



**DEVELOPMENT OF STRUCTURE AND PAVEMENT
INSPECTION USING MOBILE LASER SCANNING
POINT CLOUDS: A CASE STUDY OF THAILAND
EXPRESSWAY**

BY

EKARIN LUEANGVILAI

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DISSERTATION

BY

EKARIN LUEANGVILAI

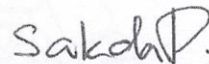
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DEVELOPMENT OF STRUCTURE AND PAVEMENT INSPECTION USING MOBILE
LASER SCANNING POINT CLOUDS: A CASE STUDY OF THAILAND EXPRESSWAY

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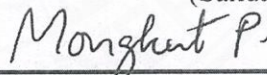
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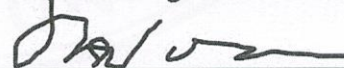
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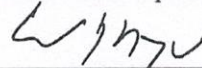
(Associate Professor Mongkut Piantanakulchai, Ph.D.)

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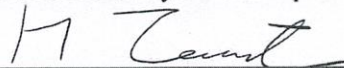
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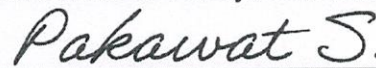
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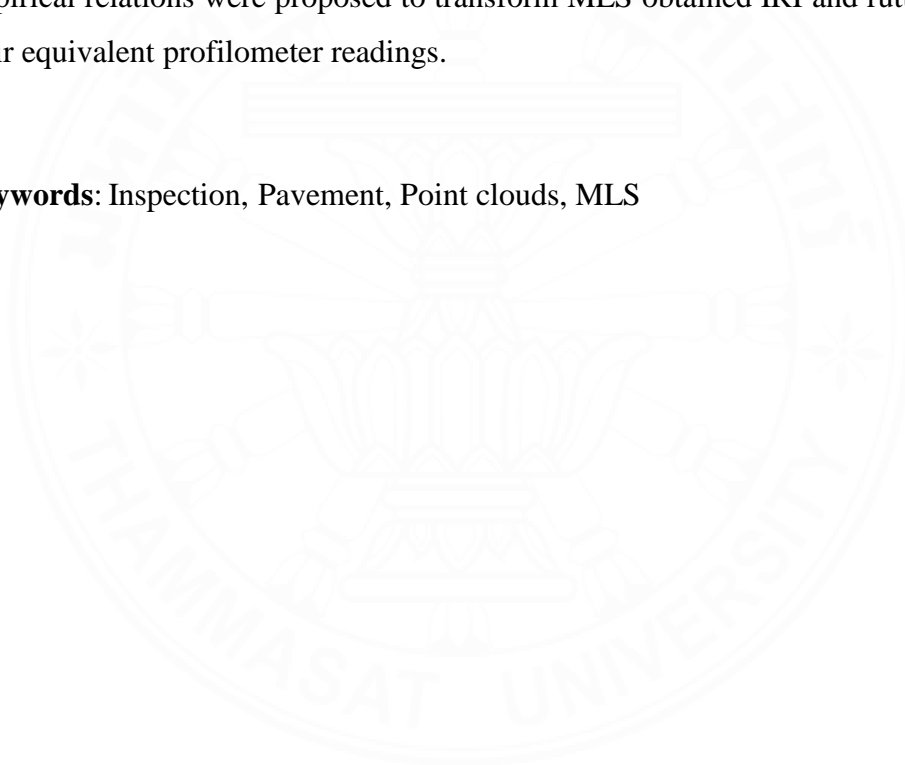
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Author	Ekarin Lueangvilai
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Faculty/University	Sirindhorn International Institute of Technology/ Thammasat University
Dissertation Advisor	Associate Professor Mongkut Piantanakulchai, Ph.D.
Dissertation Co-Advisor	Associate Professor Taweep Chaisomphob, D.Eng.
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ABSTRACT

Infrastructures must be inspected regularly in order to ensure serviceability and public safety. In case of Thailand expressway, a 200 km of elevated structure must be inspected once a year. The visual inspection for detecting defects and structure movements cannot be performed due to several limitations. Therefore, a mobile mapping 3D laser scanning (MLS) which is high resolution 3D laser scanners (Trimble MX-8) equipped on a vehicle was introduced. The scanning by MLS was performed on live traffic on expressways. Point cloud data was rectified and cleaned out of unwanted data by MLS operator. The dimension measurement by point cloud was validated with a total station. This study aimed to assess the performance of MLS in performing the health monitoring of a cable stayed bridge for the first time. A 450 m long cable stayed

bridge deck profile, bridge deck twist angles, and pylon curvatures were measured using point cloud data. MLS scanning on expressway gave not only structure geometry data but also pavement point cloud data. Every road agency in Thailand relies on laser profilometer as a default machine. Each pavement segment was executed for IRI and rut depth using “Pavement inspection program” which is the program developed by Tokyo University and Shotoku engineering of Japan. Correlation between these two methods of IRI measurement were observed. Even though they have not much good agreement, MLS can be applied to estimate IRI. The results revealed that IRI and rutting depth measured by MLS were higher than those obtained by profilometer. However, empirical relations were proposed to transform MLS obtained IRI and rutting depth to their equivalent profilometer readings.

Keywords: Inspection, Pavement, Point clouds, MLS



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Ekarin Lueangvilai

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CHAPTER 1

INTRODUCTION

1.1 Background

Bridges are one of the most important constituents and a vital part of a country's infrastructure. The health of an aging bridge needs to be assessed with fast yet effective methods for the sake of updated load limits that a bridge can sustain without accumulating extensive damage. Further, the knowledge of a bridge condition can help in devising effective maintenance programs to maintain or improve the declining condition. Cracks formed in a bridge can have a substantially detrimental effect: ranging from the reduction in load capacity to the change in dynamic characteristics of the bridge. The design of a bridge is carried out for a particular traffic limit. However, the rapid expansion of modern cities around the globe has seen a dramatic increase in the number of vehicles. In 2008, a report by the American Association of State Highway and Transportation Officials (AASHTO) stated that truck miles over existing bridges nearly doubled in two decades (AASHTO, 2008).

The visual inspection of bridges for the sake of their health assessment has been the most primitive method. The Federal Highway Administration (FHWA) recommends that the cycle of visual inspection for existing bridges should be repeated after every two years (Administration, 2012). However, health assessment by visual inspection can only be considered an initial step toward detailed monitoring. This is because defects that are invisible to the naked eye cannot be detected by visual inspection. In addition, considerable variability within the results of visual inspection has been found in the past. For instance, Moore et al. (2001) compared the visual inspection ratings of the same bridges estimated by different inspectors. Surprisingly, an average of four to five different ratings were assigned to the same bridge. Phares (2001) stated a key disadvantage of visual inspection: the method could only work when damage endangers the structure's life. Rehman et al. suggested combining the visual inspection method with other advanced methods for a bridge health assessment (Kashif Ur Rehman et al., 2016)

Bridge health assessment using non-destructive methods has emerged as a viable solution to primitive visual inspection in the last three decades. Breña et al. (2013) conducted live load tests on a simply supported bridge. The resulting strains were measured. A finite element model (FEM) was created for the bridge, and strains within the bridge were measured using similar loading details. Chajes et al. concluded that non-destructive testing aims to locate the damage at the material level. Subsequently, this type of health assessment is suitable in the case of concentrated damage (Chajes et al., 1997).

The measurement of the global response of a bridge has the potential to reveal damage and defects. The idea is to obtain the global response in terms of velocity or acceleration by attaching several sensors to the bridge. From the measured vibrations, it is possible to extract modal characteristics of the bridge, such as natural frequency, damping ratio, or mode shapes. These modal characteristics correspond to a deteriorated bridge and can be compared to the modal characteristics of the same bridge in healthy conditions (usually obtained from FEM) to assess the extent of deterioration. Structural health monitoring (SHM) in this realm can be performed either by forced or ambient vibrations. The forced vibrations are disruptive in nature but accompany lower magnitudes of noise (Dyke et al., 2001; Thurgood et al., 2006). On the contrary, SHM via ambient vibrations is less disruptive for the traffic. However, the installation and management of various sensors and their wires is a clumsy task (Agdas et al., 2016). Ambient vibrations are polluted by significant noise levels and need a thorough understanding of signal processing techniques to denoise them. Further, an assumption of the stationarity of the captured signal is often made during its processing. Studies have shown that dynamic nature and structural faults often invalidate this assumption (Feng et al., 2013; Staszewski & Robertson, 2007).

Until now, a 3D terrestrial laser scanner (TLS) has been introduced for deformation monitoring of different applications in the field of survey engineering. Lovas et al. (2008) studied the possibilities of a laser scanner for deformation monitoring of the Pentele bridge. The deformation monitoring of the Felsenau viaduct by using TLS was performed by Zogg et al. (2008). The results from TLS were then compared with the precise levelling method. Truong-Hong et al., (2016) presented a

framework for bridge inspection using TLS data. Although TLS can provide point clouds with millimetres precision, these are often needed to be installed within the proximity of bridge lanes. As a result, the traffic flow over the bridge can be affected (Lin et al., 2021). In recent years, Mobile Mapping Systems (MLMs) have emerged as an efficient and time-saving technique for SHM purposes. Efficient field surveys of large areas can be conducted without disrupting the traffic flow. MLMs utilize trajectory information obtained from the Global Navigation Satellite System (GNSS) to establish point clouds in a common frame (Lin et al., 2021).

Infrastructure must be inspected regularly to ensure serviceability and public safety. In the case of the Thailand expressway, 200 km of the elevated structure must be inspected once a year. The present study investigates the performance of an MLS system for monitoring the Thailand expressway. Mobile mapping laser scanning (MLS) also provides pavement point cloud data. Pavement is normally checked for International Roughness Index (IRI) and rut depth which is calculated from pavement geometry. Every road agency in Thailand relies on a laser profilometer as a default machine. MLS point cloud data could be used for IRI calculation as well. So, expressway point cloud data were extracted for only pavement. Each pavement segment was executed for IRI and rut depth using the “Pavement inspection program” which is the program developed by Tokyo University and Shotoku engineering of Japan. Correlation between these two methods of IRI measurement was observed. The use of MLS is new in Thailand. Performances of MLS need to be examined. The procedure of measurement, data handling, data accuracy, and data exportation will be studied to achieve the monitoring by MLS.

1.2 Technical Collaboration with Japanese Expressway

The Metropolitan Expressway Company Limited: MEX, who is responsible for expressways in Tokyo, has introduced “InfraDoctor”. The InfraDoctor is a newly web-based application for Japanese expressway asset management system. The application is currently under development.

It is aimed to apply the InfraDoctor in Thailand and Southeast Asia. So, a Memorandum of Understanding (MoU) in Collaborative Research Project and Technical Cooperation between Sirindhorn International Institute of Technology and

Shutoko Engineering Company Limited (subsidiary company under MEX) took place to adopt infrastructure management system using InfraDoctor in Thailand and South east Asia. This project is fully supported by Ministry of Economy, Trade and Industry Japan, Metropolitan Expressway Co.Ltd., Elysium Co.Ltd., Aero Asahi Corporation, Nikon-Trimble Co.Ltd. and Expressway Authority of Thailand. The collaboration is shown in **Figure 1.1**

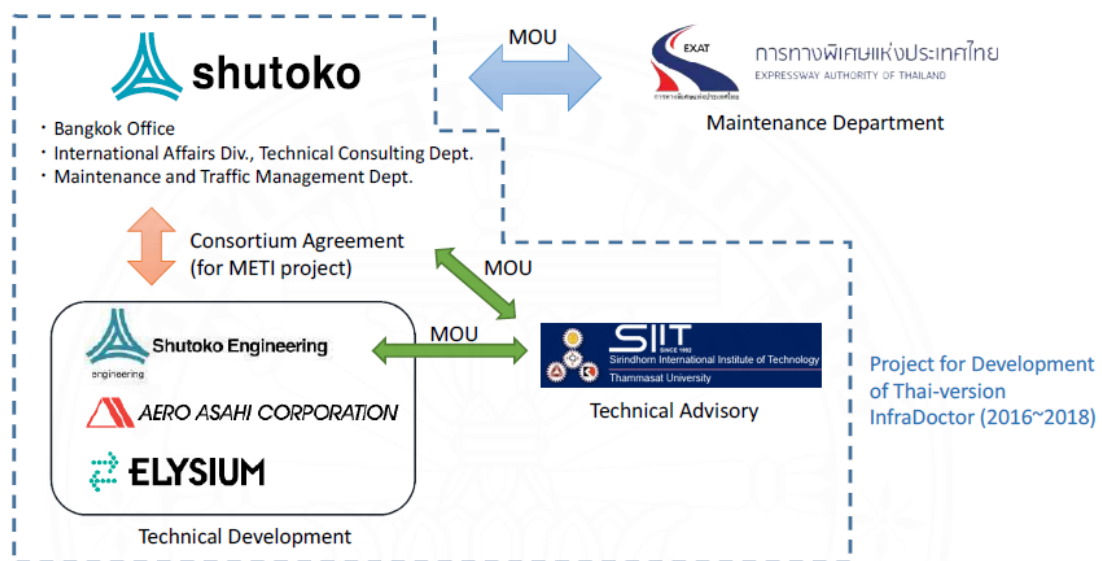


Figure 1.1 Structure of Technical Collaboration

1.3 InfraDoctor

The InfraDoctor is a web-based application for expressway asset management as shown in **Figure 1.2**. The content of the website is 3D point cloud data of expressway and related documents such as drawings, inspection reports and so on. Final development of the website is online-asset database which contain all information of structure history on GIS platform.

