STATE OF CALIFORNIA • DEPARTMENT OF TRANSPORTATION

TECHNICAL REPORT DOCUMENTATION PAGE

TR0003 (REV 10/98)

1. REPORT NUMBER CA15-2194	2. GOVERNMENT ASSOCIATION NUMBER	3. RECIPIENT'S CATALOG NUMBER
4. TITLE AND SUBTITLE Application of Mobile Laser Scanning for Lean and Rapid Highway Maintenance and Construction		5. REPORT DATE 08-28-2015
		6. PERFORMING ORGANIZATION CODE AHMCT Research Center, UC Davis
7. AUTHOR Bahram Ravani, Kin Yen, Ty A. Lasky, Stephen Donecker, and Zhenxiang Jian		8. PERFORMING ORGANIZATION REPORT NO. UCD-ARR-15-08-28-01
9. PERFORMING ORGANIZATION NAME AND ADDRESS AHMCT Research Center UCD Dept. of Mechanical & Aerospace Engineering Davis, California 95616-5294		10. WORK UNIT NUMBER
		11. CONTRACT OR GRANT NUMBER 65A0368, Task 2194
12. SPONSORING AGENCY AND ADDRESS California Department of Transportation P.O. Box 942873, MS #83 Sacramento, CA 94273-0001		13. TYPE OF REPORT AND PERIOD COVERED Final Report June 2010 - September 2015
		14. SPONSORING AGENCY CODE Caltrans

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Mobile Terrestrial Laser Scanning (MTLS) is an emerging technology that combines the use of a laser scanner(s), the Global Navigation Satellite System (GNSS), and an Inertial Measurement Unit (IMU) on a vehicle to collect geo-spatial data. The overall research question addressed in this project was: what are the parameters that can enhance the integration of this technology into Caltrans workflow to achieve leaner operations in maintenance, design, and construction and to improve the safety of Caltrans workers? In response to this rather broad question, this research aimed to identify the technical issues important to understanding the MTLS technology, its cost-benefits, and the key parameters to facilitate its integration into Caltrans' operations for leaner and more efficient operations.

17. KEY WORDS LiDAR, Mobile Terrestrial Laser Scanning, MTLS Accuracy, Software Evaluation, Work Flow, Cost-Benefit Analysis, Feature Extraction, Inertial Measurement Units, Multi Attribute Utility Theory, Reverse Engineering	18. DISTRIBUTION STATEMENT No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.	
19. SECURITY CLASSIFICATION *(of this report)* Unclassified	20. NUMBER OF PAGES 65	21. COST OF REPORT CHARGED

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Advanced Highway Maintenance and Construction Technology Research Center

Department of Mechanical and Aerospace Engineering
University of California at Davis

Application of Mobile Laser Scanning for Lean and Rapid Highway Maintenance and Construction

Bahram Ravani: Principal Investigator
&
Kin S. Yen, Ty A. Lasky, Stephen Donecker, Zhenxiang Jian

Report Number: CA15-2194

AHMCT Research Report: UCD-ARR-15-08-28-01

Final Report of Contract:

65A0368, Task 2194

August 28, 2015

California Department of Transportation

Division of Research, Innovation and System Information

ABSTRACT

Mobile Terrestrial Laser Scanning (MTLS) is an emerging technology that combines the use of a laser scanner(s), the Global Navigation Satellite System (GNSS), and an Inertial Measurement Unit (IMU) on a vehicle to collect geospatial data. The overall research question addressed in this project was: what are the parameters that can enhance the integration of this technology into Caltrans' workflow to achieve lean operations in maintenance, design, and construction and to improve the safety of Caltrans workers? In response to this rather broad question, this research aimed to identify the technical issues important to understanding the MTLS technology, its cost-benefits, and the key parameters to facilitate its integration into Caltrans' operations for leaner and more efficient operations.

