OPTIMAL CLOUD TOPOGRAPHIC MODEL BY STATISTICAL EVALUATION FOR LARGE SCALE MAPPING USING GEODETIC TERRESTRIAL LASER SCANNER

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DEDICATION

This thesis is dedicated to my beloved parents, wife, kids and siblings

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ABSTRACT

Terrestrial laser scanning (TLS) technology is increasingly being used for diverse types of applications such as surface reconstruction, forestry, metrology, cultural heritage preservation, reverse engineering, mine volume estimation, topographic mapping, architecture, urban planning, forensics, visualization and modelling artificial features. This technology has caused a paradigm shift in surveying from measurement of individual points to fast acquisition of accurate and highly dense 3D points. Acceptance of this technology for topographic surveying and mapping of large area and scale warrant the development of standardized specifications for data capture. Presently, most surveyors adopt the methodology of scanning as dense as possible due to fear of incomplete data, which is not the appropriate approach. Besides, the technology of geodetic TLS is almost matured, and not much research has been reported in deciding the optimal geometrical arrangements for undertaking surveys. Furthermore, previous scanning practices are qualitative in nature and present no or limited guidance or standards and practices for surveyors towards optimization. This study generated an optimal cloud topographic model using geodetic TLS technology through mathematical modelling, statistical and/or experimental evaluation for large areas and scale topographic surveying towards the development of Digital Terrain Models (DTM). In this study, scanning geometry parameters were studied/evaluated through mathematical modelling and practical experimentation in the field along with the evaluation for fast and accurate registration/georeferencing technique. Initially, during a survey, surveyors in the field can regulate scanning geometry parameters of TLS whereas other factors such as object properties, atmospheric effects and scanning mechanisms cannot be controlled. However, the critical scanning geometry parameters of TLS which include resolution, range, incident angle, laser footprint, scanner location and/or overlaps can be controlled. Experiments were carried out to verify the developed mathematical models and investigate the effects of scanning geometry parameters on the survey results. The result of these experimental investigations verified the mathematical models, which can assist surveyors prior to locating the optimal position of the scanner even for specific surveys such as archaeological sites, historical buildings and other types of survey to attain optimal results. In addition, topographic surveys through experiments and statistical analysis produced optimal range identified as ±100 m with high speed mode, optimal spatial density corresponding to angular increment of 50mm @ 10 m, maximum incident angle was ±85° and registration/georeferencing technique was occupation-backsight for large area and scale DTM. These mathematical models and experiment results can act as standards and practices guiding surveyors to carry out large area and scale topographic surveying or other specific surveys. These will help in reducing time for data collection and processing, labour and final cost of project besides assuring completeness of data. The developed mathematical models may be incorporated in the new generation of TLS that are likely to have capabilities of total station, which will further help surveyors to manage scanning geometry parameters for optimal cloud.

