43"	241^0 24' 24''	-- -- --
A1	216^0 29' 01''	216^0 28' 56"	216^0 28' 42"	216^0 28' 56'	-- -- --
A9	232^0 28' 38"	232^0 28' 47"	232^0 28 31"	232^0 28' 58"	232^0 28' 39"

Table A2: Calculation of Direction from the Measured Horizontal Angle

STATION	CLOCKWISE ANGLES	INTERNAL ANGLES	ADJUSTED INT. ANGLES	ADJUSTED EXT. ANGLES	DIRECTION
A9	-- -- --	-- -- --	-- -- --	-- -- --	081^0 20' 50"
T001	270^0 42'30"	89^0 17' 30"	89^0 17' 25.8"	270^0 42'34.2"	352^0 03' 24.2"
T002	223^0 21'36"	136^0 38' 24"	136^0 38' 19.8"	223^0 21'40.2"	035^0 25' 04.4"
BEACON	237^0 29'19"	122^0 30'41"	122^0 30' 36.8"	237^0 29'21.2"	92^0 54' 27.6"
T003	80^0 32' 12"	279^0 27' 48"	279^0 27' 43.8"	80^0 32' 16.2"	353^0 26' 43.8"
T004	261^0 24'56"	98^0 35' 04"	98^0 34' 59.8"	261^0 25'00.2"	074^0 51' 44"
B3	216^0 07'08"	143^0 52' 52"	143^0 52' 47.8"	216^0 07'12.2"	110^0 58' 56.2"
B21	241^0 24'04"	118^0 35'56"	118^0 35' 51.8"	241^0 24'08.2"	172^0 23' 04.4"
A1	216^0 28'54"	143^0 31' 06"	143^0 31'1.8"	216^0 28'58.2"	208^0 52' 02.6"
A9	232^0 28'42"	127^0 31' 17"	127^0 31' 12.8"	232^0 28'47.2"	261^0 20' 49.8"
		1260^0 00' 38"	**1260^0 00' 00.2'**		

Figure A1: Setting up of Instrument on Control Beacon Coordinate

Figure A2: Survey of the Control Beacon with Leica Total Station

Figure A3: Survey of the Control Beacon from an existing Control points.

Table A3: Adjusted Horizontal Angles Measurement using Leica TCR +1201 Total Station

STATION	12TH SEPT, 2017	15TH SEPT, 2017	18H SEPT,2017	21ST SEPT, 2017	28TH SEPT, 2017	CLOCKWISE ANGLES	INTERNAL ANGLES	ADJUSTED INTERNAL ANGLES	ADJUSTED EXTERNAL ANGLES
A9	-- -- --	270^0 42’32”	270^0 42’ 42”	270^0 42’ 16’’	-- -- --	270^0 42’30”	89^0 17’ 30”	89^0 17’ 25.8”	270^0 42’34.2”
T001	223^0 20’ 44’’	223^0 22’34”	223^0 22’ 08”	223^0 20’ 53’’	223^0 21’ 42”	223^0 21’36”	136^0 38’ 24”	136^0 38’ 19.8”	223^0 21’40.2”
T002	237^0 28’ 50”	237^0 28’ 45”	237^0 30’ 00”	237^0 29’ 32”	237^0 29’ 28”	237^0 29’19”	122^0 30’41”	122^0 30’ 36.8”	237^0 29’21.2”
BEACON	80^0 32’ 14”	80^0 32’ 02”	80^0 32’ 34”	80^0 31’ 58”	-- -- --	80^0 32’ 12”	279^0 27’ 48”	279^0 27’ 43.8”	80^0 32’ 16.2”
T003	261^0 24’ 32”	261^0 24’ 57”	261^0 25’ 24”	261^0 24’ 52”	-- -- --	261^0 24’56”	98^0 35’ 04”	98^0 34’ 59.8”	261^0 25’00.2”
T004	-- -- --	216^0 07’ 00”	216^0 06’ 38”	216^0 07’ 10”	216^0 07’ 42”	216^0 07’08”	143^0 52’ 52”	143^0 52’ 47.8”	216^0 07’12.2”
B3	241^0 23’ 44”	241^0 24’ 28”	241^0 23’ 43”	241^0 24’ 24’’	-- -- --	241^0 24’04”	118^0 35’56”	118^0 35’ 51.8”	241^0 24’08.2”
B21	216^0 29’ 01’’	216^0 28’ 56”	216^0 28’ 42”	216^0 28’ 56’	-- -- --	216^0 28’54”	143^0 31’ 06”	143^0 31’1.8”	216^0 28’58.2”
A1	232^0 28’ 38”	232^0 28’ 47”	232^0 28 31”	232^0 28’ 58”	232^0 28’ 39”	232^0 28’42”	127^0 31’ 17”	127^0 31’ 12.8”	232^0 28’47.2”
TOTAL							**1260^0 00’ 38”**	**1260^0 00’ 00.2’**	