EXECUTIVE SUMMARY

This research study focused on developing the knowledge to enhance the integration of the Mobile Terrestrial Laser Scanning (MTLS) technology into Caltrans' operations to achieve leaner and safer operations. The MTLS technology investigated in this study uses a terrestrial laser scanner on a vehicle equipped with the Global Navigation Satellite System and an Inertial Measurement Unit. These additional systems tag the laser scanner measurements with geo-spatial coordinates, allowing the generation of point cloud data in the form of a digital terrain model of a highway section that is properly referenced to a known location. The resulting digital terrain model can be used for many purposes, including performing pavement surveys, extracting bridge height measurements off line, and developing a digital model of the roadway and its surrounding area. These digital terrain models can also be used for various other applications within Caltrans, including planning and operational purposes. The integration of MTLS technology can not only lead to leaner operations in surveying, design, construction, maintenance, and highway operations, but can also improve worker and highway safety since measurements are collected from a moving vehicle rather than by employees who are on foot and exposed to live traffic.

Research Objective and Methodology

The main objective of this research study was to identify the technical issues important to understanding the MTLS technology in order to enhance its integration into Caltrans' workflow and thus achieve leaner operations in maintenance, design, and construction and improve the safety of Caltrans workers. In addition, the research investigated innovative methods to improve the accuracy and the repeatability of data gathered.

The methodology or approach used in this research study had both applied and basic research components. The applied component involved developing a cost-benefit analysis of MTLS use in highway applications and guidelines for control point spacing to achieve survey-grade measurements or desired accuracy. In addition, as part of the applied portion of this research, several commercially available software packages related to point cloud processing were evaluated, and workflows were developed integrating them into Caltrans operations.

As part of its basic research component, this study evaluated the capabilities of reported point cloud processing techniques in the open literature and identified some of the best methods for feature extraction applicable to highway operations. Furthermore, the research study developed a kinematic registration method for point cloud data processing that significantly reduces human processing of the data. Kinematic registration is the process needed for connecting point cloud data that have been obtained for two separate, but adjacent, highway sections or for connecting data from two different MTLS systems.

Results and Recommendations

This research resulted in a methodology for a cost-benefit analysis that would allow for the evaluation of different options in terms of utilizing an MTLS system. The cost-benefit analysis method was developed based on historical data from certain uses of MTLS technology on California highways, and it can be adapted to other and future uses of the MTLS technology in

transportation applications. The cost-benefit analysis compared the cost effectiveness of different options for survey-grade projects. The conclusion from the cost-benefit analysis was that the cost effectiveness for different ways of contracting or performing a survey-grade project using MTLS technology depends on the work capacity in terms of the number of projects that a unit would have per month. Using the cost-benefit analysis, this research study provided MTLS recommendations, limitations, and best practices to Caltrans for bridge clearance measurements and for pavement survey applications.

In order to be able to collect survey-grade point cloud data, engineering and survey-grade MTLS data collection requires ground controls and targets for accuracy improvement and data validation. No standard guidelines existed that provided a recommendation for control point spacing that correlated to an expected level of accuracy in data collection. This research study performed experiments and developed a set of guidelines for ground controls and targets to achieve a certain level of accuracy. The reduction in the number of control points in any MTLS data collection improves safety and efficiency, leading to leaner operations.

Furthermore, as part of the applied component of this research study, surveyors were trained on the use of the MTLS equipment, and workflows were implemented for MTLS software in Caltrans.

The results in the basic research component of this effort included the adaptation of methods from the field of computer vision for feature extraction to highway applications and the development of a method for kinematic registration of point cloud data. The results lead to the improved visualization of point cloud data and the development of complete digital terrain models of highways.

The basic research component of this study also addressed Information Technology (IT) requirements for handling and maintaining MTLS data and digital terrain models. IT issues are becoming important as digital models are developed for highway infrastructure challenging the data storage and processing capabilities needed to support such models.

The following recommendations are made based upon the results of this research study:

- For bridge clearance measurements using MTLS, contracting out the work to a service provider is the most cost-effective option (based on current cost estimates) unless an MTLS Light Detection and Ranging (LiDAR) system is purchased and operated for six or more years and also used in other projects. Even in this latter scenario, the data from the cost-benefit analysis indicates that contracting with a service provider for such a task is very competitive.

- For pavement survey applications, the decision to purchase and operate an MTLS system heavily depends on the number of projects that would need to be completed per month. The data indicates that if the number of projects to be completed per month is ten or higher, purchasing and operating an MTLS system is the most cost effective. Otherwise, other options should be considered.

- The results from the experimental evaluation of accuracy in MTLS data collection indicates that the vertical errors are on average approximately three times the horizontal errors if no adjustment or control point targets are used.

