Advanced Highway Maintenance and Construction Technology Research Center

Department of Mechanical and Aerospace Engineering
University of California at Davis

Using Mobile Laser Scanning to Produce Digital Terrain Models of Pavement Surfaces

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ABSTRACT

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DISCLAIMER/DISCLOSURE

The research reported herein was performed as part of the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center, within the Department of Mechanical and Aerospace Engineering at the University of California – Davis, and the Division of Research and Innovation at the California Department of Transportation. It is evolutionary and voluntary. It is a cooperative venture of local, State and Federal governments and universities.

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California, the Federal Highway Administration, or the University of California. This report does not constitute a standard, specification, or regulation.

LIST OF ACRONYMS AND ABBREVIATIONS

ADA	Americans with Disabilities Act
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
ANSI	American National Standards Institute
ASPRS	American Society for Photogrammetry and Remote Sensing
ASTM	American Society for Testing and Materials
CAD	Computer-Aided Design
Caltrans	California Department of Transportation
CMAG	Construction Metrology and Automation Group
CMS	Changeable Message Sign
CORS	Continuously Operating Reference Station
COTS	Commercial-Off-The-Shelf
CSM	Caltrans Survey Manual
DEM	Digital Elevation Model
DMI	Distance Measuring Indicator
DOF	Degree-of-Freedom
DOT	Department of Transportation
DRI	Caltrans Division of Research and Innovation
DRWLS	Caltrans Division of Right of Way and Land Surveys
DTM	Digital Terrain Model
FOV	Field-of-View
FTE	Full-Time Equivalent
GAMS	GPS Azimuth Measurement System
GNSS	Global Navigation Satellite Systems
GLONASS	GLObal'naya NAvigatsionnaya Sputnikovaya Sistema
GTMA	Geospatial Transportation Mapping Association
IMU	Inertial measurement unit
ISO	International Organization for Standardization
ITAR	International Traffic in Arms Regulations
KF	Kalman Filter
LADAR	Laser Radar
LAS	Log ASCII Standard
LASER	Light Amplification by Stimulated Emission of Radiation
LIDAR	Light Detection and Ranging
LOS	Line-of-Sight
MS	Microsoft
MTLS	Mobile Terrestrial Laser Scanning
MUTCD	Manual on Uniform Traffic Control Devices
NGS	National Geodetic Survey
NIR	Near Infrared
NIST	National Institute of Standards and Technology
OEM	Original Equipment Manufacturer
OLS	Caltrans Office of Land Surveys
QA/QC	Quality Assurance / Quality Control
RFIP	Roadside Feature Inventory Program
RMS	Root Mean Squared
RMSE	Root Mean Squared Error
RTK	Real-Time Kinematic
SIMMS	Sign Inventory Database, Bridge, and Signal Maintenance Management System
S/W	Software
SWIM	Storm Water Information Management
TIN	Triangulated Irregular Network
TOF	Time-of-Flight

ADA	Americans with Disabilities Act
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
WSDOT	Washington State Department of Transportation
UV	Ultraviolet
VIM	International Vocabulary of Basic and General Terms in Metrology
XYZI	X, Y, Z location and Intensity

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CHAPTER 1: INTRODUCTION

Background and Motivation

Land-based mobile scanning is a new and rapidly emerging technology and market. The capabilities of these mobile systems in the DOT context must be carefully evaluated for use in DOT applications. It is anticipated that the accuracy of these systems will not equal that of tripod-mounted scanners. However, the high mobility (scanning at highway speeds), capture of multiple highway areas (roadways, roadsides, structures), fusion of multiple sensors (laser scanners, cameras, GPS, inertial sensors, etc.), and massive amounts of data collected in a very short time will combine to enable new approaches to highway surveying, evaluation, data collection, operations, and management, which can only be glimpsed at this time.

A freeway pavement surface survey is the most hazardous task that Caltrans surveyors face. Small survey crews often work on the roadside, next to live traffic, without the protection of elaborate work zone setup such as traffic control, Changeable Message Sign (CMS) warning, and cone zone to warn drivers of their presence. In addition, high-accuracy pavement elevation survey work is time-consuming, involving surveyors setting up control points and sometime targets in the right-of-way. In the traditional survey process, surveyors, particularly the rod-man, are often exposed to all manner of environmental hazards including walking across the roadway exposed to high-speed traffic, climbing steep slopes, and standing close to high-speed traffic or other dangerous areas to place the prism or rod. The use of reflectorless Total Stations has improved safety, but due to the large incidence angle the measurements can be inaccurate. Stationary laser scanners are capable of obtaining this accuracy, but the instruments must be set up within the right-of-way to obtain the measurements. In urban areas, road widening and addition of sound walls have eliminated shoulder and median areas that are traditionally the safest areas for surveyors to occupy without lane closures. As a result, surveyors' safety risks increase significantly and the mobility of the public decreases due to lane closures.

The current positional accuracy specified in the Surveys Manual for pavement is 10 mm horizontal and 7 mm vertical for hard surfaces. To improve safety and efficiency, Caltrans Surveys and Photogrammetry have investigated a variety of technological solutions including low-altitude helicopter photogrammetry, GPS airborne photogrammetry, a photogrammetry pre-mark trailer, Vangarde 505 Survey Systems, and stationary laser scanning. Photogrammetry methods (achieving decimeter level accuracy) do not yield results that meet the pavement survey accuracy requirement.

Since the mid 1990's, Vangarde 505 Survey Systems have been used to keep the Total Station operator inside a protective vehicle while performing pavement elevation surveys [18]. The reflectorless Total Station inside the Vangarde system removes the need for an additional surveyor holding a retroreflective prism at a dangerous area. The Vangarde system and terrestrial laser scanning produce accurate results at high speed, but they do require precious shoulder or median space often not available in urban area.

Urban highway expansion and sound wall construction eliminate these pockets of safe parking areas. While each solution has its strengths, they are inadequate in dealing with the growing problem of lack of shoulder and median space for survey operations. A new tool is needed to perform pavement surface survey while traveling with traffic flow—the tool must also produce accurate digital terrain models for Caltrans Surveys' customers' needs.

Mobile terrestrial laser scanning (MTLS) systems—a new class of survey instrumentation—have recently become commercially available for roadway survey including roadside inventory, bridge structures, bridge clearance and highway pavement surveys. These systems combine recent technological advances in GPS, inertial measurement units (IMUs), digital cameras, laser ranging scanners and advanced post-processing software. Mobile laser scanning systems have been used in pavement condition surveys. AHMCT had experimented with a vehicle-mounted laser scanner system for bridge clearance measurement for Caltrans Structures Maintenance.

The point cloud can then be post-processed to create detailed 3D Computer-Aided Design (CAD) model. These solutions have significant advantages over existing methods. It eliminates surveyors' exposure by keeping them inside the vehicle and improves survey speed and traffic flow. An MTLS system may collect up to 10 to 20 miles of field data a day. Furthermore, it does not require space on the shoulder or median. This system would replace traditional surveying methods. A mobile laser scanning system would increase the safety of surveyors, reduce the need for lane closures, and possibly increase productivity. The resulting point cloud data may be used for other Caltrans applications such as roadside inventory and bridge height clearance generation. It meets the Caltrans goals of Safety, Mobility, and Stewardship. However, further research is required to determine the system accuracy in practical real-world situations. The goal of the current research is to determine these systems accuracy and if they can perform pavement surface surveys that meet the accuracy requirements. If the system does not meet the required vertical accuracy of 7 mm, can the data be adjusted using additional survey points within the scan area to increase the accuracy?

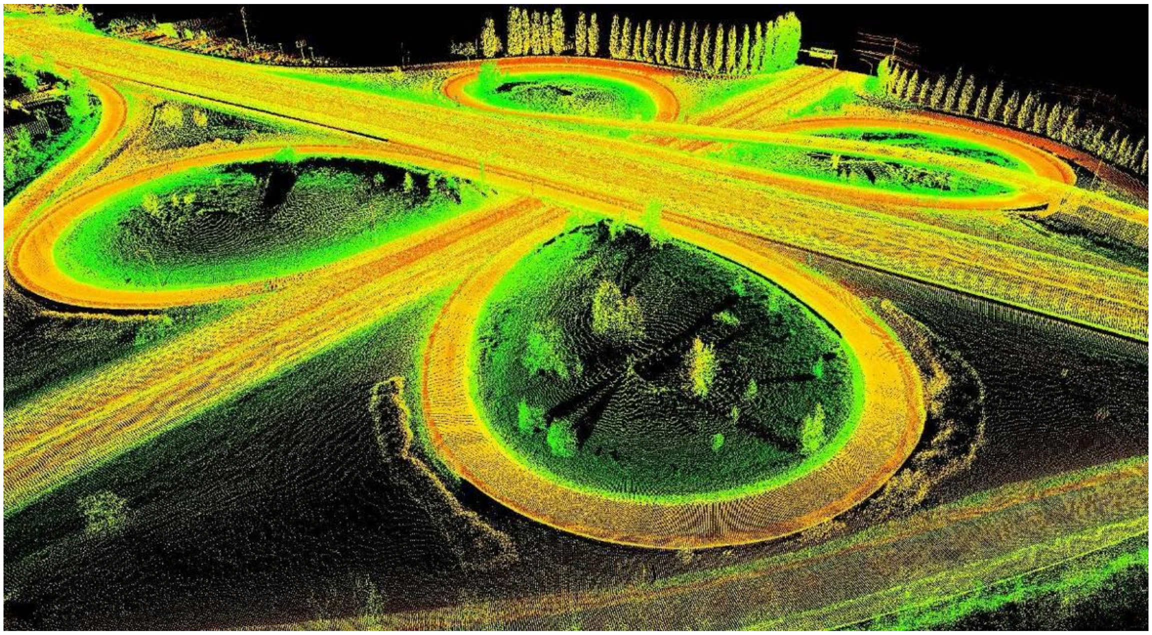

Figure 1.1: Example point cloud of a highway interchange produced by an Ambercore TITAN MTLS system (Data courtesy of David Evan & Associates)

Figure 1.2: Example point cloud of a highway produced by StreetMapper MTLS system (Data courtesy of Terrametrix)

Research Objectives

In the current research, the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center at the University of California-Davis investigated the possible use of a combination of vehicle-mounted mobile laser scanner, dual-frequency GPS receiver, digital camera, and IMU for pavement surface survey. The research objective was to determine if these survey systems would meet the current Caltrans survey accuracy requirements. In addition, we explored the use of adjustment methods to improve the overall accuracy.

Working closely with Caltrans to clarify the survey needs and requirements, the research team evaluated commercially available mobile laser pavement surface survey systems. If the system meets the current accuracy requirement, Caltrans may implement a widescale deployment throughout California. This new survey tool has the potential of reducing surveyors' exposure by keeping them inside the vehicle, improving survey speed and traffic flow by reducing lane closures.

Research Approach

To achieve the research objective, we conducted feasibility study and theoretical error analysis of the system, and experimental verification and validation based in real-world environments. Literature review provides a partial answer to the accuracy question. Based on the available information and preliminary analysis, achieving the 7 mm vertical survey accuracy will push the limits of existing technology. However, the available sensor error model may not be complete. Therefore, in order to obtain the true achievable accuracy in practical conditions, we experimentally validate our analysis and the effectiveness of adjustment methods.

The current research started with a thorough a literature survey and standards review, as well as a detailed investigation into existing related commercial products that could be employed in the system. Moreover, meetings were conducted with Caltrans Office of Land Survey personnel to gain a better understanding of current pavement surface survey requirements. Then, we established appropriate performance measures that the system should meet. After that, the researchers conducted in-depth error and accuracy analysis of the system based on error of individual sensors: GPS, IMU, and laser range scanner. The analysis focused on currently available state-of-the-art COTS laser range scanner, GPS and IMU integrated systems, and post-processing software. Then, we developed software components for experimentation to verify performance under various real-world conditions on available data.

The literature review included the latest GPS and IMU Kalman filter integration and sensor alignment techniques to determine if these latest technological developments may be used to improve accuracy. The results highlighted the error sources and effects on the total system error. In addition, new augmentation and control adjustment methods, based on survey methodologies, were investigated to improve the system accuracy. For example, how can point cloud data be "cleaned up" or "filtered"? And how can the point clouds be registered together better from different vehicle passes?

Currently, there are several commercially available mobile laser scanning systems. Each system has different on-board 2D scanners configuration, GNSS/INS sub-system, and digital camera. Direct comparison based solely on specifications is nearly impossible. Final system accuracy depends on its components accuracy and its sensors configuration. Literature review examined the available commercial mobile laser scanning systems for their strength and weakness for various DOT applications. This research explored the best practices on QA/QC for deliverable from mobile laser scanning.

Is mobile laser scanning appropriate to be used on pavement surveys? At the beginning of this project, there were no known guidelines that specify the use of mobile laser scanning systems in DOT survey applications. Without such guidelines, the mobile laser scanning systems would continue to be used on a trial-and-error, *ad hoc* basis, which may be costly in time, money, and safety. Therefore, to fully realize the benefits of this new tool, a set of Caltrans guidelines defining the appropriate use of mobile laser scanning systems for different types of Caltrans applications were created [6]. These standards will promote consistent and correct use of mobile laser scanning systems throughout Caltrans and by its contractors. This research aimed to develop the needed recommendations and guidelines that are essential to deployment of this technology into Caltrans operations.

This report documents the research effort, including:

- Literature review on GPS/INS systems, 2D laser scanners, and mobile laser scanning systems,
- Commercially available mobile laser scanning systems,
- Application of mobile laser scanning systems,
- Real project data analysis
- Propose recommendations for Quality Assurance / Quality Control (QA/QC),
- Considerations in employing mobile laser scanning system, and
- Recommended data format for exchange and archival purposes.

CHAPTER 2:
LITERATURE OVERVIEW

We performed a thorough literature review, as well as a detailed investigation into existing related commercially available MTLS systems and their components, such as integrated GNSS/IMU systems and LiDAR scanners. Currently, there are several commercially available MTLS systems. Each system has a different on-board 2D scanner configuration, GNSS/IMU sub-system, and digital camera configuration. Direct comparison based solely on specifications is nearly impossible. The literature review examined the strength and weakness of available commercial MTLS systems for various survey applications. Moreover, meetings were conducted with Caltrans Office of Land Survey personnel to gain better understanding of current pavement surface survey operation and its requirements. Furthermore, literature review included the latest GNSS and IMU Kalman Filter (KF) integration, 2D laser scanners, fully-integrated mobile laser scanning systems, and adjustment techniques to improve accuracy. In addition, the latest developments in GNSS are briefly reviewed.

General Mobile Laser Scanning System Description

Land-based mobile laser scanning systems are similar to airborne LiDAR (laser scanning) systems. Figure 2.1 illustrates the basic system architecture concept. The system consists of a dual-frequency RTK GNSS receiver(s), a six degree-of-freedom (DOF) IMU (typically three accelerometers and three gyros orthogonally mounted), Distance Measuring Indicator (DMI), LiDAR scanner(s), data synchronization electronics, data logging computer(s), and digital camera(s) [13,16,22,26,28]. The computer(s) collects the synchronized data of GNSS carrier-phase measurements, IMU and DMI outputs, digital photographs and LiDAR scanner data for the post-processing software. Combining GNSS base station raw data collected at the same time, the GNSS measurement, IMU, and DMI data of the rover, the software will provide position and orientation solution (at 100 to 1,000 Hz update frequency) of the sensors platform containing the LiDAR scanners and digital cameras. To achieve the highest possible accuracy, the raw GNSS/IMU data is post-processed with GNSS base station(s) raw data with high accuracy satellite orbital measurements. Furthermore, the system may have multiple LiDAR scanning sensors with digital cameras in visible light wavelength, Near Infrared (NIR) or Ultraviolet (UV) wavelength. NIR and UV camera may be used to better determine health of certain plant species or in poor lighting conditions.

The land-based LiDAR scanners are usually shorter in range but higher in accuracy than those used in airborne systems. The LiDAR scanner produces distance and angular measurement to objects as well as the amplitude of the light return signal. The amplitude depends on the reflectance of the object surface as well as range and incidence angle to the object. It allows the software to identify the highly reflective painted lane lines, signs, and raised pavement markers. By combining the GNSS/IMU and laser range scanner data, the global coordinate of every scan point can be calculated using equation 3.1. Thus, the position of the painted lane line will also be established. After that, the digital terrain model (DTM) of the road surface can be generated for Surveys' customers. In addition, other roadside and roadway feature can be identified and located using the resulting point cloud and geo-referenced photographs.

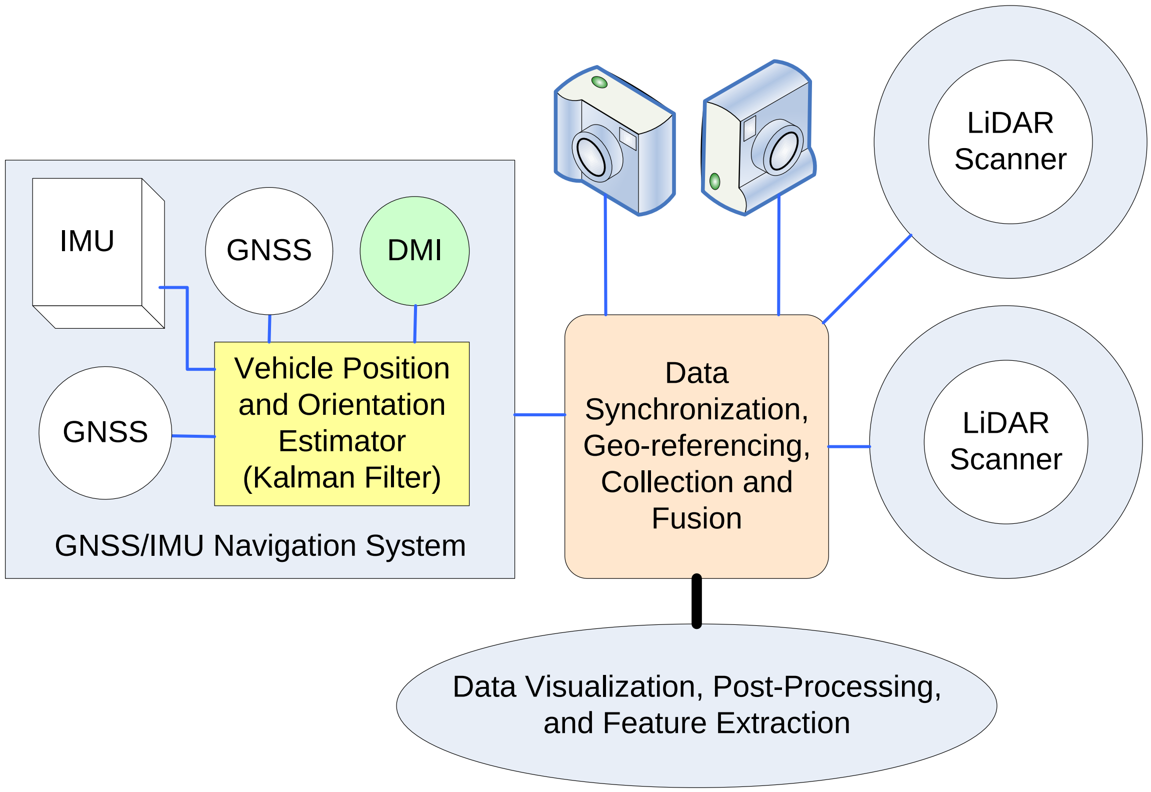

Figure 2.1: MTLS system architecture block diagram

2D Laser Scanner Overview

The 2D LiDAR scanner uses advanced laser measurement technology capable of obtaining thousands of point measurements per second. The 2D LiDAR scanner system consists of a motorized spinning mirror with encoder and a LiDAR sensor. Its accuracy depends on the rangefinder accuracy and the encoder resolution. Moreover, some scanner performance can be adversely affected by surface reflectivity, edges, temperature, atmospheric conditions, and interfering radiation such as bright lights or direct sunlight [4]. 2D LiDAR scanners for MTLS systems use either the Time-of-Flight (TOF) measurement method or phase-based measurement to obtain target point distance.

Time-of-Flight measurement technology determines range by sending out a laser pulse and observing the time taken for the pulse to reflect from an object and return to the instrument. Advanced high-speed electronics are used to measure the small time difference and compute the range to the object. The LiDAR scanner also has a high-resolution angular encoder to provide orientation of the rotating mirror at the time of each range measurement. This type of technology is similar to that used in Total Stations. However, the difference between 2D LiDAR scanners and Total Stations is the speed of measurement. Typical Total Stations may measure up to eight distances per second. In contrast, the 2D LiDAR scanner is capable of measuring up to half a million distances per second. Some LiDAR sensors can detect and provide range measurement for multiple light returns from a single light pulse. This technology enhances the LiDAR sensor's ability to detect the structure or an object positioned behind vegetation.

In phase-based measurement technology, the phase difference is measured between the reflected beam and the transmitted amplitude modulated continuous wave laser beam. The target distance is proportional to the phase difference and the wavelength of the amplitude modulated signal. In addition, the amplitude of the reflected beam provides the reflected power. Typically, phase-based scanners are capable of achieving a much higher number of point measurements in a second relative to time-of-flight scanners—their point measurement rate is from about five to one hundred times greater. However, they have shorter useful range (typically 25-100 m). Time-of-flight scanners have the technological adaptability to provide longer range, typically between 75 m to 1000 m. Currently available phase-based LiDAR sensor do not have multiple return capability.