Table A4: Results of Measured Distance using Leica TCR +1201 Total Station

STATION	BS & FS	12TH SEPT, 2017	15TH SEPT, 2017	18H SEPT, 2017	21ST SEPT, 2017	28TH SEPT, 2017	MEAN DISTANCES
A9	A1		20.441	20.440	20.439		20.440
	T001	38.164	38.168	38.169	38.169		38.168
T001	A9	38.168	38.166	38.169	38.169	38.167	38.168
	T002	7.058	7.062	7.061	7.061	7.061	7.061
T002	T001	7.062	7.060	7.061	7.060	7.061	7.061
	WMI	11.237	11.237	11.237	11.237	11.237	11.237
BEACON	T002	11.238	11.237	11.237	11.239		11.238
	T003	10.887	10.883	10.882	10.882		10.884
T003	WMI	10.882	10.882	10.882	10.881		10.882
	T004	13.035	13.034	13.032	13.033	13.034	13.034
T004	T003	13.033	13.033	13.033	13.033	13.701	13.033
	B3	13.698	13.698	13.700	13.700	13.701	13.700
B3	T004	13.702	13.699	13.698	13.699		13.700
	B21	19.402	19.404	19.404	19.405		19.404
B21	B3	19.403	19.403	19.403	19.403		19.403
	A1	34.243	34.243	34.240	34.243		34.242
A1	B21	34.241	34.241	34.240	34.242	34.240	34.241
	A9	20.441	20.442	20.442	20.441	20.442	20.442

Table A5: Calculation of Coordinates

DIRECTIONS	JOIN DIRECTION	MEAN DISTANCE	DY	DX	COORDINATE Y	COORDINATE X
A9 - A1	081^0 20’ 50”	20.440			97262.063	2898377.089
A9 - T001	352^0 03’ 24.2”	38.168	-5.278	37.802	97256.785	2898414.891
T001- A9	172^0 03’ 24.2”	38.168	5.275	-37.802		
T001- T002	035^0 25’ 04.4”	7.061	4.092	5.754	97260.877	2898420.645
T002- T001	215^0 25’ 04.4”	7.061	-4.092	-5.754		
T002- WMI	92^0 54’ 27.6”	11.237	11.223	-0.570	97272.1	2898420.075
BEACON - T002	272^0 54’ 27.6”	11.238	-11.224	0.570		
BEACON - T003	353^0 26’ 43.8”	10.884	-1.242	10.813	97270.858	2898430.888
T003- WMI	173^0 26’ 43.8”	10.882	1.242	-10.811		
T003- T004	074^0 51’ 44”	13.034	12.582	3.404	97283.44	2898434.292
T004- T003	254^0 51’ 44”	13.033	-12.581	-3.404		
T004- B3	110^0 58’ 56.2”	13.700	12.792	-4.906	97296.232	2898429.386
B3 - T004	290^0 58’ 56.2”	13.700	-12.792	4.906		
B3 - B21	172^0 23’ 04.4”	19.404	2.572	-19.233	97298.804	2898410.153
B21 - B3	352^0 23’ 04.4”	19.403	-2.571	19.232		
B21 - A1	208^0 52’ 02.6”	34.242	-16.531	-29.987	97282.273	2898380.166
A1 - B21	028^0 52’ 02.6”	34.241	16.531	29.986		
A1 - A9	261^0 20’ 49.8”	20.442	-20.209	-3.076	97262.064	2898377.09