ABSTRAK

Teknologi pengimbas laser bumi (TLS) semakin banyak digunakan untuk pelbagai jenis aplikasi seperti pembinaan semula permukaan, perhutanan, metrologi, pemuliharaan warisan budaya, kejuruteraan yang bertentangan, anggaran isipadu lombong, pemetaan topografi, seni bina, perancangan bandar, forensik, visualisasi dan pemodelan butiran titik-titik. Teknologi ini menyebabkan pertukaran paradigma dalam mengukur dari pengukuran individu kepada pemerolehan cepat dengan titik 3D yang tepat dan sangat padat. Penerimaan teknologi ini bagi ukur topografi dan pemetaan kawasan berskala besar menjamin pembangunan bagi spesifikasi standard untuk pemerolehan data. Pada masa kini, kebanyakan jurukur mengamalkan metodologi pengimbasan yang terlalu padat kerana khuatir data tidak lengkap, yang merupakan pendekatan yang kurang sesuai. Selain daripada itu, teknologi TLS geodesi hampir mencapai tahap matang, dan tidak banyak kajian telah dilaporkan dalam menentukan susunan geometri optimum untuk menjalankan pengukuran. Selain itu, amalan pengimbasan sebelumnya adalah bersifat kualitatif dan tiada panduan atau piawai dan amalan yang terhad untuk para jurukur ke arah pengoptimuman. Kajian ini menghasilkan model topografi awan yang optimum menggunakan teknologi TLS geodesi menerusi pemodelan matematik, statistik dan / atau eksperimen untuk ukur topografi berskala besar ke arah pembangunan Model Paramukaan Berdigit (DTM). Dalam kajian ini, pengimbasan geometri telah dikaji / dinilai melalui pemodelan matematik dan eksperimen praktis di lapangan bersama dengan penilaian untuk teknik pendaftaran geodesi yang cepat dan tepat. Pada mulanya, semasa tinjauan, juruukur di lapangan boleh mengawal selia pengimbasan geometri TLS sementara bagi faktor lain seperti sifat objek, kesan atmosfera dan mekanisma pengimbasan tidak dapat dikawal. Walau bagaimanapun, parameter geometri pengimbasan kritikal TLS yang merangkumi resolusi, julat, sudut insiden, jejak laser, lokasi pengimbas dan / atau tindihan boleh dikawal selia. Ujian telah dijalankan untuk mengesahkan model matematik yang telah dibangunkan dan mengkaji kesan pengimbasan parameter geometri hasil kajian. Keputusan ini mengesahkan model matematik, yang dapat membantu juruukur sebelum mencari kedudukan optimum pengimbas walaupun untuk pengukuran tertentu seperti tapak arkeologi, bangunan bersejarah dan jenis ukuran lain untuk mencapai hasil yang optimum. Selain itu, ukur topografi melalui eksperimen dan analisis statistik menghasilkan jarak optimum yang dikenal pasti sebagai ± 100 m dengan mod kelajuan tinggi, ketumpatan spatial optimum yang sepadan dengan kenaikan sudut 50mm @ 10 m, sudut insiden maksimum ialah ± 85° dan teknik pendaftaran adalah kedudukan – pandangan belakang untuk kawasan besar dan skala DTM. Model matematik dan hasil eksperimen ini boleh dijadikan sebagai piawaian dan amalan yang membantu juruukur untuk menjalankan ukur topografi kawasan besar atau pengukuran khusus yang lain. Ini akan membantu mengurangkan masa pengumpulan dan pemprosesan data, kos buruh dan kos akhir projek selain memastikan kesempurnaan data. Model matematik yang dibangunkan mungkin dimasukkan ke dalam generasi baru TLS, yang mungkin mempunyai keupayaan stesen penuh, yang akan membantu jurutera untuk menguruskan parameter pengimbasan geometri untuk pengumpulan awan yang optimum.

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LIST OF ABBREVIATIONS

ALS	Airborne Laser Scanning
AMCW	Amplitude Modulated Continuous Wave
CW	Continuous Wave
DEM	Digital Elevation Model
DPS	Digital Photogrammetric Systems
DTM	Digital Terrain Model
EDM	Electronic Distance Measurement
EOPs	Exterior Orientation Parameters
FM	Frequency Modulation
FOV	Field of View
GCP	Ground Control Point
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRS	Geographic Reference System
ICP	Iterative Closest Point
IRS	Internal Reference System
LiDAR	Light Detection And Ranging
LOD	Level of Detail
MLS	Mobile Laser Scanner/Scanning
PRR	Pulse Repetition Rate
RMSE	Root Mean Square Error
SAR	Synthetic Aperture Radar
SNR	Signal to Noise Ratio
SOP	Standard Operating Procedures
TLS	Terrestrial Laser Scanner/Scanning
TOF	Time of Flight

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Surface of earth comprises of relief, natural features and man-made features which are generally referred to as topographic features or simply the topography of earth. The planimetric locations and elevations of all the features are determined through topographic surveys which are performed to prepare highly detailed topographic maps and digital databases. The features along with their details are processed through cartographic rules and then are represented in hard copy cartographic maps or used in Geographic Information System (GIS) for future reference in a diverse nature of applications/requirements. The geographic feature data is captured as per some scale which depicts the level of details (LOD) to be represented in the topographic map. The scale is usually represented by a ratio of map distance to ground distance e.g. 1:1000, which means one unit on map is representing 1000 units of ground. Map scale is generally confused or misinterpreted because the larger the map scale, the smaller the reference number and vice versa. For example, a 1:1000 scale map is considered a larger scale than a 1:25000 scale map.