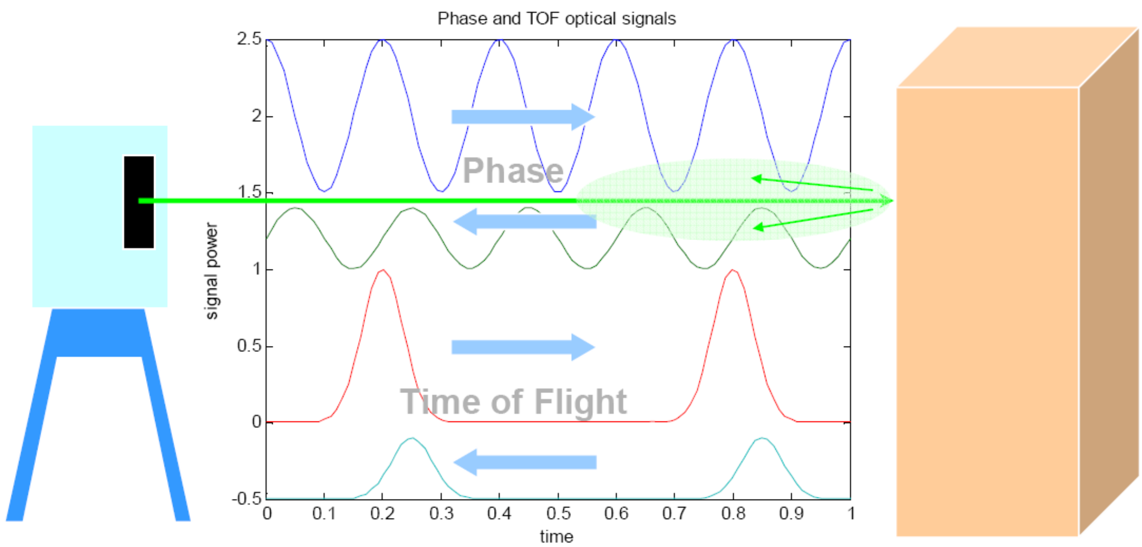

Figure 2.3: Working principle of phase-based and time-of-flight 3D laser scanners

Table 2.1 lists some of the most common 2D LiDAR scanning systems used by MTLS systems. Their detailed specifications may be found on their manufacturer's website listed in Table 2.1. While scanner measurement rate (point per second) is often used to promote the superiority of a LiDAR scanner technology, the "scan rate" is more critical in affecting the vehicle's speed in data collection. The "scan rate" is the LiDAR scanner's mirror rotational rate. The points in the point cloud produced by MTLS system are not evenly spaced as shown in Figure 2.4. The point cloud in Figure 2.4 is produced by a system with two LiDAR scanners mounted orthogonal to each other and approximately 45 degrees to the vehicle travel direction. Each point represents a single LiDAR measurement, and each line of dense points corresponds to a series of measurements from a single sweep of the LiDAR scanner mirror. The high LiDAR measurement rate creates small point spacing within each "line". The spacing between the line of points is equal to the vehicle speed divided by the "scan rate". For example, a "scan rate" of 100 Hz and vehicle speed of 25 m/s would produce a line spacing of 25 cm

(10 inches). The maximum line spacing depends on the application. Generally, it should be below 6 inches. Therefore, higher "scan rate" is more important than LiDAR measurement rate in mobile mapping applications. While most LiDAR scanners have only one laser emitter and detector, the Velodyne LiDAR scanner has multiple sets of emitters and detectors mounted at different angle. For example, their HDL-64E has 64 sets of emitters and detectors covering from +2° to -24.8° (~0.4° spacing). It produces dense line spacing despite low scan rate of 15 Hz. However, the line space increases with the measurement range.

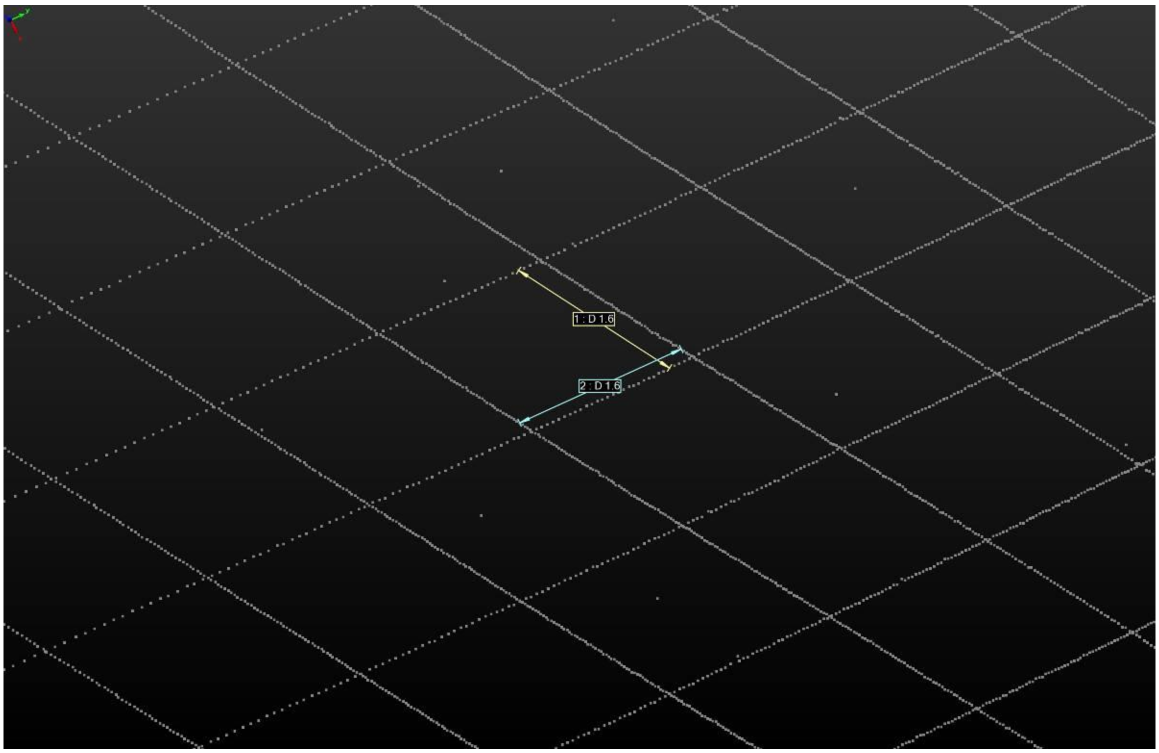

Figure 2.4: Typical "scan line" produced by MTLS systems

LiDAR requires unobstructed line-of-sight to the measurement surface. Obscured by the internal structure and scanner body, some 2D LiDAR scanners have less than 360 degree field of view (FOV) by design. New generations of 2D LiDAR scanner designs enable 360 degree FOV. Thus, the number of scanners on a MTLS system may be reduced, resulting in a smaller and more compact system. In real-life applications, the LiDAR measurement range generally is smaller than 1/3 to 1/2 the maximum range claimed in their specifications. The maximum measurement range is degraded by the object's surface reflectivity and the laser light angle of incidence.

Since these mobile systems are operated on public highways, the laser on the LiDAR scanner must be rated "eye-safe". Human retinas can be damaged by concentrated coherent laser light beams emitted by the LiDAR scanner. Most modern LiDAR scanners have Class I laser which produces low power invisible infrared laser light incapable of damaging human retina.

One of the MTLS system error source is the LiDAR scanner range accuracy. The MTLS system relative accuracy is approximately twice the LiDAR range accuracy. In addition, the LiDAR range error directly adds to the overall MTLS system absolute error. Therefore, only a few LiDAR scanners are suitable for high-accuracy pavement survey work. Most survey/engineering grade MTLS systems use the Optech Lynx V100, V200, or M1, or the Riegl VQ-250 LiDAR TOF scanners. Both Optech and Riegl scanners have long range and high range accuracy. A few custom engineered MTLS systems [5,16] employ Z&F or Faro phase-based laser scanners which have higher range accuracy. However, their practical range is much shorter than the TOF scanner. Consequently, the operator may have to drive multiple passes on different lanes of the multi-lanes freeway to gather all the required data. In addition, these systems may not provide adequate point cloud data for areas with wide median and shoulder. Nevertheless, MTLS systems with phase-based laser scanner would yield higher relative accuracy point cloud data and are better suited for urban areas.

Maker	Optech	Riegl	Riegl	Z+F	Phoneix Sci	Sick	Sick	Faro	Velodyne	Velodyne
Photo										
Model	Lynx V200 Lynx M1	LMS-Q120i	VQ-250	5010 Imager / Profiler	PPS-2000	LMS291	LMS511	Focus 3D	HDL-64E	HDL-32E
Range Accuracy	+/- 7 mm (1 σ) (0.02 ft)	20 mm (0.07 ft)	10 mm (0.03 ft)	~ 3 mm (0.01 ft)	0.15mm (0.05 ft)	+/- 35 mm (0.11 ft)		~ 3 mm (0.01 ft)	+/- 15 mm (0.05 ft)	+/- 20 mm (0.07 ft)
FOV (degree)	360	80	360	320	90	180 or 90	190	305	360	360
Scan Freq.	80-200 Hz	100 Hz	100 Hz	Imager: 50 Hz Profiler: 100 Hz	1000 Hz	75 Hz	100 Hz	97 Hz	15 Hz	5-20 Hz
Long Spacing @ 55mph	0.12 m (0.4 ft)	0.25 m (0.8 ft)	0.24 m (0.8 ft)	0.16 m (0.8 ft)	0.03 m (0.08 ft)	0.32 m (1 ft)	0.24 m (0.8 ft)	0.24 m (0.8 ft)	0.03 m (0.8 ft)*	0. m (0. ft)**
Point/s	Up to 500,000	10,000	Up to 300,000	1,016,000	945,000	13,500	19,000	Up to 976,000	1,000,000	800,000
Practical Range	~ 75 m	~ 50 m	~ 75 m	~ 50 m	~ 3 m	~ 25 m	~ 40 m	~60 m	~ 75 m	~ 75 m
Eye Safety	Class 1, Yes	Class 1, Yes	Class 1, Yes	Class 1, Yes	Class IIIb, No	Class 1, Yes	Class 1, Yes	Class 3R, Yes	Class 1, Yes	Class 1, Yes
Multi-return	Yes	No	Yes	No	No	No	Yes	No	No	Yes
Cost	~ $200,000	N/A	~ $200,000	~ $150,000	N/A	~ $5,000	~ $5,000	$40,000	$75,000	$30,000
Website	Optech.com	Riegl.com	Riegl.com	Zf-laser.com	Phnx-sci.com	Sickusa.com	Sickusa.com	Faro.com	Velodyne.com/ lidar	Velodyne.com/ lidar

Table 2.1 Commerially-available 2D LiDAR scanning systems

GNSS/INS Land Vehicle Positioning Systems Overview

Land vehicle positioning systems, composed of GNSS receiver(s), IMU, and DMI, are crucial in providing accurate continuous vehicle position and orientation for the MTLS system. Tightly-integrated RTK GNSS receivers and IMU systems have been developed and used in mapping and vehicle guidance. Performance has significantly improved, and many COTS systems have recently become affordable. The accuracy of the final point cloud largely depends on the GNSS/IMU system accuracy.

Global Navigation Satellite System (GNSS) Modernization

Today, GNSS provides autonomous geo-spatial positioning with global coverage. GNSS receivers determine their location and precise time using time signals transmitted along a line-of-sight by radio from GNSS satellites. Today, there are four GNSS systems (GPS, GLONASS, Galileo, and Compass) in operation and initial deployment phase.

The United States Global Position System (GPS) has been operational since 1994. It is current being modernized and upgraded. RTK GPS has become the standard survey tool for large areas. It is capable of delivering centimeter accuracy under ideal conditions. Producing a high-accuracy RTK GPS solution requires data from two dual-frequency (L1 and L2) GPS receivers—one stationary base station and one rover—collecting signals from at least five GPS satellites at the same time. The solution may be calculated in real-time by the rover GPS if it receives the base station data in real-time through a radio data link. The solution may also be calculated by post-processing software using the coordinated data collected by the base station and rover GPS after the end of the survey. Real-time solutions allow the surveyor to see the accuracy of the solution at the time of survey occupying the location point of interest. However, this requires a live radio data link to the GPS station. Post-processing does not require a live radio link, but the surveyor does not know they have an accurate solution until the solution is post-processed in the office at the end of the survey. In this case, the surveyor runs the risk of not having enough satellite signals to generate good survey data. The RTK GPS solution accuracy depends on many factors, such as GPS data processing algorithms, GPS receiver noise, multi-path of GPS satellite signals caused by buildings or terrain, ionosphere conditions, troposphere conditions, the number of visible GPS satellites, GPS satellite geometry in the sky, and the distance between the base station and rover GPS. The error relationship is quite complex and difficult to quantify. Significant efforts have been made by the U.S. government, research institutions, and GPS equipment makers to reduce the error and improve the speed to resolve and calculate the RTK solution.

The current GPS system is undergoing a major modernization. The ground control and monitoring station facility are being upgraded, and new GPS satellites are being launched with new civilian and military signals, including L1C, L2C and L5 frequencies. The current GPS constellation consists of 32 satellites. At the same time, new GPS receivers have been developed to take advantage of the new signals. The GPS industry expects to see GPS accuracy and availability improve continuously throughout the next several years as a result of this modernization effort.

The former Soviet Union, and now Russia, developed and deployed GLObal'naya NAvigatsionnaya Sputnikovaya Sistema (GLONASS). It had a fully functional navigation constellation. However, it fell into disrepair after the collapse of the Soviet Union resulting in gaps in coverage and only partial availability. Recently, the restoration and modernization of the GLONASS satellite constellation is in process. Currently, there are 23 operational satellites. The modernized GLONASS satellite will transmit new signal in L1, L2, L3 and L5 frequencies. The majority of new survey-grade GNSS receivers support GLONASS. Mobile LiDAR system operators found that combining GPS and GLONASS significantly improves satellite availability and position solution accuracy in GNSS challenged areas such as urban canyons.

In addition, the European Union (EU) is expected to bring Galileo, a Global Navigation Satellite System (GNSS) similar to GPS, online in the next several years. The recent agreement between the EU and the U.S. ensures both GNSS systems will be compatible and interoperable. As a result, Galileo effectively doubles the number of GPS satellites in the sky with its 30 satellite constellation. This compatibility will certainly improve the overall performance of GPS and Galileo receivers. Two experimental Galileo satellites are currently in orbit; however, the full operational date of Galileo has been delayed several times and is quite uncertain at this time. Nevertheless, modern GNSS receivers are designed and produced to support Galileo.

Lastly, the COMPASS system, also known as Beidou-2, is a GNSS being developed by the People’s Republic of China as an independent global satellite navigation system. It will be a constellation of 35 satellites, which include 5 geostationary orbit (GEO) satellites and 30 medium Earth orbit (MEO) satellites. The ranging signals are based on the CDMA similar to Galileo or modernized GPS. The full operational constellation covering the entire globe is expected to be completed in 2020.

When all four GNSS systems are deployed as planned in the next several years, there will be a combined constellation of 90+ satellites, which will significantly improve the signal availability and position accuracy, especially in urban canyons, forest, and high-latitude areas. While the availability of these new and improved GNSS is welcomed by users, it also presents a risk of technological obsolescence to the users. To take full advantage of new and modernized GNSS, users may have to upgrade their expensive survey grade GNSS receivers more often than in the past. Upgrading the GNSS receiver(s) on a highly-integrated mobile LiDAR mapping system may not be an option, making the entire system obsolete.

Inertial Measurement Unit (IMU)

Inertial Measurement Units (IMUs) are composed of accelerometers and gyros. The most common configuration is three accelerometers and three gyros mounted orthogonally to each other. More inertial sensors may be used to provide redundancy and increased accuracy. Accelerometers give body acceleration data in three directions, and gyros provide yaw rate (body rotational rate) data in three directions. By integrating this sensor data, the body position and orientation may be calculated at all times. The integration process does introduce cumulative errors. Therefore, the error of this dead-reckoning method increases as the integration duration increases, i.e. the solution drifts.

The IMU system cost varies enormously from a few hundred dollars to several hundred thousand dollars depending on accuracy and drift rate. Unlike GNSS which provides positional solutions at a low rate (1 to 20 Hz), the IMU provides positional and orientation updates at a high rate (256 Hz to 1000 Hz).

IMUs are used in airplanes, ships, submarines, and missiles navigation. The Honeywell HG1700 and Litton LN200 IMU are often used in the GNSS/IMU positioning system for MTLS systems. Since these IMUs are used in military applications, they are subjected to International Traffic in Arms Regulations (ITAR). Besides regulating the import and export of these components, ITAR also restricts the access of the IMU created data to "foreign agent." In the case, the foreign agent could be a non-US citizen or a foreign country. In other words, the IMU data must be guarded from access from any non-US citizen. In addition, laptop or USB drive storage of the IMU data must not be taken outside U.S. ITAR details can be found at the U.S. State Department website. The users should educate themselves so that ITAR is not breached. Recently, higher-accuracy, non-ITAR restricted IMUs were made available with competitive prices. Lately, most MTLS system operators chose to buy system with higher-accuracy IMU without ITAR restrictions.

IMU accuracy plays a curial role in the orientation accuracy of LiDAR scanners, and in turn affects positional accuracy of each point in the final point cloud. There are several parameters used to describe performance of the accelerometers and gyros inside an IMU. Typically, IMU designers choose accelerometers with performance specifications complementary to that of the gyros used in an IMU. To determine the IMU accuracy, users can focus on one key performance parameter, the gyro bias. The IMU gyro bias should be less than or equal to 1 degree/hr for MTLS applications. Some "survey grade" MTLS systems utilize fiber optic gyro (FOG) with gyro bias less than 0.5 degree/hr. These tactical and navigation grade IMUs cost from $40,000 to over $100,000. Higher IMU accuracy enables GNSS/IMU system to maintain accurate positional and orientation solution accuracy for longer GNSS signal outage.

Integrated GNSS/IMU Navigation System

Integrated GNSS/IMU systems are often used in terrestrial mobile mapping, aerial photogrammetry mapping, and navigation applications. GNSS data align and calibrate the IMU sensors when GNSS satellites and solution are available. The IMU provides positional solution when a GNSS solution is not achievable. It also "smoothes" out the GNSS solution, and provides a high sample-rate solution between relatively sparse GNSS samples. Without the GNSS positional solutions, the IMU integrated positional solution will drift out of bound over time. The integrated GNSS/IMU system may provide an accurate positional solution from up to 1000 Hz while a standalone GNSS system may only yield a 20 Hz positional solution. The Kalman Filter (KF) proved to be the optimal method for the estimation and compensation of the system errors in GNSS/IMU system integration [27]. Several KF approaches have been put into practice, such as the Linearized KF, Extended KF, and the sigma-point or Unscented KF. Much research has been conducted in GNSS/IMU integration in significant depth [8-10,27,30]. GNSS/IMU systems may be classified as tightly-coupled and loosely-coupled. In a loosely-coupled system, the GNSS position solution is calculated independent of the IMU. Both IMU and

GNSS positional solutions are combined by a KF to give an optimal position. In a tightly-coupled system, the GNSS positional solutions are calculated with the aid of the IMU data. Thus, the GNSS may still be able to provide a positional solution with four or less satellites where a stand-alone GNSS receiver may not.

Regardless of system integration methods, the positional solution may be calculated in real-time or post-processed depending on the availability of the real-time GNSS base station data. In a post-processing environment, the KF may be run forward and backward in time, and the combined forward and backward solution could effectively cut the effect of a GNSS outage interval by more than half. Positional solution error can be reduced significantly. Figure 2.5 shows a typical error reduction by combining the forward and backward KF solution in post-processing. Post-processing of the GNSS/IMU data can yield much better results especially if the GNSS outage is long.

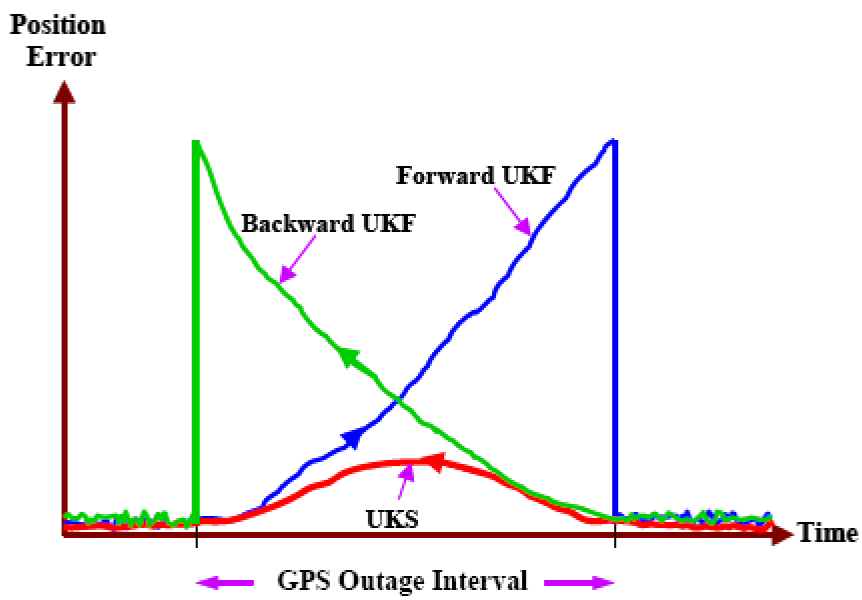

Figure 2.5: Positional error comparison of Forward KF, Backward KF, and Combined Forward and Backward KF (UKS) solutions [27]

There is limited number of COTS GNSS/IMU system hardware and post-processing software providers. NovAtel, a GNSS/IMU system provider, recently purchased Waypoint Consulting Company, which provides a wide array of post-processing GNSS/IMU software. In addition, Applanix, a Trimble company, has both GNSS/IMU system and post-processing software for land and aerial survey applications. Over half of MTLS system manufacturers use the Applanix POS LV GNSS/IMU in their system.