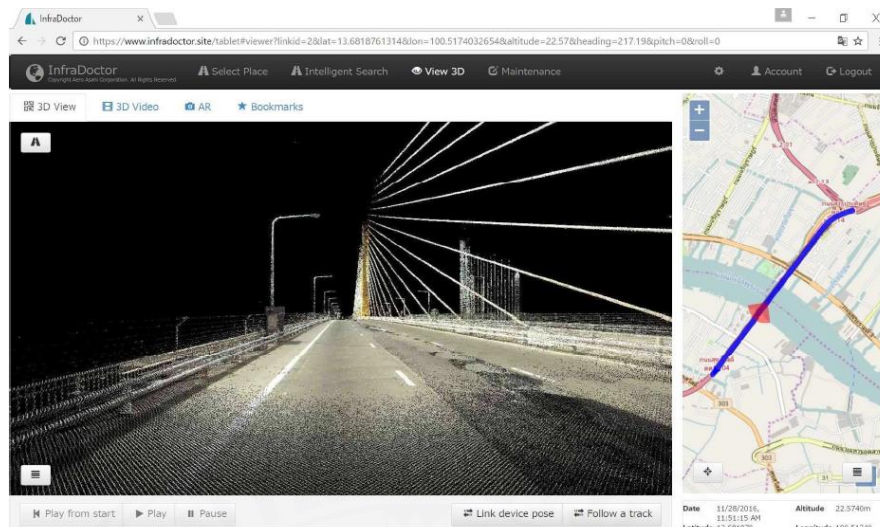


Figure 1.2 InfraDoctor Web Page

1.4 Mobile Mapping 3D Laser Scanner

The main part of the InfraDoctor is 3D point cloud data of structures. The point cloud data is created from Mobile Mapping 3D Laser Scanner (MLS). MLS is a vehicle equipped with 360° laser scanners, cameras, GPS antennas and data loggers, as shown in **Figure 1.3**. The scanning is performed during driving such that long distances can be scanned quickly. Structures along roadside, especially viaduct structure are scanned conveniently. Scanning results can be used for structure inspection. This can overcome the limitations of the visual inspection which will be helpful for expressway inspection.

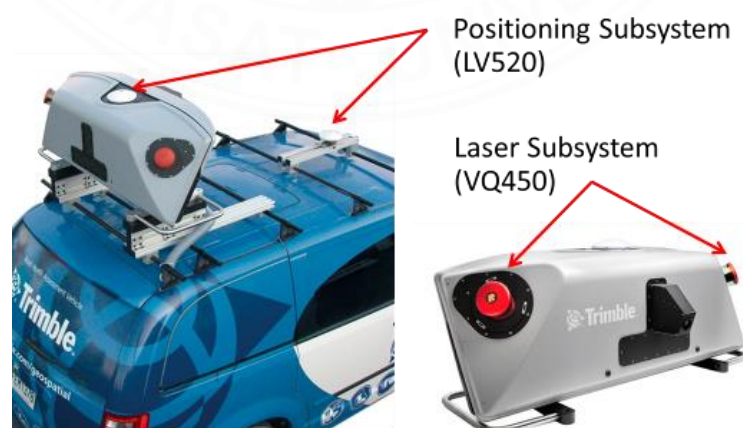


Figure 1.3 Mobile Mapping 3D Laser Scanner (MLS)

1.5 infiPoint™

Point cloud management program is “infiPoint™”, as shown in **Figure 1.4**. Each point in the point cloud contains values of coordinates in UTM spatial reference system and color code in RGB system. In overview picture, point cloud can be seen as digital image. InfiPoint provides tools for point cloud data handling. It has custom tools to create 2D CAD drawing but not 3D which is currently under developing. Therefore, it is used as point cloud management in this research.

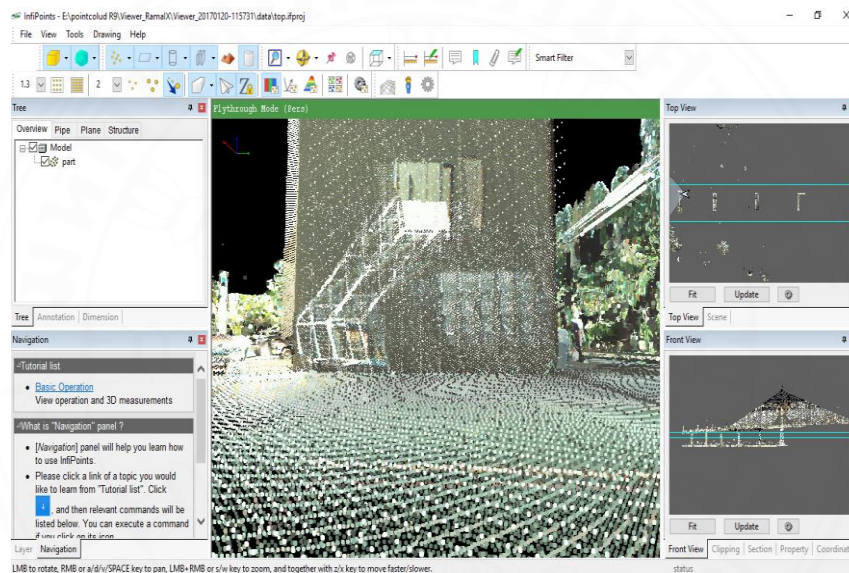


Figure 1.4 Point cloud management program

1.6 Objectives and Scope

Japanese expressway has a pilot project using point cloud data for International Roughness Index (IRI) measurement. Thailand expressway uses laser profilometer as a default for IRI measurement. Once Thailand expressway point cloud was obtained, it was needed to prove that the obtained point cloud can be used for IRI in a similar way as Japanese expressway does. In order to save time for IRI calculation programming and to gain confidence on IRI calculation (from Japanese side), the “Pavement inspection program” developed by Tokyo University and Shotoku engineering will be

used for IRI calculation in Thailand case. After that, comparison of the results by IRI and laser profilometer will be conducted. The salient of scopes of this study are:

- a. Extract point cloud data of the target pavement areas on expressway in Thailand.
- b. Compare the result of IRI measured by point cloud data with IRI measured by laser profilometer.

Whereas, the present study aimed to achieve the following objectives.

- To use MLS for roadway geometry measurement. The accuracy of dimension measurement will be examined to use point cloud data properly. Finally, roadway 3D mapping would be created for traffic simulation purposes.
- To use MLS point cloud data for structure deformation measurement. GPS position and elevation accuracy will be examined to obtain the accuracy of measurement. Finally, a cable-stayed bridge movement will be measured for the health monitoring propose.
- Roughness of pavement will be calculated using MLS point cloud data. Then, the calculated roughness will be compared to the conventional method using a profilometer. Finally, the measurement of the International Roughness Index (IRI) by using MLS will be compared to the one obtained using conventional methods.

CHAPTER 2

LITERATURE REVIEW

2.1 The MLS

The available MLS is Trimble MX-8 as shown in **Figure 2.1**. The MLS is composed of GNSS, POS/LV520 model by APPLANIX. The laser scanners are VQ450 model by RIEGLE, whereas the CCD camera model is Grasshopper by Point Grey. A 360-degree camera of model Ladybug-3 by Point Grey is used as well. The external distance measurement is performed by Trimble. Everything is equipped on a Toyota Fortuner model.

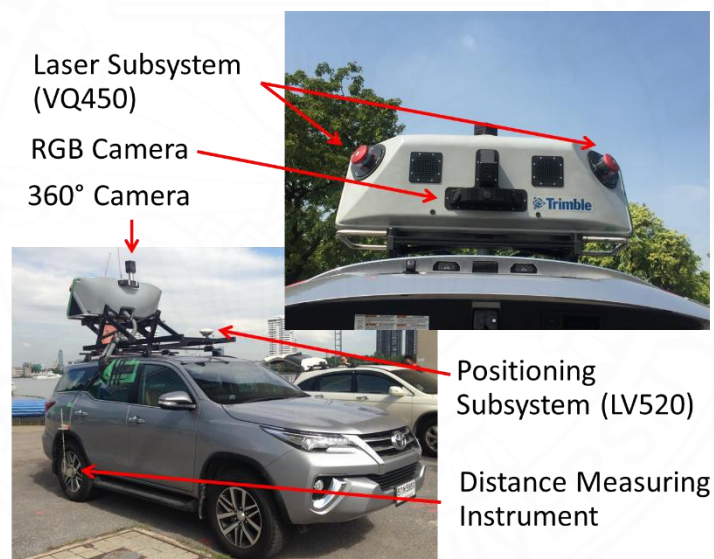


Figure 2.1 MLS in this research

Accuracy of VQ450 is about 8 mm with the precision of 5 mm as prescribed in specifications. The maximum effective measurement rate is 1.1 million point/second. The measurement range is up to 800 m. POS/LV520 which is GNSS antenna has X- and Y-direction position accuracy of 20 mm, whereas this accuracy is 50 mm in Z direction.

2.2 Existing Studies on MLS

Puente et al. (2013) made a systematic comparison of the navigation and LiDAR specifications provided by the manufacturers. MLS can mainly be divided into two categories. They are mapping and surveying depending on their final purpose, accuracy, range and resolution requirements. The RIEGL VMX-250, TRIMBLE MX8 or STREETMAPPER, also demonstrate good characteristics for applications such as road inspection. The ROAD SCANNER, LYNX MOBILE MAPPER, VMX-250, MX8 and STREETMAPPER produce higher point densities than the others. This capability enables the use of this laser scanner for the evaluation of the condition of pavements (potholes, ruts and cracks).

Toschi et al. (2015) evaluated the precision and the accuracy of a commercial Mobile Mapping System (MMS) with advanced statistical methods. RIEGL VMX-450 Mobile Laser Scanning System was tested. Reference measurements were derived from photogrammetric and Terrestrial Laser Scanning (TLS) surveys. Precision was within ± 5.2 mm while accuracy was within ± 8.6 mm. The errors fell within the values described by datasheet.

Wang et al. conducted a comprehensive survey on MLS techniques and their utilization in urban areas. They concluded that though existing MLS technology can perform inspections, there is still a need to develop more sophisticated MLS techniques such as special processing framework and machine learning-based methods (Y Wang et al., 2019).

Terrestrial laser scanner (TLS) can acquire surface details of structures quickly and accurately. L. Truong-Hong et al. (2016) provided a framework for bridge inspection by using point cloud data by TLS. TLS data for structure deformation measurement, damage detection, and reconstruction of three dimension (3D) as-built models were explored.

Deformation measurement involves overall displacements of the bridge. For damage detection. There are 1) spalling/scaling 2) corrosion/crushing 3) cracking and 4) chemical attack. Because cracks are small, point cloud data may not provide sufficient information for detection. In such case, RGB values in point cloud give more

attribution. Chemical attack is mostly related to the steel corrosion. RGB values in point cloud also play a major role for such detection.

The area and location of spalling and scaling can be determined directly from the point cloud; however, the volume of the damage is calculated by comparing a fitting surface of the damage area to the surface of original data. There are several approaches to achieve that.

TLS generates million data points per second with millimetre level accuracy. There is a possibility of changing how vertical deflections of bridge girders checked. Truong-Hong and Laefer (2014) performed primary study on vertical bridge displacements measurement during dynamic loading using TLS. A point -surface based method was used for post processing the bridge deflection.

However, for the river bridge inspection, shadows and water reflectivity may affect the quality of the point cloud generated from images. They cause difficulty in data processing. Chen et al. (2018) developed a workflow for removing outlier data points.

Vežočník et al. (2009) proposed methodology for high precision monitoring of deformations with a long-term perspective using TLS. In order to solve the problem of a stable reference system, high quality static GNSS positioning and precise tacheometry were studied. TLS proved to be capable of providing high precision data.