There are many techniques used in topographic surveying which can be categorised as manual or remote sensing techniques (Gallay *et al.*, 2013). The use of total station, Global Navigation Satellite System (GNSS) e.g. Global Positioning System (GPS) or geodetic Terrestrial Laser Scanning (TLS) are the manual methods whereas the use of aerial photogrammetry, aerial LiDAR (Light Detection And Ranging), Synthetic Aperture Radar (SAR) and satellite imagery are the remote sensing techniques. All the techniques have varying accuracy, time and cost associated with them which are kept in mind before conducting any topographic survey. If we critically analyse all the techniques, we conclude that use of total station and GPS are relatively low cost, more accurate but are time and labour intensive and results in very low density of points. Aerial photogrammetry, aerial LiDAR and satellite remote sensing on the other hand are relatively less labour intensive, less time consuming, medium in accuracy but high in cost and results in high density of points. Geodetic TLSs can be placed in between above two domains of topographic surveying techniques as these are medium in cost, highly accurate, moderately time and labour intensive and yielding high density of points with high level of completeness. Barber (2011a) characterized the 3D survey technologies based on the scale i.e. the object size they could measure, spatial density required to define small and complex objects and accuracy (Figure 1.1).

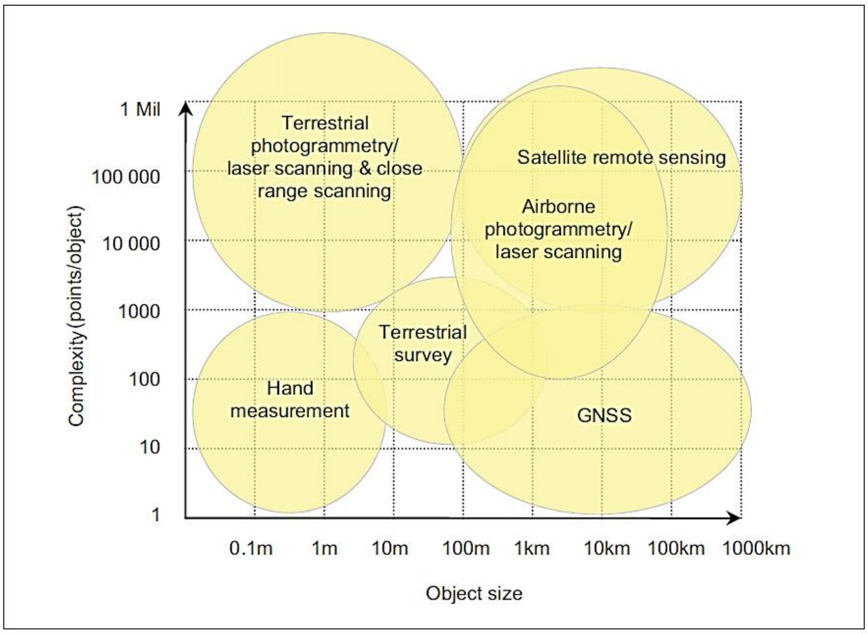

Figure 1.1 3D survey systems categorised by object size vs probing density of points for detection (scale) adopted from (Barber, 2011a)

Since last decade and half, the technology of geodetic TLS is becoming popular amongst the surveying community for topographic surveying because of its capability of collection of millions of points within seconds with high accuracy. But the adaptation of this technology for mainstream land surveying is slow due to some of following factors:

(a) Both surveyors and clients lack understanding of its potential applications.

(b) Its benefits compared with other technologies are not completely understood.

(c) The limitations lack understanding.

(d) Shortage of trained personnel in this technology.

(e) Lack of knowledge about capital outlay compared to other technologies.

Despite the above mentioned factors, currently geodetic TLSs are increasingly been used for a diverse type of applications like surface reconstruction, forestry, metrology, cultural heritage preservation, reverse engineering, mine volume estimation, topographic mapping, architecture, urban development, forensics, visualization and modelling artificial features etc. This technology has made a paradigm shift in surveying from measurement of sparsely dense individual points to fast acquisition of accurate and highly dense 3D point cloud. Now the geodetic TLS systems are also equipped with external or in-built cameras to acquire images of areas being scanned, thus capable of providing photorealistic 3D coloured point cloud (Luh *et al.*, 2014). The primary advantages of this technology include following, derived from Lichti *et al.* (2005b) but not limited to:

(a) **Data Acquisition Speed**. Very fast speed of data collection of even more than one million points per second thus allowing no disruption to routine activities like traffic stops etc.

(b) **Safety**. Because of its reflectorless nature i.e. it don't require prism pole to be placed at some point, it offers obvious advantages to both surveyor and the road user.

(c) **Additional Information**. Many useful information like power line clearances above land, height of electric and light poles, types and height of fences etc which are usually not available with conventional surveying techniques are captured.

(d) **Cost**. Although it has larger capital cost compared to total station/GPS but it can be compensated in any project cost which require lane closures or other traffic control measures during survey. The cost advantage and safety advantages are closely linked.