Table 2.2 provides a summary of various Applanix POS LV GNSS/IMU model performances with and without GPS outage for 1 minute. The Applanix POS LV 420 system has Litton LN200 IMU containing FOGs of 1 degree/hr gyro bias. It is subjected to ITAR restrictions. Both Applanix POS LV 520 and 510 systems have an IMU that is more accurate than the one employed by the POS LV 420 system, and they are not subjected to ITAR restrictions. Table 2.2 shows that the X, Y, Z position accuracy is not improved by higher accuracy IMU when there is no GNSS signal outage. However, the better IMU improves the system orientation (roll, pitch, and heading) accuracy [27]. The better orientation accuracy increases the accuracy of the LiDAR mirror orientation in the global coordinate, and thus improved the overall point cloud accuracy. On the other hand, the better IMUs provide significant system performances when there is a long GNSS signal outage as shown in Table 2.2. Recently, most “survey / engineering grade” mobile LiDAR system operators have chosen to purchase their system with GNSS/IMU system with higher-accuracy IMU such as the Applanix POS LV 520 or 510.

Table 2.2 Applanix GNSS/IMU system performance with post-processing

	Accuracy without GPS outage			Accuracy with 1 km or 1 min GPS outage		
Applanix POS LV Model	420	510 / 520	610	420	510 / 520	610
X, Y Position (m)	0.02	0.02	0.02	0.12	0.1	0.1
Z Position (m)	0.05	0.05	0.05	0.1	0.07	0.07
Roll & Pitch (degree)	0.015	0.005	0.005	0.02	0.005	0.005
Heading (Degree)	0.02	0.015	0.015	0.02	0.015	0.015

The GNSS/IMU system accuracy increases as on the baseline length decreases. The baseline length is the distance between the GNSS base station to the rover (the vehicle with the GNSS/IMU system). To achieve maximum possible accuracy, the GNSS base station should be located on a local control point with a known height and horizontal location with the survey project area. The use of local control eliminates systematic vertical offset in point cloud data due to difference in the vertical datum. The baseline should be kept less than 10 miles. A short baseline of 5 miles or less is preferred in high accuracy applications. Short GNSS baseline also reduces the time for GNSS positional solution recovery after GNSS signal outage. Consequently, the duration relaying on IMU dead reckoning for position solution is lowered.

Before performing data collection by the MTLS system, the GNSS/IMU system must carry out an alignment process in which the system determines the IMU orientation with respect to local gravity and true North. The GNSS can provide orientation using multiple antennas, such as the GPS Azimuth Measurement System (GAMS) with a second GNSS Receiver. Some GNSS/IMU systems, such as the Applanix POS LV 420 and 520, have two GNSS receivers and antennas to provide direct heading aiding. These systems could recover accurate heading faster than a system with same IMU with GAMS after GNSS signal outage. A system with a single GNSS receiver can implement gyrocompass and dynamic heading alignment. Gyrocompass technique makes use of the IMU gyro to measure the earth rotation to determine the IMU heading relative to true North. Alternatively, the system could determine its orientation by moving in a long straight line, a figure-8 maneuver, or a circle on the ground. Most GNSS/IMU system providers recommend a 5 to 10 minute static session for the alignment process. It is performed before and after the LiDAR and photo data collection. During the static session, the vehicle remains stationary for the session duration, and the operator should not disturb the vehicle.

Digital Camera

Digital images or video are often collected in conjunction with LiDAR data by MTLS systems. The camera shutter is synchronized with the GNSS/IMU clock. Consequently, the collected digital images are accurately georeferenced. The color images are often used to overlay / colorize the points in the point cloud. In addition, they are instrumental in helping users to identify features that are not possible by using the point cloud alone. For example, point cloud density is often too sparse to determine text printed on a road sign. The digital images are critical to resolve and establish the Manual on Uniform Traffic Control Devices (MUTCD) code of road signs. Furthermore, they help users to recognize features such as drainage and advertising billboards. Therefore, the quality and performance of the digital camera on-board of a MTLS system is equally important as the LiDAR sensors in system selection. They are particularly important for roadside asset inventory and mapping applications. In addition, some systems apply photogrammetric techniques on the images to provide position of features in the images without the aid of data from a LiDAR scanner.

The orientation of the camera mounted on the vehicle should be determined by the applications of the final data. A forward looking camera is important in capturing details of road signs. Side looking cameras are better in attaining features of building facade, drainage, sound walls, and median barriers. In most cases, users may select the photograph spacing. The minimum image spacing will depend on the vehicle speed and the camera maximum frame rate (number of photograph per second). Typical image spacing is between 25 to 50 feet. The optimum image spacing would depend on the user application. While lower image spacing will capture more detailed information, it will also drastically increase the size of the data because multiple high-resolution cameras are often used. In fact, the digital image data size is often 2 to 10 times bigger than that of the LiDAR data. While data storage is not a big issue for a small project, the data size for an entire California State roadway network would add up to huge size.

Commercially-Available MTLS Systems

Recently, several MTLS systems are commercially available for purchase, contract services, and rental through their dealers. Their cost and performance varies and depends on their target applications and configurations. In general, they may be classified into two classes: “mapping grade” systems and “survey/engineering grade” systems. However, some systems can be configured into either class based on the LiDAR scanner(s) and IMU employed. Mapping grade systems are designed to provide data with adequate accuracy at a low cost for mapping and asset inventory purposes. Their data’s absolute and relative accuracy are 1 foot and 0.1 foot representatively. However, in practice, these systems often achieve higher accuracy, particularly when GNSS signal conditions are good. Their IMU and LiDAR scanner(s) are less accurate than that of the “survey/engineer grade” systems. Some MTLS systems even eliminate the use of LiDAR scanner and rely on digital cameras and photogrammetric techniques to generate a "point cloud". A deliberate engineering decision was made to trade off performance with cost to provide cost-effective solutions.

Figure 2.6: Available MTLS systems

On the other hand, "survey/engineering grade" systems are designed to achieve maximum possible accuracy with current available geodetic grade GNSS receivers, IMU, digital cameras and LiDAR scanners. These systems produced centimeter-level absolute accuracy data, and could maintain data accuracy with short GNSS signal outage. In addition, their LiDAR scanners' range accuracy is 7 to 8 mm. They are designed for survey applications which require the system to deliver highly-accurate and precise data reliably. DOT surveying and engineering applications have unique requirements that other applications do not share. Accuracy of the work product carries certain financial and legal liability implications. These systems cost 2 to 5 times more than that of the "mapping grade" system. Some engineering grade MTLS systems are shown and discussed in detail below, and other systems are either not available in U.S., designed for other applications, or in prototyping stage.

Optech Lynx

Optech develops, manufactures, and supports advanced LiDAR and imaging-based survey instruments. Based in Toronto, Canada and with operations throughout the world, Optech provides LiDAR sensors and camera solutions in airborne mapping, airborne laser bathymetry, mobile mapping, mine cavity monitoring, and industrial process control, as well as space applications.

The Optech Lynx M1 system is highly-configurable, and users may choose to have up to four LiDAR scanners, four cameras, and accuracy grade of the IMU. The system sensors (LiDAR scanners, cameras, GNSS antennae, and GNSS/IMU positioning system) are mounted on rigid platform which can be fixed to the roof of an automobile or golf cart, or a boat [2,23,29,35]. It is designed for the engineering grade survey market. The current Lynx M1 system is Optech's third generation mobile LiDAR mapping system following their Lynx V100 and V200 system. The scan rate and point measurement rate has been increased in each subsequent generation. The Lynx M1 scan rate is user selectable. Its maximum scan rate is 200 Hz, the highest among commercially available 360º FOV LiDAR scanners. Higher scan rate allows the data collection vehicle to travel at higher speed while maintaining high point density with even distribution. However, the maximum LiDAR sensing rate reduces as the scan rate increases. A typical Lynx configuration has two 360º FOV LiDAR scanners mounted orthogonal to each other to reduce shadow caused by line of sight obstruction from objects. It captures all three sides of a building facet in a single pass. If only one LiDAR scanner is used, one side of the building facet is blocked from view of the scanner by the other building facet. The M1 LiDAR scanner is also capable of detecting up to 4 returns from a single laser pulse. This feature permits the system to detect and measure surfaces obstructed by light vegetation. As indicated in Table 2.1, the Lynx LiDAR scanner has range accuracy of 7 mm.

Users may choose any available Applanix POS GNSS/IMU positioning system for their Lynx. Survey services providers often choose either the POS LV 420 or 520. Recently, Lynx systems have been delivered with the POS LV 520 system. Both the POS LV 420 and 520 have GAMS for better heading accuracy, as well as DMI. In addition, the user has two options for the on-board cameras: camera with 2 megapixel (MP) resolution with a frame rate of 5 frame/s or camera with 5 MP resolution with a frame rate of 3 frame/s. Higher frame rate permits the system to take pictures at a closer distance interval.

Optech sells and provides support for the hardware and post-processing software. Their DASH Map post-processing software processes the raw GNSS/IMU and LiDAR data to output point cloud data in Log ASCII Standard (LAS) format file for 3rd party post-processing data extraction software. Their user-friendly data collection software utilizes Google Earth for mission planning and data collection execution. The estimated system cost is from $500,000 to $850,000 depending on the system configuration. Leasing options are available. The majority of survey/engineering grade MTLS systems in U.S are made up of different generations of Lynx system. North American survey services provider with Lynx systems are: Aerial Data Services, Inc.; McKim & Creed, Inc.; Michael Baker, Jr., Inc.; Photo Science Inc.; Sanborn Map Company; Surveying and Mapping, Inc.; WHPacific, Inc; and Woolpert, Inc. Further detail about the Optech Lynx M1 system may be found at their website (http://optech.ca/lynx.htm).

Figure 2.7: Optech Lynx MTLS system

Figure 2.8: Optech Lynx MTLS system mounted on a boat

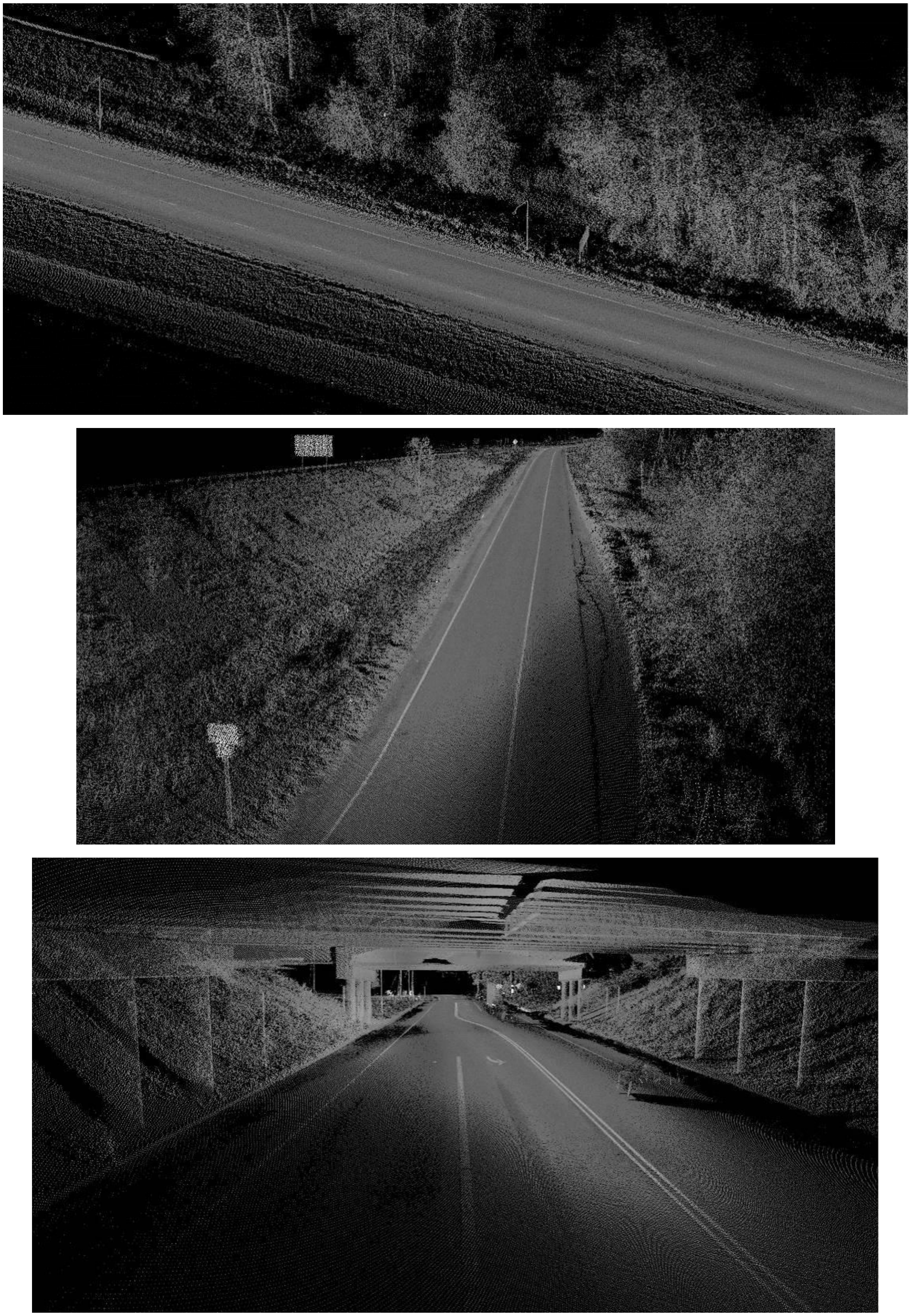

Figure 2.9: Point cloud produced by Optech Lynx MTLS system

RIEGL VMX-250

Based in Horn, Austria with operations and staff worldwide, RIEGL has 30 years of experience in the research, development and production of laser rangefinders, distance meters and scanners. RIEGL also cooperates with OEM-partners to deliver turnkey solutions for multiple fields of application. RIEGL has regional offices located in Orlando, Florida to provide sales, training, support, and services for U.S. customers.

The Riegl VMX-250 system is a compact and portable system that delivers engineer grade survey data for users. The system sensors (two VQ-250 LiDAR scanners, GNSS antenna, and IMU) are mounted rigidly to each other in a compact package as shown in Figure 2.10. The sensor platform can be easily taken out of the protective transportation case and installed on the vehicle roof by two persons. The VQ-250 LiDAR scanner's scan rate is user selectable with a maximum scan rate of 100 Hz. Its maximum point measurement rate is 300,000 points/s. A typical VMX-250 system configuration has two 360^{o} FOV VQ-250 LiDAR scanners mounted orthogonal to each other in order to reduce shadows caused by line of sight obstruction from objects. It captures all three sides of a building facet in a single pass. If only one LiDAR scanner is used, one side of the building facet is blocked from view of the scanner by other building facet. The VQ-250 LiDAR scanner is also capable of detecting multiple returns from a single laser pulse. The full waveform analysis capability of the VQ-250 provides a practically unlimited number of target returns per pulse. However, the number of returns for a single laser pulse are less than four in most practical situations. This feature permits the system to detect and measure surfaces obstructed by light vegetation. As indicated in Table 2.1, the Riegl VQ-250 LiDAR scanner has range accuracy of 10 mm. Other VQ-250 specifications are listed in Table 2.1.

The standard VMX-250 system is configured with the POS LV 510 system. Compared to the POS LV 520, the POS LV 510 does not have GAMS. The current system provides mounting points for digital cameras or video equipment. Nevertheless, a tightly-integrated digital camera option is not yet available for the VMX-250 system.

RIEGL sells and provides support for their hardware and post-processing software. The system is bundled with RIEGL's software suite (RiACQUIRE, RiPROCESS, and RiWORLD) for data collection, sensor alignment adjustment, and GNSS/IMU/LiDAR raw data post-processing. Their RiPROCESS post-processing software processes the raw GNSS/IMU and LiDAR data to output point cloud data in standard LAS format file for 3rd-party post-processing data extraction software. The estimated system cost is about $700,000 depending on the system configuration. Currently, R.E.Y. Engineers, Inc is the only U.S. survey service provider with the RIEGL VMX-250 system. Further detail about the RIEGL VMX-250 system may be found at their website (http://riegl.com/).

Figure 2.10: Riegl VMX-250 MTLS system

Figure 2.11: Point cloud produced by Riegl VMX-250 system

3D Laser Mapping StreetMapper 360

Based in Nottinghamshire, United Kingdom, 3D Laser Mapping (3DLM) provides LiDAR software and hardware, and support for both RIEGL LMS and third-party products. Working with RIEGL and IGI mbH, 3D Laser Mapping developed the StreetMapper 360 system. Located in Kreuztal, Germany, IGI mbH specialize in the design and development of guidance, navigation, precise positioning, and attitude determination systems.

The 3DLM StreetMapper 360 system is designed to deliver engineer grade survey data for its users [11,12,17,20,31]. It is a 2nd generation MTLS system developed by 3DLM. The StreetMapper 360 system is composed of two VQ-250 LiDAR scanners, digital cameras, GNSS antenna, and an IGI IMU rigidly mounted in a compact package as shown in Figure 2.12. The VQ-250 LiDAR scanner specifications are listed in Table 2.1 and were discussed previously. Like the RIEGL VMX-250, the StreetMapper 360's twin VQ-250 LiDAR scanners are also mounted orthogonal to each other minimized shadows caused by line-of-sight obstruction. However, their scanner mounting orientation is slightly different from the RIEGL VMX-250.

Figure 2.12: StreetMapper 360 system mounted on a Terrametrix vehicle (copyright The American Surveyor Magazine© 2011)

The StreetMapper 360 employs a highly-accurate IMU with FOG bias of 0.1 degree/hr. The IMU has an update rate of 256 Hz. The current system provides up to four 4 MP resolution digital cameras operating at 7.5 frame/s. The cameras are synchronized and time-stamped with the GNSS/IMU system. The resulting geo-referenced images are stored in the data logging computer along with the LiDAR scanners and GNSS/IMU raw data.

3DLM sells and provides support for their hardware and post-processing software. Their post-processing software outputs point cloud data in standard LAS format file for

3rd party post-processing data extraction software. Moreover, TerraPhoto or PHIDIAS may be used to extract information from the geo-referenced images. Currently, Terrametrix is the only U.S. survey services provider with StreetMapper 360 system. Terrametrix has scanned over 400 bridges in Nevada to provide the NV DOT with bridge clearance data. It has also performed similar services for Caltrans as well.

StreetMapper is now being offered on a Fractional Ownership basis. The plan aims to reduce entry cost and allow owners to achieve high utilization rates on their fractional asset. In addition, the risk of technological obsolescence is significantly curtailed, since a much smaller investment needs to be recouped on a fractional share. The detail of StreetMapper 360 Fractional Ownership is available at 3DLM website (http://3dlasermapping.net/).

Ambercore's Titan

Ambercore is headquartered in Ottawa, Canada. Ambercore's first kinematic terrestrial LiDAR system (called TITAN®) was developed in 2002 for helicopter-based low-level aerial LiDAR survey. In 2003, the system was modified to be mounted on a truck to perform survey of Highway 1 in Afghanistan between Herat and Kandahar. Since then, a 2nd generation TITAN was developed to overcome the short comings of the first generation system.

The current Titan system has four Riegl LMS-Q120i LiDAR scanners, a high-accuracy navigation grade IMU, GPS antenna, and up to 4 digital cameras mounted in a rigid assembly [13-15,34]. The entire assembly can be deployed on a variety of moving platforms such as trucks, sport utility vehicles, or boats. Figure 2.13 shows the system mounted on a hydraulic lift platform at the rear of a truck. The evaluated platform provides better line of sight for the LiDAR scanners, particularly the downward facing LiDAR scanner. As shown in Figure 2.13, the quad LiDAR configuration consists of one upward and one downward facing LiDAR scanner as well as two sideway facing scanners angled slightly forward on each side of the enclosure. As a result, the TITAN system has a total of 360º field of view. Each LMS-Q120i has 80º FOV and maximum scan rate of 100 Hz. The LiDAR scanner measurement rate is 10,000 points/s with 20 mm range accuracy. Other LMS-Q120i specifications are listed in Table 2.1. In addition, the TITAN system has integrated cameras with 1280x1024 resolutions. They were upgraded with better integrated cameras in 2010.

Figure 2.13 Ambercore Titan MTLS system

Ambercore developed its own proprietary GPS/IMU post processing package, CAPTIN (Computation of Attitude and Position for Terrestrial Inertial Navigation) to process the GPS/IMU data. Their custom post-processing software processes the raw GNSS/IMU and LiDAR data to output point cloud data in standard LAS format file for 3rd party post-processing data extraction software. Ambercore sells and provides support for the hardware and post-processing software. David Evans and Associates (DEA) is one of the U.S. survey services providers with the Titan system.