Zhou et al. (2017) proposed a tunnel clearance inspection approach based on 3D point clouds obtained by MLS. A rail line extraction algorithm based on 3D linear fitting was implemented from the segmented point cloud. Based on the rail alignment and the track clearance, types of false work were introduced for the tunnel section to realize the tunnel properly.

MLS has millimetre-level accuracy and high point cloud density. Yanjun Wang et al. (2019) presented key characteristics, challenges and opportunities of using the MLS data. Applications of using MLS over urban areas, including transportation infrastructure mapping, building information modelling, utility surveying and mapping, vegetation inventory, and autonomous vehicle driving were reviewed.

Lantieri et al. (2015) used the MLS point cloud data to identify the critical issues related to drainage and water runoff. MLS data was used to verify gradients, evenness, proper design of the drainage elements, and the surface characteristics of the pavement and calculation of water depth.

Road roughness is the deviation of a road surface from a designed surface grade. MLS provide dense 3D point cloud data along a route corridor. Kumar et al. (2015) developed an algorithm for the automated estimation of road roughness from MLS data. The elevation difference between the lidar points and their surface grid equivalents provided heights that were used to estimate roughness. The first step was the extraction of pavement. Then, pavement data was rotated to the perpendicular direction. Next, the random sample consensus (RANSAC) algorithm was used to fit a surface grid. The final step, the difference between the elevation of LiDAR points and surface grid was established. However, direct comparison with standard IRI was not performed.

Kumar and Angelats (2017) continued developing their algorithm. They found that the use of normalized intensity values improved the process of road roughness detection. Point thinning process was effective in interpolating smooth intensity surfaces. Closing morphological operation provided smooth roughness regions. The three-level Otsu thresholding was found useful dividing the image into dim which approximately corresponded to toughness.

Li et al. (2019) used UAV LiDAR point cloud to identify pavement distress using random forest classification method. After a spectral and spatial feature analysis of pavement distress, multiscale features were extracted based on strength of the point cloud elevation and reflection intensities. Pavement distresses from the multifeatured dataset were extracted by utilizing random forest classification method.

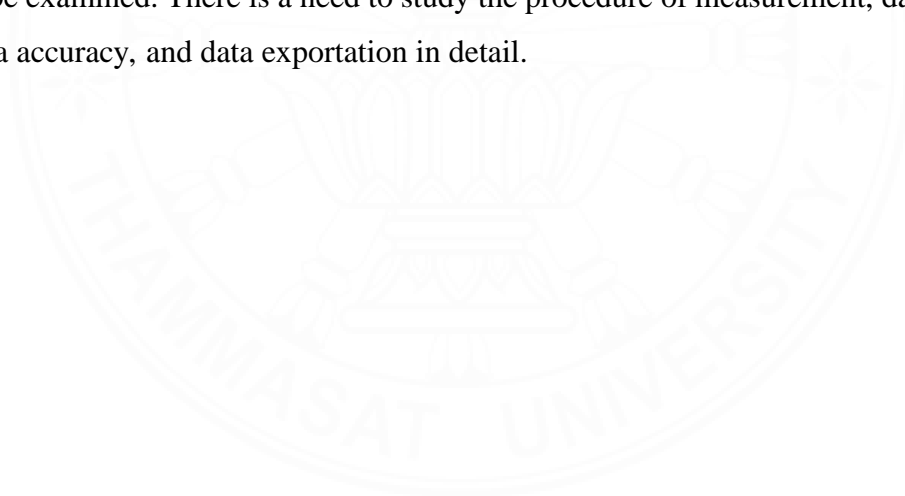
De Blasiis et al. (2021) compared the roughness index (International Roughness Index, IRI) derived from high speed inertial profilometer with two other roughness indices, one dynamic and one geometric computed on a digital elevation model (DEM) built by using MLS data. DEM employed 2 methods for grid cell elevation, ordinary kriging, and inverse distance weighting. The kriging method was used because of a more robust interpolation even though the computation cost was higher. Road

roughness by MLS showed the similar trend and a high correlation with the values acquired by the profilometer was obtained.

Summary

MLS can scan everything along the roadside while running. Result is represented as million points of UTM coordinate data called “Point cloud”. Distance between each arbitrary point can be measured. So, this would be an ideal tool for expressway applications. By the literature review, MLS point cloud can be used for bridge inspection especially for the term of structural movement. MLS point cloud can be a good tool for roadway geometry measurement such as gradient and slope. By high density of point cloud pavement, pavement inspection can be achieved. The fact that this research is focusing on MLS for actual applications.

At present, no study is conducted on the use of MLS in Thailand. Therefore, this kind of technology is new to Thailand. However, the performance of MLS needs to be examined. There is a need to study the procedure of measurement, data handling, data accuracy, and data exportation in detail.



CHAPTER 3

METHODOLOGY

3.1 Thailand Expressway Scanning

Thailand expressways scanning was performed in December 2016. There were five locations. They are 1) RamaIX Bridge, 2) Buraphawithi Expressway (BBBE), 3) Clong-Toei Overpass (Site 3), 4) Sukhumwit Overpass (Site 1,2), 5), and at-Narong Interchange. Prior to the measurement, a base station was established. The measurement can be done within the radius of 20 km from the base station. This length of radius covers nearly all Bangkok area including five target locations. So, a single base station was considered enough. The base station was setup at Chulalongkorn university which is located at centre of Bangkok.

On expressway, MLS measurement range was set to 100 m with measurement rate of 0.5 MHz per laser head. Data was acquired at 1 million points per second. The machine preparation took around 20 minutes waiting for GNSS signal. MLS moving speed can be up to 80 km/h. A shadow car was provided by 5 m-6 m interval to prevent another vehicle cutting the scanning line. However, due to safety concerns, the measurement was done at a speed of about 40 km/hr. During the measurement, neither sound nor light is noticed. Just like the other car is running on expressway as shown in **Figure 3.1**. After 2-3 hours of measurement, the MLS was paused to cool down.



Figure 3.1 MLS while scanning

3.2 Point Cloud Data Preparation

Point cloud data was prepared by the machine operator (AERO Ashi Corporation). Global coordinate was rectified with known coordinates, as shown in **Figure 3.2**. Unwanted points such as noise and irrelevant objects such as vehicles or humans were removed. The resulting data was in the form of point cloud image of pavement and expressway structure without any vehicle as shown in **Figure 3.3**. Two-km of road scanning produced about 33.5 GB of data. So, enough storage should be prepared in advance. The data were ready for further action.



Figure 3.2 Point cloud data rectification

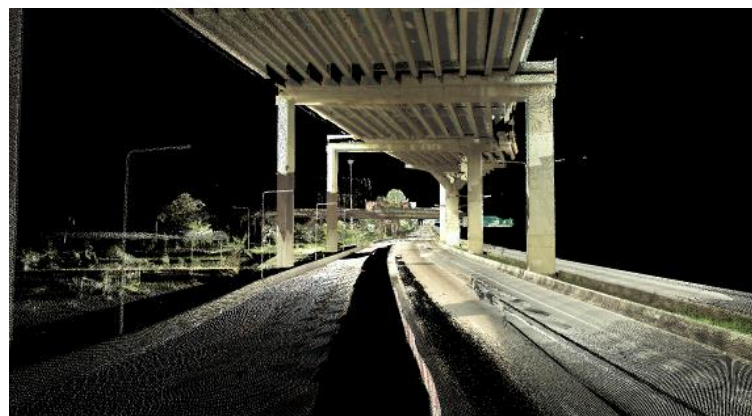


Figure 3.3 Sample of point cloud image

3.3 Roadway Geometry Measurement

First expressway in Thailand was opened to traffic in 1981. Until now, 226 km of the expressway is in service. Average daily traffic is approximately 1.77 million trips/day. Growth rate is around 5.5% per year. By this increasing demand, traffic is always congested especially during rush hours. The authority wanted to solve traffic problem especially the conflict points.

At-Narong Interchange is a part of the first stage expressway, BangNa-Port section. This interchange is one of the most congested areas in Bangkok. Queue length is approximately 5 km during weekdays. By the observation, bottleneck would be the source. This interchange is a connection of 4 lanes at-grade road and 3 lanes-ramp then merge into 3 lanes + shoulder elevated road, as shown in **Figure 3.4**. This bottleneck is confirmed by traffic report on the google map.

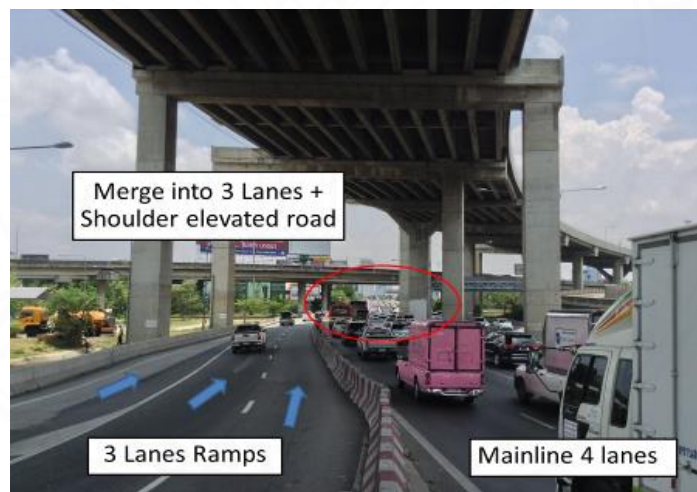


Figure 3.4 Bottleneck at interchange

In order to find out the mitigation, roadway dimensions must be known first. The road geometries such as road width, road elevation and surrounding objects, which will be obstructed, must be surveyed. The primary information is drawings. Unfortunately, this area has been modified 4 times in the past. The first modification was at-grade road widening. The second and third modifications were the construction of new expressways. The fourth modification was the construction of an additional

ramp. Furthermore, at-grade road has been releveled and repaved many times during 36 years of service. So, the available drawings may not give correct present condition. Therefore, topography survey was needed to be performed on site.

Topography survey using total station or Real Time Kinematic (RTK) takes time and gives insufficient information. In addition, these methods cannot be performed without disrupting the traffic, due to surveyor's safety concerns. At this point, point cloud data could provide great information. Distance between each arbitrary point can be measured and topography can be built up. However, the accuracy of point cloud distance needs to be examined first. Therefore, topographic survey was conducted by using both total station and point cloud data. The comparison is presented in Chapter 4.

3.4 Structure Movement Measurement

The Rama IX Bridge crosses the Chao Phraya River to link the eastern and western sides of Bangkok. This 30-year-old bridge is a single plane symmetric cable-stayed bridge carrying six lanes of traffic, with a total length of 782 meters and composed of a clear span of 450 meters and two side spans of 166 meters each, as shown in **Figure 3.5**.

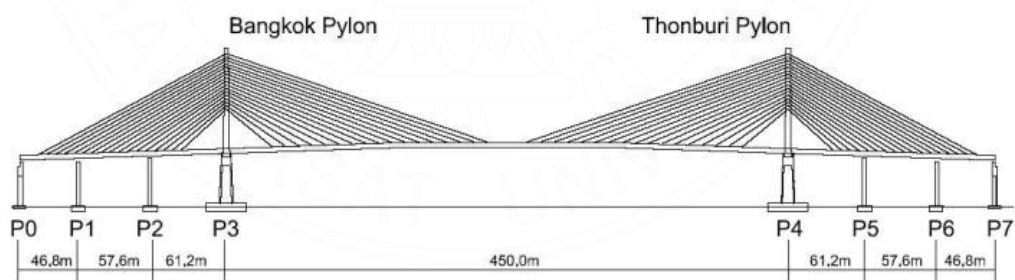


Figure 3.5 The Rama IX Bridge Elevation

Bridge deck was a three-cell steel box girder, 33 meters wide, and 4 meters deep at the centre, as shown in **Figure 3.6**. Asphaltic surface provides for traction and wearing resistance on the top plate.

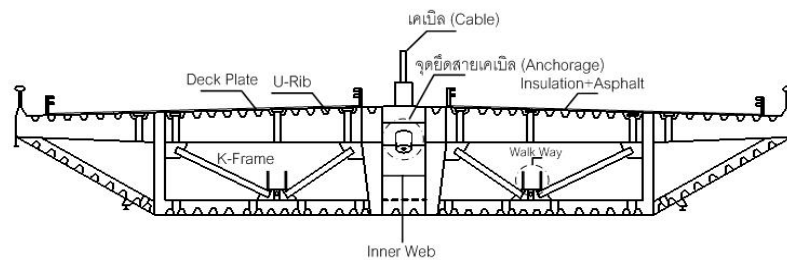


Figure 3.6 Deck cross section

The 87-meter-tall pylons pass through the bridge deck on the top of concrete piers. The steel pylons are closed rectangular boxes with additional internal framing to carry the cable anchorages. The piers that support the pylons have hollow concrete sections. The appearance of the bridge is shown in **Figure 3.7**.