- Furthermore, this research study confirms that the use of ground control targets can be effective for vertical and horizontal error reduction. At a minimum, it can reduce the vertical error by 50% and the horizontal error by 18%.

- The errors become insensitive to target spacing when vertical errors of 13 or 14 millimeters or higher and horizontal errors of 8 millimeters or higher can be tolerated.

- This research study recommends the use of extra ground control targets for validation in addition to the adjustment targets.

- A minimum of one validation target between each pair of adjustment targets is recommended.

- If a contractor collects MTLS data, then this research study recommends that the survey crew consider withholding one set of validation target coordinates from the contractor to check the accuracy of the delivered point cloud. This means that the contractor will use one set of validation targets for their internal quality control, and the survey crew would use the other set of validation targets to check the accuracy of the delivered point cloud.

- The use of open source software and systems is highly recommended to allow for the interchangeability and interoperability of data and systems from different service providers, MTLS systems, and digital terrain models.

- Additional research is needed in incorporating automated methods for kinematic registration and feature extraction into open source point cloud data processing software.

- Efforts should be made to develop a comprehensive and unifying framework for MTLS data management that would be consistent with and be incorporated into the Caltrans' geo-spatial strategic direction and to improve Caltrans' geo-spatial data collaborations.

- Methods for the storage and the distribution of MTLS data should consider:
  - Automated data cataloging
  - Including tools to "crawl" over data directory structures to catalog data
  - Using open, common file formatting and thus being able to extract metadata
  - Creating databases to store file metadata

- Allowing Web-based data selection and distribution
- Allowing intuitive web application with data collection boundaries overlaid on a map
- Supporting the user selection of files by data collection boundary, area, or layer
- Delivering selected files to a user via internet download

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

ADA	Americans with Disabilities Act
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
BrIM	Bridge Information Management System
Caltrans	California Department of Transportation
CHP	California Highway Patrol
CORS	Continuously Operating Reference Station
DMI	Distance Measuring Indicator
DTM	Digital Terrain Model
DOE	Caltrans Division of Equipment
DOT	Department of Transportation
DRISI	Caltrans Division of Research, Innovation and System Information
GAMS	GPS Azimuth Measurement Subsystem
GB	Gigabyte
GIS	Geographic Information System
GLONASS	Globalnaya Navigatsionnaya Sputnikovaya Sistema (A Global Navigation Satellite System)
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IMU	Inertial Measurement Unit
IT	Information Technology
JPEG	Joint Photographic Experts Group
LAS	Log ASCII Standard
LiDAR	Light Detection and Ranging
LSU	Laser Scanning Unit
MTLS	Mobile Terrestrial Laser Scanning
NCHRP	National Cooperative Highway Research Program
PCA	Principal Component Analysis
QA/QC	Quality Assurance / Quality Control
RANSAC	Random Sample Consensus
RTK	Real Time Kinematics
STLS	Stationary Terrestrial Laser Scanning
3D	Three-Dimensional
2D	Two-Dimensional
UTC	Coordinated Universal Time

ACKNOWLEDGMENTS

The authors thank the California Department of Transportation (Caltrans) for their support, in particular Mark Turner, John Adam, Kevin Akin, John Gilmore, and Robert MacKenzie with the Division of Right of Right of Way and Land Surveys, Nelson Aguilar and District 4 Field Surveys, Nick Zike and the North Region Office of Land Surveyors, the Caltrans' MTLS Technical Advisory Group (TAG), and Arvern Lofton with the Division of Research, Innovation and System Information. We also thank Larry Orcutt for his vision regarding the potential applications of this technology for Caltrans and for his efforts, together with those of his staff at the Caltrans' Division of Equipment, to actively support the MTLS vehicle integration.

INTRODUCTION

Mobile Terrestrial Laser Scanning (MTLS) combines the use of a laser scanner(s), the Global Navigation Satellite System (GNSS), and an Inertial Measurement Unit (IMU) on a mobile platform such as a vehicle to produce geo-spatial data. The data is initially adjusted by post-processed kinematic GNSS procedures from separate GNSS base stations placed throughout the project area. The GNSS solution is combined with the IMU information to produce geo-spatial data in the form of a point cloud. This point cloud is adjusted by a local transformation into well-defined points throughout the project area to produce the final geo-spatial values. The final values are then compared to independent check-point measurements.

