Evaluation of Laser Scanning Technology for Bridge Inspection

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DEDICATIONS

To my parents, who have always encouraged and supported me through all of life's endeavors. Without them I would have never made it this far.

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ABSTRACT

Evaluation of Laser Scanning Technology for Bridge Inspection

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Anu Pradhan, Ph.D.

In United States, there are almost 600,000 highway bridges. The average life time of these bridges is about 70 years. When bridges reach their mid-life, some damages on structures may occur. The prospective causalities for unproductive bridge inspection can cause serious problems. The main purpose of the bridge inspection is to satisfy the public safety in bridge structural capacity and to protect the public investment. All these emphasize the importance of the accurate and reliable geometric information of the bridges. Geometric data, such as maximum span and minimum vertical clearance are the main parameters of bridge inspection process. All these challenges highlight the importance of terrestrial laser scanner for bridge inspection. Laser scanner is a reliable technology for geometric data collection. Although laser scanners enable surveyors to acquire the data in shorter time, data accuracy should be investigated. The main objectives of proposed study are to investigate and evaluate the accuracy of laser scanners for bridge inspection and to determine the reliability of laser scanners data.

The objective of the proposed study was to investigate laser scanner data reliability on bridge inspection projects. Based on laser scanner data, specific bridge component dimensions have been measured and a 3D model of the bridge was created.

On the field, the laser scanner was set up on four different locations and captured the bridge substructures data. The office work consisted of registering different point clouds from individual scans together into a single coordinate system. By using registered point cloud, a 3D model of the bridge was created. Afterwards, dimensions of substructure components of the bridge were measured and compared with design drawing data. As a result, error ratio of the compared results is mostly under 1% aside from some irregular conditions at the edges. Comparisons showed that the scanned data is reliable in terms of accuracy. Also data acquisition is faster and data density is much higher than other surveying methods.

CHAPTER 1: INTRODUCTION

1.1 Problem Statement

In the United States, there are almost 600,000 highway bridges (Ref. National Bridge Inventory). The average life time of these bridges is about 70 years since most of the bridges were built around 1945. When bridges reach their mid-life, some damages on structures may occur. Those damages could be corrosion, cracking and other types of damages. All these external effects can reduce bridge's load carrying capacity. Thus, all bridge members are inspected periodically.

The prospective casualties for unproductive bridge inspection can cause serious problems, such as closure or collapse of a bridge. The collapse of bridges rarely occurs but the consequences are dramatic. The collapse of the Silver Bridge in 1967 and the collapse of I-35W Mississippi River Bridge in 2007 are some examples that had dramatic consequences. In 1996, National Bridge Inventory (NBI) indicated that 182,407 bridges out of 589,243 on American Highways are not meeting the minimum requirements, and this number is increasing by 10,000 every year. However, funding to maintain and extend the life time of the bridges are limited and insufficient (Prader 2007).

The main purpose of the bridge inspection is to satisfy the public safety in bridge structural capacity and to protect the public investment. The NBI explains the bridge inspection parameters with different record indicated below;

- Identification
- Structure Type and Material
- Age and Service
- Geometric Information
- Navigation Data
- Classification
- Condition
- Load Rating and Posting
- Appraisal
- Proposed Improvements

(Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges, FHWA, 1995)

All these above parameters emphasize the importance of the accurate and reliable geometric information of the bridges. Geometric data, such as maximum span, and minimum vertical clearance over bridge roadway are the main parameters of bridge inspection process. At present, such geometric data is acquired through visual inspection which often fails to provide reliable and accurate data.

All these challenges highlight the importance of terrestrial laser scanner for bridge inspection. Laser scanner is a reliable technology for geometric data collection. The advantages of the laser scanner over visual inspection are high accuracy, construing the 3D data easily, saving time and integrating the data with existing asset management system. Currently structural engineers and land surveyors use the laser scanners to acquire the geometric data and generate the 3D models of bridges.

The main objectives of the proposed study are: (a) to investigate and evaluate the accuracy of terrestrial laser scanners for bridge inspection and (b) to determine the reliability of laser scanners data.

1.2 Background Research

Surveying is the technique and science of determining the three-dimensional position of points, distance and angle between them. These points are usually on the surface of the Earth. American Congress on Surveying and Mapping (ACSM) defined surveying as "the science and art of making all essential measurements to determine the relative position of points and/or physical and cultural details above, on or beneath the surface of Earth, and to depict them in a usable form, or to establish the position of points and/or details". Also ACSM defined "land surveying" as "the detailed study or inspection, as by gathering information through observations, measurements in the field, questionnaires or research of legal instruments and data analysis in the support of planning, designing and establishing of property boundaries." Surveying is used for mapping, construction surveys, precision measurements of length, angle, elevation, between two locations or points, area estimation, last but not least horizontal and vertical control surveys.

Surveying, is the one of the most important aspect of design and construction process. It basically includes performing the boundary surveys, mapping the topography of land for engineering design, establishing the elevations of home sites for flood insurance. It can also be used in certifying the built of structures according to design, laying out buildings and subdivisions on construction process. Surveying is needed from initial concept to design and construction, to monitoring the condition and performance of constructed structure.

1.2.1 Previous Techniques

Theodolite, set on a tripod, is used to measure the distance and angles (i.e., horizontal and vertical angles) of the unknown point with respect to a known location and elevation (Figure 1.1). Theodolite is used as a surveying device. It has been adapted for other particularized purposes in other fields, such as methodology and rocket launch technology.

Figure 1.1: One of the oldest theodolites (Source: novalynx.com)

Total station is another electronic distance measurement device which is more advanced than theodolite by integrating theodolite functions with an EDM (electronic distance meter) (Figure 1.2). The primary function of a total station is mapping and surveying. Total station measures the distance with the help of reflected infrared light beam (emitted by total station) t from the prism back to the total station. By measuring the time it takes for the light to return, the total station calculates the distance between the prism and total station. All of the information gathered with the total station can be stored in an external computer where data can be manipulated and added to CAD programs. The modern total stations can even email point data to the computers and connect to satellite positioning system, such as Global Positioning System (GPS).

Figure 1.2: Trimble S6 Total Station (Mensi.com)

GPS is a device which is used for precise positioning of points (Figure 1.3). The GPS data points are accurate within a few millimeters. GPS systems have improved the speed of surveying rapidly, and the accuracy is about 20 mm horizontally and 30-40 mm vertically.

Figure 1.3: A Figure of Surveying GPS (bsurveying.com)

1.2.2 Terrestrial Laser Scanning

3D laser scanner is a new data acquisition system used in surveying and geographic data collection (Figure 1.4). 3D laser scanner (aka terrestrial laser scanners) can be used to acquire 3D information of objects or real scene. It has become one of the most accurate and the fastest data acquisition techniques compared to existing surveying techniques, such as theodolite, total station (Chen et. al. 2005). The application of laser scanner can be found in multiple domains, such as archeology, architecture, aviation, meteorology, defense, surveying and construction (Lichti et al. 2006).

LIDAR is an optical remote sensing technology which measures properties of scattered light to find range and other information of a distant target. It is similar to radar technology, but in LIDAR, the range of an object is measured by the time delay between transmitted and reflected signals. Since laser has shorter wavelengths (10 micrometers), it is possible to image a feature or object up to the wavelength of the laser. Thus, for large objects, laser scanner can acquire detailed and high resolution image due to its shorter wavelength. The LIDAR systems are used in civil/structural engineering field to produce a 3D model of interested object. There are primarily two steps involved in creating 3D model from laser scanned data: (a) scan registration, and (b) scan merging. Multiple scans (i.e., dense collection of points) are required to represent an entire object (e.g., bridge) since it is often challenging to acquire 3D view of an entire object from one scan location. To create a 3D model of the scanned object, such multiple scans need to be stitched together based on a common coordinate system. Thus, each scan will be registered under one common coordinate system. Such process is called scan registration. After the registration step, multiple scans are combined together to create a 3D model based on either semi-automatic or automatic algorithms. Such process is called scan merging.

Figure 1.4: Leica Scanstation 2 terrestrial laser scanner (slcassociates.co.uk)

3D laser scanners create a 3D coordinate system by sending and receiving the laser pulses. The origin of the system is the position of the laser scanner and every point in the coordinate system has its own $\boldsymbol{X_i}$, $\boldsymbol{Y_i}$, $\boldsymbol{Z_i}$ components. Having known the distance between the laser scanner and a point on the surface of the object (L) and vertical and horizontal angles $\boldsymbol{\theta}$ and $\boldsymbol{\varphi}$ respectively, we can calculate the coordinates of a point in a 3D coordinate system shown in the formula;

$$Y_i = L \cdot \sin \phi$$
$$X_i = L \cdot \cos \phi \cdot \sin \theta$$
$$Z_i = L \cdot \cos \phi \cdot \cos \theta$$

$$\begin{bmatrix} L \\ \theta \\ \phi \end{bmatrix} = \begin{bmatrix} \sqrt{X_i^2 + Y_i^2 + Z_i^2} \\ \tan^{-1}(\frac{Y_i}{X_i}) \\ \tan^{-1} = (\frac{Z_i}{\sqrt{X_i^2 + Y_i^2}}) \end{bmatrix}$$

Equation : 1.1 (Soudarissanane et al. 2009)

All of these technologies aid land surveyors and civil engineers with determining the location, the distance and angles between three-dimensional points. During the past several years, through the development of the technology, many improvements in surveying systems in junction with terrestrial laser scanning have been made.

Terrestrial laser scanning provides faster methods of obtaining measurements, and during the process, the deployment of targets on to the object are necessary. In general, 3D laser scanning is suitable for obtaining the surveying data, inspecting the infrastructures, detecting the deformations, and it has many other pertinent applications. However, regarding the accuracy level of each application, other measurement methods are dispensable.

As mentioned earlier, 3D laser scanners provide highly accurate, three-dimensional imaging. These features enable designers to experience and work directly with real-world conditions by viewing and controlling deviously rich point clouds in computer aided softwares. Technically, laser scanners provide high point density data. And also they ensure a complete topographic survey. They give oversampling to guarantee accuracy and that all objects, structures, geometry are captured. Because high speed of data capture, laser scanners reduce time consuming and cost of the project. They increase efficiency and safety of surveyors.

Although laser scanners enable surveyors to acquire the data in shorter time, data accuracy should be investigated. One of the goals of this paper is to focus the application areas of laser scanners in a real-life project and to inspect the accuracy assessments.

1.3 Technical Challenges of 3D Laser Scanners

Although 3D laser scanners can measure the distance to the object surfaces with accuracy with a few millimeters at ranges up to hundreds of meters, the orientation of object with respect to the position of a scanner can affect the quality of results of single points in cloud data. Due to environmental conditions, an ideal set-up is practically impossible. These similar reasons influence the range accuracy.

The major factors that affect the accuracy of the final results are relative object surface orientation and the local point cloud density. There are four major factors which influence the quality of the point cloud. These are;

- Instrument Calibration
- Atmospheric Conditions
- Object Properties
- Environmental Conditions

1.3.1 Incidence angle

Incidence angle is defined as the angle between the laser beam and the normal of the considered surface (Figure 1.5). It is known that the object surface orientation influences the quality of the point cloud data. (Soudarissanane et al. 2008) It is generally known the lower the incidence angle, the higher the accuracy of the range distance measurement.

Practically, it is difficult to scan the surface with 0 degree of incidence angle due to on-site conditions. Higher incidence angle can dramatically influence the data accuracy. The footprint of the laser beam is circular. If the incidence angle is 0 degree, laser scanner beam is perpendicular to the surface object. It is desired to have the laser beam footprint circular. If the laser beam is not hitting the surface of an object perpendicularly due to higher incidence angle, the laser beam footprint is more elliptical in shape. The change of the footprint of the laser beam affects the data accuracy.

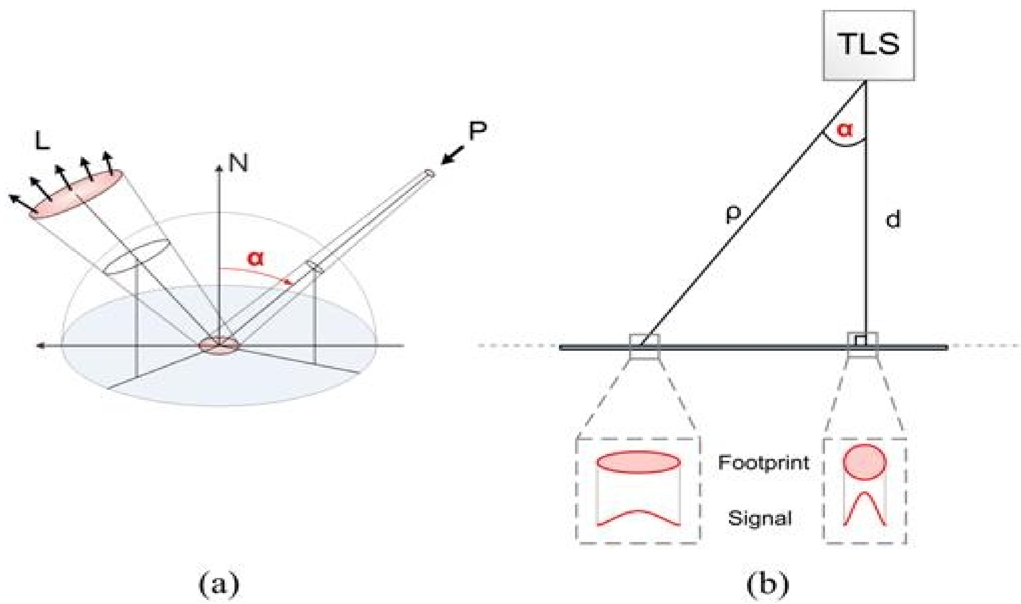

Figure 1.5: Incidence angle (Soudarissanane et al. 2009)

1.3.2 Range Accuracy

Another problem which civil engineers face during the 3D laser scanning process is range accuracy. Larger the distance between the scanner and scanned object affects the quality of data. The spot size influences the range accuracy. Generally, larger laser spot size can cause less accurate measurements. Laser beam width increases with increasing distance. An emitted laser beam expands in radius *w*, from a minimum called the beam waist, w_o, according to Weichel, a laser beam width can be expressed as;

$$w(\rho w) = w_o \sqrt{1 + \left(\frac{\lambda \rho_w}{\pi w_o^2} \right)^2}$$

Equation: 1.2 (Weichel et. al. 1990)

where ρ_w is range relative to the beam waist location. In this paper, we focus on data accuracy obtained by terrestrial laser scanners, mainly related to incidence angle and distance.

CHAPTER 2: PREVIOUS APPROACHES ON TERRESTRIAL LASER SCANNERS

2.1. Classification of Laser Scanners

Terrestrial laser scanning is a new and efficient method for surveying tasks, which allows acquiring the complex geometric data of objects. The laser scanners open up a new industry with data capturing in civil engineering surveying systems. Different industrial sectors demand precise data of the environment in order to be able to have an as-build documentation of the facility. Every facility needs different types of laser scanners for data capturing. In contrast to previous surveying instruments such as theodolite or total stations, terrestrial laser scanners are well specified regarding accuracy and resolution.

Classification of terrestrial laser scanners varies based on a few categories. There are several different categories to classify the laser scanners regarding range measurement systems, deflection units, imagining system, geometric quality and software systems.