Figure 3.7 The Rama IX Bridge, Bangkok, Thailand

The bridge geometries such as deck profile and pylon top movement shall be regularly measured according to bridge inspection manual. The manual stated that the movement should not larger than span/1000. Thus, deflection of 450 m main span should not greater than 450 mm. The lateral movement on the top of pylon should not be larger than 87 mm. Normally, movement is measured by total station. Only 5 points on bridge deck were measured in 2001 and 34 points on the bridge were measured in 2012 while pylon top movement has never been checked. The better measurement technique is expected to examine bridge geometry change.

Once point cloud data of the bridge was acquired. Overall bridge geometry was acquired as well. However, elevation by point cloud needs to be validated.

3.5 Methodology for IRI Measurement

In order to verify IRI calculation by the 2 methods, point cloud and laser profilometer, the same piece of pavement must be extracted. IRI data from laser profilometer normally come with GPS position. These GPS positions can be used for point cloud extraction. Width of the extracted pavement can be adjusted up to 3.5 m according to Thailand expressway lane width. Length of extracted pavement is dependent on IRI profilometer GPS data which is normally 25 m. Length will be an arbitrary number according to profilometer GPS data. Working steps are as shown in **Figure 3.8**.

Figure 3.8.

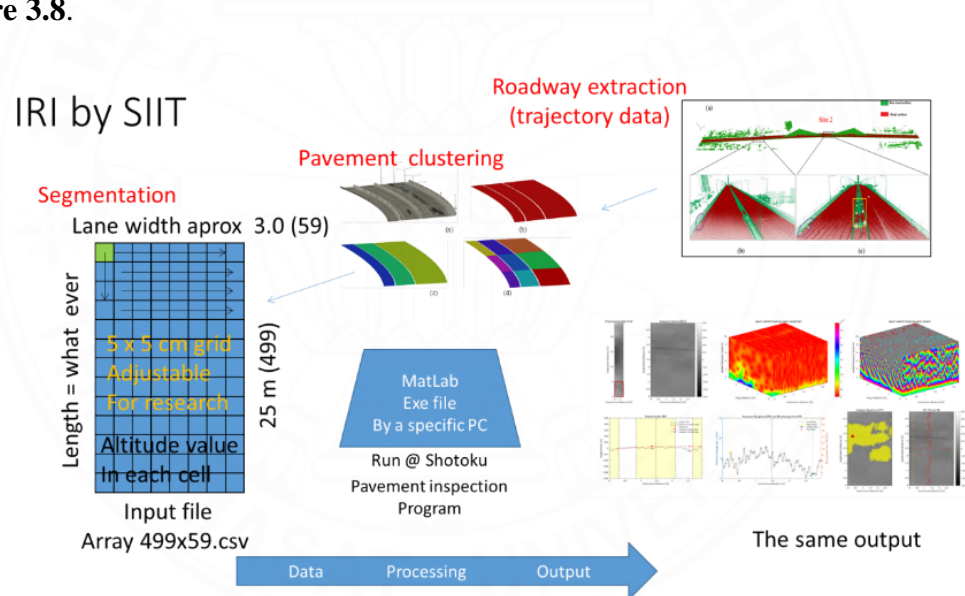


Figure 3.8 Working process for Expressway IRI calculation

First Step: Extract all point clouds along the desired length of the road using “infiPoints” or “Cloud Compare”. In this research case, point cloud data of 1.6 km of BBBE, 6 lanes expressway were extracted (Area P-Q-R-S in **Figure 3.9**). There were 96 million data points which were extracted in *.txt file format. The size of 96 million data points file was around 12GB. Road surface extraction employed voxel-based region growing method. Tran and Taweep (2020) refined the road boundary using the

curb-based segmentation algorithm. The algorithm extracts the road surface with high accuracy.

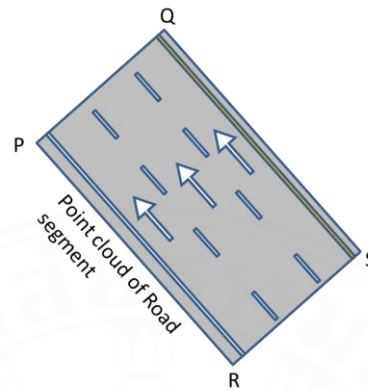


Figure 3.9 Point cloud of entire road

Second Step: “Input file” is generated from MATLAB. GPS data from profilometer, point P1 and P2, were used to create “Crop area” (Area A-B-C-D in **Figure 3.10**). Width of the cropped area (A-B) can be set between 3.0 m - 3.5 m depending on lane width. In this case, width was set to 3.0 m. Length of the cropped area was dependent on distance between points P1 and P2. So, the cropped area was 3.0 m x 25.0 m, according to profilometer GPS data. Then, point cloud only in the “Crop area” were selected. One section of the road was 3.0 m x 25.0 m having around 144,000 points. Point density was about 1,900 points/square meter.

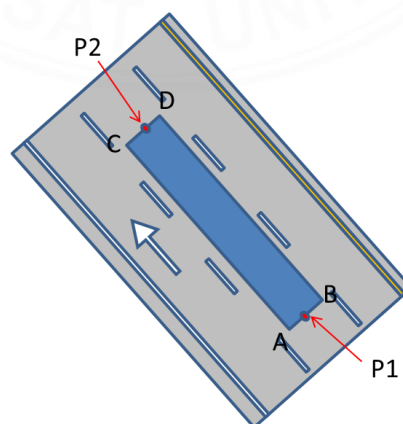


Figure 3.10 Crop area A-B-C-D for segmentation

Third Step: Rotate data in cropped area to perpendicular direction for ease of meshing, as shown in **Figure 3.11**

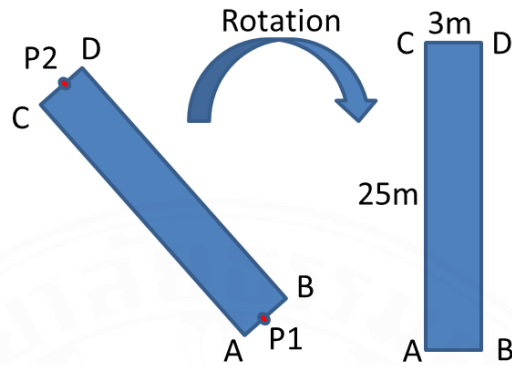


Figure 3.11 Cropped area Rotation

Forth Step: Mesh the cropped area into small pieces. The smallest mesh size was 5 cm. Mesh area (area a-b-c-d) was created, as shown in **Figure 3.12**. Then, point cloud in the meshed area was selected and their elevation (z) was returned. An average elevation of points was representative elevation in mesh [1,1]

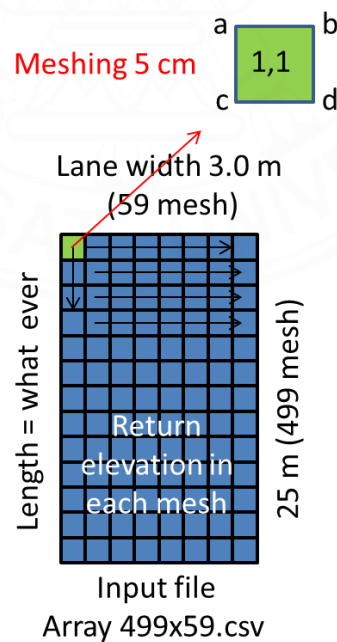


Figure 3.12 Cropped area meshing

Point density was about 1,900 points/sq.m. Mesh area of 5 cm x 5 cm had 4.82 points in average. There are enough points to estimate the average elevation. Once mesh [1,1] was finished, the same process moved forward to mesh [2,1] by a loop operation. Finally, cropped area of 3.0 m x 25.0 m was operated having 59 x 499 mesh (5 cm mesh). Then, a file with name of “inputfile.m” was created. This file was an array of 59x499 and was ready to be executed in “Pavement inspection program”.

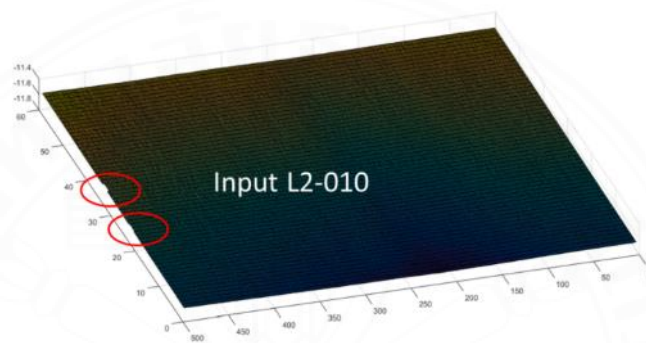


Figure 3.13 Sample of “inputfile.m”

Fifth Step: The “inputfile.m” must not have blank elements. This can happen because of blank point cloud data (in some area). Small area of blank element can be fixed by using elevation of the neighbouring elements. For large area of blank element, input data was considered incomplete and rejected.

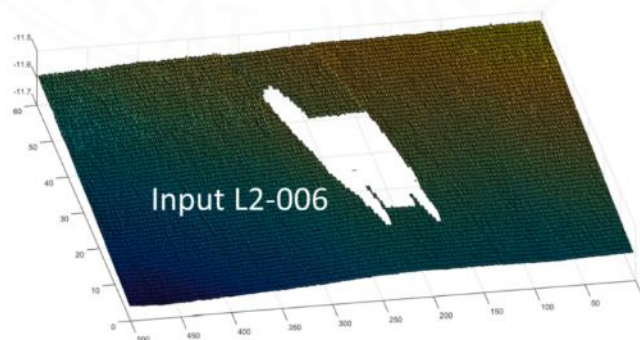


Figure 3.14 large blank element inputfile

In some cases, “inputfile” was corrupted by non-pavement point cloud data. Therefore, corrections were needed to be done.

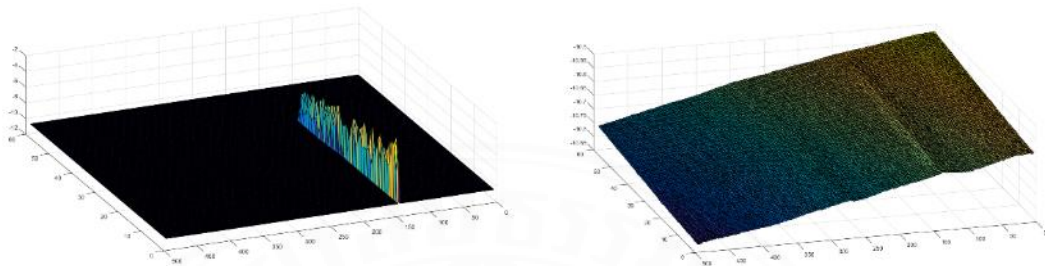


Figure 3.15 Corrupted and corrected “inputfile”

Sixth Step: “Pavement inspection program” was executed. IRI and maximum rut depth under left and right wheel track were returned. The results were then validated with results by laser profilometer.

CHAPTER 4

ACCURACY ASSESSMENT AND APPLICATIONS

4.1 Dimension Comparisons

A total station (Topcon ES-105 model) was used to validate the dimension. The Topcon could measure the distance up to 500 m with the accuracy of ± 3 mm. Distances between some arbitrary points were measured using the total station and compared to the distance measured by point cloud, as shown in **Figure 4.1**. The comparison is shown in **Table 4.1**.

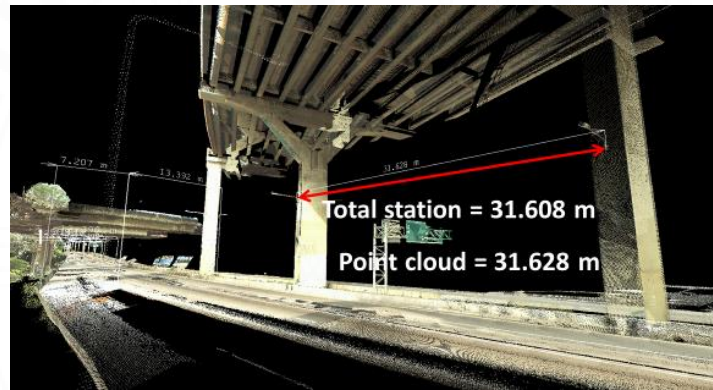


Figure 4.1 Distance comparison

Table 4.1 Comparison of dimension between 2 methods

Total Station, m	Point Cloud, m	Difference, cm
31.608	31.628	-2.0
29.878	29.892	-1.4
31.757	31.820	-6.3
28.522	28.518	0.4
27.868	27.909	-4.1

Dimensions measured by point cloud may deviate up to 6 cm. This deviation was attributed to the marginal error generated during the registration process. This process combined several point cloud data from separate measurements into a single data set. Another reason was the wrong selection of point in the cloud. Some location may have less points of data for selection. So, distance or dimension can be created but

they can be deviated for ± 6 cm. This range of deviation is acceptable for urban mapping, mining or environment monitoring applications and geometry survey where accuracy does not play an important role. The measurement of distance between neighbouring points is cumbersome when surface is modelled (Boehler & Marbs, 2003).