Caltrans began investigating laser scanning technology with stationary terrestrial laser scanners. These systems are mounted on tripods, much like other survey instruments. Stationary scan technology is now being implemented throughout the state. The main drawback of stationary laser scanning is that the scanner must be set up on or near the roadway shoulder. Stationary Terrestrial Laser Scanning (STLS) does not always reduce workers' traffic exposure, and it is slow to cover large areas due to the fact that it needs to collect data from fixed positions in multiple locations. However, the expertise gained from processing stationary scan point clouds can be applied to mobile laser scanning. Currently, seven districts within Caltrans receive training on the specialty software used for fixed laser scanning.

In contrast to STLS, MTLS mounted in a vehicle can collect geo-spatial point cloud data at or close to highway speeds and, therefore, can improve the safety and efficiency of Caltrans' operations (see, for example, [1-2]) by reducing worker exposure to roadway traffic and expediting survey operations. MTLS has been effectively used in pavement condition surveys, but its applications are broader; the use of MTLS will potentially result in leaner maintenance operations, leaner construction, more rapid project delivery, and enhanced safety. Specific applications can include:

- Surveys to support construction work such as:
    - New roadway alignments
    - Bridge rehabilitation
    - Site distance upgrades
    - The reconstruction and the repair of sound walls
    - Heaving pavement and asphalt conrete leveling repair projects
- The assessment of culverts and railroad crossings
- The damage assessments and the replacement of underground and other structures
- The asset management of roadways and roadsides

The data acquired through the more efficient method of Mobile versus Stationary Terrestrial Laser Scanning can lead to leaner operations of functional units including: Surveys, Design, Construction, Project Management, Hydraulics, Geotechnical, Environmental, Cultural Resources, Right of Way, Legal, and Maintenance. This research therefore aimed to develop a knowledge base and workflow to increase the applicability and utilization of MTLS in both Caltrans and general highway maintenance and construction. This research study extends the previous work reported by the National Cooperative Highway Research Program (NCHRP) [1] and builds upon the previous work performed by the Advanced Highway Maintenance and Construction Technology (AHMCT) research center [2]. The NCHRP report establishes simple guidelines for use of MTLS in transportation application. These guidelines, however, do not include any method for cost-benefit analysis or any recommendation on control point spacing to achieve certain level of accuracy. This research study addresses these two important issues using the experienced gained in the previous work of AHMCT [2] to develop data and experiments that can provide the basis for cost-benefit analysis as well as developing a recommendation for control point spacing to achieve a desired accuracy of data collection.

BACKGROUND

MTLS uses STLS as well as other subsystems on a mobile platform such as a vehicle or a trailer that can operate on a highway and collect data in motion. Most MTLS systems combine three subsystems: a Laser Scanning Unit (LSU), a Global Navigation Satellite System (GNSS), and an Inertial Measurement Unit (IMU). Figure 1 depicts a vehicle system equipped with MTLS together with a diagram describing its functional subsystems. The GNSS and IMU subsystems provide data on vehicle location, and the laser scanner produces scan data in its coordinate system. The data acquisition rates in each of these subsystems generally differ from one another and need to be synchronized so information can be combined to provide geo-spatial point cloud data. This process is usually done through Point Cloud Generator (PCG) software that is proprietary for each commercially available MTLS system.