An overview of use of this technology for different projects including the accuracy achieved, efficiency and analysis can be found in Pinkerton (2011). Kościuk (2012) tried to classify the main deliverables of TLS based on accuracy and loss of original data reliability while elaborating data. Table 1.1 displays the main classification of TLS deliverables for visualization and documentation of architectural heritage and structural analysis which are also applicable for other types of topographic surveys. The table is represented in descending order of accuracy and data reliability.

Table 1.1 Main classification of TLS deliverables based on accuracy and loss of original data reliability while elaborating data (Kościuk, 2012)

3D Point Cloud of TLS		
Serial	**3D Representation**	**2D Representation**
1.	Point cloud visualization in reflection intensity mode	Intensity image orthophoto delivered from 3D point cloud
2.	Point cloud visualization in colour (RGB) mode	Colour (RGB) intensity orthophoto delivered from 3D point cloud
3.	Manual or semiautomatic delivery of 3D line wireframe drawings (plans, views, sections) from 3D point clouds	Manual or semiautomatic delivery of 2D line wireframe drawings (plans, views, sections) from 3D point clouds
4.	Delivery of 3D mesh models from 3D point clouds	Textured black & white or colour orthophoto delivered from mesh models
		Delivery of 2D line drawings (plans, views, sections) from 3D mesh models
5.	Direct delivery of 3D solid models manually or semi automatically from 3D point clouds	Delivery of 2D line drawings (plans, views, sections) automatically from 3D solid models
		Delivery of 2D line drawings (plans, views, sections) through manual or semiautomatic on-screen digitization from orthophoto or photomosaic

1.2 The Research Gap

Choice of the survey method depends upon the requirement of accuracy which ultimately depends on the application, accessibility of the area to be surveyed, the sampling density required, time, expertise and budget available. Gallay *et al.* (2013) assessed four methods of surveying namely total station, GPS survey, TLS point cloud and Airborne Laser Scanning (ALS) for creation of Digital Terrain Model (DTM). They collected data on two types of terrain comprising of almost flat (height difference ≤ 2 m) alluvial plain having low cut meadows with area of 0.95 ha (9500 m^2) and an uneven terrain (height difference ≤ 70 m) with slope varying between 8 – 26 degrees with area 2.5 ha (25000 m^2). The TLS data was reduced about 10 times and an average point density of 4 points/m^2 was used and this density was still more than other methods. The GPS results were more accurate than TLS and ALS in both types of terrain whereas TLS was accurate than ALS in flat ground but ALS exhibited more accuracy than TLS in uneven area.

Since 1990, when the world's first 3D commercial laser scanner was launched in USA by Ben Kacyra, an Iraqi expatriate and civil engineer (Kościuk, 2012), this equipment is advancing technologically as well as its utility in diverse type of applications. It can be seen by just typing "laser scanner and its applications" phrase into Google Scholar, one can see thousands and thousands of papers published on this subject. Geodetic Terrestrial laser scanners are becoming more available because of the increase in demand of affordable, user friendly and efficient devices for widespread applications. Currently it has been broadly recognised as a reliable 3D measuring instrument in many disciplines and is being used for a variety of applications requiring different accuracy standards in the last two decades. Abellán *et al.* (2006) used Ilris3D TLS from OPTECH which can exhibit an accuracy comparable to a reflectorless total station of 4 mm at 100 m for study of rock fall in an area of 300 x 500 m. They acquired about 4 million points using range between 180 to 870 m for generation of high quality Digital Elevation Model (DEM).

Eisenbeiss and Zhang (2006) generated a Digital Surface Model (DSM) using Riegl LMS-Z420i TLS of the cultural heritage site Pinchango Alto in Peru having an approximate area of 3 ha (30,000 m^2). They acquired 144 million points from 57 scans having point spacing between 1 – 35 cm depending on the range and registered the data using 48 Ground Control Points (GCPs). The data was further reduced to 14.8 million points and further split into two files to overcome the computer's memory limitation. This resulted into 5 cm grid size data which was then used for DEM generation. Kwoczynska *et al.* (2016) used FARO Focus 3D scanner for survey of historic buildings and scanned a castle and a crypt for generating a 3D model for visualization. Pukanská (2012) used Leica ScanStation C10 scanner for fast survey and visualization of spatial information about objects present inside four different laboratories at BERG faculty. The objects were subsequently modelled from point cloud having spatial density of 2 cm on 5 m distance using Leica Cyclone and SketchUp soft wares. O.C Wei *et al.* (2019) used TLS for reconstruction of photorealistic 3D model for virtual museum applications