4.2 Topography Build-up and 3D Model Creation

Topography comprises not only road width or column height but also road elevation and road gradient. Road profile was extracted from point cloud data as well. Elevation (in UTM) along left and right of the solid line was plotted against distance. It was found that the road is elevated for 6.3 m with 3.5% of slope gradient as shown in **Figure 4.2**. The gradient was found to confirm with the drawings. Additionally, crown slope and super elevation was also acquired. The measured crown slope was 2.6%, which is considered slightly high comparing to the standard value of 2.5%. The super elevation was about 1.7%. This is also considered high comparing to the maximum value of 1.5%. Although crown slope and super elevation are not considered for the traffic modelling, they are useful for drainage design and clearance check.

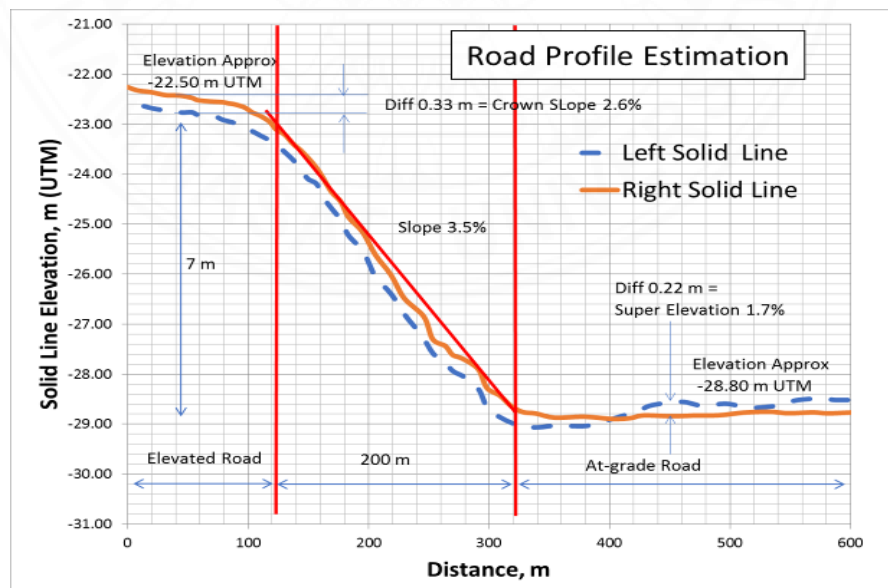


Figure 4.2 Road profile measurement

The 3D sketch up is created and put into a traffic micro simulation software (Aimsun) successfully as shown in

Figure 4.3. The model was more realistic and wonderful presentation. The traffic simulation model was used for further analysis.

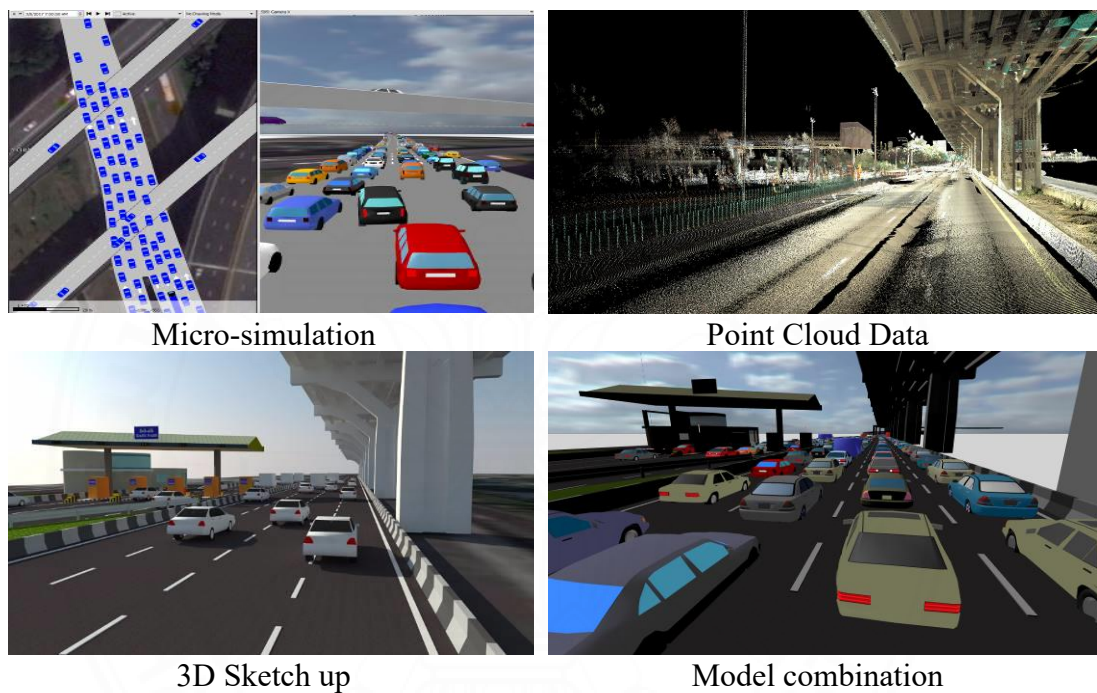


Figure 4.3 Realistic traffic simulation model

4.3 Validation of Bridge Profile Measurement

Real time kinematic survey, RTK (South S82T model) was used to validate the point cloud data. By specifications, the horizontal accuracy was ± 8 mm. The vertical accuracy was ± 15 mm. Elevations were measured by the RTK for 66 points as shown in **Figure 4.4** (Left: 20 points, Right: 20 Points, Centre: 24 points and each 1 on top of each pylon).



Figure 4.4 RTK survey.

The bridge profile between MLS and RTK survey are plotted together, as shown in **Figure 4.5**. Elevations measured by point cloud matched well to the elevations measured by RTK. This examination provided a high confidence on point cloud data for further assessments.

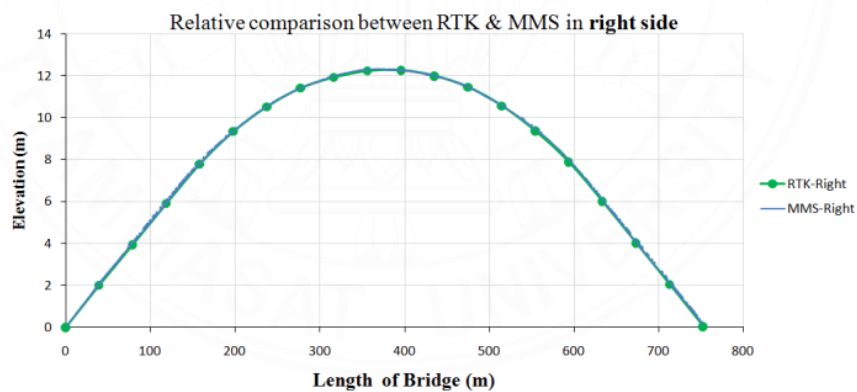


Figure 4.5 Elevations between RTK & MLS

4.4 Bridge Health Monitoring System

4.4.1. Bridge Deck Twist Angle

Based on MLS data, twist of the bridge deck was examined. By comparing elevations on each side of the deck, twist angles could be obtained. Note that, elevations were measured on asphalt pavement. By subtracting the pavement thickness (20-30

mm) and elevation measurement accuracy (± 15 mm), twist angle measurement of $\pm 0.05^\circ$ was possible assuming that the deck was perfectly horizontal. The results show that most of the measured twist angles were within the threshold (i.e., $\pm 0.05^\circ$) as shown in **Figure 4.6**. Angles at the pylons were low as expected. Twist happened in both directions, clockwise and counter clockwise. It can be concluded that, no sign of permanent twist was observed for the deck.

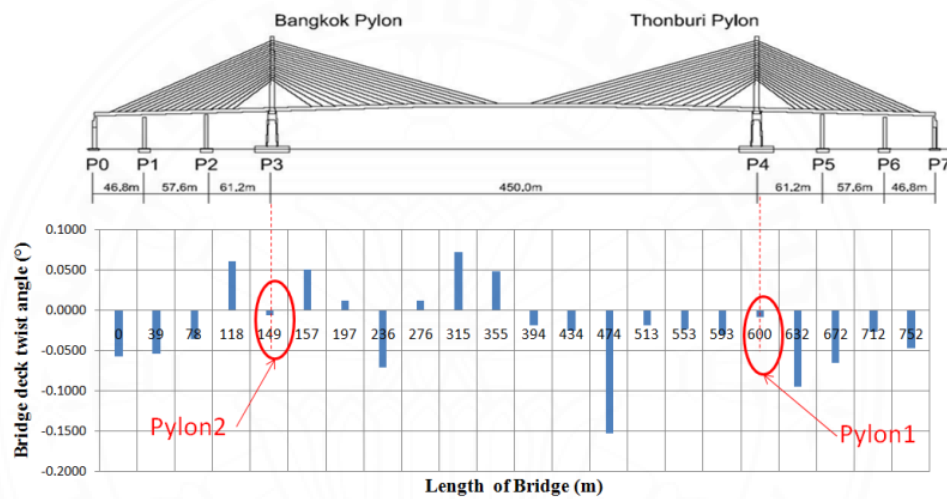


Figure 4.6 Twist angle along bridge length

4.4.2. Pylon Deflections

Pylons are not prismatic members. The size of pylons was 3.0 m x 4.5 m at the bottom and 2.5 m x 3.5 m at the top. The point cloud data of pylon was cut into 3 sections, bottom, middle and top using the InfiPoints. In order to check the top movements, coordinates of each section were plotted together and the position of their centroids was compared, as shown in **Figure 4.7** and **Figure 4.8**. The movement was calculated on the assumption that the pylon was originally vertical. The results show that the differences between the actual positions and the ideal positions were 104 mm for the west pylon in the transverse direction and 138 mm for the east pylon in the longitudinal direction.

These values are larger than the maximum value stated in the inspection manual, but the original position just after the construction was not available. Therefore, a periodical monitoring was recommended.

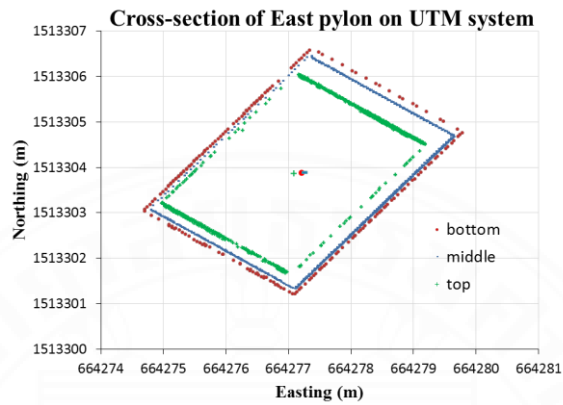


Figure 4.7 East pylon section comparisons

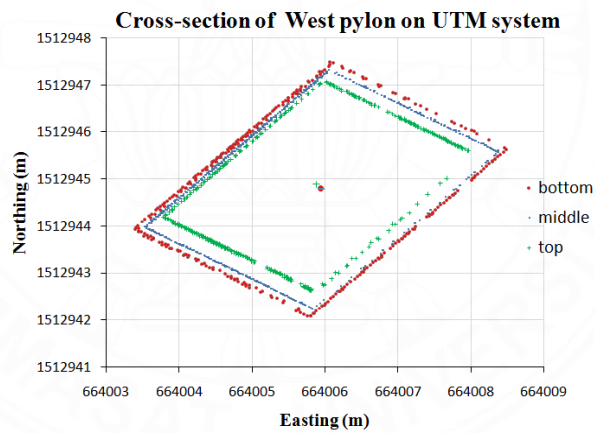


Figure 4.8 West pylon section comparisons

4.5 Expressway Pavement Inspection

Expressway Authority of Thailand (EXAT) established inspection manual in 1994 by cooperation with Japan International Cooperation Agency (JICA). Rating for pavement can be done using five criterions. They are faulting, rutting, cracks roughness, and potholes, as shown in **Table 4.2**

Table 4.2 JICA pavement rating criteria

Rating	Faulting	Rutting	Crack	Roughness	Potholes
A (Urgent repair)	Hazard to traffic Annoyance to the 3 rd party	Do	Do	Do	Do
B (Repair is required)	Between 15 mm and 30 mm in depth	Between 15 mm and 30 mm in depth	Cracking ration is large than 20%	Standard deviation is larger than 3.5 mm	Larger than 20 mm in depth Larger than 20 cm in diameter
C (Minor repair is necessary)	Less than 15 mm in depth	Less than 15 mm in depth	Cracking ration is between 10% and 20%	Standard deviation is between 2.5 mm and 3.5 mm	Between 10 mm and 20 mm in depth Between 10 cm and 20 cm in diameter

Change of pavement geometry, rutting, was measured by straight edge at an interval of 20 m. Rutting was defined by a bigger value between D1 and D2, as shown in **Figure 4.9**.