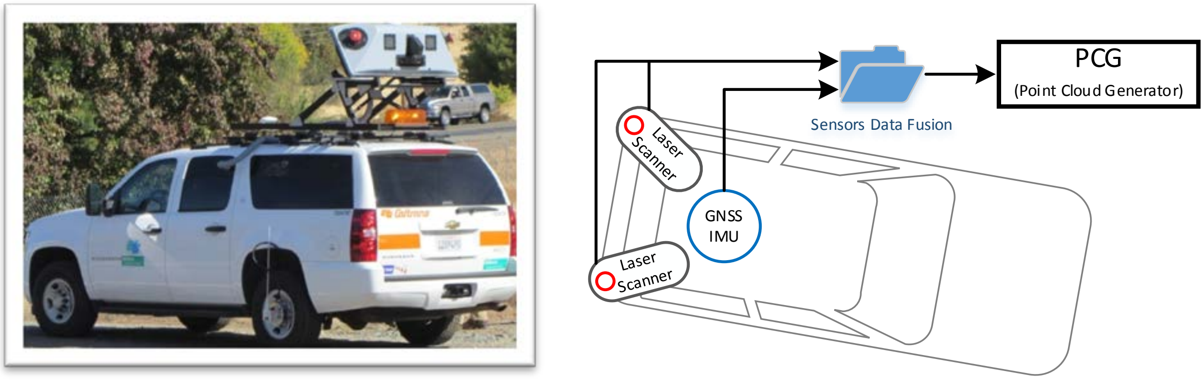

Figure 1. A mobile laser scanning vehicle and the functional diagram of its subsystems.

Using MTLS, the workflow of a highway construction or maintenance task can start with first developing a digital model of the highway section. As depicted graphically in Figure 2, the point cloud data generated from the scanning can then be used to help define the project scope and limitations, which can possibly accelerate the final project schedule. MTLS typically produces a massive raw point cloud data set that needs to be processed into a functional point cloud data set that represents the actual highway or highway assets. Once processed, the point cloud data can be used to extract important highway features and create a Digital Terrain Model (DTM). This model can then be used to produce the 3D layout of the project; next, the solid model representation is created from this layout. Lastly, the solid model can be combined with a kinematic model for planning the construction operations and performing clash detection to produce a final project schedule.

Figure 2. MTLS workflow.

RESEARCH APPROACH

The approach used in this research study had both applied and basic research components with the goal of better understanding the MTLS system's capabilities and thereby paving the way for its integration into more Caltrans' applications. The applied research component involved cost-benefit analysis, experimentation, performance evaluation, and the development of methods for integrating the system into Caltrans' workflow. The basic research component focused on better understanding MTLS point cloud processing in terms of calibration, kinematic registration, and Global Positioning System (GPS) drift correction procedures and feature extraction.

Understanding MTLS technology requires understanding all of its subsystem technologies, which include the IMU, the GNSS, the laser scanning system, and the PCG software. However, understanding these subsystem technologies is not enough to properly plan MTLS' integration into business practices at a state Department of Transportation (DOT), such as Caltrans. Other considerations include:

- The need to develop an understanding of the cost-benefits of the use of this technology so that different cost options can be evaluated to facilitate proper decision-making on when and how to utilize this technology.
- The need to develop guidelines for control point spacing to achieve the required level of accuracy since, in using MTLS for survey-grade applications, there is typically a need for accurately surveyed control points or locations to achieve a certain level of accuracy for the point cloud generated by the MTLS system.
- The need for research on feature extraction, kinematic registration, and visualization of point cloud data that would be useful for highway applications. Data on highway features such as lane and edge lines, K-rails, and so forth need to be extracted in an efficient manner in order to minimize the personnel time in processing point cloud data and thus create leaner operations.
- The need for methods for the kinematic registration of point cloud data, since highway sections are usually scanned separately and possibly by different scanning systems, creating patches of point cloud data that need to be matched and patched together.
- The need for the evaluation and development of workflows for Caltrans for some of the commercially available point cloud processing software packages.

Work in each of these areas, starting with the cost-benefit analysis, is described in the subsequent sections of this report.

COST-BENEFIT ANALYSIS

Cost-benefit analysis can be an important tool for proper resource allocation to achieve lean operations. This is especially the case when considering the integration of a new technology such as MTLS into the workflow of an organization. The cost and benefits of a new technology need to be properly assessed with respect to those of existing and legacy systems and methods used within the organization to evaluate whether investing in the new technology is justified for a given application. Any cost-benefit analysis, however, requires making certain assumptions; the set of unit and option costs upon which it is determined, for example, has to be adjusted based on market changes.

Cost-Benefit Analysis Assumptions

Caltrans' Land Surveys and Structure Maintenance have been the major users of MTLS technologies to date. Currently, the primary land survey applications for MTLS are roadway pavement surveys and Americans with Disabilities Act (ADA) feature surveys; the Office of Structure Maintenance uses MTLS to obtain bridge clearance data. The historical and current expenditures for these two offices (Land Surveys and Structure Maintenance) are therefore used in this cost-benefit analysis because their data and functional requirements are well defined.