2.1.1. Range Measurement Systems

There are a number of ways to gain 3D data of the environment. Terrestrial laser scanners can be categorized by the principle of the range measurement systems. The range measurement system corresponds to range accuracy of the system. Range measuring methods can be divided into three major principles.

2.1.1.1. Time of Flight Principle

The most common range measurement system used by laser scanners, also used by total stations in a different form, is the time of flight principle. In this method, laser scanners measure the travel time of the laser beam. An internal stopwatch counts the time of flight of the laser beam while it is emitted, reflected from the object surface and received back. This technique lets high precise measurements of distances up to several hundred of meters.

2.1.1.2. Phase Measurement Principle

Another common range measurement method is the phase measurement principle. In this method the phase shift, between the send and the received signal with a certain wavelength, is measured. The maximum range which can be measured by a certain modulation is half of the modulation wavelength. Laser scanners which use this measurement system, scan the concerned object faster than the scanners which employ the time of flight principle. However, the range is restricted to one hundred meters. Also, point clouds are noisier than those that were acquired by the laser scanners that use the time of flight principles. Accuracy may differ up to several millimeters, amongst the different range measurements.

2.1.1.3. Triangulation Method

Another method of range measurement is the optical triangulation method. There are three components in the triangulation method. These are the laser dot, the camera and the laser emitter. This technique is called “triangulation” because these three components' locations form a triangle. The distance between the camera and the laser emitter is known, the angle of the laser emitter corner is also known. The other angles can be determined by looking at the location of the laser point in the camera view. Thus, these components can fully determine the shape and the size of the triangle. Laser scanners which use triangulation method are more for the use in industrial applications and online monitoring in construction processes. The range of such laser scanners is limited by a few meters.

Classification by technical properties is more useful as shown possibilities and the performance of the each system. Table 2.1 shows the classification of laser scanners based on range measurement principle. As we can see from the table, time of flight principle lets the surveyors measure the area of field with the range up to 1000 meters,. Optical triangulation principle gives the most accurate results among these three but the range is limited by just a few meters.

Table 2.1 : Classification of Laser Scanners based on Measurement Principles (Frohlich et al. 2004)

<table>
<tr><th>Measurement Technology</th><th>Range (m)</th><th>Accuracy (mm)</th><th>Manufacturers</th></tr>
<tr><td rowspan="2">Time of flight</td><td>< 300</td><td>< 10</td><td>Leica, Mensi, Optech, Rieghl</td></tr>
<tr><td>< 1000</td><td>< 20</td><td>Optech, Rieghl</td></tr>
<tr><td>Phase measurement</td><td>< 100</td><td>< 10</td><td>IQSun, Leica, Z+F</td></tr>
<tr><td>Optical triangulation</td><td>< 5</td><td>< 1</td><td>Mensi, Minolta</td></tr>
</table>

2.1.2 System Components of Laser Scanners

The range measurement system of terrestrial laser scanners is a combination of a deflection and direction of a laser beam. First, a laser scanner emits a laser beam and receives the reflected laser beam. The intensity of the reflected laser light directly affects the accuracy of distance measurements. The reflectivity depends on the surface properties and the incidence angle.

For the last few years, specific procedures for calibration of laser scanners were developed to increase the accuracy of the measurements. Different measurement systems are used in the industrial fields which are mainly based on an active measuring principle for a precise, long-range, and fast 3D surveying.

Rieghl and Optech laser scanning systems employ the time of flight principle. The accuracy of these systems is in the centimeter area. However, the field area of these two systems are limited by 360^o horizontally and 60^o vertically. The Rieghl system also offers a colorful scanning area obtained by a combination with a color camera. So, unlike the point clouds acquired by different scanning systems, the point clouds scanned by Rieghl are colorful. However the duration of the scanning process is too long for the measuring of the complete field of view.

The systems of Trimble and Leica also use the time of flight principle and they are suitable for long distances. In addition to this, these systems have a large field of view, they can reach up to 360^o horizontally and 310^o vertically. A disadvantage of these systems, when scanning a field of 360^ox270^o with a high point density, these systems unacceptably needs at least couple hours to capture the entire field for one scan. Since time of flight systems have a maximum measuring rate of 20 kHz, these results in a long surveying period for a large environment scan. Surveyors can pick the scan area by using Cyclone software produced by Leica Geosystems to avoid time consuming.

Scanners which use the phase measurement principle offer high sampling rates and they are a good solution for capturing the scanning area with high speed. These laser scanners are very useful for applications which require data capture of moving platforms such as trains, cars etc. There are several phase difference scanner manufacturers like IQSun, Z+F, and VisImage. These scanners are based on the AMCW principle. Generally, the advantage of AMCW scanning systems is very high speed measuring. Some scanners like Z+F Image 5003 can receive 625,000 points per second. However, AMCW principle can cause edge loss and noisy point clouds.

2.1.3 Beam Deflection Units

There are two beam deflection principles that are employed by laser scanners for capturing the data. These are profiling systems and imaging systems.

2.1.3.1 Profiling System

The laser beam of the scanner is reflected by a mirror. This allows the optical axis of the laser measurement system to reach a 360^{o} profile measurement. The laser measurement system of the scanners determines each data points, which are a part of a 360^{o} profile. The deflection mirror is encoded to capture these points and angular accuracy as well.

Only a few systems - mainly AMCW laser scanners – employ the profiling system. This system’s prerequisite is high data capturing rates, in order to have space between the established points of the scan area. The Zohler- Frohlich AMCW laser scanners can measure up to 300 profiles per second with a maximum data sampling rate of 625,000 points per second. These types of laser scanners are useful to capture an object that has a dynamic motion, such as a train that runs with 120 km per hour.

2.1.3.2 Imaging System

Laser scanner manufacturers combined 2-D deflection unit with spot laser measurement systems to determine a survey of a 3-D data of the environment. The deflection unit of the laser scanners allows capturing the data in horizontally and vertically. For laser scanners which use imaging systems capture the data with two different technologies. These are a camera view and panoramic view. Table 2.2 shows the classification of laser scanners based on imagining system.

2.1.3.2.1 Camera View

These types of laser scanners use two synchronized mirrors. One of the mirrors deflects the laser beam horizontally, while the other one deflects the beam vertically (Figure 2.1). The advantage of this technology is that both mirrors can be positioned individually and a very high accuracy with angular measurement can be achieved. The disadvantage of this technology is the limitation of the view of the field. The laser scanner let the surveyors capture the data from a camera view which is 60^o x 60^o. There are some improvements in this system, thus, view of field can reach up to 360^o x 60^o maximum by positioning the mirrors automatically.

Figure 2.1.: A sample for laser scanner with camera view (Faro LS880)

2.1.3.2.2 Panoramic View

Panoramic view laser scanners use a single rotation mirror. At the same time, the system is rotating on the center axis (Figure 2.2). The system is similar to a total station. It is also more advanced than the camera view, which allows the surveyors to scan the environment with a view of 360^o horizontally and up to 310^o vertically. The limitation in the vertical direction is due to mechanical set-up but there is no major restriction.

Figure 2.2: A sample for l laser scanner with panoramic view (Mensi Trimble)

Table 2.2: Classification of Laser Scanners based on view

	Field of View hor. x ver. (^{o})	**Manufacturer**
Camera View	60 x 60	Optech, Rieghl
	360 x 60	Mensi GS 200, Callidus, Rieghl
	360 x 270	Leica HDS 3000
Panoramic View	360 x 320	IQSun
	360 x 270	VisImage
	360 x 320	Leica HDS 4500, Zohler+Frohlich Imager 5003

Table 2.2 shows different systems and shows the scanning field of view. Camera view systems are normally combined with based deflection units and used with pulse measurement technology (Frohlich, C. et. al.) This system is suitable to acquire highly accurate data measurements. Panoramic view systems provide the user high-speed deflection.

2.2 Previous Research

Although laser scanners provide high accuracy in a short time, the data accuracy may not be reliable in several points. There are many factors such as, instrumental factors, which can reduce the accuracy of the data. Researchers investigate the data accuracy of terrestrial laser scanners, and create new calibration methods in terms of incidence angle, point cloud and mixed pixels. Some of the investigations and experiments related to terrestrial lasers scanners are mentioned in the following paragraphs:

Rietdorf (et al. 2003) made the first report on terrestrial laser scanner calibration. He presented point-on-plane condition models and create a self calibration of TLS in terms of vertical index error, horizontal collimation error and eccentricity. They mentioned about their use of planar targets rather than point targets and some aspects of their network design on their publications.

Gielsdorf (et al. 2004) proposed error models and a calibration method using planar targets for the low-cost 3D laser scanner they built in order to increase the data accuracy. The parameters of this research are trunnion axis error, vertical index error, horizontal collimation error, additive rangefinder constant and eccentricity. The determination of calibration parameters, which they used is based on a calibration field. They used a calibration environment which consists of suitably arranged planes in different special positions. As a result, they determined the additive constant, trunnion axis error, horizontal collimation error and eccentricity of instrumental axes.

Parian (et al.2005) used some of the common features used by panoramic cameras and 3D laser scanners. They presented the use of 2D image point observations derived from the scanner data in an extended panoramic camera model calibration of the Z+F Imager 5003. They developed a sensor model for a linear array based rotating panoramic camera. This sensor model is based on a projective transformation the form of many equations, which maps the 3D object space information into 2D image space. The sensor model uses pixel coordinate system, linear array coordinate system and auxiliary coordinate system and object space coordinate system. Their calibration of laser scanners by extending the sensor model for panoramic cameras and established 3D testified. Their results and accuracy evaluations can be a good example for considerable development as a result of their modeling.

Lichti (et al. 2005) analyzed the issue by determining the similarities between theodolites and laser scanners. They reported a seven-term additional parameter error model and 3D free-network, self-calibration procedure and tried to find the advantages of laser scanners in comparison of theodolites. Improvements in the RMS of residuals can be seen up to %73 for the IQSun 880 laser scanner.

Abmayr (et al. 2005) also pointed -calibration of the Z+F Imager 5003 with error models originating from theodolite modeling. They applied a new calibration model on laser scanners. Their presentation is a simple, non-simultaneous calibration method for estimating trunnion axis error, collimation axis error and vertical circle index error.

Lichti (et al. 2005) presented recent advances in TLS error modeling and self-calibration. The efficiency of these researches has shown both internally relating to residuals and externally by independent examination. Advancements of up to 36% of co-ordinate differences and 80% for self-calibration residuals RMS were accomplished.

Soudarissanane (et al. 2007) checked the quality of laser scanner end-product influenced by surface orientation and local point cloud density. They checked the different parameters such as point intensity, influence angle and concluded that the position of the laser scanner affects the quality of individual scan points. In their paper, they quantified the effect by presenting a notion of point cloud quality which incorporates both the point density and the individual point quality. They improved the point cloud quality by an ample 2 meters up to %25.

Tang (et al. 2009) investigated a new aspect of laser scanning accuracy. They developed and edge loss estimation model in order to reduce mixed pixels at the edges of the scanned objects. The model focuses scanning distance, angular resolution of a scanner, rotation speed of a scanner, incidence angle, laser spot size and divergence and their effects on data accuracy. They tested AMCW and PTOF scanners individually in terms of those parameters and approximated the impact of these parameters. By their calibrations and experiments, they increased the accuracy of the laser scanning data greater than 80%.

2.3 Error Sources on Data Accuracy

Due to the growing importance of terrestrial laser scanning systems, it is pertinent to match each laser scanning system with an appropriate application. The producers of laser scanners publish a statement of requirements which must be satisfied for the advantages of their devices to be differentiated. However, these statements cannot be solely reliable since the accuracy differs among each device and its influences by individual calibration. Research has been conducted to analyze the sources of error in terrestrial laser scanning.

Observations can be made regarding the accuracy in many activity fields where terrestrial laser scanning displays its benefits. If the models of irregular surfaces and point clouds are affected by point cloud noise or some other effects, the accuracy of the data cannot satisfy the needs.

The analyses of the research of laser scanners by the institutes yield the conclusion of possible error sources which can influence terrestrial laser measurements. Instrumental errors, errors related to the form and nature of the scanned object, errors resulting from the environment in which the scan was performed, and methodological errors are the four error source categories.

To reduce, eliminate or avoid the effect of these errors, individualized calibration of each type of instrument is necessary, according to previous research. Most specialists will confirm the assertion that these error sources are the deterministic accuracy parameters in delivering a project, in comparison of measurement equipment.

2.3.1 Instrumental Errors

Instrumental errors can be separated in two sections, systematic and random error. Random Errors influence the precision of measurements such as distance and angles in the case of instruments which is the time of flight principle. Systematic errors can be created by non-linearity of the time and temperature measuring system, which can affect the electronic distance measurements.

2.3.1.1 Laser beam width

Laser beam width is the one of the most important parameters of a scanner which can significantly affect cloud resolution and positional uncertainty. As mentioned before, laser beam size increases respectively with the distance travelled. Laser beam width can be expressed as;

$$w(\rho w) = w_o \sqrt{1 + \left(\frac{\lambda \rho_w}{\pi w_o^2} \right)^2}$$

Equation 2.1 (C. Cosarca et al.)

- $\boldsymbol{\rho_r}$ is range relative to the beam waist location
- $\boldsymbol{r}$ is the radius of the laser beam
- $\boldsymbol{r_o}$ is the minimum radius of the radius of the laser beam called beam waist

Laser beam width enlargement is linear for long distances so divergence is indicated in terms of initial diameter. The divergence of the laser beam simply has an effect on the distance and angle measurements. The location of the observation is along the centerline of the laser beam.

2.3.1.2 Boundary Effects

Boundary effects are can influence the data accuracy. When the laser beam hits a boundary of a surface, it is divided into two parts. Since the same beam hits two different surfaces, a part of the beam will be reflected when the other part will be reflected from a neighboring surface. So it causes noise at the point cloud and therefore affects the accuracy.

2.3.1.3 Range Accuracy

In 3D laser scanning systems, ranging is put in effect in two different ways: triangulation or measuring time of flight of the laser signal. Measuring phase difference between transmitted and received signal is another way to determine the travelling time.

As noted in this paper previously, the expression of the range resolution for the triangulation is;

$$\delta_z \approx \frac{Z^2}{f \cdot D} \cdot \delta_\rho$$

Equation 2.2

2.3.1.4 Angular Accuracy

A small rotating device is assembled into the laser scanners to deflect the laser beam in a certain direction, such as mirrors or prisms. The rotation of the device causes small angular differences; these differences depend on the distance from the device to the investigated object. These small rotations may cause considerable errors in the coordinates of the points. The greatest factors that impact the angular accuracy are positioning inaccuracies of the rotating instrument and the precision of angular calculation apparatus.

Depending on previous research, effects of these errors can be detectable. Calculating acute horizontal angles and the spatial distance between objects, placed an equal distance from the scanner can assist in detecting the influence of these errors.

2.3.1.5 Axis Errors

Another error often encountered during laser scanning is axis inaccuracy. Laser scanner calibration development yields a geometric model which forces to consider the vertical, horizontal and collimation axes. The vertical axis, which is also called the principal axis allows the system to move the laser beam horizontally. This is the rotation axis of the scanning unit depending on the type of the scanner. The horizontal axis is described by the rotation axis of the deflecting prisms or mirrors. The collimation axis is the axis of the scanning mirror and the center of the laser spot deflected on the scanned object. These axes are not completely corresponded and accordingly still have the possibility to match with the influence of the errors gained by classical measurement instruments.