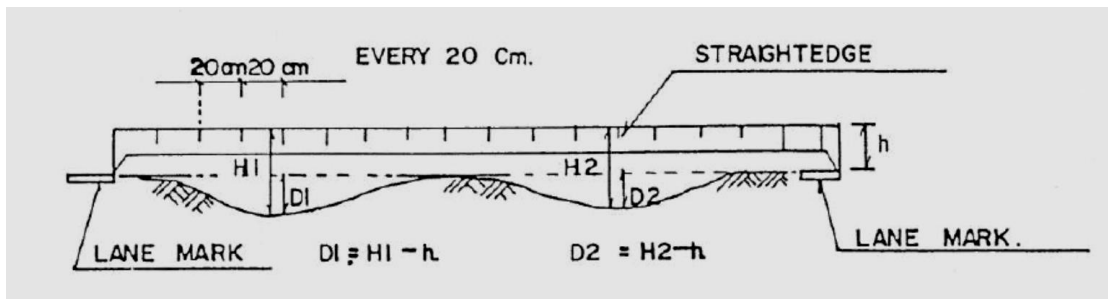


Figure 4.9 Straight Edge for rutting measurement

Roughness and corrugation in the longitudinal direction were measured by laser profilometer. The meter was travelled along left wheel track for a distance of 100 m. The depth was measured by laser after every 1.5 m. Standard deviation of the depth was taken as longitudinal roughness, as shown in **Figure 4.10**.

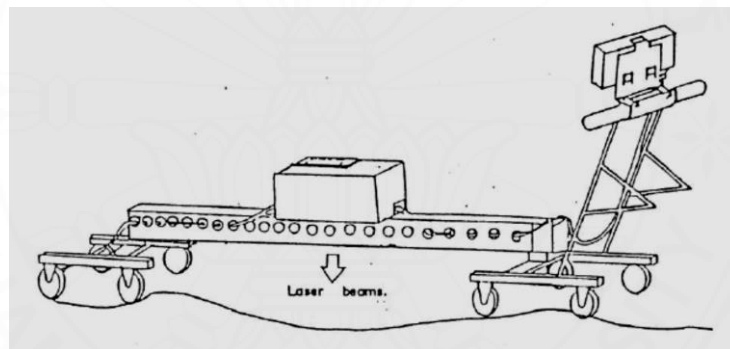


Figure 4.10 Laser Profilometer

The latest one in 2019, EXAT utilized highway survey vehicle for collecting pavement survey data. The vehicle was equipped with a laser profilometer, video logging modules (5 cameras), distance measurement instrument (DMI), and GPS receivers, as shown in **Figure 4.11** **Figure 4.12** and **Figure 4.13**.

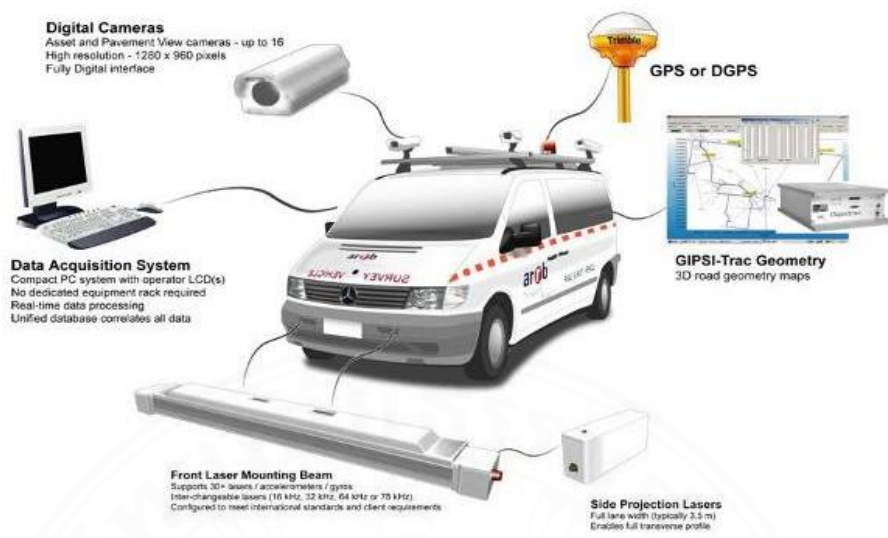


Figure 4.11 Survey vehicle and equipment

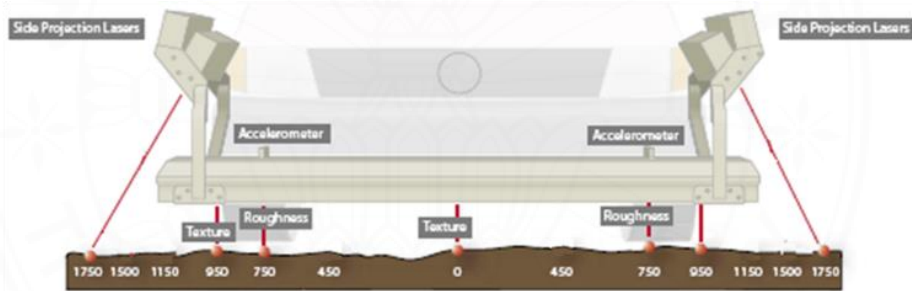


Figure 4.12 Laser profilometer



Figure 4.13 Inspection vehicle appearance

The vehicle collects distress data after every 25 m. International Roughness Index (IRI) and rutting were measured by profilometer. Cracks and other kind of distress are recorded by cameras. All collected data were referenced with GPS coordinates. Thresholds for IRI, rutting, and surface friction directed by EXAT is shown in **Table 4.3**

Table 4.3 EXAT pavement condition rating

Value	Condition	Rating
IRI, m/km	Very smooth	< 2.0
	Smooth	2.0 – 2.5
	Rough	2.5 – 3.0
	Very rough	> 3.0
Rut Depth, mm	Normal	< 10
	Low Severity	10 - 15
	Medium Severity	15 - 20
	High Severity	> 20

DonMuang Tollway (DMT) is an elevated road from Dindang in central Bangkok to DonMuang International Airport as shown in **Figure 4.14**. There are 3 lanes in each direction. Total length is 22 km. DMT is BTO concession contract until 2034 with Department of Highway.

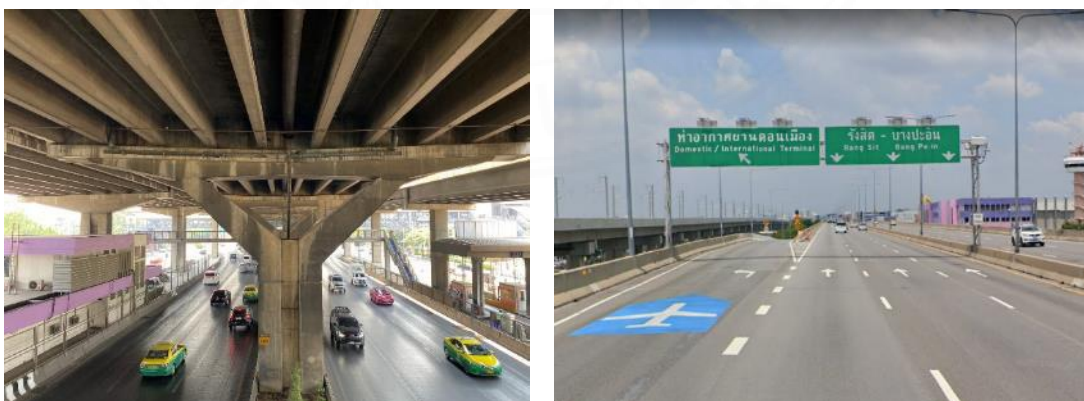


Figure 4.14 DonMuang Tollway Elevated Road

DMT perform pavement inspection in 2020. Pavement is measured for IRI and rutting by difference device. ROMDAS Laser crack measurement system (LCMS) from New Zealand is used as shown in **Figure 4.15**. LCMS is equipped with 2 laser line projectors from Pavemetrics™ and advanced optics to acquire high resolution 3D profile of the road surface.



Figure 4.15 Laser crack measurement system

Two laser projectors cover 4 m wide profile of pavement measurement. LCMS records 4096 points per profile as shown in **Figure 4.16**. So, pavement cracking down to 1 mm can be detected. Distance between each profile is 5 mm. As result, measurement resolution is 1x5 mm. In the area of 5x5 cm there will be 500 points of measurement. Survey speed can be up to 100 kmph.

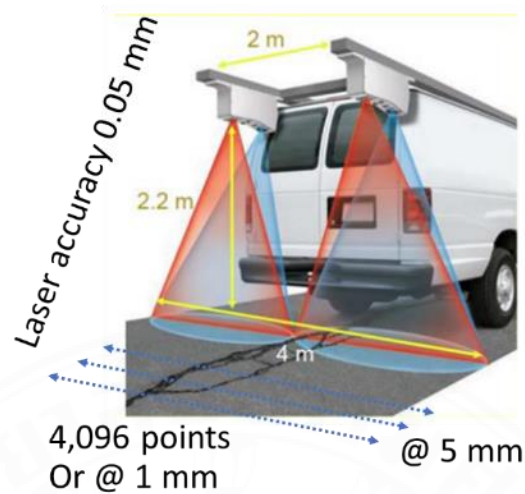


Figure 4.16 LCMS laser projection

By employ 3D profile road surface, several outputs will be cracking, potholes, rut depth, MPD, bleeding while IRI is become optional to upgrades. This device is newly available in Thailand. Bangkok Expressway and Metro Public Company Limited (BEM) who responsible for expressways in Bangkok also use this device to measure 222 km of expressway in 2019. IRI were measured every 1 m and then converted into 5 m and 25 m length of pavement.

4.6 IRI Pavement Condition Rating

Laser profilometer is a common pavement inspection vehicle among road agencies in Thailand. Condition rating varies time to time and documentations. Comparisons among them are as shown in **Table 4.4**.

Table 4.4 IRI rating among road agencies

Condition	World Bank	Motorway Thailand	DOH, DMT, BEM	Expressway Thailand	Rural Roads Thailand
Very smooth		< 2.5	< 2.5	< 2.0	<3.5
Smooth	< 2.5	2.5 - 3.5	2.5 - 3.5	2.0 – 2.5	3.5 – 4.5
Rough	3.5 – 4.5	3.5 – 4.5	3.5 – 5.0	2.5 – 3.0	4.5 – 7.5
Very rough	> 4.5	> 4.5	> 5.0	> 3.0	> 7.5

Each road agency performs their pavement assessment by difference machine. Method of measurement is also different. Even road length segment ranges from 1 m to 100 m in Thailand. Múčka (2017) reviewed IRI measurements around the world. Segment length ranged from 20, 50, 500, 161, 200 and more than 500 m. There were several types of machines utilized including inertial profilers and inclinometer-based devices. Measurement methods were also different including single profile, two longitudinal profiles, and more than two profiles. So, large differences in IRI limit were observed for the same segment length among various countries as shown in **Figure 4.17**.