Feagin *et al.* (2014) used Leica ScanStation 2 TLS for assessing temporal coastal geomorphic fluctuations in vegetation and sediments of sand dunes after Hurricane Ike by collecting data on an area 100 m × 100 m in Texas. They performed the analysis on interpolated gridded surfaces having 0.05 m, 0.10 m, 0.50 m, 1.00 m and 5.00 m spatial resolutions. Their analysis conceded 0.5 m × 0.5 m grid size as the best grid size because it best handled errors induced by shadows in point cloud and at the same time yielded well resolved sand dune topography. Jalonen *et al.* (2014) employed TLS for applications in hydraulic engineering for vegetation properties and information about flood plain ground level. They scanned a 4 – 6 m wide and 200 m long channel using Leica ScanStation 2 and Leica ScanStation C10 in 2011 and 2012 using resolution of 2 cm at 20 m and 1 cm at 20 m respectively and generated DTMs for both times for further analysis.

TLS has also been used by construction industry for variety of applications, one such is deformation monitoring which require very high accuracy of mm level. Mill and Ellmann (2014) monitored the deformation in a large suspension acoustic screen under snow weight in Estonia using temporal measurements aiming at an accuracy of ±5 mm. They used Leica ScanStation C10 having one scan at temperature of -1ºC. Yang *et al.* (2017) used Z + F IMAGER 5006 TLS for investigation of deformation in an arch-shape edifice having a span of 2 m and thickness of 10 mm, made of concrete and brick material under 13 epochs of load pressure.

Applications of TLS in engineering geological domain are numerous where it has been used for different varieties of circumstances. Nguyen *et al.* (2011) acquired temporal data for investigation of volcanic rock slopes in Portugal using Optech ILRIS-3D scanner. The TLS data was used for volcanic environment characterization, structural analysis and for unstable rock mass detection.

Very few authors have tried to exploit the potential of use of TLS for topographic surveying and mapping. The existing surveys are limited to small areas for some specific discipline or study. Lichti *et al.* (2005b) investigated the use of TLS for digital survey of a road intersection in terms of accuracy. They used two TLSs Riegl LMS-Z210 and a Cyra Cyrax 2500 for scanning of road intersection having extents of 170 m along all four legs. The accuracy was tested for five different road classification standards of Main Roads Western Australia having horizontal accuracy ranging from ±20 mm to ±250 mm and vertical accuracy from ±15 mm to ±40 mm for point and linear features against a ground truth data obtained with Leica TCR 1105 total station. They observed that both scanners met the requirement of ±150 mm horizontal accuracy whereas Cyrax obtained an accuracy of ±25 mm and ±20 mm for horizontal and vertical requirements respectively. Luh *et al.* (2014) investigated the suitability of TLS for collection and production of topographic data using Leica ScanStation C10. They carried out close traversing covering an area of approximately 70754 m^2 using both the scanner and the total station occupying same traverse stations. They used medium resolution (0.1m point spacing at 100 m for both horizontal and vertical), full Field of View (FOV) of C10 and maximum range of up to 200 m and obtained a linear misclosure of 1:66541 which means first class survey. After data processing, the features were digitized manually and contours generated from DTM resulting into a 2D topographic map of scale 1:1000. N. A. S. Russhakim *et al.* (2019) compared TLS with MLS during a building survey and mapping application and found better accuracy results for TLS. Its data can be integrated with other sensors like ALS for better reconstruction of 3D objects like building reconstruction done by Abdullah *et al.* (2017).

Above are very few examples on use of TLS whereas since its inception, its applications are increasing day by day in all disciplines. It is enough to type a phrase “Applications of Terrestrial Laser Scanners” in google scholar and one will find more than 17000 search results but if the search is made year wise, the total results are even more than 50,000 till 2016 (Figure 1.2). It clearly indicates that geodetic TLS is now a well-recognized, trusted and well established technology for direct 3D measurements.