Table A6: Coordinate of Control Points

STATION	INTERNAL ANGLES	ADJUSTED INTERNAL ANGLES	ADJUSTED EXTERNAL ANGLES	DIRECTION	MEAN DIST.	DY	DX	Y COORD	X COORD	Z COORD
A1								97282.276	2898380.165	1758.7350
A9	-- -- --	-- -- --	-- -- --	081^0 20’ 50”				97262.063	2898377.089	1759.2363
T001	89^0 17’ 30”	89^0 17’ 25.8”	270^0 42’34.2”	352^0 03’ 24.2”	38.168	-5.278	37.802	97256.785	2898414.891	1760.8756
T002	136^0 38’ 24”	136^0 38’ 19.8”	223^0 21’40.2”	035^0 25’ 04.4”	7.061	4.092	5.754	97260.877	2898420.645	1760.8829
BEACON	122^0 30’41”	122^0 30’ 36.8”	237^0 29’21.2”	92^0 54’ 27.6”	11.237	11.223	-0.570	97272.100	2898420.075	1762.0062
T003	279^0 27’ 48”	279^0 27’ 43.8”	80^0 32’ 16.2”	353^0 26’ 43.8”	10.884	-1.242	10.813	97270.858	2898430.888	1760.8805
T004	98^0 35’ 04”	98^0 34’ 59.8”	261^0 25’00.2”	074^0 51’ 44”	13.034	12.582	3.404	97283.440	2898434.292	1760.8838
B3	143^0 52’ 52”	143^0 52’ 47.8”	216^0 07’12.2”	110^0 58’ 56.2”	13.700	12.792	-4.906	97296.232	2898429.386	1761.6711
B21	118^0 35’56”	118^0 35’ 51.8”	241^0 24’08.2”	172^0 23’ 04.4”	19.404	2.572	-19.233	97298.804	2898410.153	1760.4144
A1	143^0 31’ 06”	143^0 31’1.8”	216^0 28’58.2”	208^0 52’ 02.6”	34.242	-16.531	-29.987	97282.273	2898380.166	1758.7347
A9	127^0 31’ 17”	127^0 31’ 12.8”	232^0 28’47.2”	261^0 20’ 49.8”	20.442	-20.209	-3.076	97262.064	2898377.090	
	1260^0 00’ 38”	**1260^0 00’ 00.2’**								

Appendix B Levelling of the Control Beacon at WMI

LEVELLING BOOKING SHEET

Instrument No: Leica NA 320 **Observer: Peter Kolapo**

Weather: Moderate (23^0 C) **Booker: Qin Changbiao**

Job: WMI Laser Scanning Laboratory **Date: 10^{th} October, 2017.**

Table B1: Showing Levelling Result

POINT	B.S	I.S	F.S	Rise	Fall	Reduced Level	Adjustment	Final Elevation	Remarks
A1	1.561					1758.7350		1758.7350	**Control Point**
A9	2.972		1.060	0.501		1759.2360	+0.0003	1759.2363	**Control Point**
T001	1.312		1.333	1.639		1760.8750	+0.0007	1760.8757	**T001**
T002	1.338		1.305	0.007		1760.8820	+0.0009	1760.8829	**T001**
BEACON	0.242		0.215	1.123		1762.0050	+0.0010	1762.0060	**WMI**
T003	1.384		1.368		1.126	1760.8790	+0.0015	1760.8805	**T003**
T004	1.780		1.381	0.003		1760.8820	+0.0020	1760.8840	**T004**
B3	0.757		0.987	0.793		1761.6750	+0.0021	1761.6771	**Control Point**
B21	1.205		2.020		1.263	1760.4120	+0.0024	1760.4144	**Control Point**
A1			2.885		1.680	1758.7320	+0.0030	1758.7350	**Control Point**
Checks	+12.551		-12.554	+4.066	-4.069				
		-0.003		-0.003					

$\sum BS - \sum FS = \sum Rises - \sum Falls$ = Last Initial RL – First RL

Figure B1: Levelling of the Control Beacon

Appendix C Construction of the Control Beacon

Figure C1: Construction of a Control Beacon

Appendix D Coordinates from the Terrestrial Laser Scanner and Robotic Total Station