2.3.2 Errors related to the form and the nature of the scanned object

2.3.2.1 Surface Reflectance

Laser scanners are assumed to measure the laser beam reflections from the surface of an object. There are some valuable physical laws of reflection and optical features of materials of the inquired object. Depending on the surface, a laser beam can reflect in many directions (Figure 2.3).

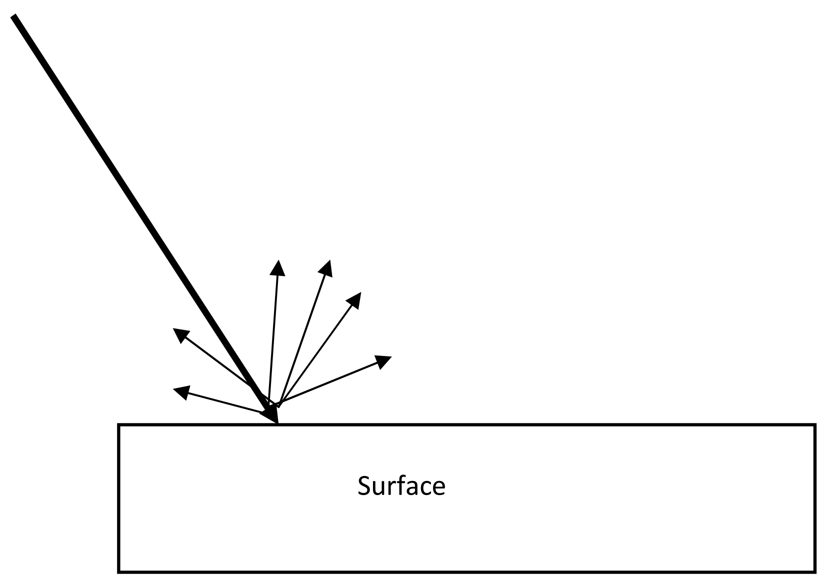

Figure 2.3: Surface reflectance (Isotropic reflection)

The basic reflection law can be defined by Lambert's cosine law;

$$I_{refl.}(\lambda) = I_i(\lambda) \cdot k_d(\lambda) \cdot \cos(\theta)$$

Equation 2.3: Lambert's cosine law

where $\boldsymbol{I_i(\lambda)}$ is the incident light intensity, $\boldsymbol{k_d(\lambda)}$ is the isotropic reflectance coefficient, $\boldsymbol{\theta}$ is the angle between the light and normal of the surface.

These formulas point that distance, atmospheric conditions, and the incident angle have a strong influence on the returning signal. That means dark surfaces can absorb a laser beam which causes weak signal. Therefore the accuracy of the point gained by the laser beam will be influenced by noises. The surfaces which have high reflection such as white surfaces yield strong signals. Nevertheless, if the surface of the object is a shinny surface, it is difficult to record; the laser beam is totally reflected in a mirroring direction and will hit another surface. When the laser beam is scattered on an irregular surface, the deflection results will cause speckle noise.

Reflectance properties of different surfaces can influence the accuracy of point determination. Color of a surface is another factor, which can cause a systematic range difference between two measured values of the same point distance.

2.3.2.2 Multipath Reflection

Multipath deflection is another effect when the laser beam bends at an interface between two transparent materials. It allows the laser beam to refract and reflect on the same surface. This effect can increase the noise ratio of point cloud, and cause ambiguous data accuracy (Figure 2.4).

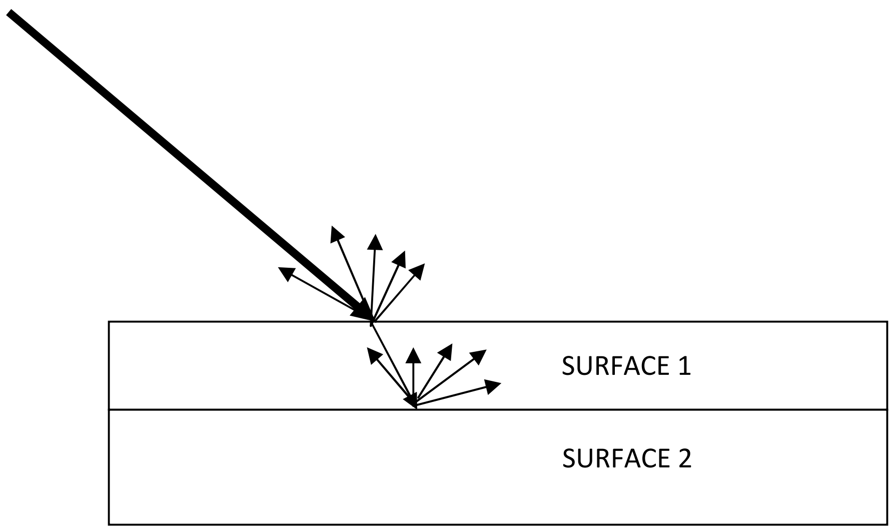

Figure 2.4: Multipath reflection on surfaces

2.3.3 Errors Caused by the Environmental in which is performed the Scanning

2.3.3.1 Temperature

Temperature is an important parameter which can affect the precision of laser scanning data. Equipment temperature may be higher than the surrounding area due to internal heating of the components and sunlight. This condition can easily merge to distortion of the scan data.

Beside this, another important factor which can distort the scan data is the surface temperature. If the scanning surface is hot, due to high temperature, the radiation on the scanned surface will reduce the signal-to-noise ratio during the deflection and can affect the accuracy of the distance measurement.

2.3.3.2 Atmosphere

Depending on the atmospheric conditions, laser scanners run efficiently when the environmental scanning has a constant temperature. Distance measuring using laser techniques can be affected by environmental conditions. Errors can be caused by atmospheric variations in temperature, pressure and humidity. All these parameters can influence the length of the laser wave, thus the speed of the laser beam can be affected due to air density. The software applications of laser scanners can calibrate the scan data results, in terms of the atmospheric conditions and reduce the effect of environmental variations.10^{o} C change in temperature or 35 hPa in air pressure can cause a distance error of 1mm/100 m.

2.3.3.3 Distortions from motions

The entire scanning process has a rate of 1 to 3 hours depending on scanning conditions. During this process, the scanner is very sensitive to vibration. Therefore, the scanned object and laser scanner must be fixed and stable. It is a requirement to mount the scanner on a stiff platform in order to avoid the vibration.

2.3.4 Methodological Errors

Methodological parameters such as wind, rain, and fog can affect the laser scanner data accuracy. For the most accurate results, we have to conduct the experiments or investigations during the most appropriate methodological conditions.

CHAPTER 3: DATA CAPTURING AND REGISTRATION TECHNIQUES

Since 3D data acquiring of objects are started to be applied in many fields such as inspection, navigation and object identification in civil engineering, it became an important technique in land surveying. In addition to this, photogrammetry is also required for precise measurements of terrestrial laser scanning process.

3.1 Capturing Points

Capturing the data is the most critical step of 3D model creation. In terrestrial range, surveyors commonly employ two techniques in order to capture the object data. These two techniques are the image based technique and the range based technique.

3.1.1 Image based technique

Using the image based technique; three main steps are taken into consideration in order to acquire a certain object or scene data. These are: photographing, determining the orientations for captured images and measuring interesting points in the images and computing the space coordinates.

3.1.1.1 Photographing

At least two images are needed to obtain a scene or object by photogrammetry. These images should be distributed around the object horizontally and vertically in order to determine the accurate space coordinates.

There are a few factors which can affect the digital photogrammetric accuracy. Base to depth ratio is the most common one which can significantly affect the precise measurement. Basically the accuracy increases with the increase of the B:D ratio. Also the accuracy can be improved by increasing the number of images. The number of control points and the number of measured points per image can significantly increase the accuracy. However control points should be distributed well to reconstruct the photogrammetric model. The ground pixel size is also an important parameter for data accuracy. Smaller pixel size increases the accuracy.

3.1.1.2 Sensor Orientations

Technical challenges during laser scanning process can reduce data accuracy. Thus, calibration of the camera may be needed in practical cases. Lens distortions forms are also a part of the elements of sensor orientations. Calibration of the zoom lens can reduce the lens distortion effect on data precise. In this case, camera focal length is obtained from the header of the digital image. Modern digital cameras capture the images, so obtained images remains as original otherwise header information can be lost.

3.1.2 Range Based Technique

Range based technique based on using the laser beam in measuring the distance. This technique allows the surveyors to measure the distance between two points by using laser pulses with high accuracy.

3.1.2.1 Laser Scanning

Laser scanners measure the distances automatically with all points on the object surface. By scanning the scene, point clouds are created. Some type of laser scanners such as Leica and Z+F can capture the entire hemisphere data from one position which is called “scanworld”. Some laser scanners have wide field of view, it can reach up to 360x310^{o}, however some types of laser scanners have a limited field of view.

3.1.2.2 Scanning Methods

Terrestrial laser scanners employ different types of scanning method. These methods are: time of flight, phase difference and the triangulation method. In time of flight method, laser scanners measure the time travel of the laser beam. The travel time of laser beam covers the time when laser beam is sent from the laser scanner, hits and reflects on the surface of the object and receives back by the laser scanner. An internal stopwatch replaced in laser scanner measures the travel time (Figure 3.1).

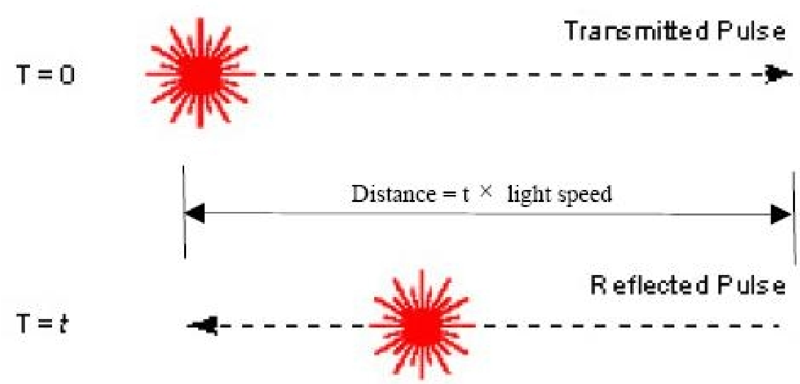

Figure 3.1: Scheme of Time of Flight Principle (Abdelhafiz 2009)

The phrase difference method, the wavelength of the send and the received signal is determined. Phase shift of the laser beam can change by the travel when it is send and received by the laser scanner (Figure 3.2). The required distance can be then measured depending on the phase shift. We can define the equation of the distance as;

$$D = \left(\frac{\Delta\varphi}{2\pi}\right) \times \left(\frac{\lambda}{2}\right)$$

Equation. 3.1.

where $\Delta\varphi$ is the phase shift and λ is the wavelength of the laser scanner. Precise distances can be obtained by high frequency modulation however measuring with a high frequency limits the range. Laser scanners which uses phase difference method like Z+F 5003 Image is called AMCW laser scanners. Those type of laser scanners also allow surveyors to select the frequency of the phase differences so an unambiguous and precise range measurement can be acquired.

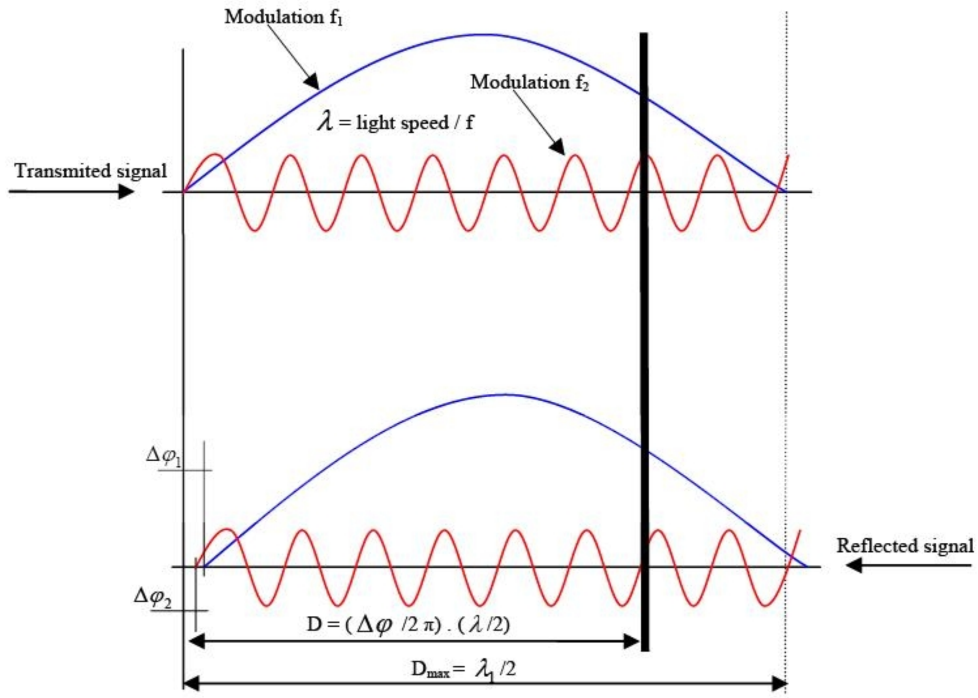

Figure 3.2: Scheme of Phase Difference Principle (Abdelhafiz 2009)

Phase difference and time of flight scanners are the most common used scanners in the field. Scanning speed of phase difference scanners are faster than time of flight scanners, however, point cloud of phase difference scanners are noisier than time of flight scanners. While the range of time of flight scanners can reach up to 200-300 m, the range of phase difference scanners are limited with 70-80 m.

Another type of scanning method which is employed by laser scanners is triangulation method. In this method, laser scanner sends a laser point on the object and utilizes a camera to search for the location of the laser point. So the distance between the camera and the laser emitter is known. The range of triangulation scanners is around a few meters, thus these types of laser scanners are the least common types of the scanners due to its range and application process (Figure 3.3).

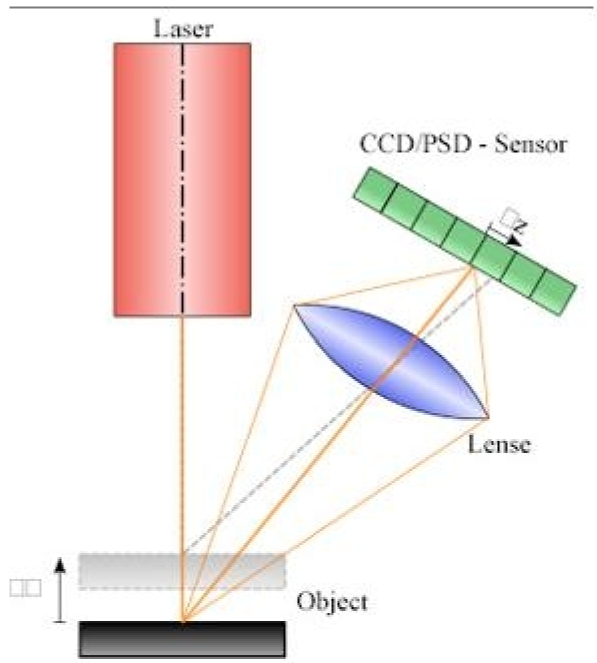

Figure 3.3: Scheme of Triangulation Principle (Abdelhafiz 2009)

3.1.2.3 Multiple Laser Scanner Point Cloud Registration

For the precise measurement of 3D objects, we need more than one laser scanning stand position. Since the point clouds are acquired from different scanning positions, each point clouds have different coordinate systems. These point clouds have to be registered together in one coordinate system to succeed the presentation of 3D model of the object. The registration of the point clouds into one coordinate system can be done manually, semi automatically or automatically. There are three types of registration methods of point clouds.