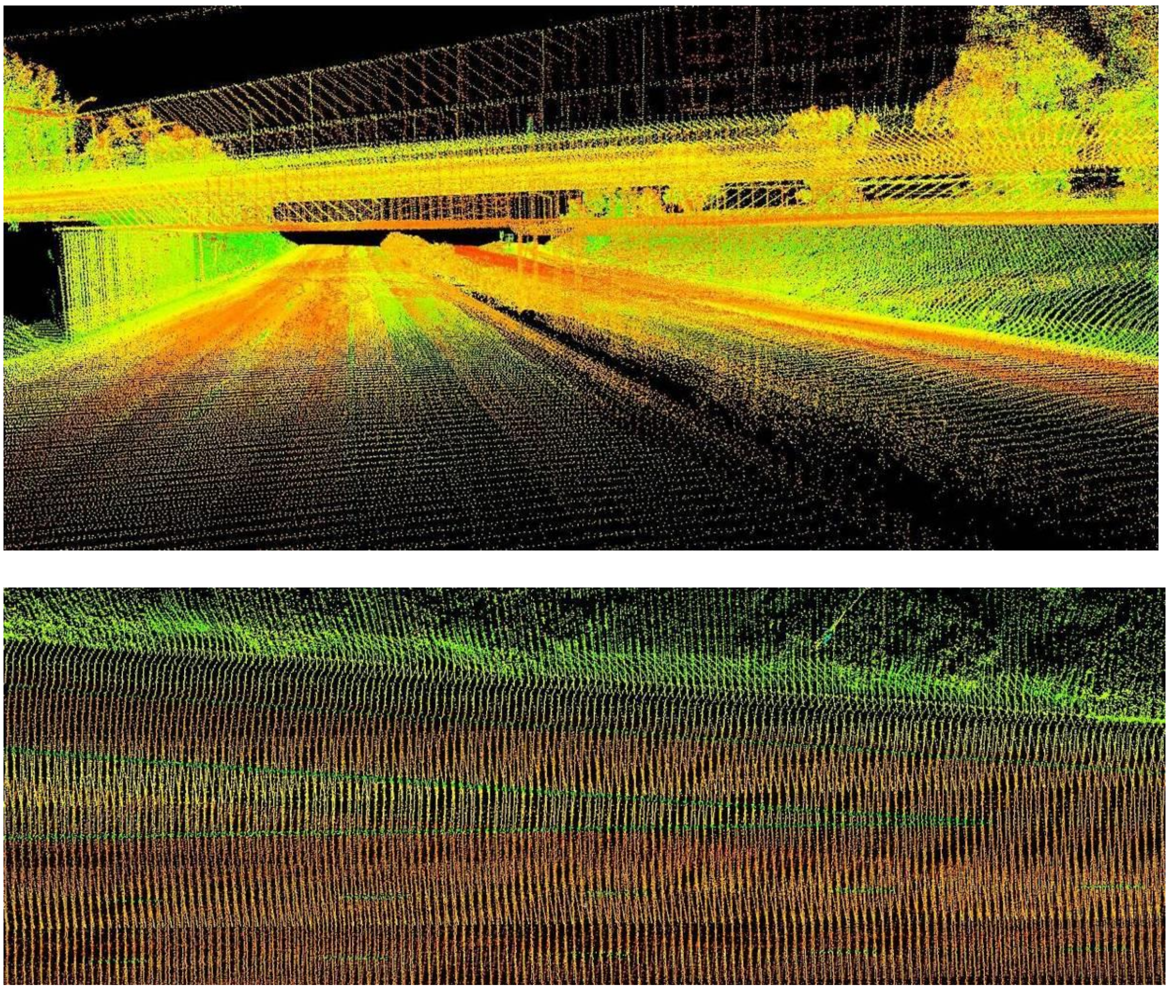

Figure 2.14 Point cloud produced by TITAN® system

Topcon IP-S2

Based in Livermore, California with operations and staff worldwide, Topcon Position System, Inc. provides survey instruments such as GNSS receivers, total stations, and digital levels, as well as machine guidance equipment for construction equipment.

The Topcon IP-S2 system is a low-cost, highly-configurable system designed primarily for GIS and mapping applications [19]. Users have a variety of digital camera and LiDAR scanner option available. The base system has a Point Grey Research, Inc. Ladybug®3 camera system, an embedded computer, a Topcon GNSS receiver, and a Honeywell HG 1700 IMU. Higher accuracy IMU options are available. The system does not have GAMS.

Figure 2.15 Topcon IP-S2 system configured with Velodyne HDL-64E

The Ladybug3 spherical digital video camera system has six 2 MP cameras that enable the system to collect video or photographs. Figures 2.15 and 2.16 show the Ladybug3 camera located next to the square GNSS antenna on top of the sensor assembly. The Ladybug3 is enclosed in a weather-resistant case. Through the system's IEEE-1394b (FireWire) interface, the JPEG-compressed 12 MP resolution images are streamed to a data collection computer disk at 15 frame per second (fps). The six images are stitched together to produce a 6144x3072 panorama photo during post-processing. The image stitching process is computationally intensive and could take a long time. Software options are available to stitch the images on a server farm to speed up this process. Additional digital cameras may be added using the available camera interfaces on the system. As shown in Figure 2.17, five more cameras are installed to the system in addition to the Ladybug3 camera. The IP-S2 system's embedded computer provides a digital interface for time synchronization, a time stamped camera shutter and LiDAR scanner with the GNSS receiver. Consequently, the collection images are geo-referenced.

The flexible architecture of IP-S2 enables it to interface and integrate various LiDAR scanners available in the commercial market. Currently, the system is available with the SICK LMS291, Riegl VQ-250, Velodyne HDL-64E, and HDL-32E LiDAR scanner. Detailed specifications of these scanners are listed in Table 2.1. The SICK LMS291 scanner's scan rate and measurement rate are too slow for a vehicle to travel at highway speeds and maintain high enough point density for feature identification and data extraction. Configurations with Riegl VQ-250 scanners are recommended for survey applications in which higher accuracy data is required.

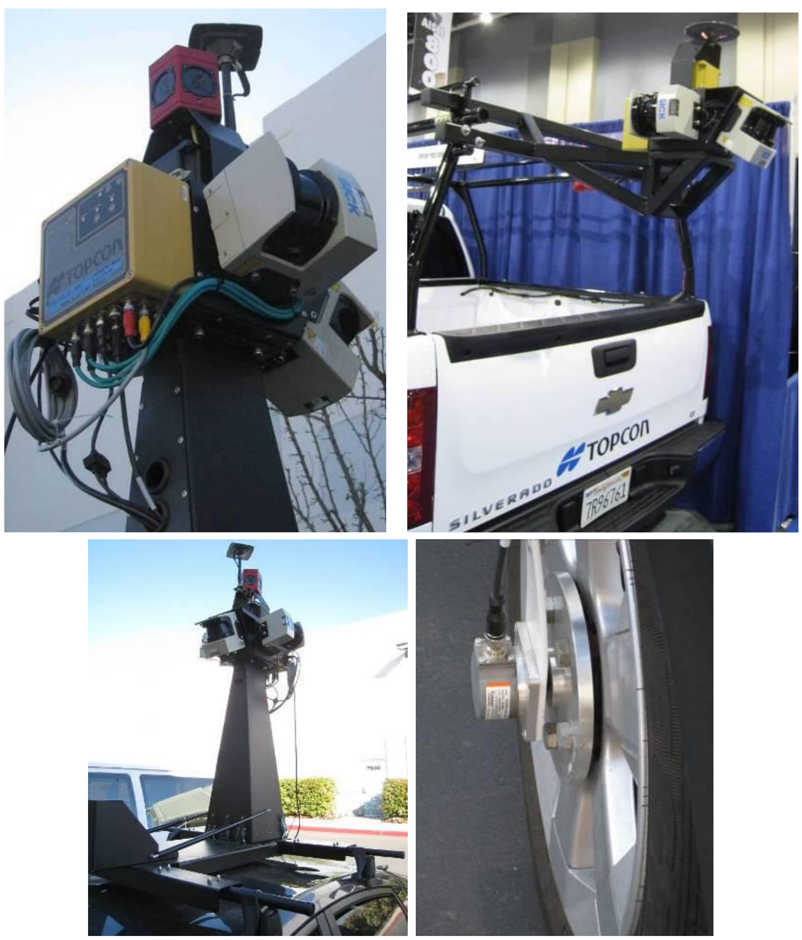

Figure 2.16 Topcon IPS-2 system configured with SICK LiDAR scanners

The system is bundled with a software suite for data collection and GNSS/IMU/LiDAR and imagery raw data post-processing on a workstation or on a server farm. Spatial Factory is used for basic feature extraction and data visualization. It could be used to perform elevation adjustment, pass-to-pass adjustment, and vehicle trajectory adjustment using external ground control points. Spatial Factory can also output point cloud data in standard LAS format file for 3rd party post-processing data extraction software. The estimated system cost is about $250,000 or more depending on the system configuration. The PPI Group is one of the Topcon IP-S2 dealers who provide sales, mapping services, support, training, and equipment rental. Working with Topcon, Fugro has a custom configured IP-S2 with a twin Riegl VQ-250 scanner. Their system is aim for high accuracy survey work. Further detail about the Topcon IP-S2 system may be found at their website (http://www.topconpositioning.com/products/mobile-mapping/ip-s2).

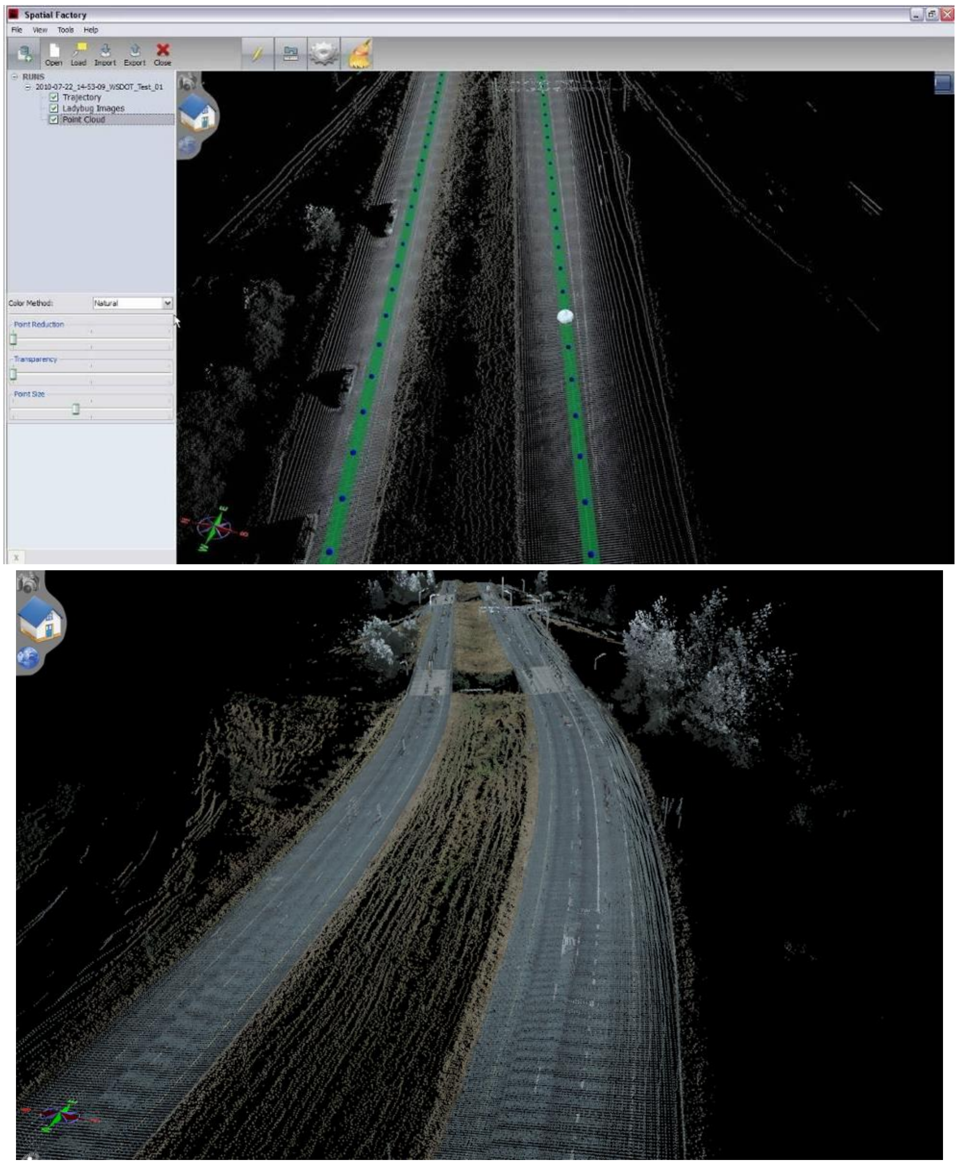

Figure 2.17 Spatial Factory screen shot

Trimble MX8

GEO-3D provides georeferenced mobile mapping technologies comprised of integrated software and hardware to government entities and service providers around the world. Founded in the mid 1990's, GEO-3D was acquired by Trimble Navigation Limited in 2008. It is now part of the Trimble Geo-Spatial Group.

Trimble Geo-Spatial Group offers several MTLS systems for different applications and markets. Their systems are highly-configurable, and users may choose to have up to six sensors of any combination of LiDAR scanners and cameras, as well as any available Applanix POS LV positioning system. Figure 2.18 shows one of their previous generation systems, configured for GIS and asset management applications. The low-cost system employs the low-cost SICK LMS 291 and/or Riegl LMS-Q120i LiDAR scanners and forward looking digital cameras. Photogrammetric techniques are used in conjunction with LiDAR to locate asset and assist feature extraction.

The latest Trimble MX8 is designed to be scalable with several sensor upgrade options. Users may choose any available Applanix POS LV positioning system for their MX8 system depending on the accuracy requirement of their applications. The MX8 system sensors: two VQ-250 LiDAR scanners, digital cameras, GNSS antenna, and IMU are mounted rigidly inside a custom enclosure as shown in Figure 2.19. The performance characteristics of the RIEGL VQ-250 LiDAR scanner were discussed in previous section. The twin 360º FOV VQ-250 LiDAR scanners are mounted orthogonal to each other in order to reduce shadows caused by line of sight obstruction from objects. It captures all three sides of a building facet in a single pass. If only one LiDAR scanner is used, one side of the building facet is blocked from view of the scanner by the other building facet. The MX8 has three forward looking cameras, three backward looking cameras, and one camera pointing toward the pavement. In addition, multi-spectrum cameras in ultraviolet (UV) and near infrared (NIR) spectrum are also available as an option. NIR cameras could provide better imagery in dark subway tunnels, and UV cameras could assist identifying the health of certain tree species and vegetations.

Trimble sells and provides support for their hardware and post-processing software. Their Trident 3D Analysis post-processing software is used for processing the raw GNSS/IMU and LiDAR data, feature extraction, and data visualization. Moreover, it can be used to perform elevation adjustment using external ground control points. In addition, it can also output point cloud data in standard LAS format file for 3rd party data extraction software. The Trident 3D Analysis software is design for GIS and asset management applications. It also provides automated feature extraction routines for poles, edge, road sign, lane line, and bridge horizontal and vertical clearance. It can also create DTM/TIN/Grid with automated break line detection. Figure 2.20 shows the Trident 3D Analysis software user interface. More software features have been added recently. The estimated MTLS system cost is from $75,000 to $700,000 depending on the system configuration. Long term rental options are also available. Further detail about Trimble MX8 system may be found at their website (http://www.trimble.com/geospatial/Trimble-MX8.aspx?dtID=overview&).

Figure 2.18: Available MTLS systems

Figure 2.19: Trimble MX8 (copyright The American Surveyor Magazine© 2011)

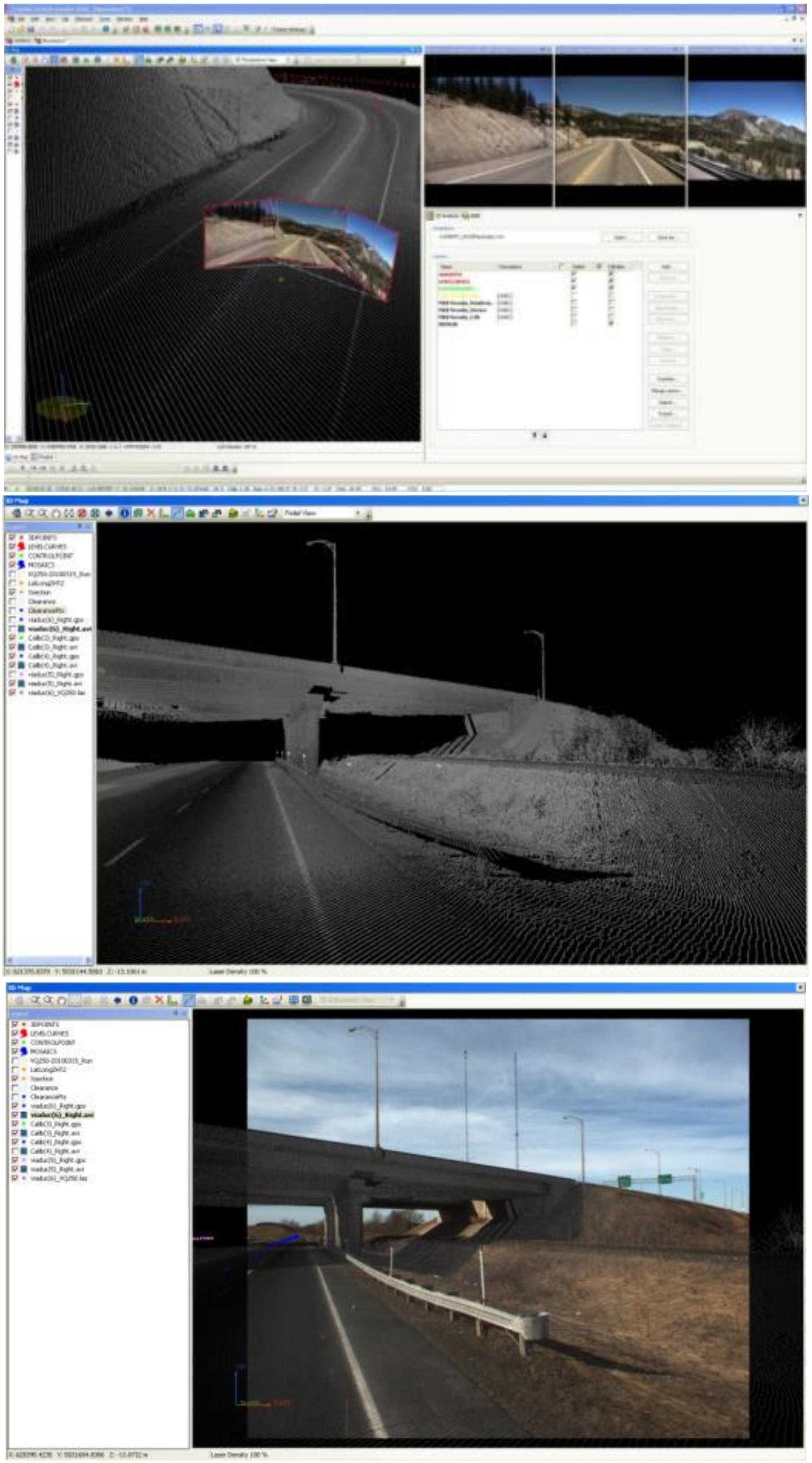

Figure 2.20: Screen shot of Trident 3D Analysis software

Data Post-Processing and Feature Extraction Software

The term "data post-processing" is not well-defined in MTLS. Depending on the context, it could mean:

1. The processing of GNSS/IMU/LiDAR raw data with GNSS base station(s) data to produce geo-referenced point cloud. Depending on project requirements, the point cloud is then adjusted to local vertical datum and ground controls. This step is often required for delivering high accuracy engineering grade data. In addition, the "noise" points caused by moving vehicle traffic are removed.

2. The extraction of data from the point cloud and geo-referenced images to create the required deliverables.

Generally, the office time required for data post-processing and feature extraction could be 2 to 10 times that of the field data collection time. The amount of office data post-processing time depends highly on the deliverable requirements; hence, point cloud and geo-referenced image post-processing and feature extraction software is critical in enhancing office productivity. The choice of software depends highly on the deliverable requirements. DOT survey deliverables are topographic maps, TIN mesh, contour maps, points, and lines, etc. On the other hand, asset management deliverables are location, dimension, and conditions of roadside feature and asset. Therefore, the user must examine their work and deliverable requirements first before selecting the appropriate software. Software evaluation was not the focus of this research project.

The software that processes the GNSS/IMU/LiDAR raw data with GNSS base station(s) data is specific to each system, and it is only provided by the MTLS system's provider. The processing time of this operation has a relatively fixed ratio with the field data collection time. If the data is collected in GNSS challenged area, the processing time may increase.

Recently, the number of point cloud processing software solutions has increased dramatically. Both the AutoDesk software suite and Bentley MicroStation have recently upgraded to support point cloud data. Currently, they provide a set of basic tools for visualization, dimension extraction, and CAD modeling. ESRI also supplies to processing point cloud for GIS and mapping applications. Other advanced 3rd party point cloud post-processing software includes Leica Geosystems Cyclone, InnovMetric PolyWorks, GeoCue software suite, TerraSolid software suite (TerraScan, TerraModeler, TerraMatch, TerraPhoto, TerraControl, and TerraOffice), PHOCAD (www.phocad.de) PHIDIAS, Pointools, TopoDOT, and Virtual Geomatics software suite. Software selection depends on the final deliverable requirements. Each software solution excels in a specific area. Service providers often have to use several pieces of software to create the final deliverable required by their customers.

Consideration on MTLS System Selection

Selection of a MTLS system depends on the application requirements. Digital camera images are crucial in asset identification and their condition assessment. On the other hand, digital camera images are rarely collected in pavement survey applications. The system's absolute accuracy refers to the position accuracy of a point in the point cloud in a global coordinate system. The system's relative accuracy refers to the position accuracy of a point relative to other points in close proximity. Measuring bridge vertical clearance requires high relative accuracy with lower absolute accuracy. Pavement survey requires high relative and absolute accuracy. Other key specifications of MTLS system have been outlined below:

- GNSS/IMU positioning system performance specifications – Its performance is directly related to the system absolute's accuracy.