While other Caltrans' functional groups can greatly benefit from the geo-spatial data produced by these MTLS systems, their program expenditures for geo-spatial data collection are not known well enough (or vary from year to year) to provide a good basis for comparisons. For example, the Attorney General's Office (Legal) demand for MTLS technology varies from year to year creating difficulty to estimate and quantify their actual need per year.

Many other applications of MTLS technology are currently being identified by Caltrans but are not included in the cost-benefit analysis due to their lack of adequate data. In addition, lower accuracy MTLS systems, such as those that are mapping grade, are not considered since they do not meet the land surveys and bridge clearance operations' requirements. The cost of data storage is also not included in this cost comparison since the cost for the data storage is the same for all deployment scenarios.

A Typical MTLS Project

In order to provide a baseline evaluation, this study assumes that a typical highway scanning project utilizing MTLS has an average length of 10 highway centerline miles and that it requires two passes in the same direction per highway centerline mile for proper data collection. This baseline was developed using historical data on contracted-out MTLS projects as well as current Caltrans' MTLS usage data (see [3]). In such a situation, the data collection time is typically eight hours for three surveyors (the driver, the operator, and the GNSS station operator). The post-processing time to produce the geo-reference point cloud from the data collected for a 10-mile project is estimated to be 12 hours. The cost-benefit analysis presented here focuses on data collection costs only and does not include feature data extraction costs due to the complexity and significant variances of feature extraction from project to project. The data extraction time depends on factors such as the software used, the number of features to be extracted, and whether the highway is in a rural or an urban area. The data extraction time can be as high as 5 to 20 times the data collection time. A lack of usable data also precludes its consideration in the cost-benefit analysis.

The required personnel time for high-accuracy data collection and raw data post-processing time is higher compared to when using the mapping-grade MTLS option. This is due to the need for a more complex setup and more sophisticated raw data post-processing due to GNSS/IMU integration. Achieving optimal accuracy requires more GNSS base station setups with closer spacing and placement of ground targets. Thus, the cost of one extra personnel per year is added to this process for data collection.

Options Considered

In performing the cost-benefit analysis, the following four options were considered:

1. Contracting for survey-grade MTLS services and for bridge clearance measurements
2. Renting and operating a survey-grade MTLS system
3. Purchasing and operating a survey-grade MTLS system
4. Purchasing a fractional ownership of a survey-grade MTLS system

Cost estimates for each of these options are discussed in five subsections below, with a final comparative summary in the next section. The cost of data storage was not included in this cost-benefit analysis since the cost for the data storage is the same for all deployment scenarios and can be an add-on to any scenarios used. In calculating the cost estimates for the survey-grade pavement survey options, the following assumptions were made:

- A project consists of 10 highway centerline miles and requires two passes (in the same direction) for each project, resulting in 20 highway miles per project.
- The overhead travel miles (going back and forth to the project site) are estimated as an average of 10 times the project travel miles (200 miles per project).
- The mileage costs basis is $0.56 per mile (this includes vehicle maintenance and depreciation costs).
- The time requirement for the data collection portion of one project is estimated as one day.
- The operational life of a survey-grade MTLS system is assumed to be six years.

Option 1: Contracting for MTLS Services (Survey-Grade) and Bridge Clearance Measurements

There are several service providers who provide survey-grade MTLS services. As mentioned earlier, the cost for survey-grade MTLS services is much higher than that of mapping grade services due to higher accuracy requirements. Data from previous Caltrans' contracts for MTLS services are used here as cost rate estimates and plotted in Figure 3. The cost data provided in this graph is a baseline and that the actual costs may vary among different contractors.