3.1.2.3.1 Target Based registration

The registration of point clouds can be successfully done by assigning the space coordinates of at least three points at each point cloud (Figure 3.4). These points are called “target points”. Those points can be either artificial or natural targets. These targets can be assigned manually or automatically. Some laser scanners with advanced algorithms can detect the target points automatically by using high reflection on the target points.

Figure 3.4: Different types of target used for 3D model registration

3.1.2.3.2 Future Based Registration

Future based registration is very accurate point cloud registration method. It is based on an algorithm which has mainly two steps. In first step, the two potential target points are chosen in the area overlap of two different scans. Second step, an optimization process determines a rigid transformation which reduces the distance between these two scans. The method is based on an idea which reduces the distance between two scans and allows for a better identification of true matching pairs.

Variations in the algorithm may vary depending on the potential matching pairs are identified.

3.1.2.3.3 Imaged Based Registration

Image based registration method uses the camera which is mounted to modern laser scanners. The basic idea is to determine the relative orientations between the camera and laser scanner (Figure 3.5). The camera has to be calibrated and then scan can be registered based on the common points between the photos. These methods only require overlap between the photos.

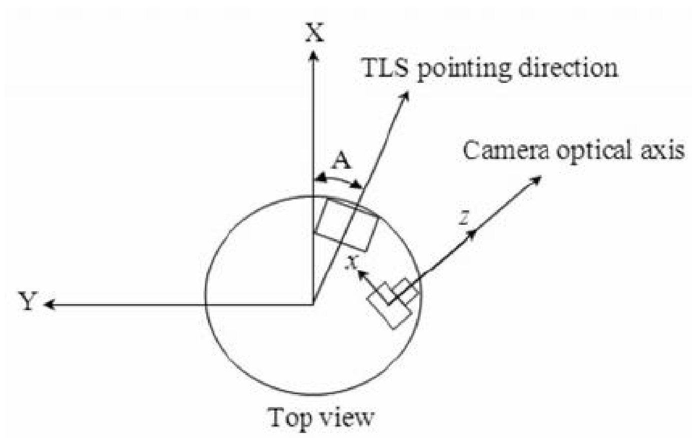

Figure 3.5: Laser scanner and mounted camera coordinate systems (Abdelhafiz 2009)

3.2 Object Recovery Using Multiple Sensors

In terrestrial laser scanning surveying, photogrammetry and laser scanning are the main techniques for 3D object acquisition. Each technique is unique and has its own advantages and disadvantages. Surveyors should choose the appropriate technique depending on the field application. Laser scanners allow land surveyors to obtain 3D data of the object while digital cameras capture the object textures.

3.2.1 Importance of Multiple Data Combination

All applications require geometric accuracy, photo-realism, automation, portability in terrestrial laser scanning. However there is no single method or approach to satisfy all the requirements. Photogrammetric methods let land surveyors to obtain the data with high geometric accuracy however laser scanners can capture all five geometric details with less accuracy. In order to succeed the satisfied combination of multiple scanned data, a registration step should be performed. The registration process is to combine the data in one coordinate system, thus all data received through photogrammetry and laser scanning method can be registered into one 3D model.

3.2.2. Review of the Combination Results

Researchers developed different techniques to combine the laser scanning data with the digital cameras in the past few years. Researchers have improved different data combination techniques to create different types of products to succeed the most accurate data combination.

Modern laser scanners use their own hardware setup to deliver the points color as extra data information (Figure 3.6). Also some of laser scanners have their own high resolution digital camera on top of the device. This allows the laser scanner to acquire better results. However, the camera cannot cover the same wide field of view captured by the laser scanner and sun or some reflection from the other surfaces might appear in some photos as the laser scanners rotates horizontally as it is shown in the picture.

Figure 3.6: A registered 3D model of point clouds acquired from Cyclone

3.3 Factors Affecting the Data Accuracy

The main factors which affect the data accuracy during the data capturing process are geometric distortions and object occlusions.

3.3.1 Geometric Distortions

Any small geometric objects with high level of details can influence the 3D model. It is critical to keep every detail in such objects. Based on the modeling procedure, laser scanners make some assumptions to present the object and simplified the final model to reduce the number of details on the target. This assumptions cause data loss and geometric errors. Weak photo registration will cause on false geometric details. Therefore the registration step is considered one of the most important step in 3D model capturing process. To prevent an expected geometric distortion, a full camera calibration has to be done.

3.3.2 Object Occlusions

Modeled occlusions present a part of the desired object. Objects can be detecting by using ordinary occlusion. The other parts of the environment such as trees could be other types of occlusions. So we can remove them during the process. There are many types of algorithms which can be employed for object occlusion. The most common one is photo occlusion finder algorithm which guides the computer automatically not to use images with such type of un-modeled occlusions in texturing the geometry of the object.

CHAPTER 4: 3D LASER SCANNING PROCESS & GEOMETRIC RESULTS

4.1 Scanning Procedure

4.1.1 Bridge Info

The structure tested during the pilot scanning program is a four span simply supported, composite, welded I-Steel plate girder bridge located on routes US 202 and NJ 23 over route US 202 ramps M&N and Norfolk Southern Railroad in Wayne Township, Passaic County, New Jersey. The structure number is 1618-150 and it was built in 1983. The length of the bridge is 429 and the width is 123.5 feet long. The type of services are highway and pedestrian walk on the bridge. There are 7 lanes on the

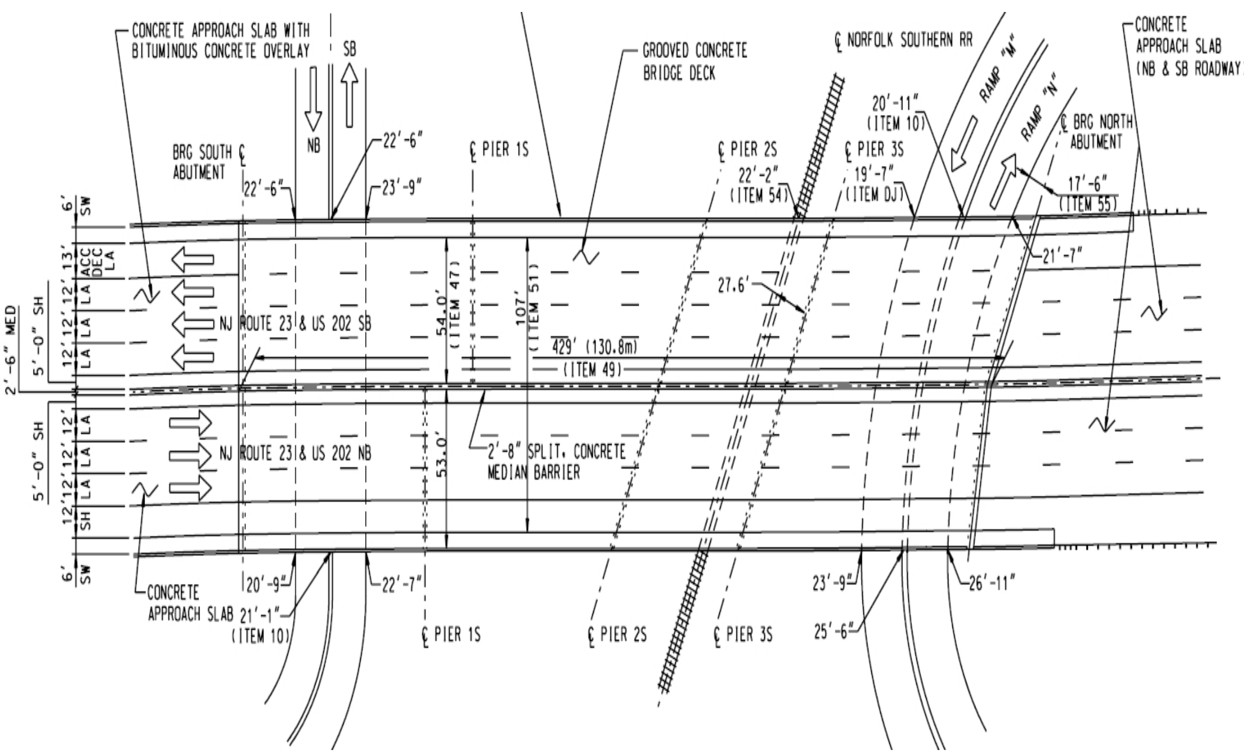

Figure 4.1: Structural plan of Route 23 & US 202 (Source: NJDOT Bridge Inspection Report)

bridge. The minimum vertical clearance is 22’-2” at the railroad under west fascia. The maximum span length is 130 feet and the curb-to-curb width is 107 feet. The deck area is 52,982 sq.ft and skew angle is 99.0 ^{0} (Figure 4.1). Super structure also contains median barriers, curbs, parapets, fence, drains and scruppers. The substructure consists of breast walls, back walls, bridge seat, wing walls, retaining walls, embankment and abutments.

4.1.2 Field Work

4.1.2.1 Set-up Process

The first step of preparation for the scanning process is to decide the scanning location of the area. After the discussion with the surveyor, we decided to scan the structure from four different points. A complete scan of the superstructure would be time consuming, thus, specific areas of underneath of the bridge were investigated and identified. The number of points on each point cloud can be assigned. Depending on the needs, high resolution scans can be obtained. However, high resolution scans can take a lot of time which is why a moderate resolution was applied.. Prior to the scanning process, these following items were accounted.

- Leica Laser Scanner
- Scanner Tripod
- Leica Power Cables
- Ethernet data cable
- Laptop with Cyclone software installed

- Targets with high reflectance
- Ladder
- Power Strip
- Extension Cord
- Portable power generator
- Total Station

Due to a time consuming of set up process, it is important to choose an area that satisfies all of the needs of the experiment. The scanning points should not have any obstructions to see, they should scan the targets directly and the area should be positioned where it maximizes the desired scan area. The set ups on the scanning points should not block any progress during the scanning session such as traffic or any other experiments. Laser scanner positioning should be determined to achieve the lowest incidence angle. There can be as many as set up points determined as possible. The

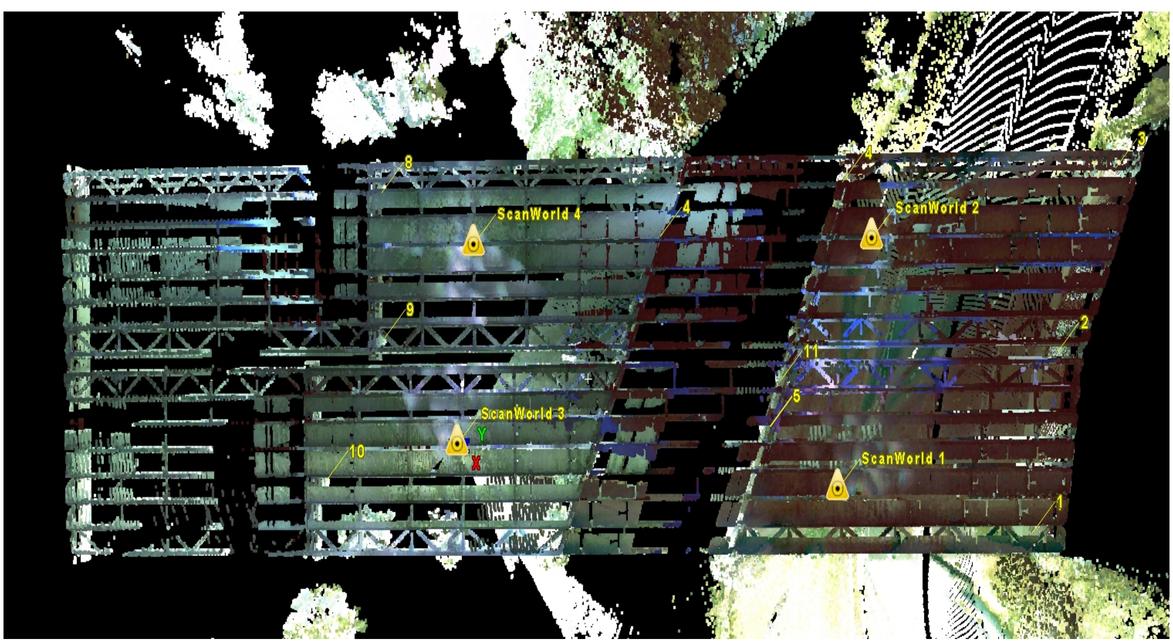

Figure 4.2: Registered scanned data of the bridge and scan locations (Scan Worlds)

more set-up points will yield more accurate results. However, that may be time consuming. One scanning process including moving, resetting all of the equipment, and scanning the infrastructure with fair resolution takes two to four hours. Therefore, the number of scans should be determined moderately depending on the needs. Even though high resolution scanning gives us more accurate results, the process may take up to 5 hours. If needed, specific areas of the infrastructure can be scanned with high-resolution while the other areas' resolution is lower. We also have to make sure to sketch and examine all laser instrument setup points before scanning in order to avoid starting over and to provide for proper geometry in post processing.

4.1.2.2 Target Set-up

We have to make sure that the targets are high enough to be scanned by a laser scanner directly. The targets also to be visible from multiple scanning points, especially when scanning a linear structure such as a bridge. Those targets are extremely important in order to register the multiple scanned point clouds into one 3D model. When we select the targets, we should choose ones made with high reflectance material (Figure 4.3). Sticker targets with white centers are the best type of target to use with laser scanners. A minimum of three targets is needed in order to produce accurate translational and rotational parameters for the registration process. Based on the distance between scanning points and the size of the structure, at least four targets can be placed. The distribution of the targets to the scanned area is important in terms of getting the accurate results. Targets should be well-distributed to the area. We have to make sure the targets are not collinear in varying positions within the scan hemisphere.

No more than three targets should be linearly located. If more than three targets are collinear, problems may occur during registration process, such as mixed point cloud registration.