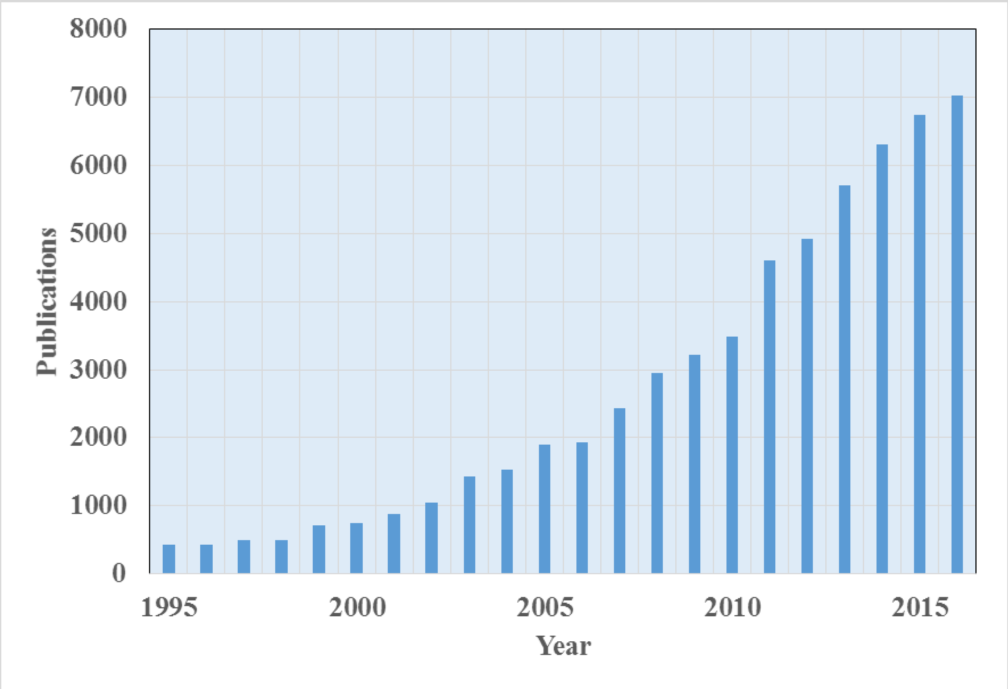

Figure 1.2 Google scholar search results on “Applications of Terrestrial Laser Scanners” phrase (Accessed on May 10, 2017)

Despite the establishment of geodetic TLS for 3D survey, many authors are involved in achieving successful results for more and more sophisticated applications, some are involved in investigations and improvements in its measurement accuracy and very few are concerned about establishment of a code of conduct and applicability principles for different disciplines. Because of lack of recognized standards or guiding principles for 3D geodetic TLS topographic survey, most of surveyors are adopting the approach of scanning as dense as possible which does not seem to be an appropriate choice at all.

Therefore, in general, it has been noted that there is a need of investigation and evaluation of effects of TLS scanning parameters like range, angular resolution, spatial density, incident angle, laser footprint size, multiple scan overlapping requirements and registration/georeferencing technique for optimal point cloud topographic surveying of different areas for mapping applications at large scale.

1.3 Problem Statement

Large scale topographic maps finds their utility in numerous disciplines extending from civil engineering to geoinformation. These topographic maps serves as basic input for decision making ranging from planning of any type of infrastructure to analysis of any disaster management activity like flood hazards. In order to help the decision makers to reach at adequate decision, the scale and quality of topographic map should be appropriate enough to serve the purpose. It is significant to collect accurate and detailed topographic data used for various applications. Many applications have basic requirement of level of accuracy and level of detail because less detailed or inaccurate data become a source of undesirable uncertainties in decision making. Surveyors must ensure to use a technology for data collection which ensure the quality and have minimum impact on other activities because unnecessary interference may cause delays, rework or low quality leading to further delays and poor decision. Geodetic TLS technology (Figure 1.3) has created space in 3D data collection and has addressed the problems of data quality with no or minimum interference with other activities.