- Range Accuracy within useful range – A scanner's single-point accuracy within its useful range is directly related to the mobile LiDAR system's relative accuracy. Each application may have different relative accuracy requirements. The range accuracy may be degraded with high laser angle of incidence and poor object reflectivity. Since a laser scanner is capable of scanning features over long distances, and the accuracy of the scan data diminishes beyond a certain distance, care should be taken to ensure that the final dataset does not include any portion of point cloud data whose accuracy is compromised by measurements outside the useful range of the scanner.

- System LiDAR Field-of-view (FOV) and 2D LiDAR scanner mounting geometry – Most modern systems have a LiDAR FOV of 360^{o} to ensure all tall structures or overhead structures are captured into the point cloud. Some systems have twin 360^{o} FOV 2D LiDAR scanners to reduce "shadows" caused by line-of-sight obstructions.

- Useful range of scanner – The manufacturer's datasheet typically provides only the maximum range of the scanner, i.e. the range at which the scanner can get an acceptable return signal to obtain a range measurement based on an object with high reflectivity (e.g. 80%), facing directly toward the scanner so that the laser incidence angle is near 0°. In a DOT project or practical scenario, where the object to be scanned is black-top asphalt of approximately 5% diffuse surface reflectivity with a high incidence angle, the useful range of the scanner is greatly reduced when compared to the maximum range.

- Scan rate (Hz) – This refers to the revolution rate of the LiDAR scanner mirror. Higher scan rate enable higher vehicle speeds while maintaining required point density of the resulting point cloud. Thus, it improves operational efficiency and reduces hindrance to the moving traffic on the highway.

- Built-in digital camera – The image assists in feature recognition and sign recognition. The color images are often used to overlay / colorize the points in the point cloud. The proper camera orientation is vital in ensuring the critical features are captured within the camera's FOV.

- Rental or partial ownership options exist to reduce the risk of technological obsolescence and entry cost.

- Eye safety: Most MTLS system uses eye-safe laser scanner. However, users should always follow OSHA Regulation 1926.54 and manufacturers' recommendations when using any laser equipment. The eye safety of the traveling public and other people should be considered at all times, and the equipment should be operated in a way to ensure the eye safety of all.

CHAPTER 3: MTLS ACCURACY ASSESMENT

The researchers conducted error and accuracy analysis of the system based on errors of individual sensors: GNSS, IMU, and laser range scanner[3,14]. The analysis focused on currently available state-of-the-art COTS laser range scanner, GNSS and IMU integrated system and post-processing software. The results highlight the error sources and effects on the total system error. Simulations were conducted to demonstrate causal effects. Secondly, new augmentation and control adjustment methods, based on survey methodologies, were investigated to improve the system accuracy.

A single point (Target) position in a point cloud produced by a MTLS system is calculated using equation 3.1. The vehicle position (P^{Nav}_{Veh}) is the position solution from post-processing the raw GNSS/IMU system. $r^{Veh}_{Scanner}$ is the position vector offset measuring from the GNSS/IMU to the center of the scanner mirror. $R^{Veh}_{Scanner}$ is the orientation rotation between the IMU vehicle frame and the laser scanner. $r^{Scanner}_{Target}$ refers to the position vector from the scanner to the target. R^{Nav}_{Veh} is the rotation orientation between the vehicle/IMU and the global navigation frame (earth-fixed global position frame).

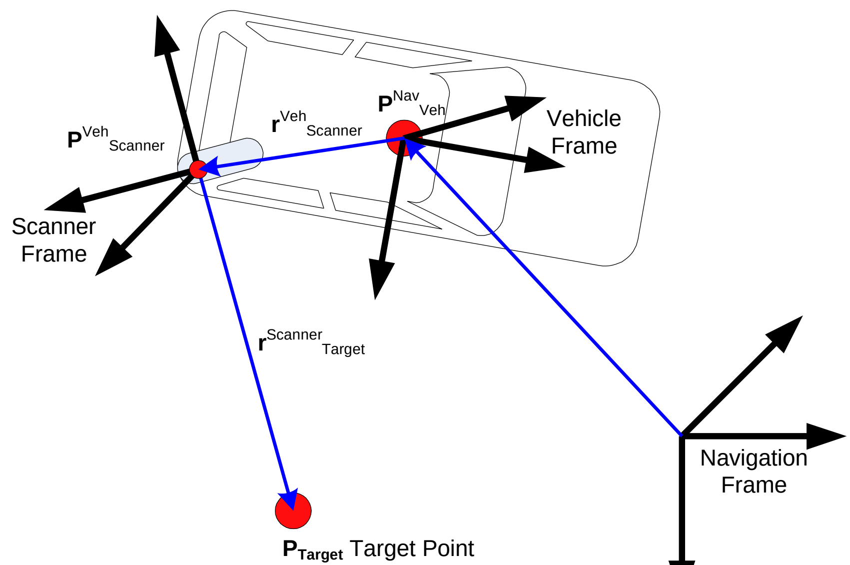

Figure 3.1: Target position calculation

<u>Equation 3.1 target position calculation equation [1]</u>

$$\mathbf{P}^{Nav}_{Target} = \mathbf{P}^{Nav}_{Veh} + \mathbf{R}^{Nav}_{Veh} \bullet \mathbf{R}^{Veh}_{Scanner} \bullet \mathbf{r}^{Scanner}_{Target} + \mathbf{R}^{Nav}_{Veh} \bullet \mathbf{r}^{Veh}_{Scanner}$$

Target Position Error sources [3,14,25]:

- Error in vehicle position (P^{Nav}_{Veh}) from GNSS/IMU system
- Error in vehicle orientation (R^{Nav}_{Veh}) from the IMU
- Error in sensor orientation alignment (boresight) ($R^{Veh}_{Scanner}$)
- Error in LiDAR sensor position offset ($r^{Veh}_{Scanner}$)
- Error in LiDAR sensor range ($r^{Scanner}_{Target}$) from the LiDAR sensor range error and encoder error.
- Timing and synchronization error

When the GNSS signal is ideal (minimal multi-path and more than seven visible satellites), the GNSS/IMU solution error is dominated by the error in GNSS solution. The accuracy of the IMU has little influence over the X, Y, Z position error as shown in Table 2.2. However, when the GNSS/IMU is operating in GNSS signal challenged conditions (low availability and/or high multi-path), the accuracy of the IMU is crucial in limiting the grown of the position error over time. In this situation, the P^{Nav}_{Veh} position error greatly depends on the accuracy of the IMU and the GNSS signal outage duration. GNSS position error is also highly-dependent on the baseline length. Shorter baseline reduces GNSS position error and the time for position solution recovery after GNSS signal outage [7,21,24]. The baseline length should be kept under 15 km or 10 miles [14,21,24]. The vehicle orientation error (R^{Nav}_{Veh}) depends highly on the accuracy of the IMU as shown in Table 2.2. Therefore, all survey/engineering grade MTLS systems use a high-accuracy IMU with FOGs of 1 degree/hour gyro bias or less. Higher IMU accuracy is highly recommended. In addition, Equation 3.1 shows that the target position error is also amplified by the target distance and the vehicle orientation error. As a result, the target position error increases as the target distance increases. Since the range error of a LiDAR scanner also increases as the target range, the points far from the vehicle travel path have larger errors than the points near the vehicle travel path.

The error source in $R^{Veh}_{Scanner}$ and $r^{Veh}_{Scanner}$ comes from improper sensor alignment with the IMU. This error would result in systematic offset (X, Y, Z offset and tilting) of the point cloud data. If the system has two LiDAR scanner, the point cloud produced by each sensor would be misaligned with the other. Careful execution of sensor alignment and calibration procedures would virtually eliminate error from both measurements. These procedures are critical if the GNSS/IMU/LiDAR scanner platform has been taken apart for transportation. Typical sensor boresight procedures involve driving through an intersection from all four directions. Then any sensor alignment error would appear in the misalignment in the point clouds between each run. MTLS operators recommend selecting an intersection with tall buildings with flat walls for this calibration process.

All MTLS system sensors must be accurately time-stamped and synchronized with the GNSS receiver clock. Any time lag in synchronization would create error in the target position calculation. A LiDAR scanner developed for mobile scanning has built-in precise timing electronics to synchronize with the GNSS clock output. The remaining MTLS system error is a result of the LiDAR scanner range error and encoder error. Survey/engineering grade MTLS systems use TOF LiDAR scanners with range error less than 1 cm. Some custom-developed MTLS systems use phase-based scanners which have range error of a few millimeters. Measuring bridge clearances relies on high LiDAR scanner range accuracy.

Error Analysis on Point Clouds Produced by MTLS Systems

Description of the Problem

In general, one would assume that the output would be an estimate of the sampled roadway and surrounding infrastructure, with additive noise from each sub-system dominated by the noise from the LiDAR scanner, as its measurements are not incorporated in the KF. However, in practice it has been observed that other errors are contained in the point cloud position estimates other than additive noise. The various errors that show up in point clouds, such as scanner to scanner alignment errors and INS/LiDAR time synchronization errors, are easily removed from the final point cloud solution through proper system calibration. It is expected that one would only see noise due to the IMU, GNSS, and LiDAR system statistics; however, additional errors in the form of systematic bias in multiple directions have been observed.

With the use of high-accuracy LiDAR scanner on a MTLS system, the majority percentage of the error is caused by the GNSS solution. The GNSS solutions have a slow moving error caused by satellite geometry and atmospheric conditions. Because of the lesser accuracy requirement on the horizontal error for hard surface pavement survey, the horizontal error of the point cloud produced by a survey grade MTLS system generally falls within the accuracy requirement. Figure 3.2 illustrates that the differential GPS vertical position, calculated using Double-Difference method, changes slowly over time. The y-axis represents the elevation solution offset from the average in meter, and the x-axis represents the time in second. In this case, the baseline length is very short (~150 meters). The amplitude of the plot would increase if the baseline length increases. By performing a spectral analysis on the signal in Figure 3.2, the frequency contents of the signal is less 0.01 Hz. In MTLS application, the data collection typically only lasted for a few hours. The aforementioned slow moving elevation error is added to the point cloud. Therefore, slow changing vertical offset exist in the point cloud along the direction of the data collection vehicle travel. As a result, if the vehicle preformed a multiple data collection pass on the same section of the highway at different time of the day, the point cloud data from each pass generally has a small by noticeable offset from each other as shown in Figure 3.3, a TIN surface of a section of point cloud with data from multiple pass. The “washboard” surface on the left hand side of Figure 3.3 is caused by elevation differences from two point clouds produced in two different data collection passes. Consequently, a smooth Digital Terrain Model (DTM) surface, representing the smooth pavement surface, cannot be generated directly from the point cloud without further processing. On the other hand, point cloud produced by fixed terrestrial 3D laser scanner does not present such problem.

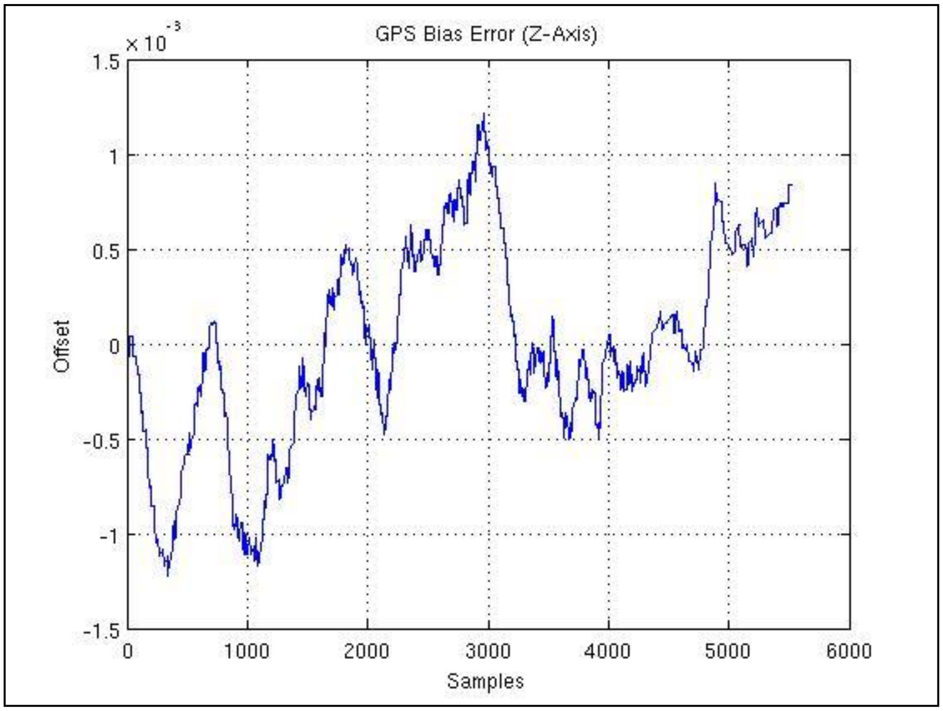

Figure 3.2: Double difference GPS elevation solution offset from average vs. time

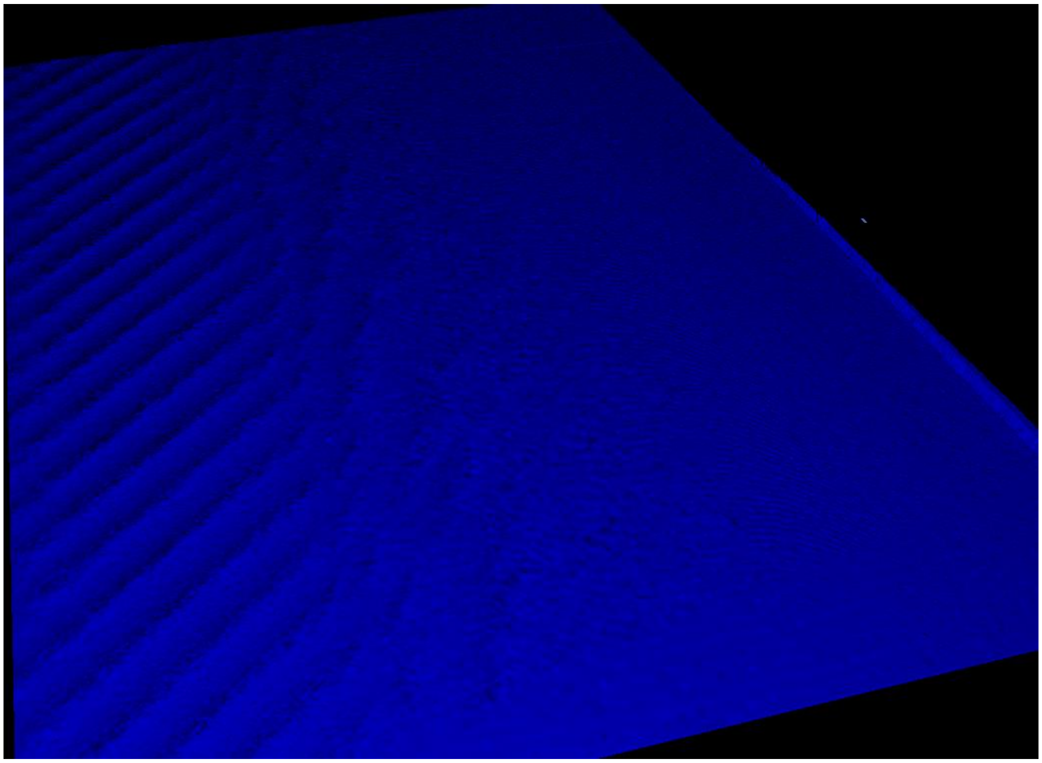

Figure 3.3: TIN surface of a MTLS point cloud with points from multiple passes

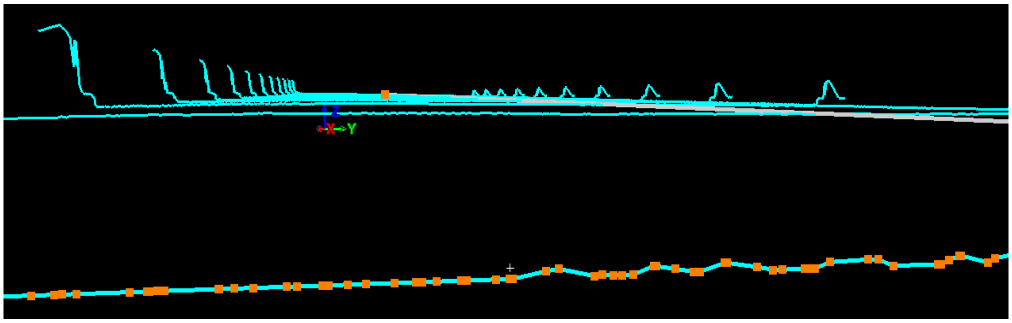

Figure 3.4: Cross-section lines created from thin strips of points along the roadway alignment from MTLS point cloud with multiple passes

These errors are manifest in the form of point cloud vertical offset variances with respect to the direction of mobile system travel. These vertical offsets can be seen clearly when available control points exist in the longitudinal direction that can be used to calculate offsets between ground truth and the estimated point cloud positions. Additionally, in the case of multi-pass scans, which are used to increase point cloud density or provide coverage of missing roadway area, it can be readily seen that offsets between subsequent scans in time show offsets that vary in the vertical direction between the scans as a function of position in the longitudinal direction. It is important to note in both cases the vertical offsets are not constant with respect to position in the longitudinal direction. As the mobile scanning system traverses down the roadway the vertical offset bias is slowly changing. Besides vertical offsets, offsets in the lateral and longitudinal directions have been observed as well.

Analysis of MTLS Point Cloud

Three sets of data were analyzed. The result illustrates the observed vertical offset bias as a function of longitudinal position. The first set of example data we acquired was post-processed point cloud data from StreetMapper for a one mile section of Interstate 15 in the HOV lane in San Diego, CA. The differential GNSS base station was located approximately in the middle of the scan section. The baseline length is less than one mile. In addition, 8 mm was added to the elevation of entire raw point cloud to improve its vertical accuracy. The data was composed of x, y, z, and intensity coordinates for each point in the point cloud along the sampled roadway. Additionally we received control points at 5 locations representing the roadway cross slope every 50 feet longitudinally. The control point locations are shown below in Figure 3.5 with yellow captions. The control point locations are measured with a TotalStation and a prism on a rod.

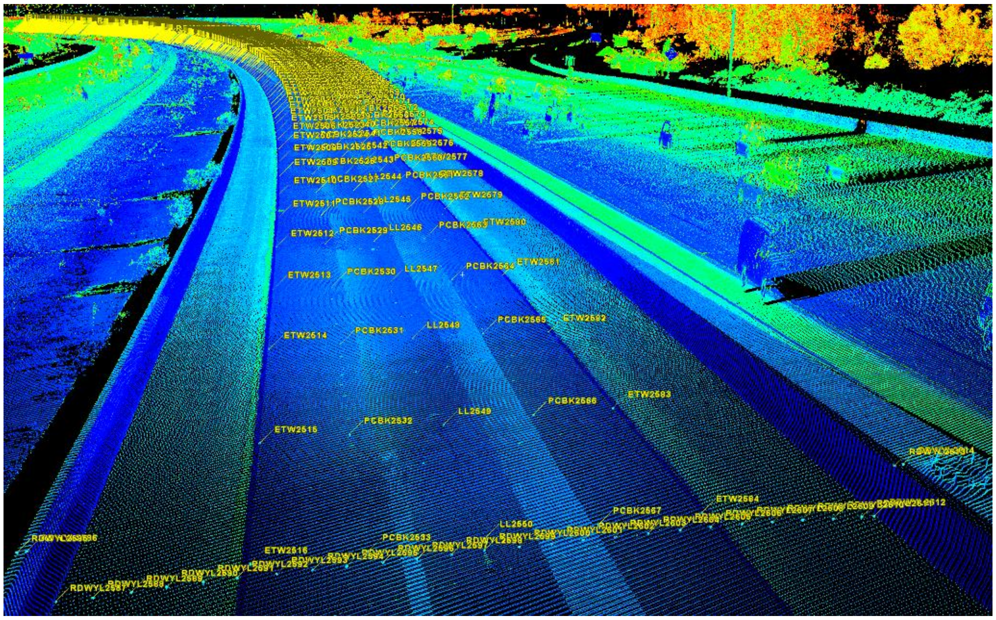

Figure 3.5: Point cloud of Interstate 15 in the HOV lane at San Diego, CA produced by the StreetMapper MTLS system with control points

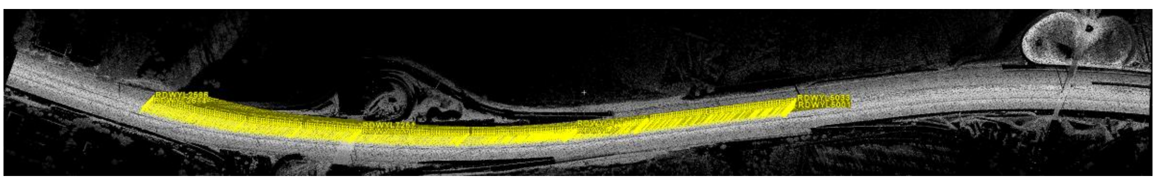

Figure 3.6: Top view of the I-15 point cloud of produced by the StreetMapper MTLS system with control points (in yellow)

The point cloud data was processed and stored in a 3D kd-tree for the purposes of fast retrieval of N nearest neighbors from a given point. For each control point, N nearest neighbors were found and a plane was fit to these points. The offset from the plane and the control point in the z-axis was then calculated and stored. The offset of the control points as a function of longitudinal position are shown below in Figure 3.7. It can be clearly seen that vertical offset is a function of the vehicle system in the longitudinal direction. The red line in Figure 3.7 represents the best fit linear line for the data. Figure 3.8 shows the frequency distribution of the control point offsets to the MTLS point cloud. The frequency distribution resembles a “normal” distribution.