Figure 4.3: An installed target on a column

4.1.2.3 3D Laser Scanning Process

Once the proper plan and pre-scanning process are established, the laser scanning process should be started. First, the tripod was set and the laser scanner was mounted on the tripod. Next, the bubble leveler on the laser scanner was leveled properly. After leveling, the revolving lock on the back of the laser scanner was locked to stabilize the position of the laser scanner on the tripod. A computer is connected to the laser scanner by using the Ethernet cable to transfer the data between

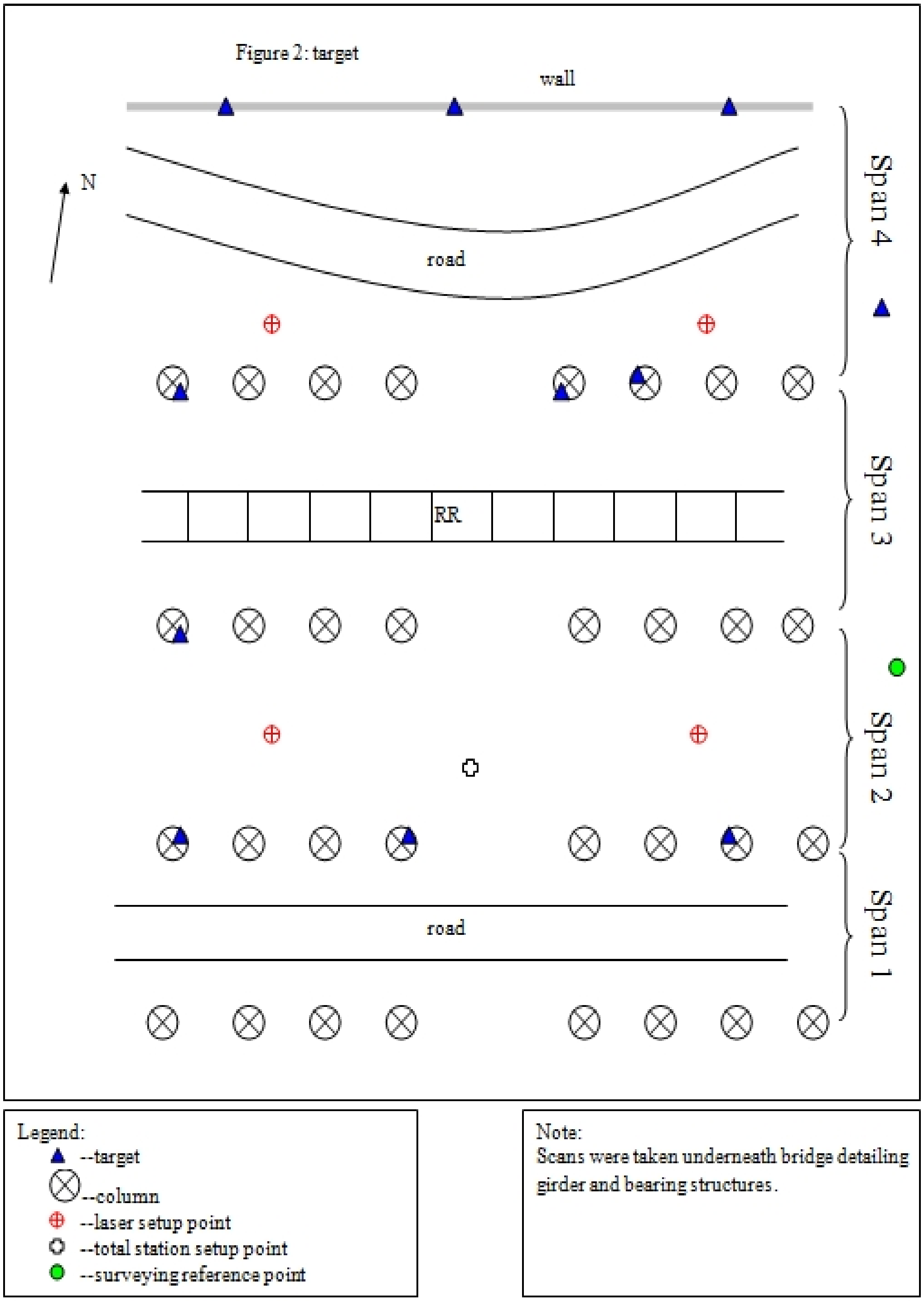

Figure 4.4: Sketch of the scanning environment

Figure 4.5: Instrument Set-up

the laser scanner and the computer. Power cables are also plugged to the power generator.

After all the equipment was set-up, as in the Figure 4.5, Cyclone software was run. Cyclone is the software which is developed from Leica Geosystems. Through Cyclone, the point clouds can be superimposed with color data from standard CCD cameras. First, a camera mounted on laser scanner took 360 degree pictures of its surroundings to construct the user interface.

These pictures were used to create a hemispheric panoramic picture of the area. Once this process is complete, the users can choose the areas on the hemispheric world, set the angles and distance and to begin the scan process. This algorithm helps users to save much time and avoid scanning the entire field. After the area is chosen and set, the resolution should be set. Different resolutions in different scanning areas may be applied. Once they are all done, scanning action starts. The laser scanner should not be moved during the scanning process it may cause data loss. We repeated this process four times at four different scan locations.

After scanning the desired areas, acquisition and the target assignment process started. The general area of the target should be assigned automatically. It does exactly not have to be the target but roughly the surface where the target should be chosen for target recognition. Once the target recognition process initiated, the laser scanner started to scan the assigned area to locate the target. The target's surface is bright, white and made by glossy paper, so reflectance of the laser beam on the target is higher than surrounding surface. Due to the reflectance difference between the target and the other surface, the laser scanner located the exact position of the target and put it to its own 3D coordinate system. This process is repeated 11 times for 11 different targets (Figure 4.6).

Not all of the targets may be visible from current scanning locations. In this condition, total station was used to locate the other targets' positions. A coordinate acquisition of the targets is needed to create precise 3D model registration while combining point clouds from each scan location into one complete model. A few locations where can shoot all or most of the targets, were decided to set up the total station. By using a total station, targets were shot, the distance and angle between targets as well as between scan locations and targets were determined. Finally coordinates of targets in scan world were found. All these processes were saved into total station and transferred to the computer. Eventually, all of the data gained from total station was loaded to Cyclone software. The 3D scanning process took two days including the travel time.

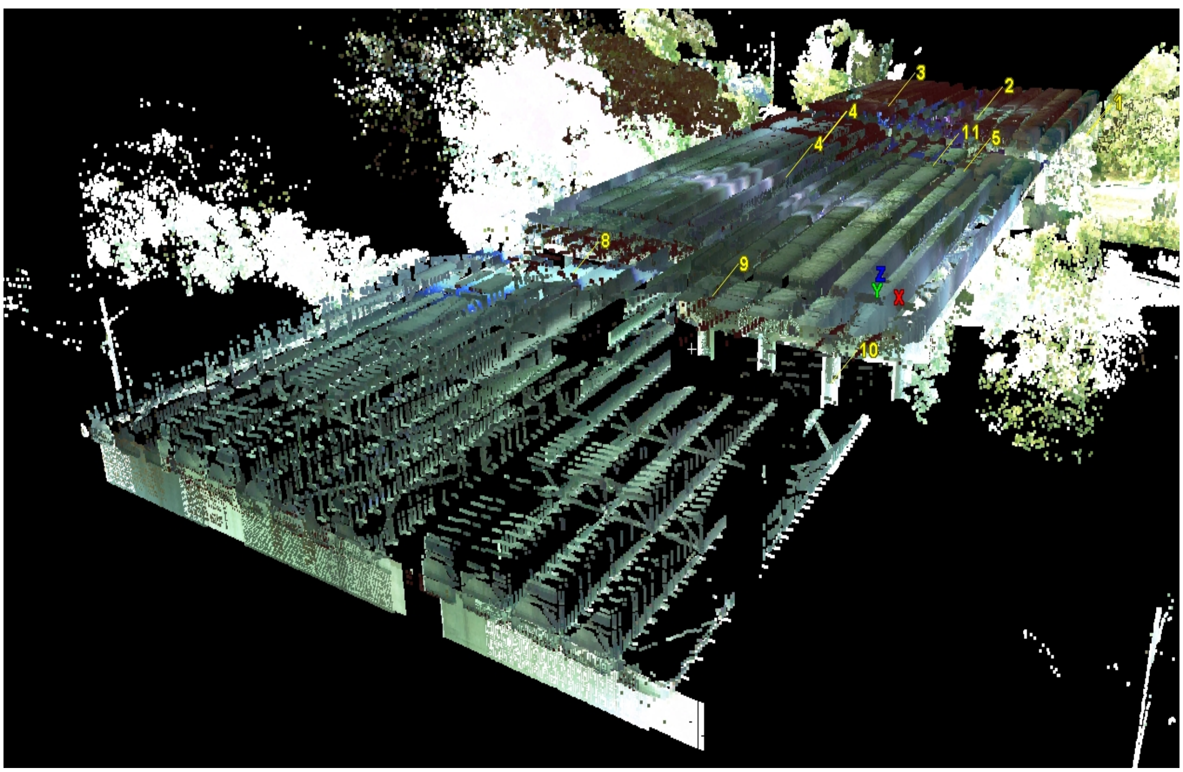

Figure 4.6: 11 different target locations on the bridge

4.1.3 Office Work:

4.1.3.1 Registration Process:

Registration of the point clouds is the process of the combination of 3D data gained from scan worlds into one 3D system. The data collected from four different scan locations was combined and registered in to one common system. Through 3D registration, the 3D model of underneath of the bridge in addition to its surroundings, was created.

In order to register four different point clouds into one system, we used Cyclone software officially provided by Leica Geosystems (Figure 4.7). Cyclone systems provided a registration option which can run automatically, semi-automatically and manually. The instructions are easy to follow, however pre-knowledge about the software is needed. In order to run an automatic registrations would need to select the scan worlds and choose the automatic registration option by right click will be enough. As mentioned previously, all targets were shot separately for each four scans after scanning the infrastructure. So for each scan we have 11 targets. By automatic registration, all of these targets for each scan will be identified and matched automatically. It is a short time process; however, the results are less accurate.

Although semi-automatic and manual registrations take more time comparing with automatic registration, they yield more accurate results. For manual registration, all targets should be identified for each scan world and should be matched separately. To create a registration, one can right click on the data tab on the left of the screen and the scan worlds that will be integrated. In our project, four different scan worlds were used. After scan worlds are chosen, we have to register one of the scan worlds as the base. Thus, in 3D model, the coordinate system and the origin of the chosen scan world will be registered as the main coordinate system. After those four scan worlds were chosen, the registration wizard was used to identify the targets and to match the similar points from each scan world.

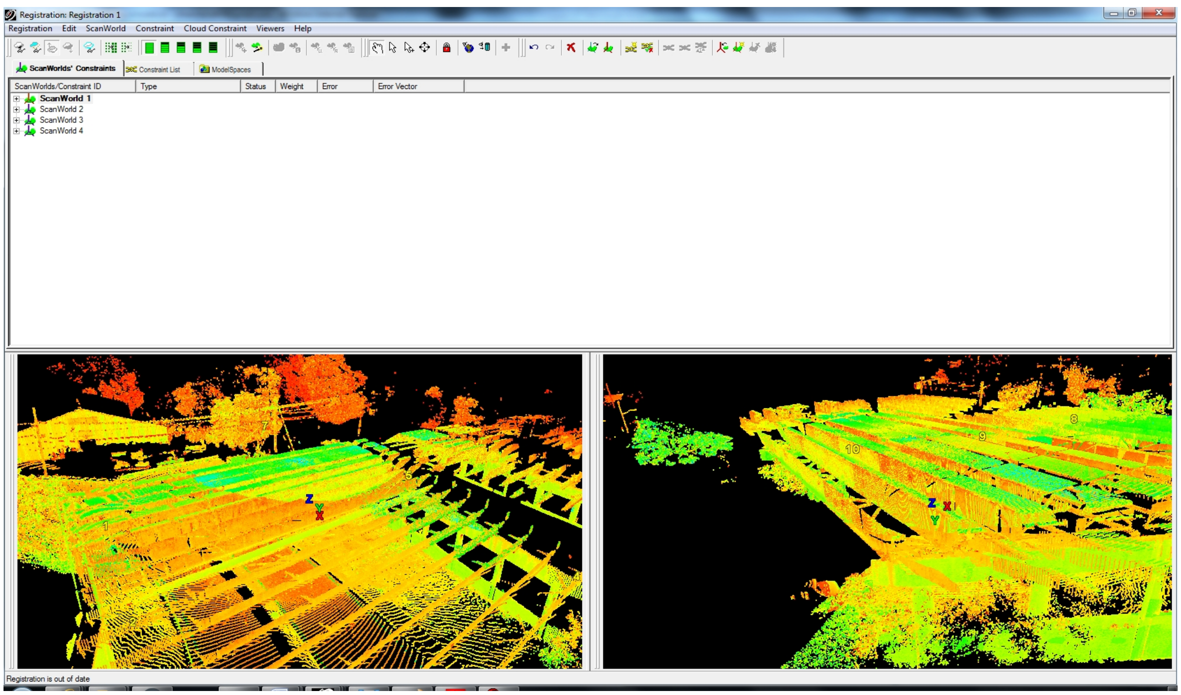

Figure 4.7: Registration process of four different scan worlds

4.1.3.2 Creation of 3D Model:

After the registration of four different point clouds into one common scan world, the 3D model creation was started. The scanning process was performed from underneath of the bridge, thus, the collected data includes superstructure and substructure of the bridge. No information of the bridge deck was acquired. The 3D model consists of bridge girders, bracings, pier caps, pier columns, footings and abutments. As mentioned earlier, depending on the scan resolution, there may be a million points on one scan. We will be using those points during the 3D creation process. Depending on surfaces, different types of geometrical shapes can be assigned manually or automatically. For this process, Cyclone has a surface fitting option where it can fit basic geometrical shapes to selected points on point clouds automatically. It recognizes what kind of prismatic object the surface looks like, identifies the surface, creates a 3D shape and fits it to the surface. This method is fairly accurate as long as the selected points are segmented and distributed to the surface properly. Different surfaces in different shapes can be chosen manually and identified and created by Cyclone automatically. First, we have to choose several points on a surface. Based on X, Y, Z, components of the points on the same surface, the software can identify what kind of geometrical shape the surface has. It may be cylindrical, conic, cubic prism or it can be an irregular surface.

3D model creation is started with modeling pier columns. These are the easiest part of 3D modeling after the combination of four different scans from two different spans. Pier columns are the best scanned part of the structure which gives the most accurate results due to the range and low incidence angle. Therefore, it is the easiest part to be identified by Cyclone. To identify the cylindrical shape of pier columns, we should choose a few points on a pier column. While choosing the points, we should distribute the points all over the pier column. Instead of vertical distribution, horizontal distribution should be considered since we can adjust the height of the cylinder manually after modeling. However, the assignation of the radius of the cylinder is the most critical point. Ergo, we should pay more attention while distributing the chosen points horizontally. Depending on desired accuracy, we can choose as many as possible. The horizontal distribution of the points will assign the radius of the cylinder. We should choose the points on the diameter of cylinder. Points on the diameter of the cylinder will be determined all the way from the bottom to the top of the cylinder through Cyclone and cylindrical shape will be created. While Cyclone running, first, we select some random points on the column, and then go to "Create Object", "Region Grow", "Cylinder" tab on the menu bar. The "Region Grow Cylinder" window will pop up (Figure 4.8). We can increase or decrease the region size, thickness and maximum gap to span of the object by this window. The column will be highlighted as it is shown in the picture. By clicking OK button, a cylinder will be created (Figure 4.9).