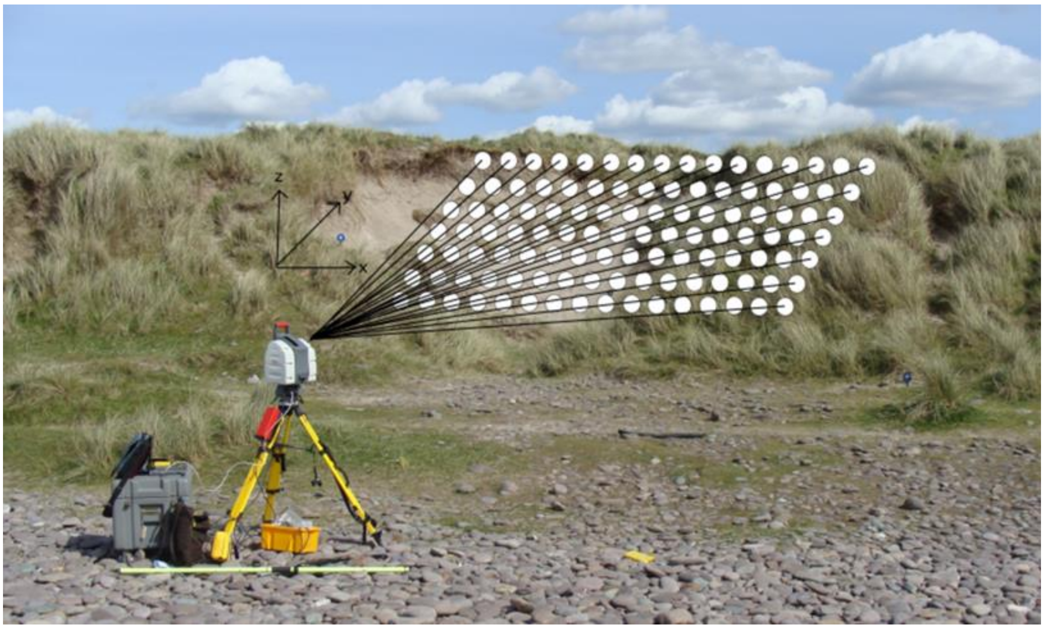

Figure 1.3 Geodetic TLS – Surface points represents the location of laser reflection (Kandrot, 2013)

Use of geodetic TLS have become popular in surveying and mapping community and are being used in many types of applications like archaeology, forest mapping, engineering constructions, geological findings etc. Surveyors who are responsible for making topographic maps are mostly using Airborne Laser Scanning (ALS), Mobile Laser Scanning (MLS), Photogrammetry, Remote Sensing imagery form Satellites or traditional equipment of Total Stations and Digital levels. Some of these technologies are either cost intensive or labour intensive giving varying accuracies. Acceptance of geodetic TLS for topographic surveying and mapping warrants the development of standardized specifications for data capture and presentation. At present the technology of geodetic TLS has almost been matured but very less work has been reported in deciding about the optimal geometrical arrangements for undertaking topographic survey for mapping (Luh *et al.*, 2014), although few authors have tried for some specific applications (Bryan *et al.*, 2004) and (Barber, 2011a). Most of previously developed scanning practices are qualitative in nature and present no or limited guidance for surveyors for optimization using trade-offs between requirement, geometrical arrangements and data collection and processing time which ultimately affect the cost of project.

Millions of points with high redundancy obtained in one scan pose difficulties for data processing especially when creation of DTM is concerned. Use of Geodetic Terrestrial Laser Scanners for large scale topographic mapping is limited due to non-availability of standardized technological guiding principles or procedures for deciding the requirements of optimal range, angular resolution, spatial density, accuracy, number of scanning stations, overlapping requirements and fast and accurate registration/georeferencing technique.

1.4 Research Questions

To improve the effectiveness of using geodetic TLS for large scale topographic surveying application, the research focuses on addressing answers to following general questions:

(a) What is the optimal range to be used which ensure required accuracy.

(b) What is optimal angular resolution required for DTM generation meeting the accuracy requirements at 1:1000 scale.

(c) How spatial density (inter point spacing) affects other geometric arrangements like scanner location, LOD and hence accuracy.

(d) How incident angle and laser footprint are related and what are their effects on 3D data for DTM.

(e) How many scan stations are required for scanning which depends on requirement of overlapping of scans, if required, i.e. what is optimal overlap or convergence angle of two scans for DTM?

(f) Which registration/georeferencing technique is fast, accurate and minimum laborious in field.

1.5 Aim and Objectives of Study

The aim of this research is to generate the optimal cloud topographic model for large scale and area topographic surveying using geodetic TLS technology. The main objectives required to achieve the aim are:

(a) **Prelude to Objectives**: To assess the current use of geodetic terrestrial laser scanning technology for topographic surveying and mapping.

(b) **Objective 1**: To generate the optimal cloud topographic model for larger area topographic surveying towards guiding standards and practices.

(c) **Objective 2**: To validate the efficacy of models through statistical and/or experimental validation.

The specific research questions which will be addressed during this study to achieve the above mentioned aim and objectives are summarized in Table 1.2.