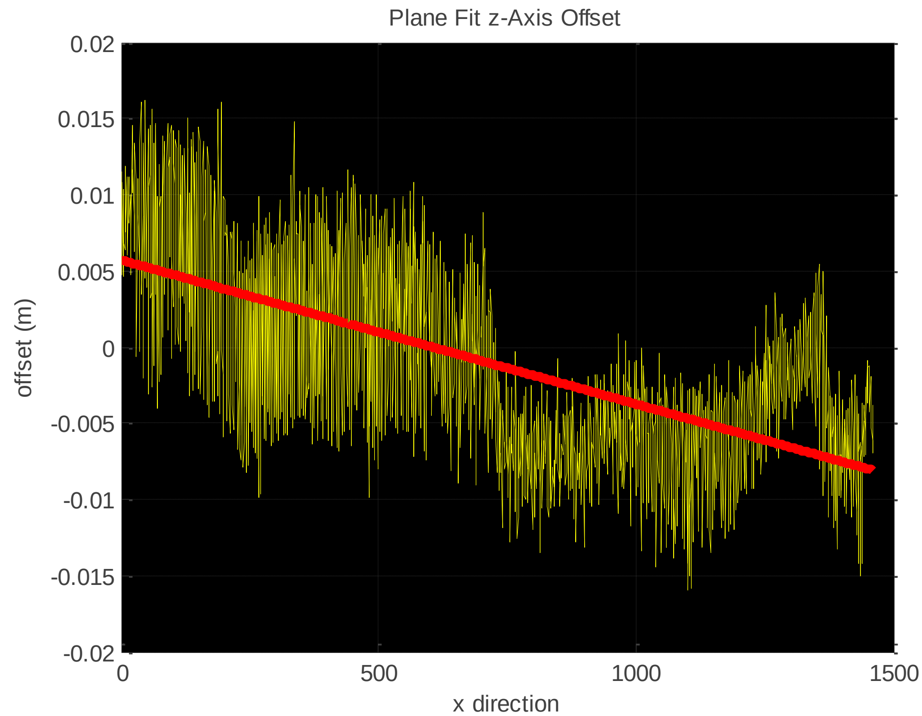

Figure 3.7: Control points vertical offset to the MTLS point cloud as a function of longitudinal position along the roadway

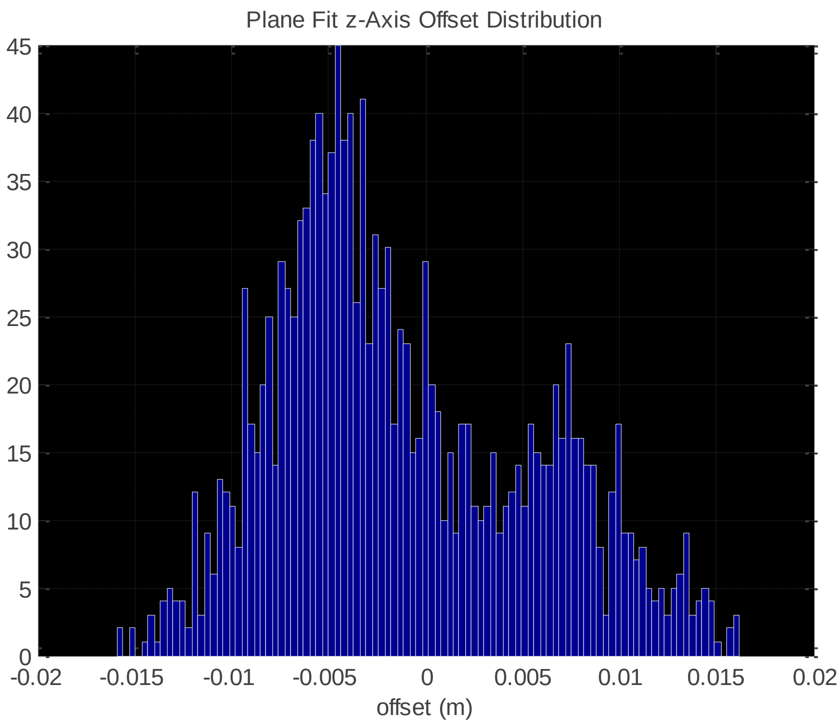

Figure 3.8: Frequency distribution of control points vertical offset to the MTLS point cloud

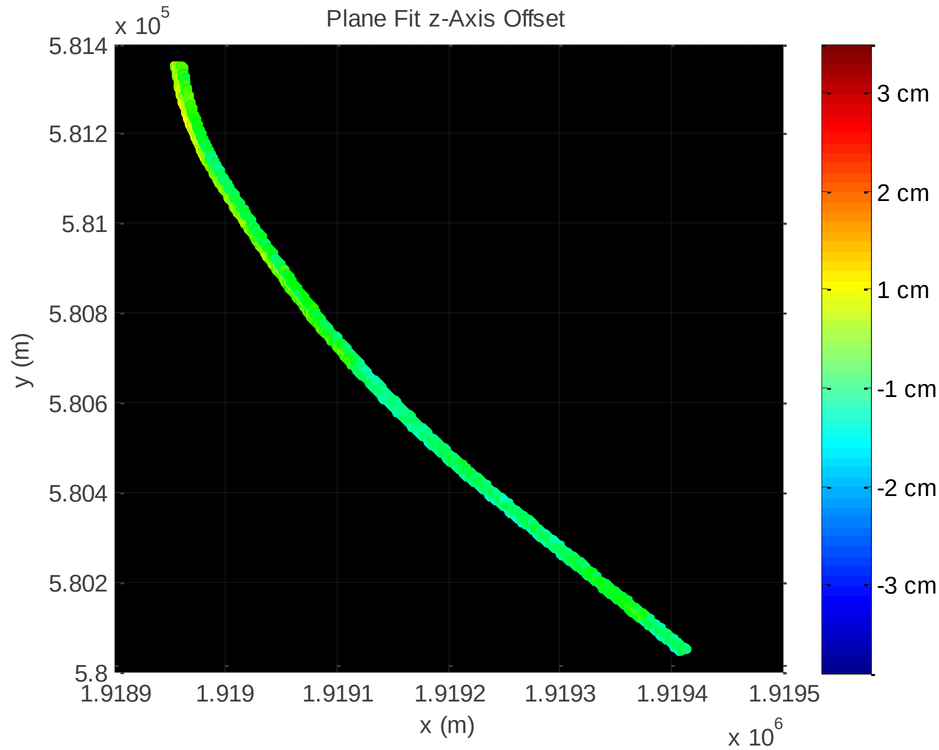

Figure 3.9: Control points vertical offset to the MTLS point cloud vs. x, y position on the roadway

The following analysis compared two set of MTLS point clouds with the point clouds produced by fixed terrestrial 3D laser scanners. The fixed scan point cloud points on the pavements are first cropped out, then an evenly spaced grid of points are selected as "control points". The elevations of selected points are compared to the MTLS point clouds in the same manner as above analysis.

The second data set is provided by David Evans and Associates (DEA), Inc. The static scan of Washington State Route(SR) 167 near Seattle, shown in Figure 3.10, was performed by DEA using a Leica HDS3000 stationary scanner. The mobile scan data is produced by an Ambercore TITAN MTLS system. The data set is divided into two sections: HWY 405 section located at top left of Figure 3.10 and SR 167 southbound section located on the right of Figure 3.10. The HWY 405 section consists of a short section of a divided highway, and the SR 167 section is a long section of southbound highway. Figure 3.11 shows the elevation differences between the static scan data and the MTLS data. There is a small average elevation offset of 1.2 cm (0.04'). Figure 3.14 shows the elevation differences between the static scan data and the MTLS data. The average elevation offset is 0.4 cm (0.01'). The summary of results are listed in Table 3.1.

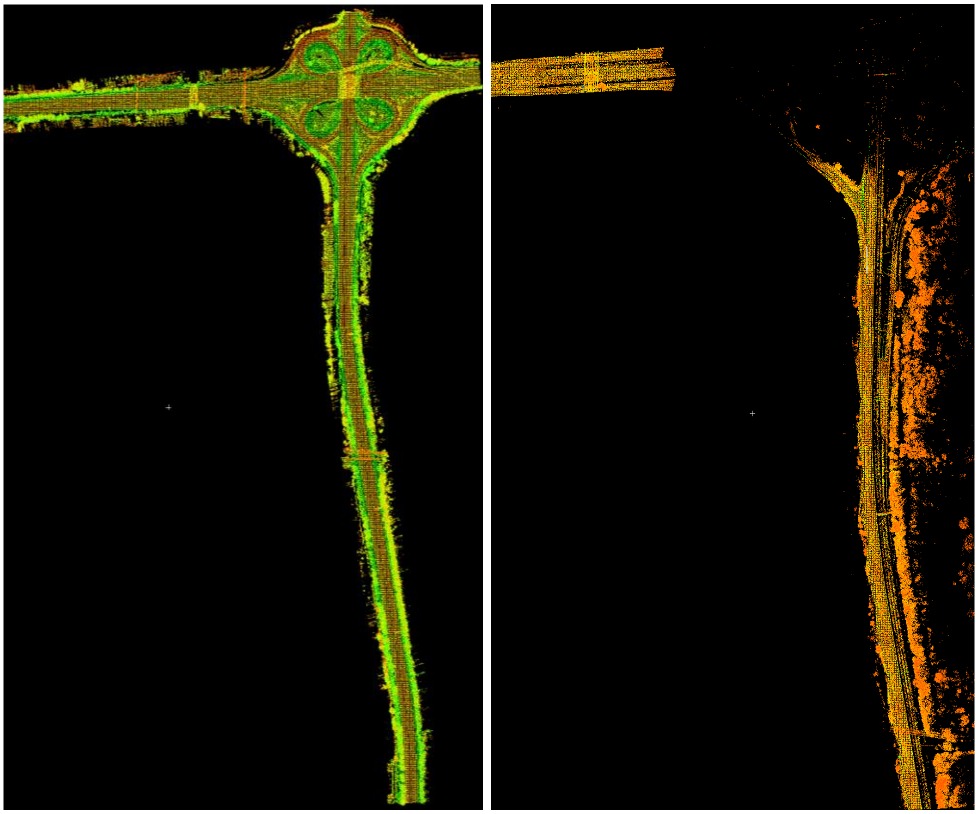

Figure 3.10: Point cloud of Washington SR 167 highway produced by Terrapoint TITAN (on Left) and fixed 3D scanner (on Right)

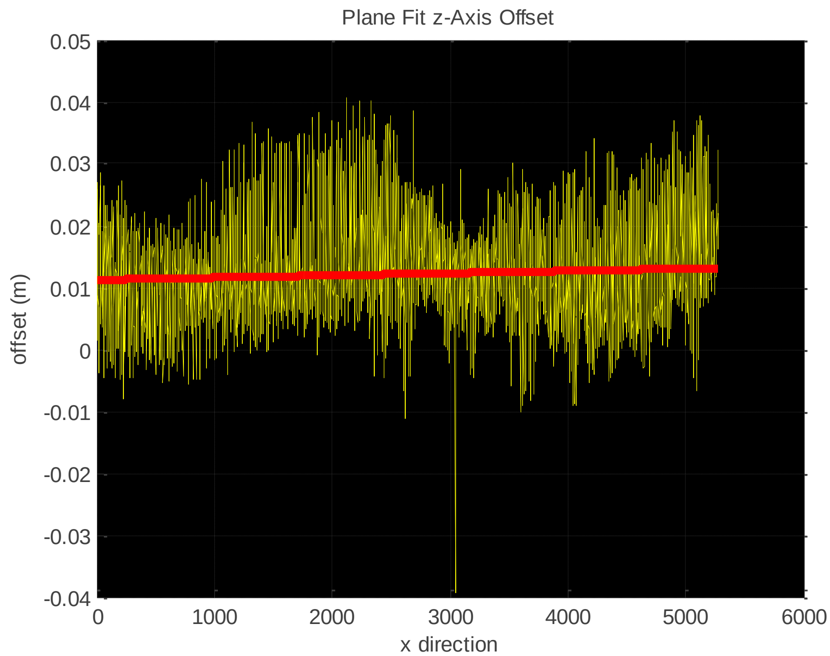

Figure 3.11: Elevation differences between static scan and MTLS of HWY 405 data as a function of longitudinal position along the roadway

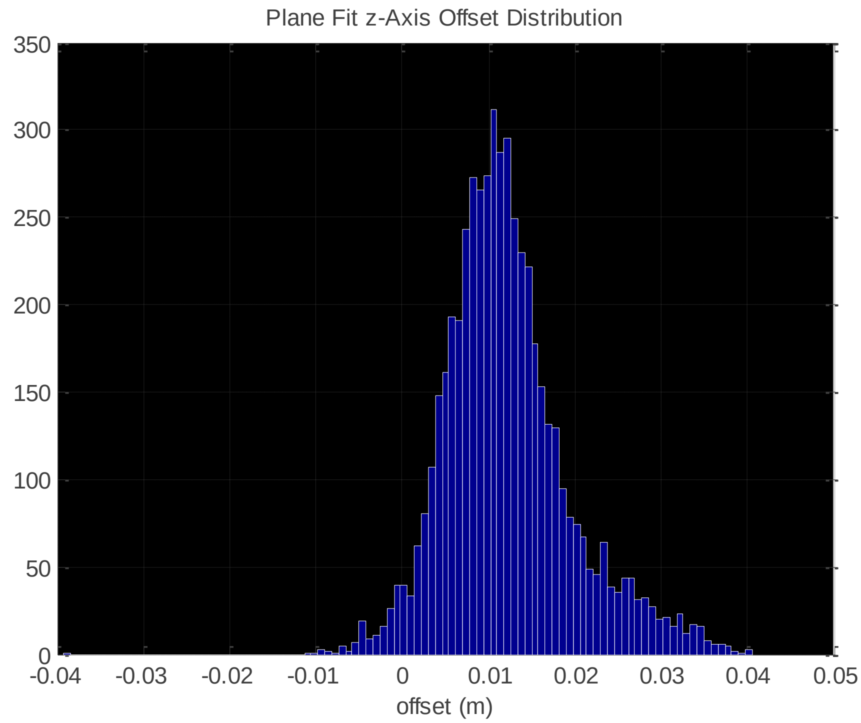

Figure 3.12: Distribution of elevation differences between static scan and MTLS of HWY 405 section data

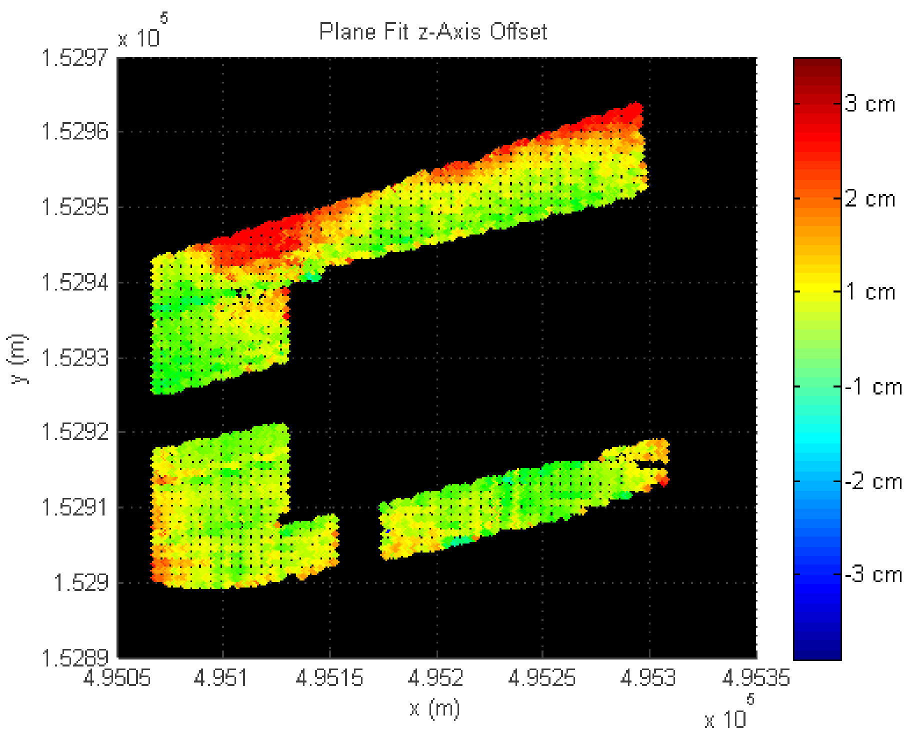

Figure 3.13: Elevation differences between static scan and MTLS of HWY 405 section data vs. x, y position on the roadway

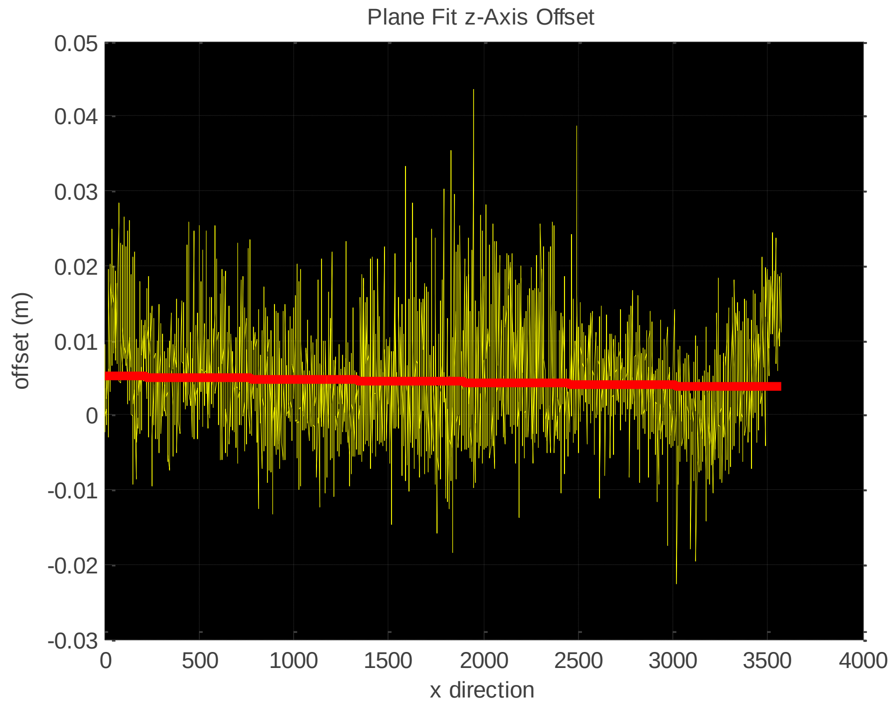

Figure 3.14: Elevation differences between static scan and MTLS of SR 167 section data as a function of longitudinal position along the roadway

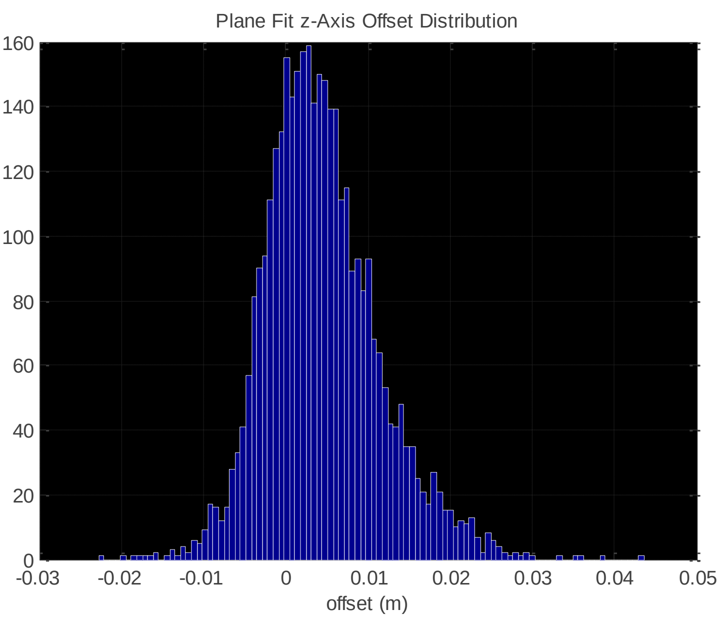

Figure 3.15: Distribution of elevation differences between static scan and MTLS of SR 167 section data

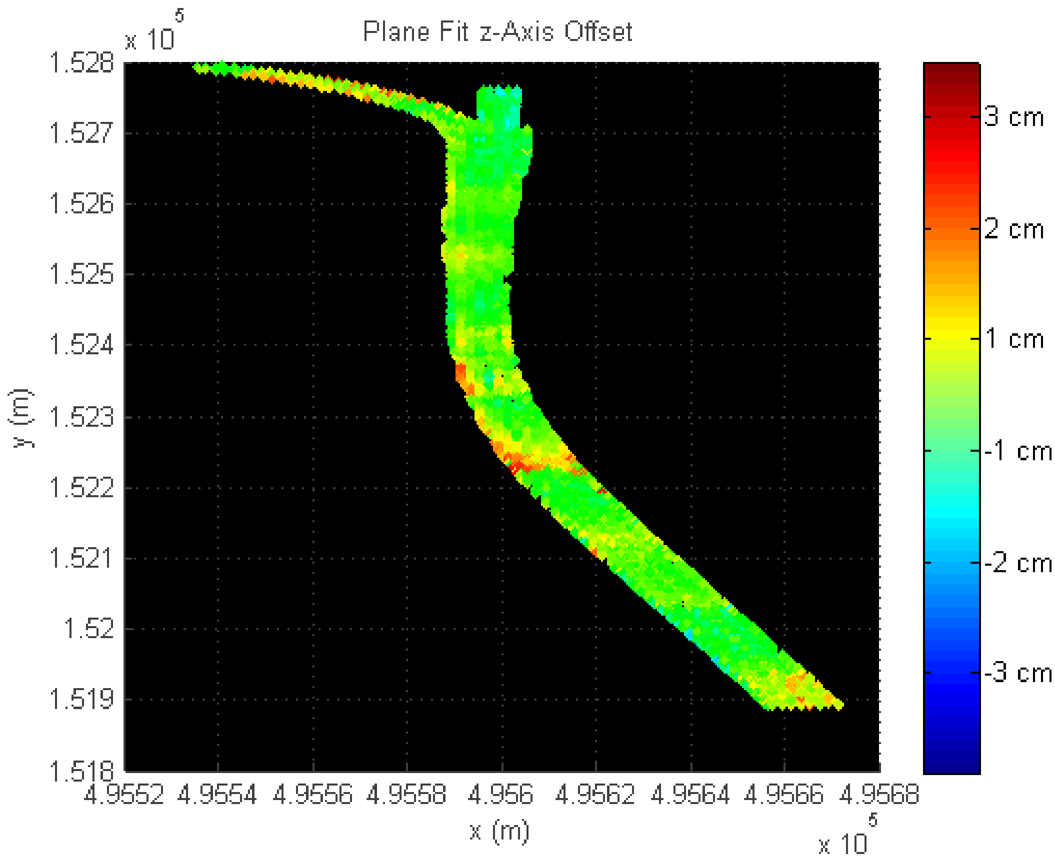

Figure 3.16: Elevation ifferences between static scan and MTLS of SR 167 section data vs. x, y position on the roadway

The third set of data is located at Doyle Drive near the Golden Gate Bridge in San Francisco, California. The mobile scan is performed by WHPacific using an Optech Lynx V100 system. WHPacific has adjusted the mobile scan data using ground controls. The five static scans, shown in Figure 3.17 in orange color, were performed by AHMCT researcher and Caltrans surveyor using a Leica HDS ScanStation2. The data analysis was performed using the same methodology as the Washington SR 167 data set. The single static scan data sets are numbered from left to right. Scan set number 3 and 4 was used in the analysis. The results are shown in Figure 3.18 to Figure 3.23.