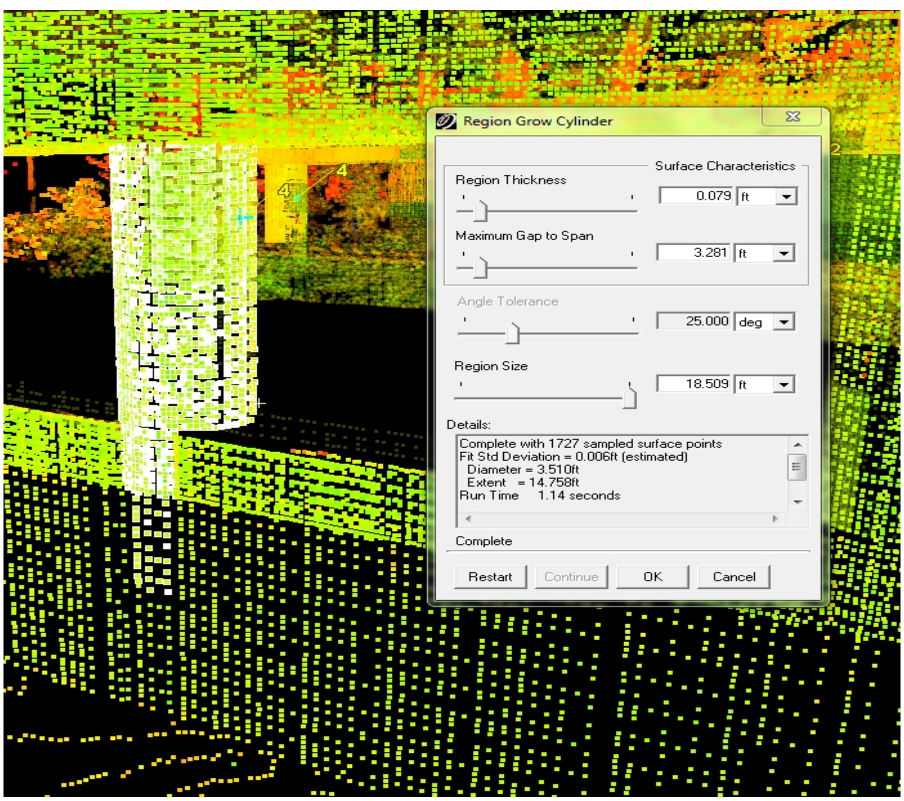

Figure 4.8: 3D Model Creation of Pier Columns

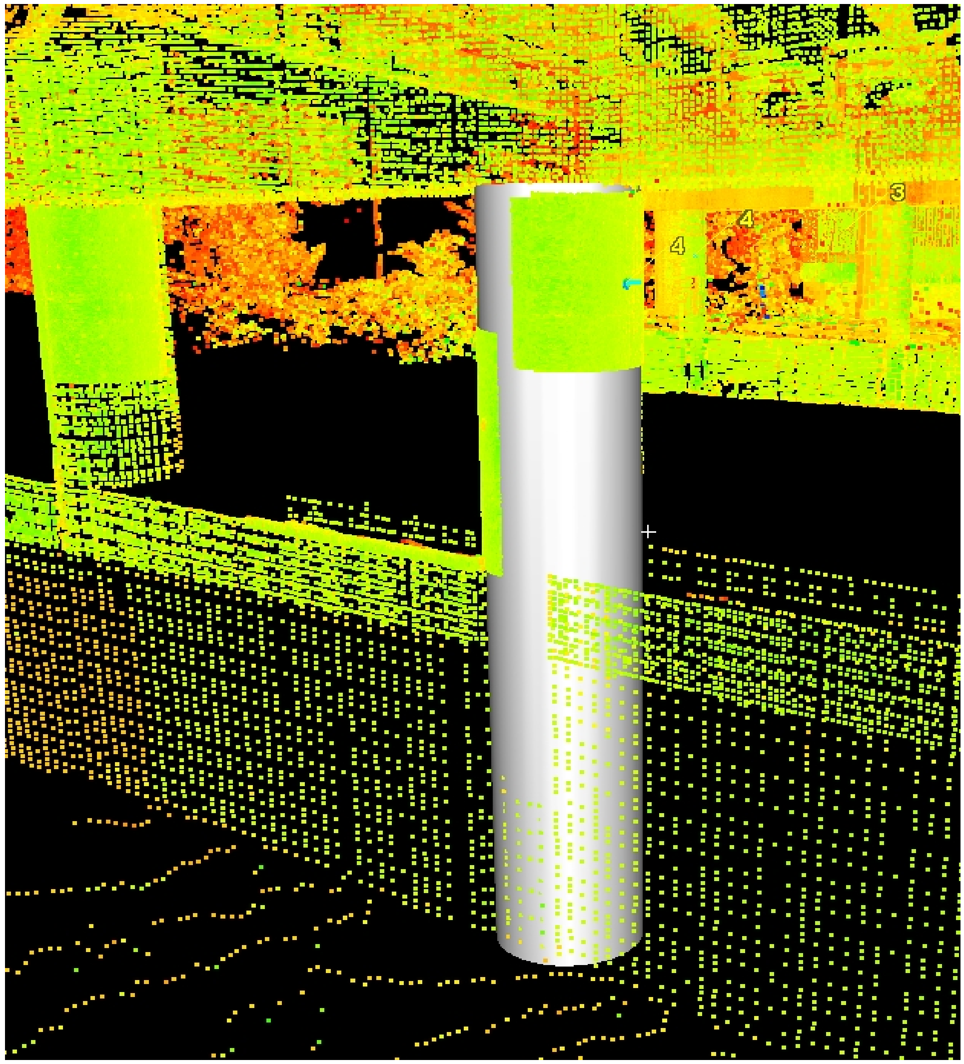

Figure 4.9: Created model of pier column

In this case, the columns are well scanned in terms of range, thus, there was no problem during the 3D model creation of cylinders. However, in some other scan projects, with low incidence angle and high range, the creation of spherical surfaces can cause some difficulties.

Once we created the cylinder, we should check if it fits on the surface properly. We cannot expect a perfect fit but it should be reasonably accurate. The most important parameter is the radius of the created cylinder. We can observe the shape by rotating the point cloud to check if there are any errors while creating the cylinder. The cylinder on the point cloud may not be covered entirely. The recognition of the surfaces by Cyclone software is limited. So if the created cylinder is offset vertically, that means the software recognized the height of cylinder as the cylinder was created. We should increase the height of the cylinder manually. For this, we should choose the created cylinder by clicking on it. The orange squares on the cylinder will appear. These are the size adjustments of cylinder. By clicking on and holding them, we can change the dimensions of cylinders. We should find the one which changes the height. Once we did that, by clicking and holding it, we can increase the height from footing to pier cap. We can also check the object's information by right-clicking on it and obtain the created cylinder's dimensions. Each of these processes of creation of a pier column were repeated 24 times for each column.

Once the 3D model creation of a pier columns is done, the process of a 3D model creation of pier caps is started. Unlike cylinders or any other regular geometric shapes, pier caps are not symmetrical through the X,Y,Z axes. Thus, the creation of a 3D model is more complicated and it requires more time. We can choose points on pier caps but there is no geometrical shape that can be assigned by Cyclone. That is why all surfaces on a pier cap were assigned manually and separately. Because of the geometric shape of pier caps, the patch insertion method is used. The process of 3d model registration of pier caps is similar with the process of cylinder. Basically we follow the same steps. Some points belonging to one surface of a pier cap were selected. Then, we click on "Create Object", "Region Grow" and "Patch". "Region Grow respectively (Figure 4.10).

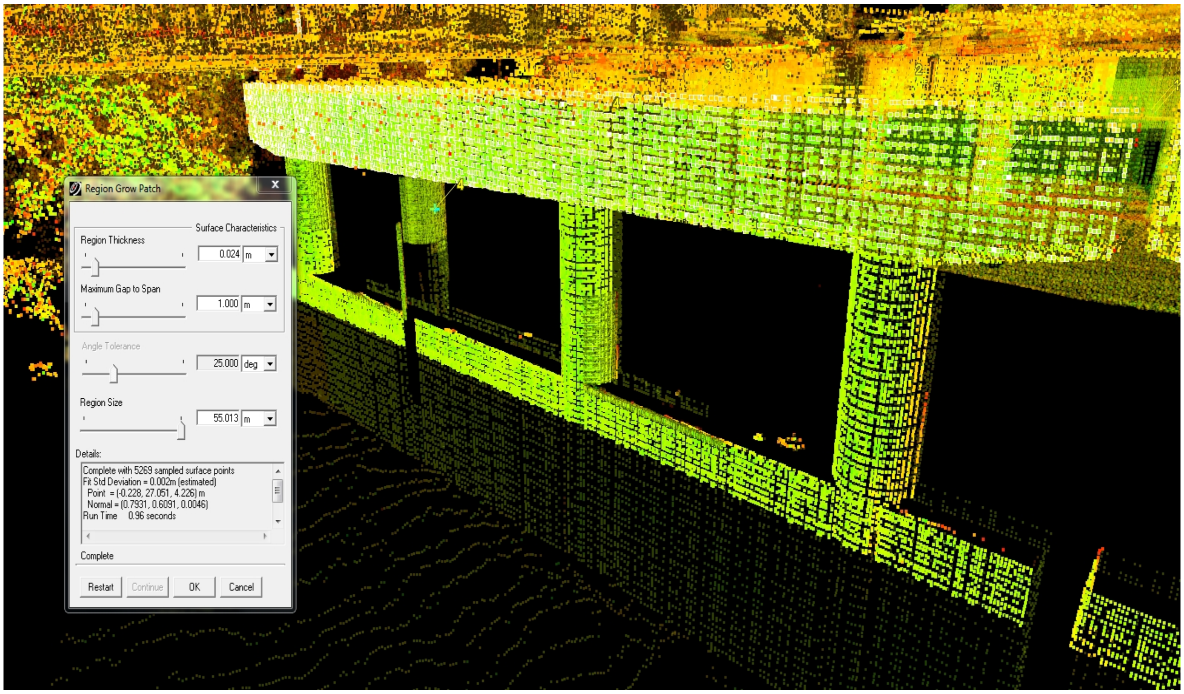

Figure 4.10: 3D model creation of pier caps

Patch" window will pop up and the points belonging to the surface will be highlighted. We can adjust the region size and the thickness of the patch by using the region grow patch window. Due to the noisiness of points, patches cannot cover the surfaces properly. Some points belong to another surface, which can be at the same level with the chosen ones horizontally and vertically. Therefore, points belonging to different surfaces may be included with the point cloud which will form the patch surface. So the surface will be created differently than the manner in which we desire.

As it is seen in Figure 4.11, because of the noisiness of the point clouds, some other points are included to the surface patch. In this case, we have to form the patch manually. By clicking and holding the orange squares on the patch, we can adjust the surface patch and form it as we wanted. We should be careful while forming the patch manually. We can also change the color of the patch. Figure 4.12 shows the patch after fixing it. If the surface is not covered by the patch, we may get the wrong data while measuring. It is a long process and it may increase the error ratio. The same process was repeated for each surface of the pier caps for six different pier caps.

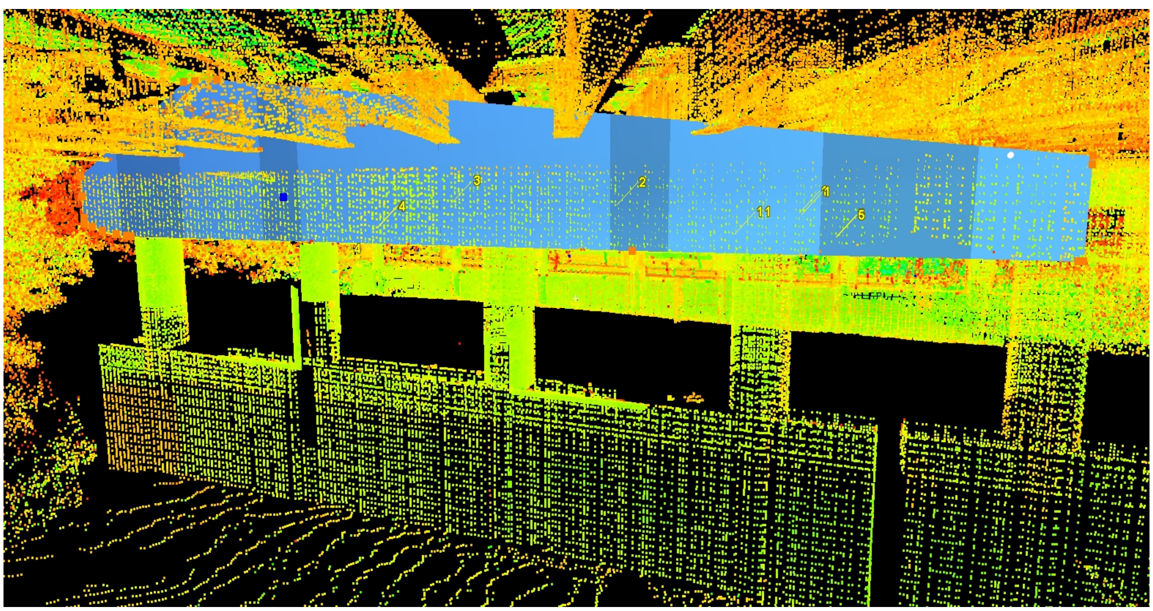

Figure 4.11: Patch of the pier cap surface due to noisy edges

3D model creation of pier footings and abutments are the easiest part of a 3D model because of the geometric shape of these parts. Footings and abutments are rectangular prisms, so, once we get the dimensions of footings and abutments, we can create the models and put them where the footings and abutments are located. First of all, we have to measure the dimensions of footings from the registered point cloud data. The edge of the footings is not noisy and not a lot data loss was, so we can make manual measurements. Two points are chosen from the edge of footing. The distances between these two points were measured by using the Cyclone measurement tool. The

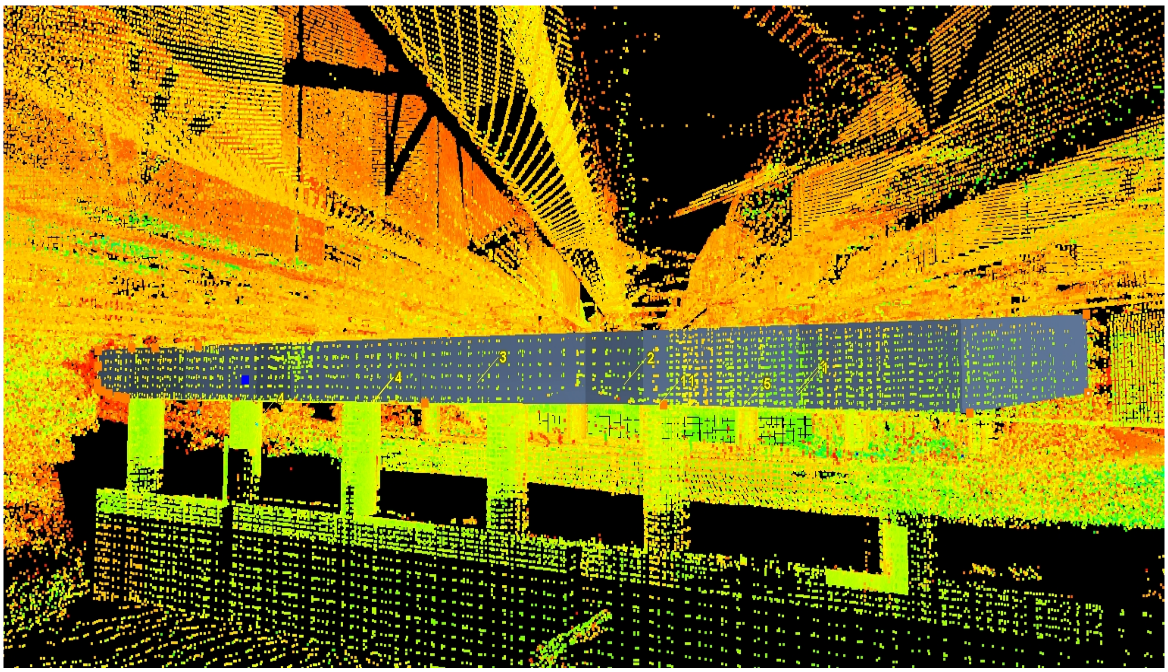

Figure 4.12: Reformed patch of the surface

same process was repeated for height and depth of footing. Once we obtained those three dimensional measurements, we can create our rectangular prism. From the menu bar, by clicking "Create Object", "Insert", "Box" option, a simple box was created. Also the "Box Insertion Properties" window popped up. We can enter the measured data of depth, width and