Table D1: FARO Focus XD Laser Scanning Coordinates

POINTS	Y (m)	X (m)	Z (m)
C1	97265.583	2898417.146	1764.192
C2	97267.200	2898417.356	1764.205
C3	97269.611	2898417.673	1764.204
C4	97269.609	2898417.679	1762.605
C5	97269.607	2898417.683	1760.990
C7	97269.780	2898416.999	1762.602
C8	97269.809	2898417.014	1760.995
C9	97269.810	2898415.828	1764.192
C10	97269.952	2898415.627	1764.184
C11	97270.938	2898415.894	1763.789
C12	97272.915	2898418.437	1764.186
C13	97273.057	2898418.743	1761.183
C14	97273.022	2898420.427	1763.191
C15	97272.785	2898423.573	1764.791
C16	97272.354	2898422.340	1762.992
C17	97272.526	2898423.858	1761.393
C18	97272.320	2898425.920	1764.798
C19	97272.034	2898424.764	1763.586
C20	97272.190	2898427.379	1762.993
C21	97271.837	2898416.984	1763.766
C23	97264.982	2898418.366	1764.005
C24	97248.069	2898420.945	1764.914
C25	97268.321	2898421.787	1763.235
C26	97268.201	2898421.133	1760.996
C27	97268.292	2898429.597	1763.518
R1	97240.692	2898426.848	1765.166
R2	97270.910	2898423.731	1765.167
R3	97269.969	2898422.387	1765.163
R4	97271.510	2898418.912	1765.159
R5	97271.624	2898418.818	1765.161
S2	97267.196	2898418.168	1763.064
S3	97264.919	2898417.847	1761.010
S4	97264.956	2898422.876	1764.733
S5	97268.549	2898424.022	1763.036
S6	97269.092	2898422.860	1761.337
S8	97268.551	2898425.398	1764.560
S9	97269.596	2898426.590	1763.077
S10	97269.910	2898427.897	1764.573
S12	97270.132	2898429.794	1763.224
S13	97270.440	2898429.790	1761.039

Table D2: Trimble S6 Robotic Total Station Survey (True) Coordinate

POINTS	Y (m)	X (m)	Z (m)
C1	97265.586	2898417.142	1764.191
C2	97267.198	2898417.352	1764.207
C3	97269.603	2898417.662	1764.209
C4	97269.605	2898417.671	1762.607
C5	97269.604	2898417.675	1760.994
C7	97269.800	2898416.984	1762.600
C8	97269.801	2898417.005	1760.991
C9	97269.945	2898415.806	1764.194
C10	97270.930	2898415.615	1764.188
C11	97272.909	2898415.880	1763.790
C12	97273.055	2898418.425	1764.185
C13	97273.011	2898418.751	1761.183
C14	97272.781	2898420.425	1763.185
C15	97272.353	2898423.562	1764.789
C16	97272.524	2898422.333	1762.989
C17	97272.314	2898423.853	1761.395
C18	97272.030	2898425.914	1764.789
C19	97272.195	2898424.753	1763.587
C20	97271.843	2898427.375	1762.992
C21	97264.976	2898416.975	1763.768
C23	97248.071	2898418.363	1764.003
C24	97268.311	2898420.938	1764.917
C25	97268.196	2898421.781	1763.238
C26	97268.294	2898421.123	1760.999
C27	97240.692	2898429.603	1763.515
R1	97270.909	2898426.826	1765.157
R2	97269.975	2898423.717	1765.163
R3	97271.510	2898422.380	1765.168
R4	97271.625	2898418.915	1765.151
R5	97267.201	2898418.813	1765.155
S2	97264.912	2898418.160	1763.064
S3	97264.951	2898417.839	1761.010
S4	97268.548	2898422.871	1764.736
S5	97269.092	2898424.013	1763.036
S6	97268.540	2898422.854	1761.338
S8	97269.597	2898425.387	1764.559
S9	97269.911	2898426.575	1763.074
S10	97270.131	2898427.891	1764.569
S12	97270.442	2898429.787	1763.222
S13	97270.373	2898429.780	1761.036

Appendix E Images showing Full Scan Area of the Laboratory

Figure E1: Panoramic View of the Scanning Laboratory with full Colour Image

Figure E2: Preview of Scanned Surrounding from the TLS Mounted on Control Beacon

Appendix F Map showing location of the scanning laboratory

Figure F1: Map Showing the General Location (WMI) of the Short-Range Laser Scanning Testing Facility (Google Map)