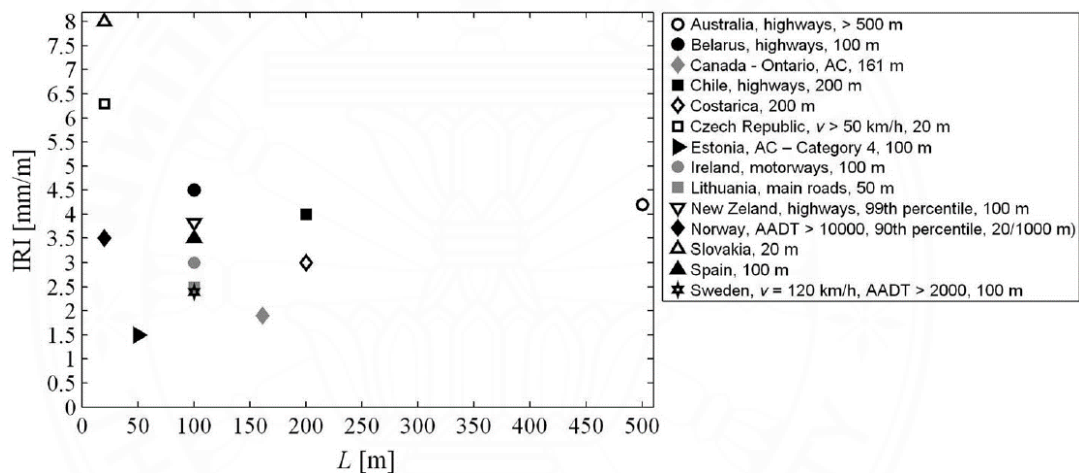


Figure 4.17 IRI and segment length in various countries

4.7 Thailand Expressway IRI Measurement

The latest measurement for IRI on expressway was performed in 2019. The length of 175 km of expressway was measured by profilometer. There were 3 lanes in each direction and 2 carriageways. So, total length of measurement was longer than 1,050 km. IRI data was exported in the form of text file or CSV file. Sample of IRI data is as shown in **Figure 4.18**.

id	Section	Distance (Sub Distance)	IRI Right	IRI Left	IRI Avg	GPS position	Speed (km/h)	Latitude (d)	Longitude (d)	Altitude (m)	Events
1	S1L1	0.025	0.025	3.2	2.43	2.81	FALSE	85.5	13.70476	100.5939	13.4
2	S1L1	0.05	0.05	2.3	1.78	2.04	FALSE	85.7	13.70457	100.5938	13.3
3	S1L1	0.075	0.075	1.32	1.22	1.27	FALSE	86	13.70439	100.5937	14
4	S1L1	0.1	0.1	2.14	1.99	2.06	FALSE	86.5	13.7042	100.5935	14.1
5	S1L1	0.125	0.125	2.42	1.88	2.15	FALSE	86.4	13.70401	100.5934	13.8
6	S1L1	0.15	0.15	2.58	2.46	2.52	FALSE	86.1	13.70382	100.5933	13.9
7	S1L1	0.175	0.175	2.4	2.48	2.44	FALSE	85.5	13.70363	100.5932	14.4 Chevron Sign
8	S1L1	0.2	0.2	2.26	1.9	2.08	FALSE	84.7	13.70344	100.593	14.5
9	S1L1	0.225	0.225	2.73	2.98	2.85	FALSE	84.1	13.70325	100.5929	15

Figure 4.18 IRI Profiler Data

IRI is measured every 25 m length of pavement. It is calculated both left and right wheel track (two longitudinal profiles). Geodetic coordinate (latitude and longitude) of each measured section of pavement is also available. IRI by laser profilometer is widely accepted in Thailand.

4.8 Japan Expressway IRI Measurement

Tokyo University and Shotoku engineering has a joint project research on “Pavement inspection program”. This program calculates IRI from pavement point cloud data measured by MLS. Pavement damage can be detected and evaluated by conducting Short-Time Fourier Transform of pavement surface in three-dimensional point cloud data. The mean value of the amplitude spectrum is linearly correlated with IRI(Hirano et al. (2018)).

First, point cloud data of 3 m x 25 m pavement was extracted. Then the data was meshed into 5 cm x 5 cm grid. Average elevation of each mesh was calculated. So, input file for “Pavement inspection program” was an array of 499 rows and 59 columns. Size of pavement can be freely adjusted in length or width. Three meters of width was wide enough for wheel track and lane width for expressway in Tokyo. Working step is as shown in **Figure 4.19**

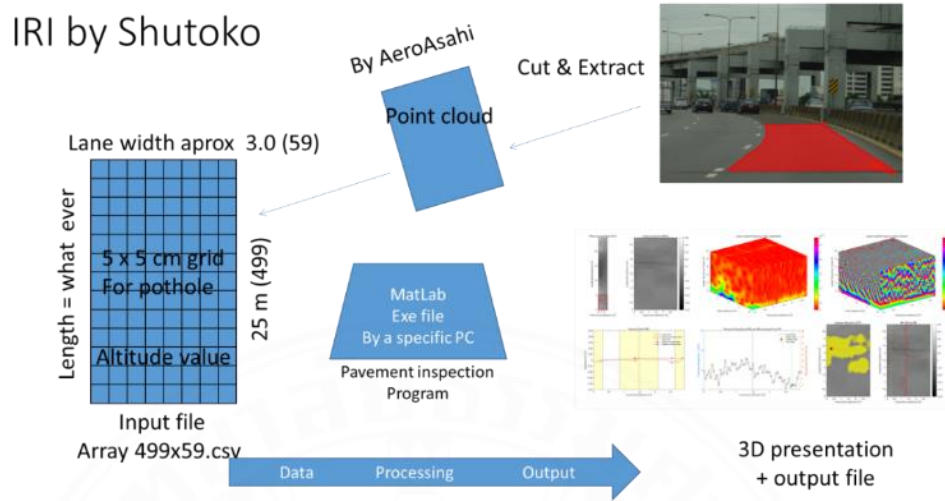
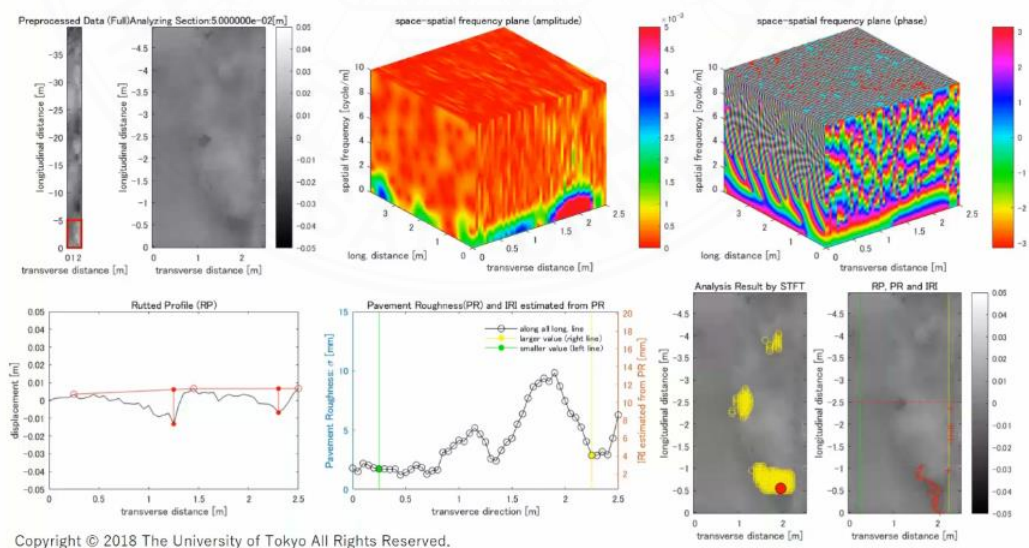


Figure 4.19 Working step for “Pavement inspection program”

Output of “Pavement inspection program” is road roughness and 3D contour of pavement. Rutting of each 5 cm step (grid size) can be examined. Potholes and other kind of distress by the resolution of 5 cm can be extracted as well. Output of the program is shown in Figure 4.20.



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Figure 4.20 Output of “Pavement inspection program”

4.9 Mesh Size Effect on IRI Measurement

As mentioned in Chapter 3, the minimum mesh size was 5 cm x 5 cm. the cropped area of 3.0 m x 25.0 m had 59 x 499 meshes. If the mesh size was 10x10 cm, there would have been 29x249 meshes. Consequently, the computation time could be reduced by 75%. In order to minimize calculation time within acceptable accuracy, difference mesh sizes were studied.

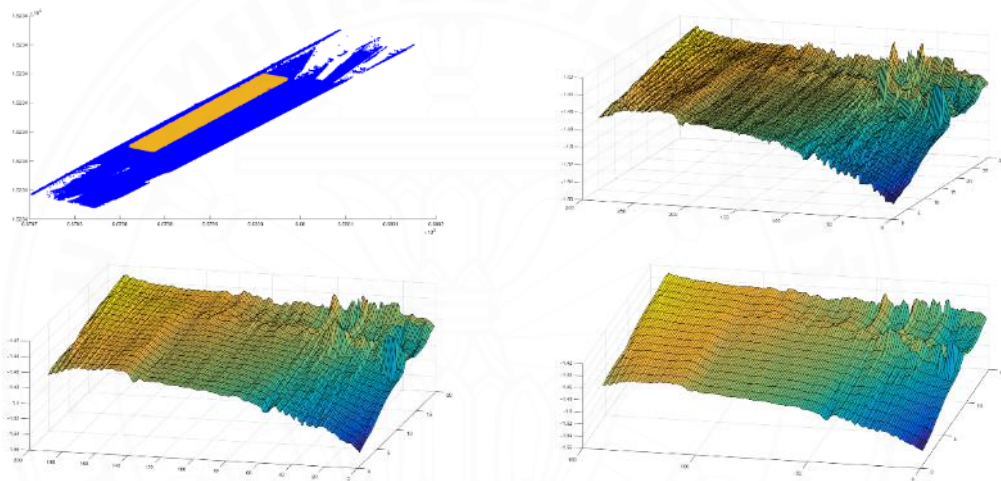


Figure 4.21 Input file with difference mesh size

Four sizes of mesh, 5x5 cm, 10x10 cm, 15x15 cm and 20x20 cm were studied as shown in

Figure 4.21. There were 17 input files generated for “Pavement inspection program” execution. Results yielded the values of rutting and IRI. The finest mesh 5x5 cm was used as a benchmark for this test. Results by “Pavement inspection program” are shown in **Figure 4.22** and **Figure 4.23**.

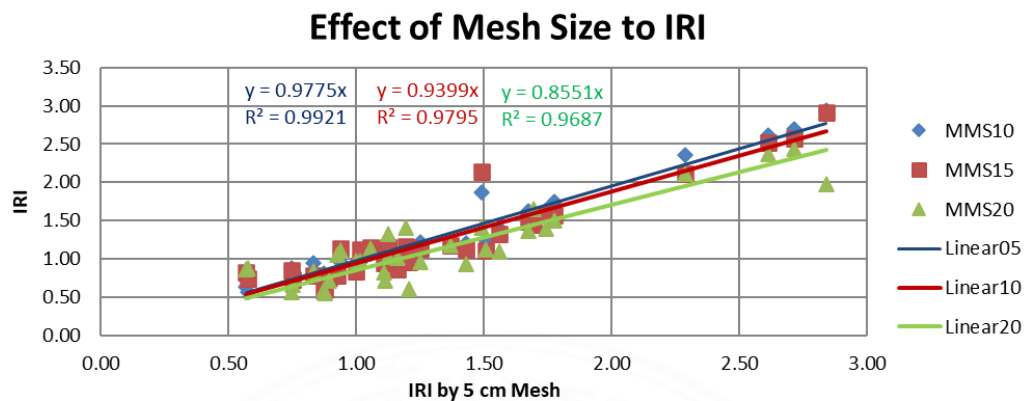


Figure 4.22 Effect of mesh size on IRI

Mesh size of 10 cm gave the best linearity to 5 cm mesh size with R^2 value of about 0.992. The value was about 97.75% of 5 cm mesh size. Mesh size of 15 and 20 cm returned $R^2 = 0.979$ and 0.969 with the value of 93.9% and 85.5%, respectively. If the value of 95% was expected, it could be concluded that 10 cm can be used instead of 5 cm mesh size in order to reduce calculation time. Adjustment factor of 0.9775 will be used for IRI value adjustment. Effect of mesh size to rut depth is as follow.

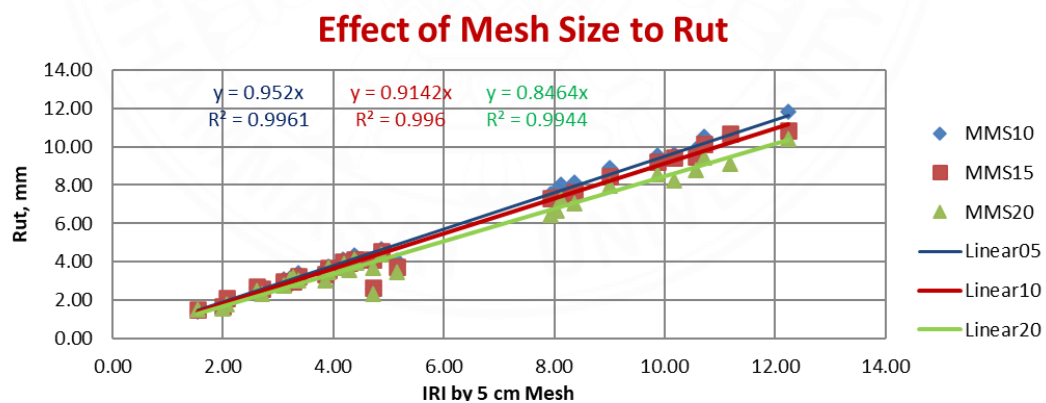


Figure 4.23 Effect of mesh size on rutting

Mesh size of 10, 15 and 20 cm gave $R^2 = 0.996$, 0.996 and 0.994 , respectively. This was about 95.2%, 91.4% and 84.6% of 5 cm mesh size. Effect to rut depth calculation was almost the same as IRI. A 10 cm mesh size gave almost the same value as that of 5 cm mesh.