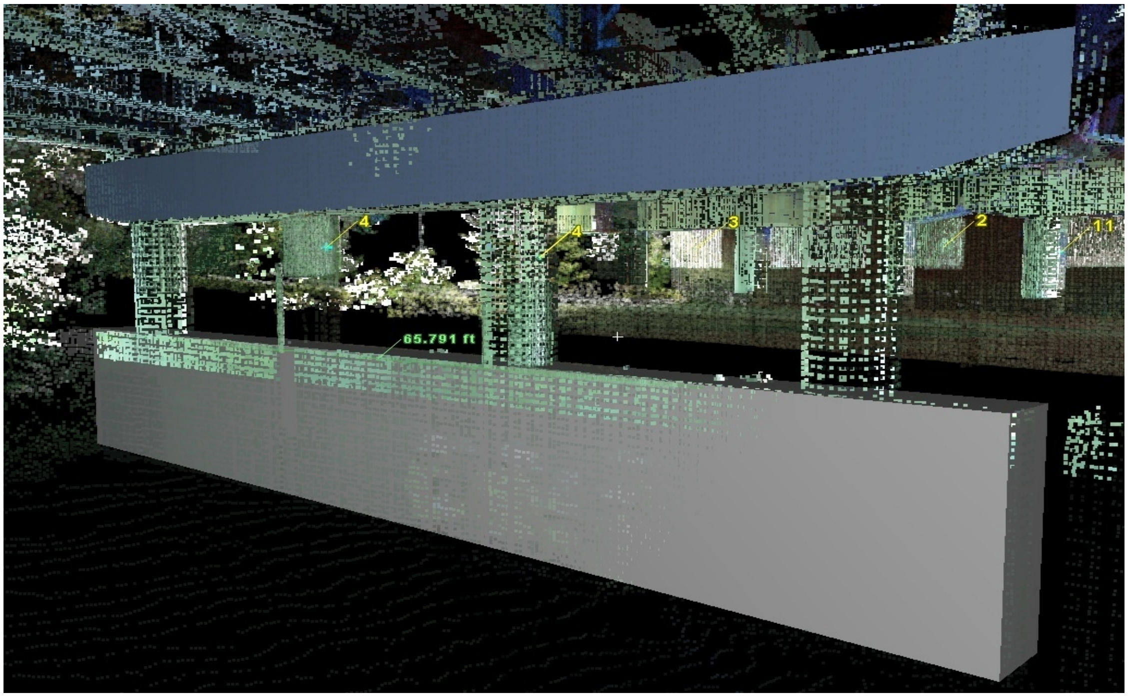

Figure 4.13: 3D model of Footing 2W

height of the footing and create the footing. Then, we can move the created 3D model of footing to its actual location on the scanned data. We repeat the same process for five other footing. Figure 4.13 shows the created footing model of 2W pier. We followed the same steps while creating 3D model of abutments.

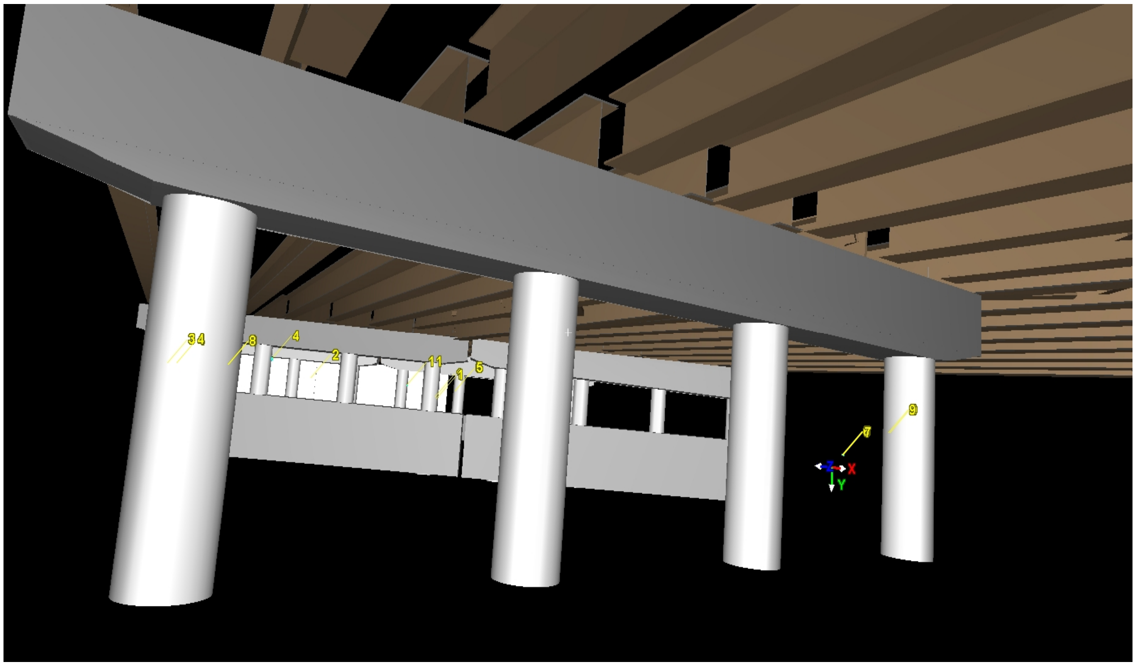

Figure 4.14 (a): 3D Model of a pier cap

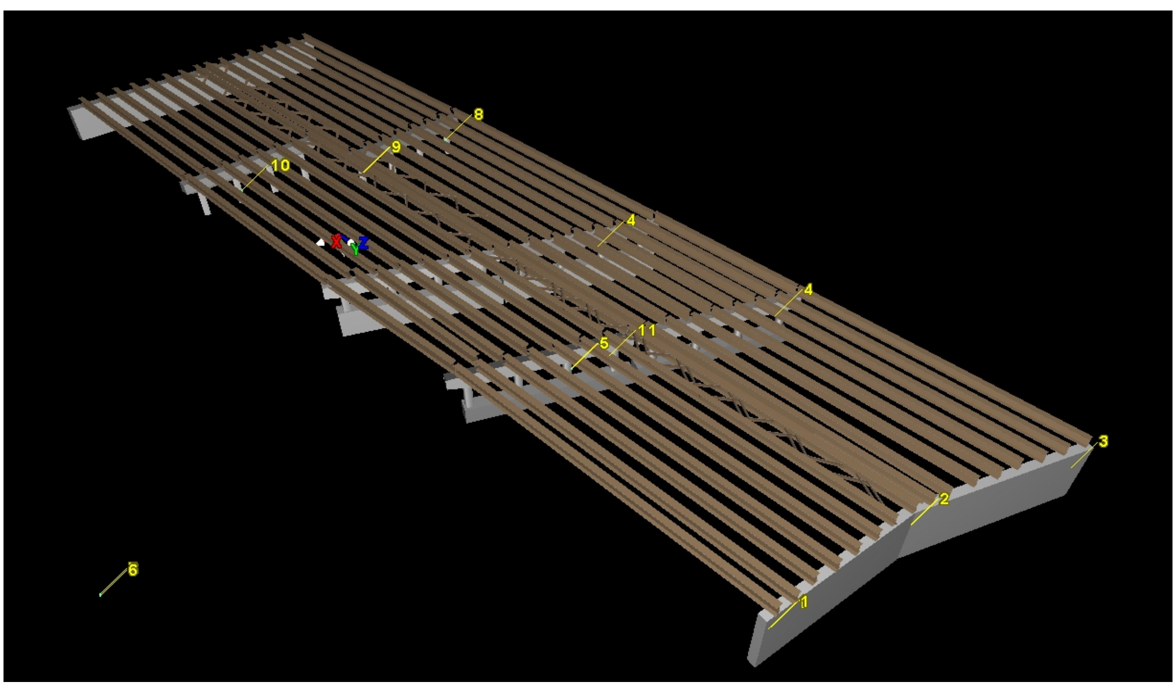

Figure 4.14 (b): 3D Model of the entire bridge

Due to the low resolution and high incidence angle while scanning underneath of the deck and girders, the scanned data of this part of the bridge is reliable. Some of the parts were not even scanned because of the limited time on the field; we mainly focused on the substructure, piers and abutments of the bridge. Girders of the bridge were created in the 3D model; however, the dimensions of the I-beams are inaccurate.

These steps are repeated for each part of the bridge. Because of its geometric shape, it took a long time to create the model of the pier caps. Each surface of the pier cap was created separately. The edge loss especially in long range with low incidence angle was high. The created patches did not cover the entire surface, so some side of the pier cap was created manually. The 3D model of the footings did not take too much time. They were created automatically and placed to their positions manually. Creation of 3D models of cylinders were made full-automatically. After selecting the points on cylinders, the software created the cylinders by itself. Some of their heights were adjusted manually.

4.2 Measurements, Geometric Results and Comparison

After all of the processes of data acquisition and model creation, it is apparent that precise geometrical data can be derived. The next step of this project will be measurements of acquired data and accuracy assessment. So far, by using Leica laser scanner and Cyclone computer software, we acquired the data, imported the data to the computer and created 3D model of the bridge by using Cyclone. By using Cyclone again, we will measure the dimensions of the bridge components and compare the results with actual bridge dimensions. As mentioned before, it is a simply supported bridge with four spans. It consists of six piers and two abutments. Every pier has one

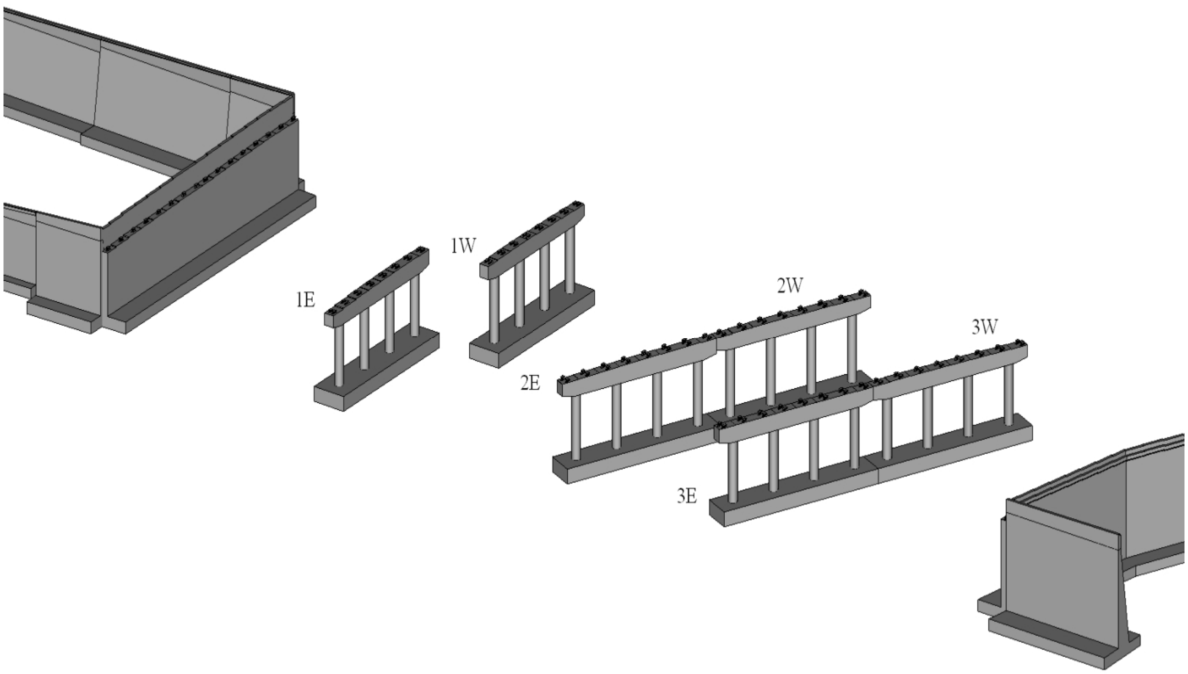

Figure 4.15: AutoCAD 3D Model of the Bridge shows the name of the piers

pier cap, four pier columns and one footing. After the registration of four different acquired scans, we measured the dimensions of those components of the bridge. To clarify the dimension comparison, we named each pier and abutment as they are named in the initial structural drawings of the bridge. Piers were named from south to north, east to west, and based on the span numbers; 1E, 1W, 2E, 2W, 3E, 3W. The components of the piers are also categorized by the pier names (Figure 4.15).

By using Microstation or AutoCAD software, and the initial structural drawings of the bridge, the dimensions of the all components of the bridge were measured. Then by using Cyclone, scanned data dimensions of the bridge were measured. The first two interested point were chosen, and then, from the tools menu, distance point-by-point option was used. It gave the distance between two points. After all measurements are saved, actual and scanned data results were compared.