Table 1.2 Research questions required for achievement of research objectives

Research Aim	Research Objectives	Research Questions
To generate the optimal cloud topographic model for large scale and area topographic surveying using geodetic TLS technology.	**Prelude**: To assess the current use of geodetic terrestrial laser scanning technology for topographic surveying and mapping	(a) What is the geodetic TLS technology? (b) How geodetic TLS have been used for digital ground surveys in the past. (c) What is the accuracy achieved and influencing factors on accuracy? (d) What are critical parameters for optimal cloud topographic model?
	1. To generate the optimal cloud topographic model for larger area topographic surveying towards guiding standards and practices	(a) Can inter point spacing be determined before specific surveys and how it affects the scanner location? (b) What is the optimal angular resolution (spatial density) for DTM? (c) What effects incident angle and laser footprint has on DTM? (d) What will be the optimal range for topographic survey? (e) Which registration/georeferencing technique is less time consuming, less laborious and meet the accuracy requirements. (f) How much overlapping is optimal within adjacent scans, if needed?
	2. To validate the efficacy of models through statistical and/or experimental validation	(a) How models of critical survey parameters will be validated through statistical or experimental evaluation. (b) What is the correlation between critical survey parameters? (c) Validation through traverse survey.

1.6 Significance of Study

Without any Standard Operating Procedures (SOPs) or guidelines, use of geodetic TLS for surveying purposes will continue to be on adhoc basis or on trial and error resulting expensive in terms of money, time and safety. Therefore, the full realization of benefits of geodetic TLS for topographic surveying merits the development of operational standards which will promote correct and consistent use of this technology. The guidelines will help the surveyors to select appropriate geometrical scanning parameters and use optimal scan settings for survey.

It is believed that standardized guiding principles will encourage the surveyors for use of geodetic TLS for topographic surveying and will add value to the survey work till the end user. Furthermore use of guidelines will have economic benefits by involving less time and labour in data collection and it will ensure that deliverables are clearly understood by client, will ensure best value due to check on provided data and will minimize requirement of further work because of completeness.

1.7 Scope of Study

The study is concerned about the development of optimal cloud topographic model for mapping at larger area and scale by using geodetic TLS encompassing following.

(a) The research has focused on generation of DTM of areas excluding forests (so applicable in approximately 70% of area in Malaysia).

(b) Geodetic TLSs have many types based on area coverage like panoramic, hybrid and camera and range measurement technology like pulse based or Time of Flight (TOF), phase difference and triangulation based. These are briefly discussed in Chapter 2. For long ranges, TOF scanners are mostly employed and since this study focuses on optimal cloud for field employment so TOF scanner of Topcon medium range GLS 2000 has been used (Figure 1.4).

Figure 1.4 Topcon GLS 2000 Laser Scanner (Topcon, 2018)

(c) For deciding on optimal parameters (scanning resolution, spatial density, range, incident angle, laser footprint, scanning overlap and registration/georeferencing technique), field tests has been carried out by scanning prism targets and natural land features. Targets provided by Topcon were small in size and large targets were not available and also has low reflectivity so tests were carried out using prisms.

(d) Since the prisms/targets needs to be placed at known distances from scanner for determination of accuracy standards so total station and measuring tapes were used for their placement.

(e) For data processing the ScanMaster software provided by the vendor was used.

(f) Since the DTMs were required to be compared so other softwares like ArcMap of ArcGIS and Erdas Imagine were used for the purpose.

(g) The accuracy standard for DTM was taken as per ASPRS standards for 1:1000 scale. The choice of 1:1000 scale is due to reasons as discussed in section 2.2, smaller scales can be generated through generalization.

(h) For statistical evaluation of data Microsoft Excel and statistical tools of ArcGIS were used.

(i) Bench marking for traversing and other tests where required was carried out using total station Trimble M3 so as to compare the survey accuracy obtained from geodetic TLS.

(j) GPS was used for establishing base line for traverse but later, the points were not used so as to avoid error contribution of GPS in accuracy comparison.

(k) The field tests were performed in available spaces within the premises of University Technology Malaysia (UTM) Johor Bahru.

(l) Optimal cloud was validated through traverse survey.

(m) Mathematical models developed were validated through experimentation and mathematical checks.

1.8 Contribution of the Study

At present most surveyors involved in survey and mapping are not following any guidelines for use of geodetic TLS in the field. They just take the instrument in the field and start scanning using as dense as possible point cloud approach resulting into extra cost, effort and time. Also the geodetic TLS technology has not been used for larger area and scale mapping at national level thus the potential of this technology has not been fully understood/utilised. This study has investigated about a computational framework by combining analytical sensor model of TLS and experimentation technique on natural landscape to optimize the data quality within minimum possible time. This study has established mathematical relationships between geometrical parameters which help in planning phase of survey and also the effects of these parameters on end product has been analysed. This study will move the mainstream surveyors for use of geodetic TLS for large area and scale surveys

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