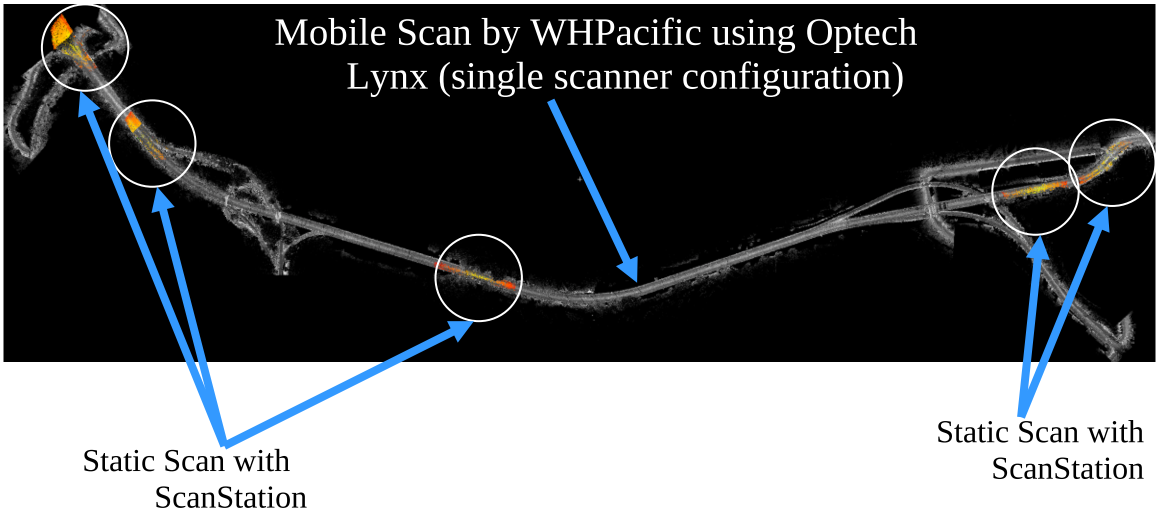

Figure 3.17: Point cloud of Doyle Drive mobile scan produced by Lynx V100 (in gray scale) and fixed 3D scanner (in orange color)

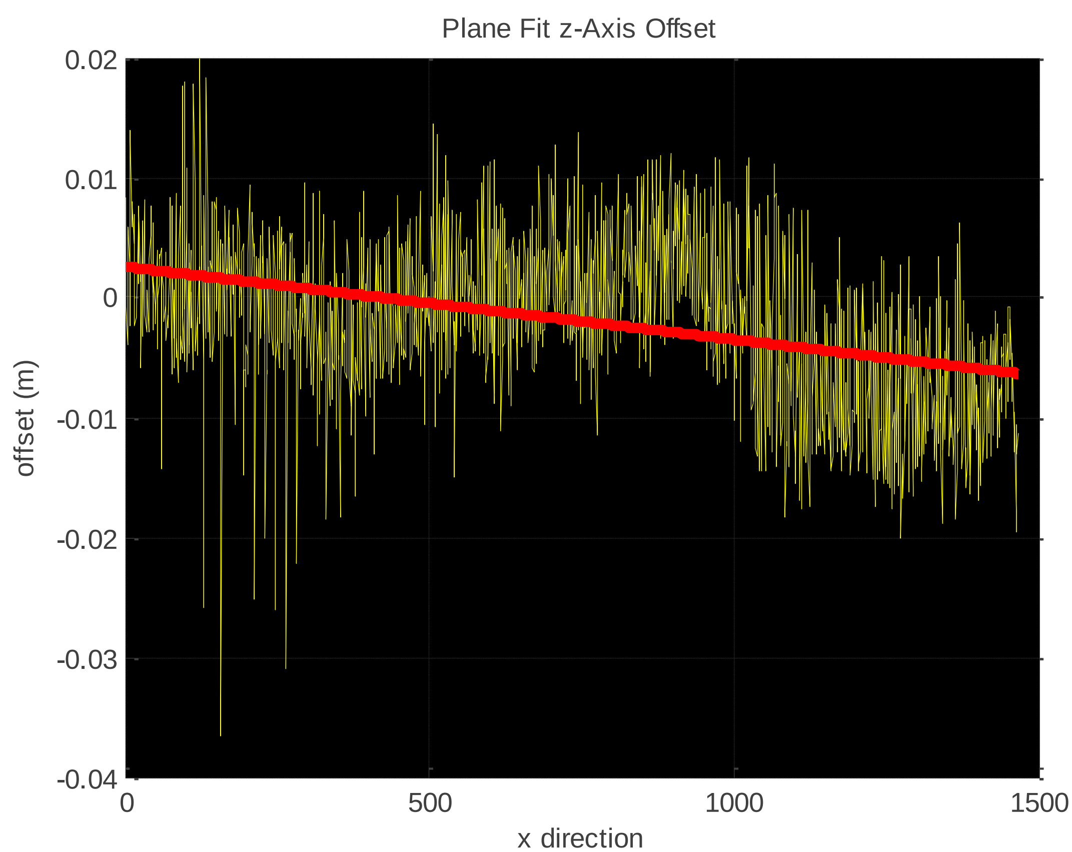

Figure 3.18: Elevation differences between static scan #3 and MTLS of Doyle Drive data as a function of longitudinal position along the roadway

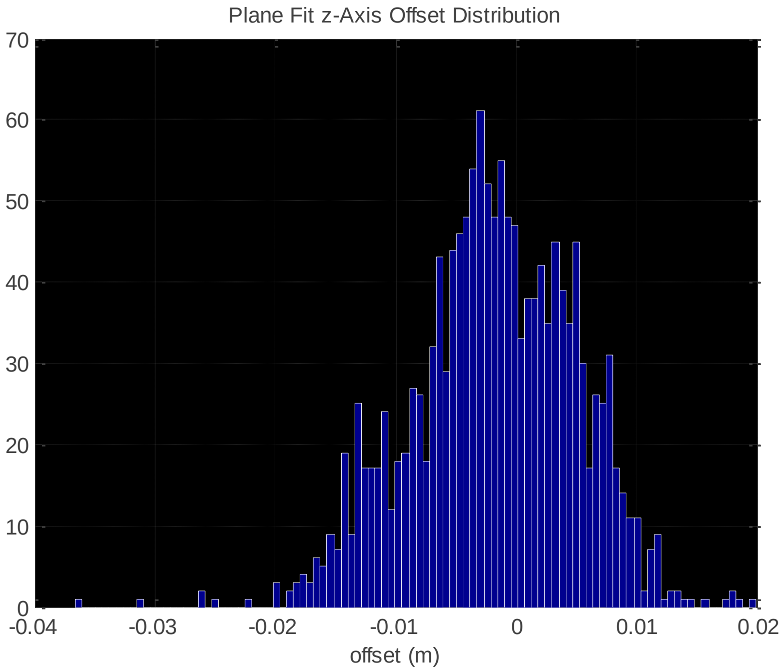

Figure 3.19: Distribution of elevation differences between static scan #3 and MTLS of Doyle Drive data

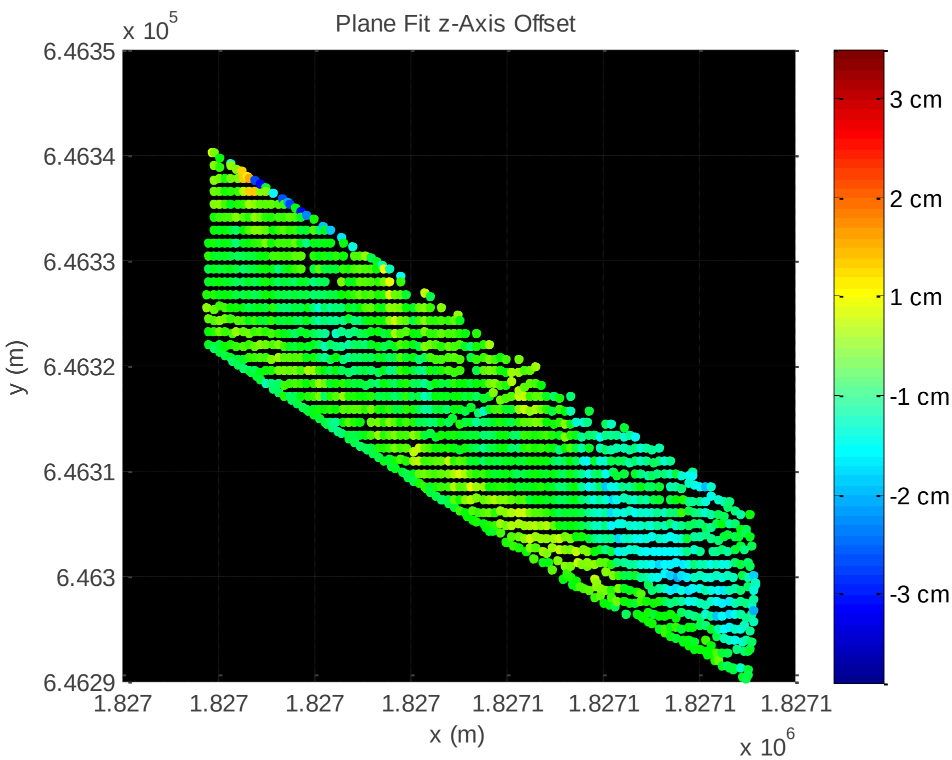

Figure 3.20: Elevation differences between static scan #3 and MTLS of Doyle Drive data vs. x, y position on the roadway

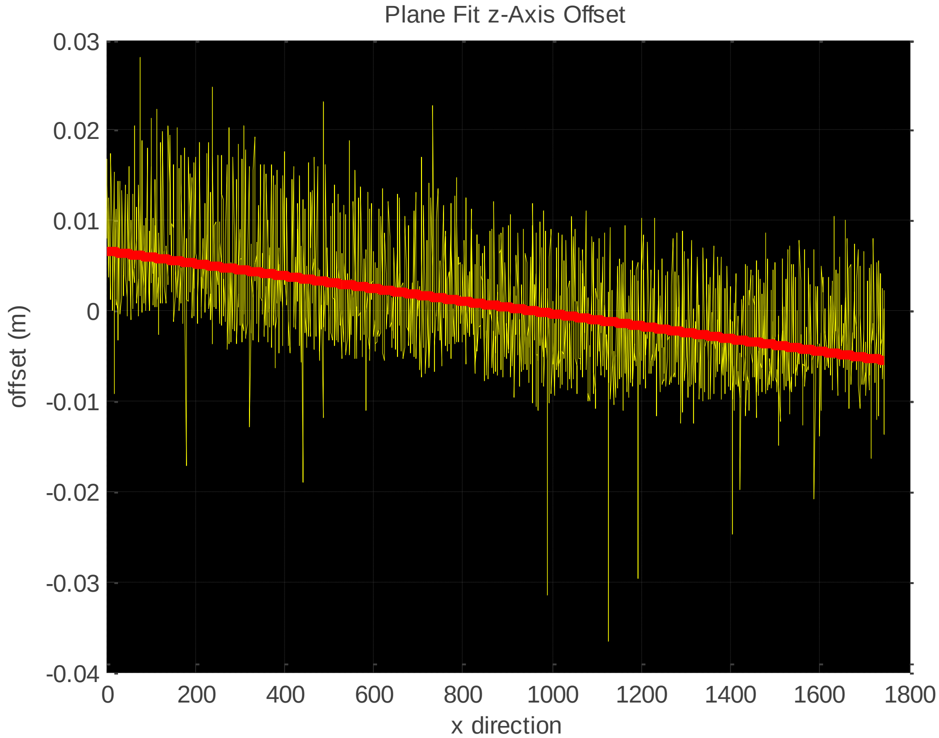

Figure 3.21: Elevation differences between static scan #4 and MTLS of Doyle Drive data as a function of longitudinal position along the roadway

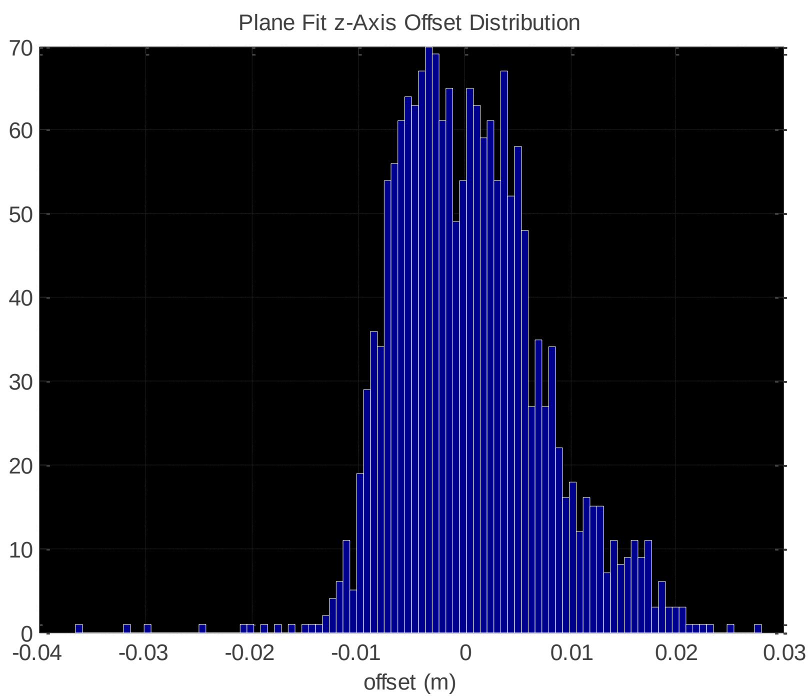

Figure 3.22: Distribution of elevation differences between static scan #4 and MTLS of Doyle Drive data

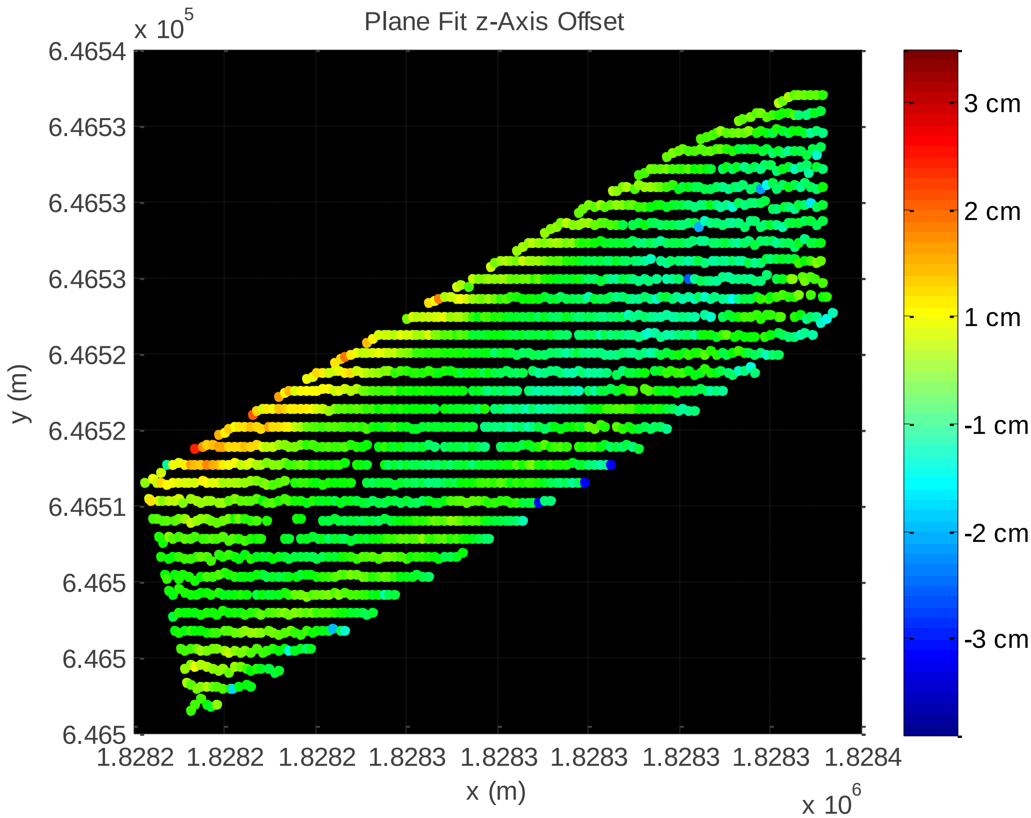

Figure 3.23: Elevation differences between static scan #4 and MTLS of Doyle Drive data vs. x, y position on the roadway

The last data set is a mobile scan of the Golden Gate Bridge in San Francisco, California. The mobile scan is performed by WHPacific using an Optech Lynx V100 system. It consists of two passes: one pass traveling northbound and another pass traveling southbound. The two mobile scans are shown in Figure 3.24. The northbound scan is displayed in color, and the southbound scan is displayed in grayscale. The data analysis was similar that on the Washington SR 167 data set. However, the two different mobile scan passes are compared to each other. The point clouds from both passes have not been adjusted. The results are shown in Figure 3.25 to Figure 3.27.