4.10 IRI Comparison to the Profilometer

IRI and rut depth were then compared to the corresponding values measured by laser profilometer. Because of the different machine and calculation method, empirical relation correlation between these 2 methods was examined. The relation of IRI value measured by two methods is as follows.

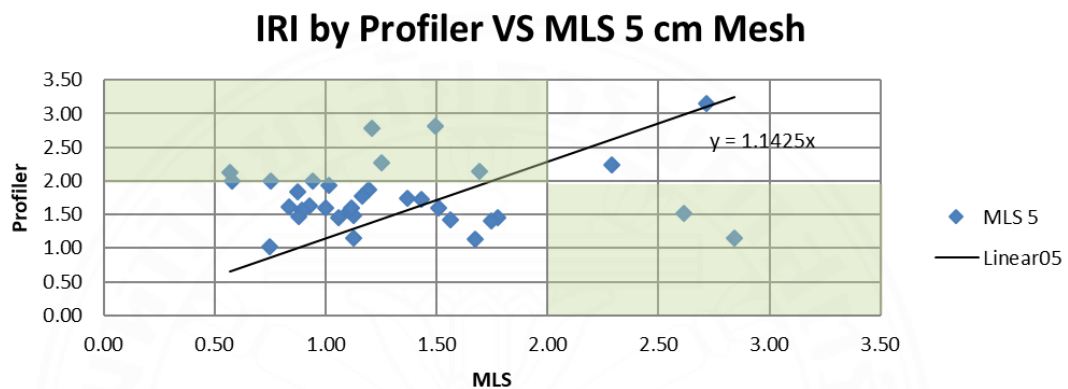


Figure 4.24 IRI by Profilometer and MLS 5 cm mesh

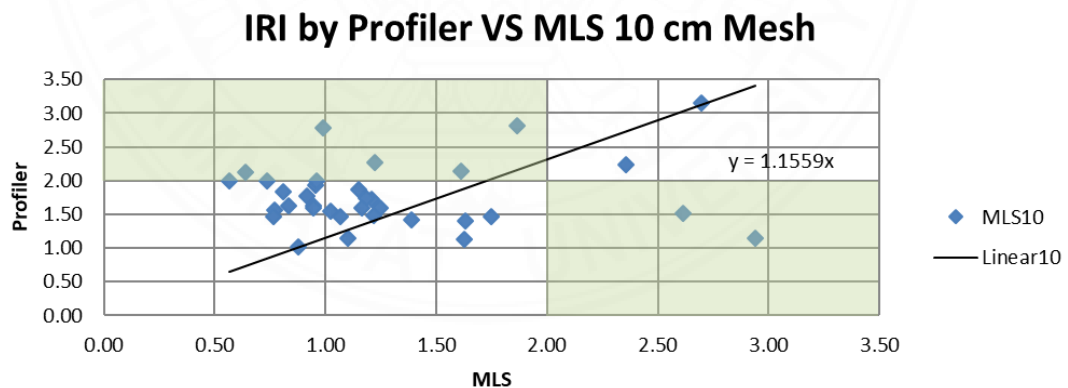


Figure 4.25 IRI by Profilometer and MLS 10 cm mesh

By graphs, IRI relations between 2 methods were observed in **Figure 4.24** and **Figure 4.25**. Mesh size of 5 and 10 cm, respectively were used for MLS IRI calculation. Correlation between these 2 methods could not be observed. It was found that IRI by MLS both 5 and 10 cm mesh must be multiplied by 1.142 and 1.156 to obtain the IRI

measured by profilometer. The 10 cm meshing can also be used in order to reduce computation time.

4.11 Rutting Comparison to the Profilometer

The same comparison was made for rut depth measurements as follows.

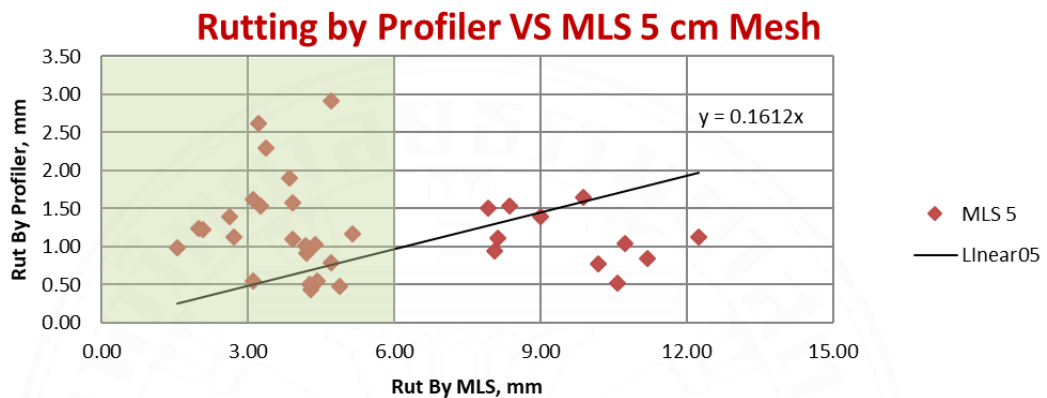


Figure 4.26 Rut by Profilometer and MLS 5 cm mesh

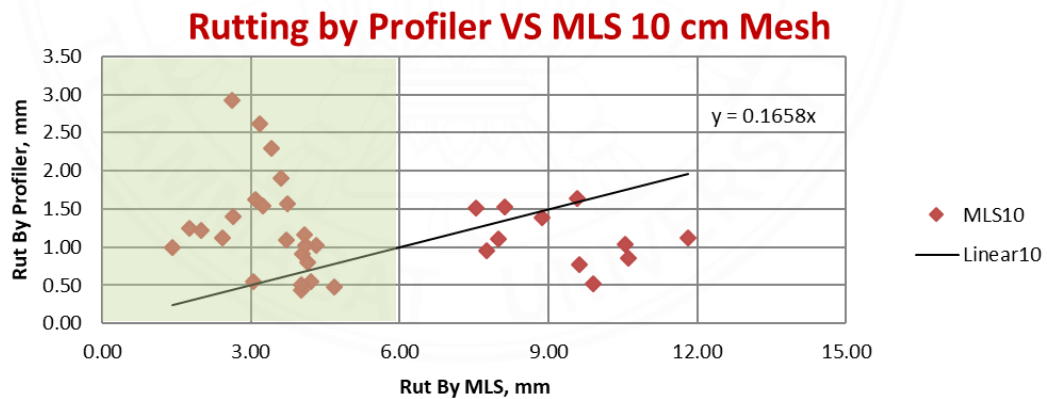


Figure 4.27 Rut by Profilometer and MLS 10 cm mesh

According to Department of highway standard, a rut depth of 6-12 is considered “low”. In **Table 4.3**, rut depth less than 6 mm is considered low. By **Figure 4.26** and **Figure 4.27**, the results show the same as those of IRI. MLS gave much larger rut depth compared to laser profilometer. If rut depth by MLS is 12 mm, the equivalent rut depth

measured by profilometer will be only $= 0.1183 \times 12 = 1.42$ mm which is more realistic. Correlation between these 2 methods could not be observed as well.

By the results, IRI and rut depth calculated from point cloud data by MLS have no correlation with IRI and rut depth by recent measurement method, the laser profilometer. The MLS pavement scanning performed several times. After data were rectified and cleaned out for unwanted points, point cloud of each scan were combined together to complete overall picture of the scan as described in Chapter 3.1 and 3.2 . There might have uneven of pavement elevation by 2 times scanning especially in Z-direction. Unlike profilometer which perform scanning by single scan, lane-by-lane basis. The scanner data no need to rectified or clean for unwanted point.

Another observation is point cloud density. Pavement scanning by profilometer gave really high point cloud density, up to 500 points within the area of 5x5 sq.cm as described in Chapter 4.5 while MLS point cloud density is about 2,000 points/sq.m or about 5 points within the area of 5x5 sq.cm. So in order to perform IRI and rut depth measurement using MLS point cloud comparable with profilometer which is “ground truth” measurement in Thailand, more focusing on pavement point cloud scanning procedure would have achieve the better result.

4.12 Summary

From experimental results, a good agreement between elevations of the Rama XI bridge in Bangkok measured by point cloud data using MMS and by RTK was obtained. The accuracy of MLS was assessed in terms of twist angles. From the point cloud data, bridge profile, twist angles of the deck, and lateral movements of pylons were assessed. The results showed that most of the measured twist angles were within the acceptable limits ($\pm 0.05^\circ$). Point clouds need refined meshing to process the results. It was found that a mesh size of 10 cm was sufficient to minimize the error when compared to the mesh size of 5 cm. This was achieved by saving a considerable amount of computation time and cost. Though IRI and rutting obtained by MLS were higher than those obtained from profilometer. The more intensive on MLS pavement data collection, data preparation and IRI calculation would be comparable with profilometer measurement.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

By technical collaboration with a Japanese expressway company, a mobile mapping 3D laser scanner (MLS) (Trimble MX-8) was introduced to Thailand. MLS is the ideal tool for geometry survey. However, performances of MLS need to be examined. The procedure of measurement, data handling, data accuracy, data exportation would be studied to achieve some practical expressway in Thailand.

The MLS measurement can be performed within a 20 km radius of the base station. Thus, a single base station was established in the Bangkok centre. MLS measurement took a short time (5 days for 5 locations), but data preparation needed some time. Data must be rectified for correct position, clean unwanted points, and combine several scanning data. This data registration process took 2-3 months. Two km of road scanning produced about 33.5 GB of data. So, enough storage and powerful point cloud management software should be prepared in advance.

- A good agreement between elevations of the Rama XI bridge in Bangkok measured by point cloud data using MLS and by RTK was obtained. It was proved that MMS is a fast and accurate acquisition method to gather structure geometry that can be used for the health monitoring system.
- From the point cloud data, bridge profile, twist angles of the deck, and lateral movements of pylons were assessed. The results showed that most of the measured twist angles were within the acceptable limits ($\pm 0.05^\circ$). No sign of a permanent twist was observed for the deck. The top movement of the west and east pylon was 104 mm and 138 mm, respectively. However, a periodic inspection was suggested due to the absence of initial readings of the pylon.
- Point cloud needs to be meshed during input file creation. The Mesh size of 5 cmx5 cm is the finest. Mesh size of 10 cmx10 cm reduced computation time by 75% but reduced the accuracy slightly. Three more mesh sizes, 10 cm x 10 cm, 15 cm x 15 cm, and 20 cm x 20 cm were studied. The results obtained were

compared to the mesh size of 5 cmx5 cm. It was found the mesh size of 10 cm, 15 cm, and 20 cm resulted in R^2 values of 0.992, 0.979, and 0.969 when compared with the results of the mesh size of 5 cm. A mesh size of 10 cm resulted in a reduction of IRI by 95%.

- IRI values by profilometer were used as a benchmark. In order to convert the IRI value obtained by MLS to IRI values obtained by a profilometer, empirical correlations between 2 methods were proposed. An R^2 of up to 0.933 for the value of IRI over 1.50-3.0 m/km was obtained from the comparison of IRI values obtained by MLS and profilometer. To convert the IRI value obtained from MLS to the corresponding profilometer value, a conversion value of 0.7597 should be used.
- It was found that the rutting values obtained from MLS measurements were significantly higher than those obtained from the profilometer.

5.2 Recommendations for Future Studies

Few recommendations for future studies are given as below;

- The MLS is applicable for elevated structure scanning, specially viaduct structure along the road. It is good for geometry scanning. The application on structure inspection such as damage detection are interesting as well as complex structure deflection measurement.
- Even though IRI and rut depth measurement by MLS was yield the practical measurement, the more focus on pavement point cloud data collection by the term of point cloud density, data preparation would be achieved. By the more powerful computer and faster for large amount of point cloud data processing will reduce computation time. The study can have more data comparison that will make highly confident in the results.

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BIOGRAPHY

- Name Ekarin Lueangvilai
- Education 1997: Bachelor of Engineering (Civil Engineering)
Faculty of Engineering, Srinakarindrawirot
University
2002: Master of Engineering, Asian Institute of
Technology
- Publications
- Chaisomphob, T., Lueangvilai, E., Tran, T. H. and Annaka, S., “Development of maintenance system for highway/expressway in Thailand using mobile laser scanning”, *10th International Symposium on Steel Structures (ISSS2019)*, Jeju, Korea, November 13-16, 2019.
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