4.2.1 Pier Cap Comparison

Table 4.1: Pier Cap 1E Measurement Results and Error Ratio

Pier Cap 1E Data	Top Length (ft)	Bottom Length (ft)	Depth (ft)	Height L ((ft)	Height R (ft)
Data from Drawings	61.00	51.50	4.00	4.00	4.89
Scanned Data	61.36	51.50	3.84	3.87	4.68
Difference	0.36	0.00	-0.17	-0.13	-0.21
Error Ratio (%)	0.59	0.00	-4.13	-3.33	-4.20

Table 4.2: Pier Cap 1W Measurement Results and Error Ratio

Pier Cap 1W Data	Top Length	Bottom Length	Depth	Height (Left)	Height (Right)
Data from Drawings	61.00	51.50	4.00	4.42	4.00
Scanned Data	61.78	52.19	3.73	4.36	4.10
Difference	0.78	0.69	-0.27	-0.05	0.10
Error Ratio (%)	1.28	1.35	-6.70	-1.24	2.43

Table 4.3: Pier Cap 2E Measurement Results and Error Ratio

Pier Cap 2E Data	Top Length	Bottom Length	Depth	Height (Left)	Height (Right)
Data from Drawings	66.50	56.00	4.00	4.15	4.02
Scanned Data	67.26	56.12	3.92	3.91	3.69
Difference	0.76	0.12	-0.08	-0.24	-0.34
Error Ratio (%)	1.14	0.22	-2.03	-5.69	-8.33

Table 4.4: Pier Cap 2W Measurement Results and Error Ratio

Pier Cap 2W Data	Top Length	Bottom Length	Depth	Height (Left)	Height (Right)
Data from Drawings	66.50	56.00	4.00	4.17	4.05
Scanned Data	66.53	55.98	3.81	3.90	3.99
Difference	0.03	-0.02	-0.19	-0.27	-0.06
Error Ratio (%)	0.05	-0.03	-4.78	-6.47	-1.53

Table 4.5: Pier Cap 3E Measurement Results and Error Ratio

Pier Cap 3E Data	Top Length	Bottom Length	Depth	Height (Left)	Height (Right)
Data from Drawings	66.50	56.00	4.00	4.57	4.40
Scanned Data	66.20	56.10	3.65	4.39	3.94
Difference	-0.30	0.09	-0.35	-0.18	-0.46
Error Ratio (%)	-0.45	0.17	-8.83	-4.00	-10.37

Table 4.6: Pier Cap 3W Measurement Results and Error Ratio

Pier Cap 3W Data	Top Length	Bottom Length	Depth	Height (Left)	Height (Right)
Data from Drawings	66.50	56.00	4.00	4.47	4.00
Scanned Data	66.30	55.97	3.62	4.45	3.92
Difference	-0.20	-0.03	-0.38	-0.02	-0.08
Error Ratio (%)	-0.30	-0.05	-9.58	-0.44	-2.00

4.2.2 Pier Column Comparison

Table 4.7: Pier Column Measurement Results and Error Ratio

Name	Diameter (ft)			
	Data from Drawings	Scanned Data	Difference (ft)	Error Ratio (%)
PIER COLUMN 1 (1E)	3.50	3.55	0.05	1.43
PIER COLUMN 2 (1E)	3.50	3.56	0.06	1.71
PIER COLUMN 3 (1E)	3.50	3.59	0.09	2.57
PIER COLUMN 4 (1E)	3.50	3.58	0.08	2.29
PIER COLUMN 5 (1W)	3.50	3.58	0.08	2.29
PIER COLUMN 6 (1W)	3.50	3.58	0.08	2.29
PIER COLUMN 7 (1W)	3.50	3.58	0.08	2.29
PIER COLUMN 8 (2E)	3.50	3.53	0.03	0.86
PIER COLUMN 9 (2E)	3.50	3.53	0.03	0.86
PIER COLUMN 10 (2E)	3.50	3.53	0.03	0.86
PIER COLUMN 11 (2E)	3.50	3.53	0.03	0.86
PIER COLUMN 12 (2E)	3.50	3.53	0.03	0.86
PIER COLUMN 13 (2W)	3.50	3.53	0.03	0.86

PIER COLUMN 14 (2W)	3.50	3.53	0.03	0.86
PIER COLUMN 15 (2W)	3.50	3.53	0.03	0.86
PIER COLUMN 16 (2W)	3.50	3.53	0.03	0.86
PIER COLUMN 17 (3E)	3.50	3.53	0.03	0.86
PIER COLUMN 18 (3E)	3.50	3.53	0.03	0.86
PIER COLUMN 19 (3E)	3.50	3.53	0.03	0.86
PIER COLUMN 20 (3E)	3.50	3.52	0.02	0.57
PIER COLUMN 21 (3W)	3.50	3.52	0.02	0.57
PIER COLUMN 22 (3W)	3.50	3.52	0.02	0.57
PIER COLUMN 23 (3W)	3.50	3.52	0.02	0.57
PIER COLUMN 24 (3W)	3.50	3.52	0.02	0.57

4.2.3 Pier Footings Comparison

Table 4.8: Pier Footing 1E Measurement Results and Error Ratio

Footing 1E	**Length (ft)**	**Depth(ft)**	**Height (ft)**
Data from Drawings	61.00	5.00	13.50
Scanned Data	N/A	N/A	N/A
Difference (ft)	N/A	N/A	N/A
Error Ratio (%)	N/A	N/A	N/A

Table 4.9: Pier Footing 1W Measurement Results and Error Ratio

Footing 1W	**Length (ft)**	**Depth(ft)**	**Height (ft)**
Data from Drawings	61.00	4.00	13.50
Scanned Data	N/A	N/A	N/A
Difference (ft)	N/A	N/A	N/A
Error Ratio (%)	N/A	N/A	N/A

Table 4.10: Pier Footing 2E Measurement Results and Error Ratio

Footing 2E	Length (ft)	Depth(ft)	Height (ft)
Data from Drawings	66.50	4.00	11.00
Scanned Data	66.67	3.29	N/A
Difference (ft)	0.17	0.71	N/A
Error Ratio (%)	0.26	17.75	

Table 4.11: Pier Footing 2W Measurement Results and Error Ratio

Footing 2W	Length (ft)	Depth(ft)	Height (ft)
Data from Drawings	66.50	4.00	11.00
Scanned Data	65.82	3.25	N/A
Difference (ft)	0.68	0.75	N/A
Error Ratio (%)	1.02	18.75	N/A

Table 4.12: Pier Footing 3E Measurement Results and Error Ratio

Footing 3E	Length (ft)	Depth(ft)	Height (ft)
Data from Drawings	66.50	4.00	11.00
Scanned Data	66.28	3.32	N/A
Difference (ft)	0.22	0.68	N/A
Error Ratio (%)	0.33	17.03	N/A

Table 4.13: Pier Footing 3W Measurement Results and Error Ratio

Footing 3W	Length (ft)	Depth(ft)	Height (ft)
Actual Data	66.50	4.00	11.00
Scanned Data	66.24	3.35	N/A
Difference (ft)	0.26	0.65	N/A
Error Ratio (%)	0.40	16.25	N/A

CHAPTER 5: SUMMARY, CONCLUSIONS AND RECCOMENDATIONS

5.1 Summary

3D laser scanner is a new data acquisition system in surveying and geographic data collection. Laser scanners are seen as surveying instruments, which satisfy the requirements of industrial needs. Laser scanners are used to acquire any object or real scene. Surveyors can then gain the 3D data of the objects or interested area. Although terrestrial laser scanners save time while data capturing, most of the available laser scanners are not well specified regarding accuracy, resolution and performance. Thus, reliability of the acquired data should be investigated.

Terrestrial laser scanners have begun to be used in civil surveying tasks such as infrastructure inspection projects. Unlike a traditional total station, making only a few measurements in an hour, terrestrial laser scanners can capture thousands of surface points. Direct digital measurement and recording of existing conditions of laser scanners reduces project execution risks and field rework. Precise geometric information of the bridges on inspection projects is also important for infrastructure design process. Geometric data such as length of the maximum span, structure length or minimum vertical clearance are some of the main parameters of the bridge inspection process. Regarding all of the above points, the main objective of the proposed research was to evaluate surveying methods of bridge inspection by using terrestrial laser scanners, in order to determine the reliability of the data acquired by laser scanners.

The objective of the proposed study was to investigate laser scanner data reliability on bridge inspection projects, with a focus on bridge substructures. Based on laser scanner data, specific bridge component dimensions have been measured and a 3D model of the bridge was created. By using point clouds, a 3D model of the bridge is created, dimensions of the pier components of the bridge were measured, and the results were compared with design drawing data. All the results and comparisons showed that the scanned data is reliable in terms of accuracy. Also data acquisition is faster and data density is much higher than other surveying methods.

The laser scanning project can be divided into two parts; field work and office work. On the field, the scanner, which is controlled by a notebook, was set up on four different locations. The scanning process was defined and completed with an appropriate density, which meets the accuracy requirements of the deliverables. Based on the requirements of survey, set up should link up with target points, which was used to register different point clouds into one coordinate system. The office work consisted of registering different point clouds from individual scans together into a single coordinate system by using the laser scanner software "Cyclone". By using registered point cloud, a 3D model creation of the bridge was made and, afterwards, the dimensions of the bridge substructures were measured.

In investigating the data accuracy of laser scanners, it can clearly be stated by looking at the data comparison tables in chapter four that, aside from some irregular conditions at the edges, error ratio is mostly under 1%. Some measurements could not be made due to some parts of the piers were underground. In general, results acquired from four scan points are satisfying.

5.2 Experience Gained

After the comparison of data by the laser scanner with design drawing data, we can say that terrestrial laser scanners are meeting the general engineering requirements. The accuracy of the measurements is dependent on the incidence angle between the laser beam and the object's normal. Generally, shorter range and sharp incidence angle will affect the data accuracy. An incidence angle less than 30 degrees of laser beam on the object's surface is preferable. An incidence angle less than 5 degrees will influence the precision of the measured points (Chow, et al. 2006).

One of the main purposes of using terrestrial laser scanners in bridge investigation projects is to measure the dimensions of the components of the bridge in a short time. However, object or scene features such as edges may not be completely measured by the laser beam due to its spot size. When spot size hits the edge of the surface, one part of the laser beam reflects from the surface while the rest of the laser spot reflects from a different surface. Thus, we will have two different measurements from the same laser spot. The surface or object edge may be missed from the data set due to noisy edges. This edging effect can be technically minimized by adjusting the resolution of the scanner to the smallest possible option. This option may avoid the possible edge loss during the scanning process. In this research, pier caps and columns were scanned with higher resolution while the other components of the bridge were scanned with moderate resolution. This gives us better measurement results on pier components with less than 1% error ratio. However, scanning process of these parts took a lot longer.

Terrestrial laser scanners demonstrate advantages over the traditional survey methods in the ground profile survey for bridges and roadways without any road closure. Field working time is relatively short in collecting the data as compared with the other surveying methods. With the ability to capture thousands of point per second, laser scanning greatly improves productivity. Also laser scanners reduce the direct labor cost and increase the safety of collection efforts. Laser scanning method on civil structure inspection projects provides a more complete capture of existing conditions and reduces the potential errors in new design work. However, laser scanning methods on civil inspection projects cannot be considered a replacement of other traditional methods. Supplementary survey by traditional methods for those areas blocked by line of sight or vegetation is still required. Total station is also used in this research. Laser scanner cannot shoot all the targets from one specific scan location due to some objects around such as electricity poles or some plants. Therefore total station is used to locate the target positions, determine the distance, and angle between them by using a reference point. In addition to this, considerable time is required to process the huge volume of data in the office. Office tasks in this research include point cloud registration, 3D model creation and measurements. Depending on the needs in the project, noise remove process at the edges, export of data to AutoCAD or different types of CAD software can be applied.

In addition, the scanning environment can be recorded with high definition camera mounted in laser scanners. By using this camera, specific scenes can be scanned instead of an entire area scan. These photos and comprehensive point clouds of the area can provide more complete and accurate data and minimize the needs of returning to the site for further investigations. A 3D model of the bridge can also be visualized for future detail design and analysis.

5.3 Technical Challenges

On the other hand, terrestrial laser scanners have limitations. It is not recommended in adverse weather conditions such as foggy, misty, rainy or windy weather, because the humidity in air may cause noise or false signals for the measurement. Also, wind may affect the stability of the laser scanner tripod. Like the other traditional survey equipment, a clear sight of the object is required. In addition, a surface with a shallow layer of water, due to its high reflectivity, may cause noisy point cloud data. In these kinds of occasions, more office time is required in order to filter the noise signals.

Another challenge faced during the laser scanning process was the environmental condition. Some dimensions on pier components could not be measured properly due to some plants and bushes around the piers. This type of problem can be avoided by removing small bushes around the piers or scanning the components from different locations.

All the comparisons are made between the design drawing and scanned data. In a construction progress, the structures may not be built as they are designed. So, the design and built model dimensions for the same structure components may be different. For a precise comparison, the bridge components need to be measured manually, so a precise comparison between the actual and scanned data can be obtained. However, manual measurements of the structures can be time consuming. Thus, another recommendation is to measure the bridge components dimensions by using a theodolite. After we received the measurements from the theodolite, our measurement comparisons can be more accurate.

Another technical challenge, which affects the data accuracy, is stability of the laser scanner. Laser scanner must be stable during the scanning process. Any kind of movement, settlement or vibration during the scanning process, can increase the error ratio of product. In this study, the laser scanner tripod was on the ground. Regardless of the stiffness of the soil ground, the laser scanner tripod may settle down. Even a millimeter of settlement can affect the data accuracy. To avoid the settlement problems, the laser scanner tripod should be set up on a triangle steel plate. The steel plate should be large and thick enough to distribute the weight of laser scanner and tripod on a larger area, thus settlement will be avoided.

5.4 Future Studies

3D laser scanners will be used more widely for the highway/bridge engineering survey applications in structural projects. Some scanning processes are combined and used with conventional survey methods for measurements, target acquisition or elevation differences. Also, laser scanners can detect the trend of movement or settlement of the whole structure by comparing the scanned 3D models captured at different times. Deformation monitoring is typically undertaken with point-wise surveying techniques, such as total station or GPS. Terrestrial laser scanners offer an opportunity to collect dense 3D point data over an object or surface of interest. A future study can be made to invest the application of terrestrial laser scanners on deformation monitoring and data accuracy.

Edge loss of scanned object is another aspect, which researchers should focus on. Mixed pixels can cause significant errors in the measurements of object dimensions in laser scanned data. Field experiments show that in most cases, the model substantially reduces the measurement percentages, by over 80% (Tang, et. al. 2009). Some algorithms can be developed which automatically detect the edge loss ratio, moderate two different measures from the same point and give more accurate results. Also, edge detection and advance filtering software related to laser scanners can be created. In this case, before the registration of point clouds, the developed software can be used to detect the edge loss and to clear the edge noises to give more accurate results.

Size of the laser spot can be another intense study on terrestrial laser scanning data accuracy assessments. As we know, laser beam spot size has a significant influence on data accuracy. The small size of the laser spot gives more accurate results. Leica HDS 3000 terrestrial laser scanner has 4.5 mm diameter spot size at 50 m range. However, the size of the laser beam is going to be bigger in a longer range. Bigger spot size will increase the risk of edge loss. To avoid this problem, another algorithm, which enables users to adjust the laser spot size, can be modeled. In this case, regarding range or incidence angle, surveyors can set the laser spot size prior to the laser scanning process to avoid the edge loss.

Another study that can be conducted in order to broaden the use of laser scanners is the integration of laser scanners with ground penetrating radar systems. As we know GPR systems are used to investigate the underground, to receive the 3D fusion data. GPR allows detailed images of sub-surface to be seen in real time. With the scanned data from scanners, 3D model of subsurface can be created. This future study can be very beneficial for geotechnical or archeological research.

5.5 Final Conclusions and Recommendations

Compared results between the design and scanned data show that terrestrial laser scanners' data accuracy is reliable. Error ratios for bridge components' measurements, such as pier cap length or pier column height, is less than expected. Even some measurements such as column diameters' error ratios are 0.05%. However, the depth measurement of the bridge components gives error ratios up to 18%. While Pier cap 1E length measurement gives 0.59% error ratio, the depth measurement gives -4.13%. Since the range remains the same, the only reason for a large difference between depth and length measurements on the same bridge component is incidence angle. Reducing the incidence angle can solve this type of problems. Also in longer range, instrument calibration may is needed for more accurate results due to laser spot size change.

To conclude, 3D data acquired data by terrestrial laser scanners is evaluated. Measurements and error ratios show that 3D laser scanners measurements are reliable in terms of accuracy. Closure of road is not required while laser scanning process. Surveys can occur with traffic. That also speeds up the construction process. A 3D model of the bridge also can be imported to CAD software such as AutoCAD or Microstation. By using scanned data, we can create surfaces and poly lines and model roadways or bridges with the created data. There are some restrictions, such as environmental or atmospheric conditions. Technical challenges, such as incidence angle, can significantly influence data accuracy. Future studies are needed to avoid those affects.

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