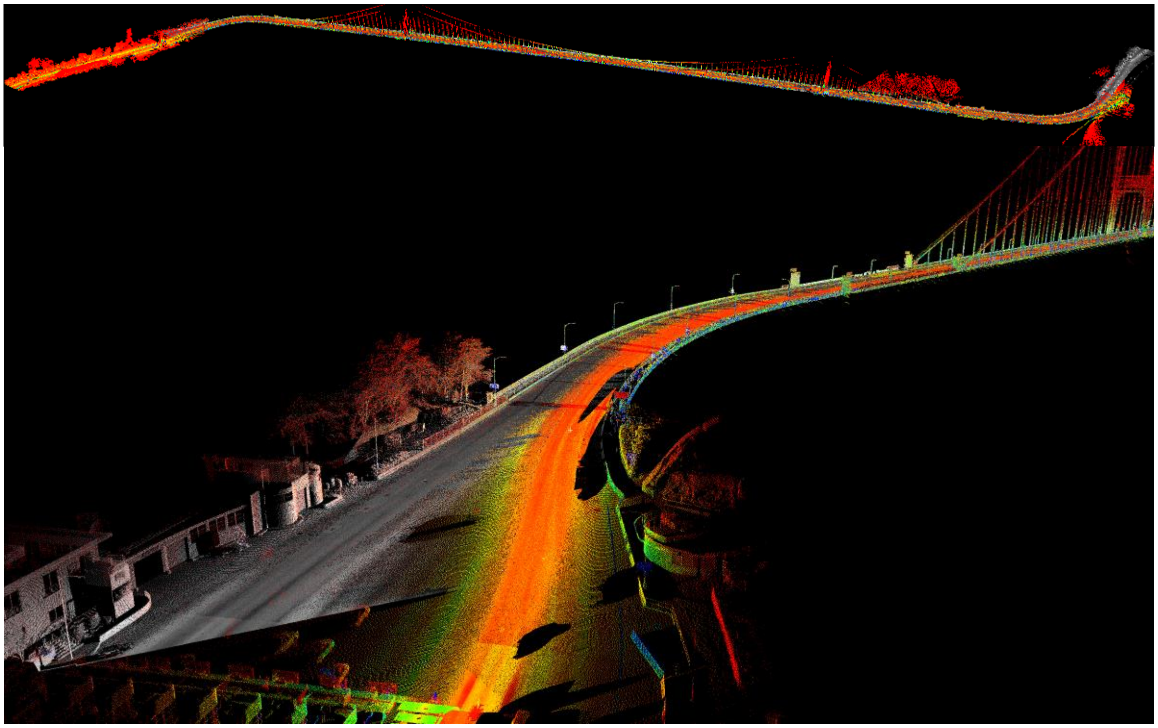

Figure 3.24: Composite Golden Gate Bridge point cloud from two mobile scan passes, northbound pass in color, and southbound pass in grayscale

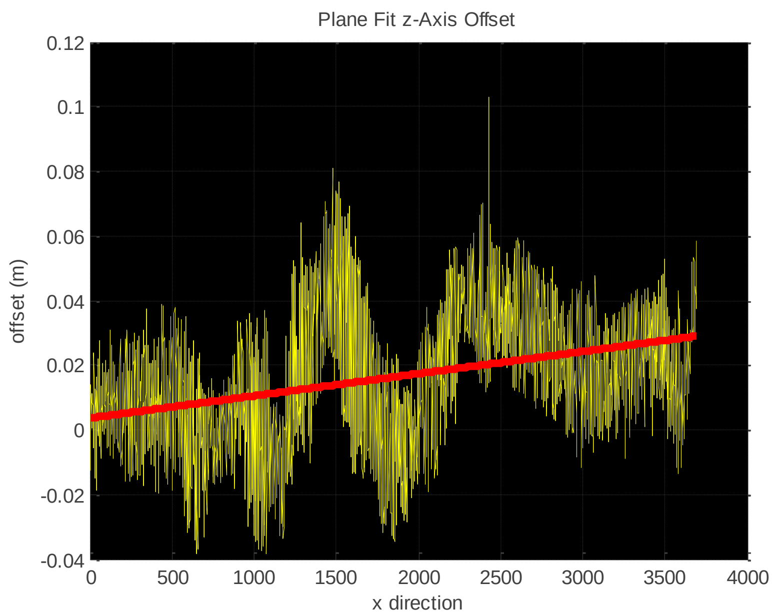

Figure 3.25: Elevation differences between two passes as a function of longitudinal position along the Golden Gate Bridge

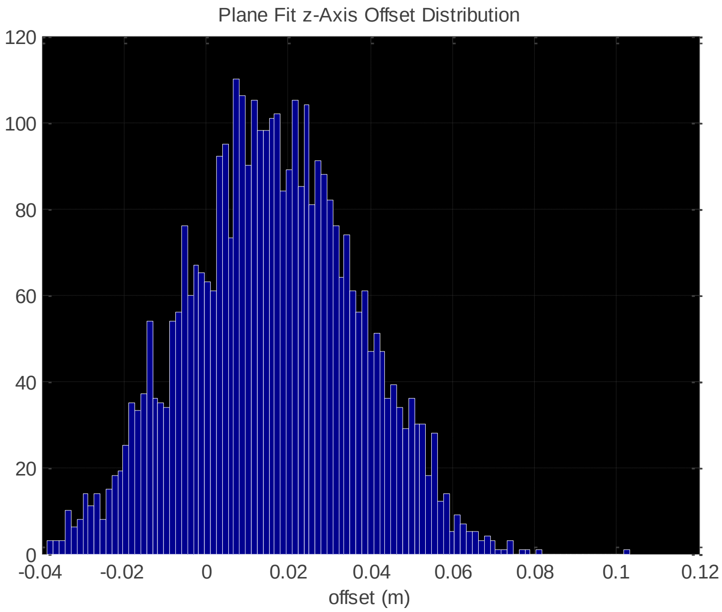

Figure 3.26: Distribution of elevation differences between two passes of mobile scan of Golden Gate Bridge

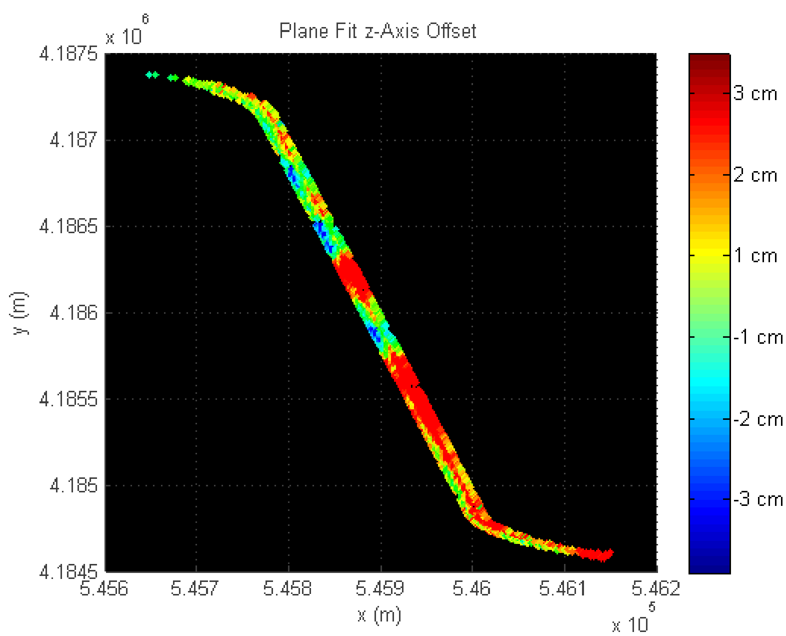

Figure 3.27: Elevation differences between two passes of Golden Gate Bridge mobile scan vs. x, y position on the roadway

Table 3.1 Elevation offset analysis summary

LIDAR Data	MTLS System	Control Point Type	Z-Axis Offset Standard Deviation	Z-Axis Offset Mean
I15_San_Diego	StreetMapper	TotalStation	0.7 cm (0.02’)	-0.1 cm (-0.003’)
sr167_HWY 405	TITAN	Static Scan	0.7 cm (0.02’)	1.2 cm (0.04’)
sr167_Southbound	TITAN	Static Scan	0.7 cm (0.02’)	0.4 cm (0.013’)
sr101_Doyle_drive_3	Lynx V100	Static Scan	0.7 cm (0.02’)	- 0.2 cm (-0.006’)
sr101_Doyle_drive_4	Lynx V100	Static Scan	0.7 cm (0.02’)	0.1 cm (0.03’)
sr101_Golden_Gate	Lynx V100	Mobile Scan	2.0 cm (0.065’)	1.6 cm (0.05’)

Table 3.1 provides a summary of the findings. There is a small average offset between mobile scan data and controls. It is usually within 1 cm. The elevation offset distributions are similar to a normal distribution with a standard distribution of 0.7 cm (0.02’). The short GNSS baseline and post-processing of GNSS/IMU raw data with the GNSS base station yields high-accuracy result that is better than typical RTK GNSS solution. In addition, other researchers and surveyors have performed similar analysis with ground controls surveyed using RTK GNSS [3,11,13-15,17,20,23,29,31,33,35]. Their results have slightly larger standard deviation errors. The discrepancy may be caused by the larger vertical errors in RTK GNSS surveyed ground control data. The analysis findings are:

- Mobile scans point clouds are “noisy” compared to static scans.
- Surface fitting of point clouds produces better elevation estimates than immediate nearest point comparison
- Average vertical offset exists in some scans and is typically addressed by vertical adjustment
- All scans suffer from linear/high-order vertical offset with respect to position or time of scan. The accuracy may be increase scan by post processing high-order z-axis offset adjustment of point cloud.
- A minimum number of known control points are required depending on the frequency of the offset
- Accurate fitting/smoothing of data is required to increase DTM generation accuracy
- GNSS Baseline should be kept short as possible (5 miles or less).

- Dual GNSS base stations should be used to provide both redundancy and accuracy
- Ground controls, used for adjustment, should be elevated using digital levels.

CHAPTER 4: PRELIMINARY RECOMMENDATIONS ON USE OF MTLS

Suitable MTLS Applications

There are many applications suitable for MTLS system. More applications are being found. Users must determine the accuracy requirement to ensure its suitability. These requirements includes: accuracy, safety, project deliverables, GNSS signal availability, and project size. The following are examples of applications suitable for MTLS system:

- Engineering topographic surveys
- As-built surveys
- Structures and bridge clearance surveys
- Deformation surveys
- Forensic surveys
- Corridor study and planning surveys
- Asset inventory and management surveys
- American Disability Act (ADA) compliance surveys
- Environmental surveys
- Sight distance analysis surveys
- Earthwork surveys such as stockpiles, borrow pits, and landslides
- Urban mapping and modeling
- Coastal zone erosion analysis
- Construction inspections

Best Practices Recommendations

All best practices recommendations from the current research are incorporated into Chapter 15 of the Caltrans Survey Manual (CSM) [6]. The following are highlights of key considerations

Mission Planning

Mission planning is critical in ensuring maximum GNSS signal availability during the data collection. The traffic volume and conditions at time of data collection should also be considered to minimize obstruction of the LiDAR sensor by other traveling vehicles.

In addition, the GNSS base station placement should also be examined carefully for maximum satellite visibility. The baseline should be kept as short as possible. Furthermore, a secondary GNSS base station should be deployed to provide redundancy and reduced baseline length. One base station location should be near the beginning of the project and another one near the end of the project. The horizontal accuracy standard of the GNSS Control Stations shall be second order or better as defined in the CSM and the vertical accuracy standard shall be third order or better as defined in this manual. GNSS signal challenged area should be identified. These areas would require extra placement of local controls for quality assurance.

Some MTLS systems may require a safe location with relatively open sky to perform GNSS/IMU alignment process. Typically, the vehicle needs to be parked safely away from traffic disturbance and remain static for 5 or more minutes. Primary and secondary locations for this process should be selected in the mission phase. Depending on the applications, the point cloud density requirement will dictate the maximum vehicle speed for data collection. The LiDAR scanners' scan rate should be set to match with the vehicle speed in the point density calculation.

Target Placement

Targets occupying known horizontal and vertical control are required for point cloud adjustment and validation points for QA/QC. Targets should be located in regular intervals as close to the MTLS vehicle path as possible without compromising safety. The MTLS vehicle operator(s) should adjust the vehicle speed at the target area so that the target(s) will be scanned at sufficient density to ensure good target recognition.

Equipment Calibration

Before and after data collection, the MTLS system calibration should be checked to ensure sensor alignments are within the manufacturer's specifications. Sensor alignment (bore sighting) procedures shall be performed on site if the system has been disassembled for transport.

Monitoring Data Collection

Each MTLS system has custom software for data collection and real-time monitoring of system components such as the GNSS/IMU positioning system. Users should carefully observe the GNSS signal availability and proper functioning of the LiDAR scanners and digital camera. The driver should vary the vehicle speed safely during data collection while not exceeding the maximum data collection speed limit determined in mission planning phase.

QA/QC

Quality assurance of the data can be achieved by redundant measurements by multiple scan runs or passes that offer overlapping coverage. In addition, the user should examine the separation of forward and reverse solution (difference between forward and reverse post-process roll, pitch, yaw and XYZ positions solution). Areas with large solution separation would indicate poor GNSS/IMU position solution. It could be caused by long GNSS signal outage or high GNSS signal multi-path condition. User should also look for areas with long GNSS signal loss or obstruction. The point cloud in these locations should be checked vigorously with other data from other passes and local controls. In addition, users should compare elevation data from overlapping (sidelap) runs. Most importantly, the result of the statistical comparison of point cloud data to validation control points provides vital proof of data quality.

Recommended Data Format for Exchange and Archival Purposes

End users and manufacturers agree that standards are needed in the following areas: best practices on the use of MTLS system in different applications, uniform result reporting, and universal data exchange formats. These standards will increase the users' confidence in the performance of their chosen systems, facilitate interoperability, and promote the overall growth of the industry. The data format in which mobile laser scan data is stored for further processing must be interchangeable and mutually acceptable to most commercial LIDAR software available today. Currently, each MTLS system stores its raw GNSS/IMU/LiDAR data in the vendor's own proprietary binary format. LAS is the preferred standard data exchange format for the point cloud produced by the MTLS system. A simple readme text file is often used to describe the project, date, data provider, units, datum, geoid, and map projection.

In addition, the final geo-referenced point cloud data may also be exported in space-delimited ASCII format ("X Y Z I R G B"), as described in Table 8. The xyz coordinate unit may be any standard unit such as meter, international feet, US survey feet, inches, etc. Therefore, the user must select the matching xyz unit during the import process. The RGB range values (0 to 255) are quite standard, and they can be left blank if digital camera image data is not available. Putting the ASCII in a compressed file may be the best long-term "future" proof archival format. It is essential that original native scanning system file format should be kept in case GPS/IMU reprocessing is required. Depending on the LiDAR scanner, the range of the intensity value, I, may be larger than 0 to 255. AHMCT has developed Java-based software to autoscale the intensity value within the range of 0 to 255. The software and its source code are available at http://hardhat.ahmct.ucdavis.edu/mediawiki/index.php/LaserScanResources.

Table 4.1: ASCII file format component description

Symbol	Description
X	x-coordinate value of a point
Y	y-coordinate value of a point
Z	z-coordinate value of a point
I	Laser return intensity value of a point (integer, 0 to 255)
R	Digital image pixel overlay red component value of a point (integer, 0 to 255)
G	Digital image pixel overlay green component value of a point (integer, 0 to 255)
B	Digital image pixel overlay blue component value of a point (integer, 0 to 255)

However, there is no standard in exchanging the geo-referenced digital images. Most 3rd party post-processing software could read the majority of MTLS geo-referenced image output. The majority of the systems produce the images in jpg format. End users should specify the images format unambiguously.

The American Society for Photogrammetry and Remote Sensing (ASPRS) is actively updating the LAS format to better address MTLS application requirements. There is on-going discussion of creating a standard universal terrestrial and mobile scanning point cloud format similar to the one created for aerial LIDAR. Users should keep track of the latest development from ASPRS, ASTM and NIST, as they are working diligently towards a standard 3D imaging system data exchange format.

National Best Practices Development

End users and manufacturers agree that standards are needed in the following areas: Best practices on the use of MTLS system on different applications, uniform result, and reporting. The ASPRS mobile mapping systems committee, chaired by Dr. Craig Glennie, is working on a best practices and guidelines document, with the goal of having an initial draft prepared for ASPRS 2012. In addition, Geospatial Transportation Mapping Association (GTMA) (www.usgtma.org), chaired by Ray Mandli, is formed recently. Their aims are:

- Educate industry on what they should be looking for
- Create a standard for quantifying results
- Create some sharing of information and data between vendors
- Create a national dataset of highway data for federal use

DOT Deployment Challenges and Considerations

MTLS systems may improve work safely and be cost-effective to collect data. Deployment of MTLS technology presented several challenges for DOT [32]:

- Extensive training is required to operate MTLS system and properly post-process the raw GNSS/IMU/LiDAR data
- MTLS systems can produce huge amounts of data in a short time, possibly requiring upgrade of the entire computing infrastructure (software, workstations, servers, data storage, and network backbone). Agency Information Technology policies must be negotiated to successfully procure and deploy systems.
- The large data set also presents a data management challenge allowing diverse users to access the available data and extract need information for it. A simple and easy to use point cloud viewer will be needed
- The high initial cost of the system may require special legislative approval to purchase the equipment. In addition, funding is also required for software, computing infrastructure upgrade, system maintenance, and creating a new program with personnel to operation the system and process the data.

- Typical DOT survey operation based on cost-recovery, and funding for purchasing an MTLS system is very limited. Outsourcing MTLS services through the procurement of architecture and engineering contracts may be an option and preferable to some DOTs.

- Best practices and workflow procedures must first be created to ensure data are collected properly to achieved accuracy expectation as well as guiding users on the proper use of the data. As the same time, the best practices and workflow procedures should be integrated into DOT standard manual and policy documents.

Risks and Mitigations

Technological obsolescence is one of the major risks. The GNSSs (GPS, GLONASS, Galileo, and Compass) are currently going through major modernization or are in the middle of deployment. More satellite navigation frequencies and signals will be made available soon. Most GNSS receivers are designed to be compatible with GNSS modernization. Their firmware may be upgraded to improve compatibility. However, the new generation of GNSS receivers with much higher number of channels for GNSS signal tracking may be needed to take advantage of over 80 satellites in the sky when all the GNSSs are fully operational. The cycle of new GNSS receiver development is about 1 to 2 years. Higher accuracy IMUs are also made available at “affordable” price for MTLS system. However, the development cycle for IMU sensors are usually longer than 3 years.

LiDAR scanners have made rapid improvement recently. For example, the Optech Lynx LiDAR scanner’s maximum measurement rate has increased from 100,000 points per second (pts/s) to 500,000 pts/s, and its maximum scan rate has also increased from 150 Hz to 200 Hz vs. the system first offered over 4 years ago. Nevertheless the total system cost remains the same. Other mapping grade LiDAR scanners are made available with higher performance and lower cost.

To mitigate risk of technological obsolescence, customer may obtain data from MTLS service providers using service contracts. In addition, MTLS system manufacturers have recognized their customer’s concern of risk of technological obsolescence and high initial system cost. They have partnered with dealer or services provider to offer equipment rental and partial ownership options. Both options enable lower cost of entry and provide a cost-effective option for low utilization. To determine which options may be most cost-effective, users should consider the expected utilization rate of the MTLS system. If the anticipated system utilization rate is low, then renting, partial ownership, or service contract may be better options.

CHAPTER 5: CONCLUSIONS

This research has investigated MTLS within the context of Caltrans surveying applications. Under the right conditions and using good methodology, MTLS can be used to create DTMs of pavement surfaces. Current MTLS systems have difficulty meeting the Caltrans vertical specification of an absolute vertical difference of 0.02 foot at a 95% confidence level. The work has developed test methodologies and analysis techniques to quantitatively and qualitatively evaluate MTLS system data for accuracy, repeatability, and usability, all as applicable for surveying, including highly demanding pavement surveys to produce Digital Terrain Models. The results presented herein provide the means to evaluate their effectiveness in field situations. However, the more important and long-term benefit of these research results is the well-documented and carefully developed methodology for Control and Pilot Testing. The methodology will allow AHMCT, Caltrans, and others to perform equivalent tests and evaluations as new mobile laser scanners, software, and related technologies emerge. Thus, the methodology provides a tool for foreseeable deployment of emerging advanced technologies for the DOT.

Table 3.1 provides a summary of the finding. There is a small average offset between mobile scan data and controls. It is usually within 1 cm. The elevation offset distributions are similar to a normal distribution with a standard deviation of 0.7 cm (0.02’). Adding both average offset error and the standard distribution error, the total error of best MTLS data does not meet the current accuracy specified in the Surveys Manual for pavement of 7 mm vertical for hard surfaces. With discipline and careful application of the MTLS technology, the resulting point clouds could have the needed accuracy. The short GNSS baseline and post-processing of GNSS/IMU raw data with the GNSS base station yields high accuracy results that are better than typical RTK GNSS-only solutions. In addition, we found that:

- Mobile scans point clouds are “noisy” compared to static scans.
- Surface fitting of point clouds produces better elevation estimates than immediate nearest point comparison.
- Average vertical offset exists in some scans and can partially be addressed by vertical adjustment.
- All scans suffer from linear/high-order vertical offset with respect to position or time of scan. The scan accuracy may be increased by post-processing high-order z-axis offset adjustment of point cloud.
- Accurate fitting/smoothing of data is needed to increase DTM generation accuracy.
- GNSS Baseline should be kept as short as possible (5 miles or less).
- Dual GNSS base stations should be used to provide both redundancy and accuracy.
- Ground controls, used for adjustment, should be surveyed using digital level.

- MTLS projects that require survey grade accuracy must have ground controls for QA/QC and further adjustment.

The research also evaluated surveying and MTLS workflows, including approaches for establishing controls, performing field surveys and scans, and post-processing of the data. In conjunction with Caltrans Office of Land Surveys, the researchers have developed best practices for workflows using laser scanners for DOT surveys. The workflow recommendations will be tested, refined, and validated in a number of real-world Caltrans applications.

Future Work

While the current research provides a solid basis for the deployment of mobile laser scanning for DOT use, there are a number of areas that have been identified in the process of this work which will benefit from focused research. This is a particularly fluid area with respect to both fundamental research and emerging technologies and systems, and the field bears watching closely from a research, development, and application perspective. Simply keeping up with the state-of-the-art in scanning, measurement, and positioning technologies can easily be a full-time effort. Of particular interest and importance, AHMCT researchers will continue to monitor the standardization efforts and results produced by ASPRS, NIST, and ASTM. NCHRP has initial a new project to develop best practices and guidelines for the use of MTLS system.

Cost benefit analysis documentation will need to be developed to convince the legislature to approve funding deploying MTLS technology. The cost benefit analysis would require detailed examination of the internal DOT business process to determine who may be benefit from the MTLS data besides Office of Land Survey. The work will include determining which deployment options may best fit the DOT.

Even though MTLS of roadway infrastructure has become more accurate in recent years, the resultant point clouds still suffer from significant errors. We seek to specifically address the cause and mitigation of the systematic bias. MTLS systems from various vendors will have varying accuracies but all seem to suffer from the same systematic bias which can be clearly shown in multi-pass scans. In these multi-pass scans there are obvious offsets in the vertical, lateral, and longitudinal directions when compared to one another from the same vendor. Further research is needed to develop methods to remove this bias from scans with a minimum number of control points in post processing of point cloud data. Future research should examine the best approaches to combine digital images with LiDAR data to increase data extraction productivity.

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