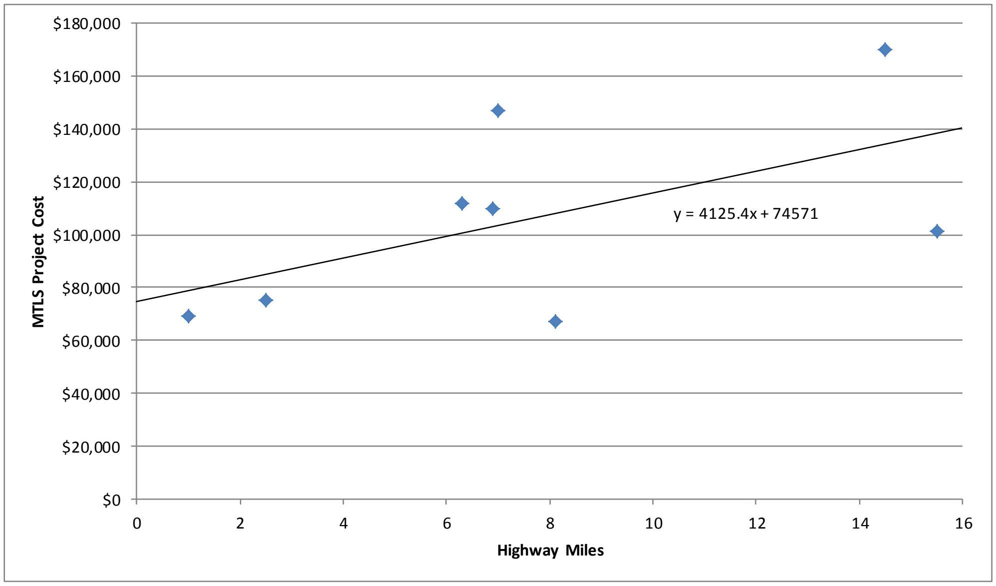

Figure 3. MTLS project cost historic data.

Some contractors charge for an MTLS equipped vehicle using a daily rate of approximately $2,100. Other contractors charge an hourly rate (including operators) of about $820. Equipment rates may vary depending on the contractor and the system configuration. The current private sector labor rates range from approximately $115 to $130 per surveyor and the rate for an MTLS specialist who performs the Georeferencing/Registration is approximately $175 per hour.

Table 1 summarizes the cost breakdown for contracting MTLS services for three cases involving one day, a half day, and no travel time to the site of data collection. The table includes both options of using a daily rate and an hourly rate contractor. All the costs are calculated for one day of data collection plus one day, a half day, or no additional days for travel. The mileage cost is calculated for 220 miles on the day of the data collection plus from zero to 200 additional miles, depending on whether or not an additional zero, half day, or one day of travel would be needed to go back and forth to the data collection site. The mileage rate is calculated at $0.56 per mile, which includes vehicle costs. The labor for geo-reference registration is calculated for 1.5 days at $175 per hour.

Table 1. Project cost break down for contracting MTLS services.

	1 Day Travel		1/2 Day Travel		0 Day Travel	
	Daily Rate Option	Hourly Rate Option	Daily Rate Option	Hourly Rate Option	Daily Rate Option	Hourly Rate Option
Equipment cost	$4,200	$0	$3,150	$0	$2,100	$0
Vehicle Mileage cost	$235	$0	$179	$0	$123	$0
Data Collection Labor Cost	$6,720	$14,912	$5,040	$11,184	$3,360	$7,456
Geo-reference/Registration Labor	$2,100	$2,100	$2,100	$2,100	$2,100	$2,100
Total Data Collection Cost	$13,255	$17,012	$10,469	$13,284	$7,683	$9,556

From the data in this table, the average project cost for this option ranges from approximately $9,600 to $17,000 for a contractor with a daily rate option and from approximately $7,700 to $13,300 for a contractor with an hourly rate option. The use of daily rate contractors has a cost benefit compared to using an hourly rate contractor when the project time duration is several days. The labor needed for data collection and geo-referencing, which can vary depending on the labor rate, represents the majority of the project cost. The vehicle mileage cost is very small by comparison, and thus the overall cost is not sensitive to vehicle mileage travel. However, the labor cost due to personnel travel is significant.

Considering six projects per month and 12 months of operations in a year, the total yearly cost of this option ranges approximately from $691,000 to $1,224,000 for the daily rate option and approximately $554,400 to $957,600 for the hourly rate option.

In the case of bridge clearance measurement services, estimating the cost is relatively simple. The time required for vertical clearance data collection for each bridge depends on the number of lanes under the structure, the density of the traffic, and the exits/turnaround availability. On average, collecting all the necessary data takes approximately 0.5-1 hour per structure. In addition, personnel time and vehicle usage costs are associated with traveling to a bridge location and back. Recently, the Division of Maintenance contracted with an MTLS service provider to collect and extract bridge clearance data throughout California. The total cost was approximately $125 per structure, including travel time and vehicle usage costs. Considering that California has approximately 12,000 bridge structures that require clearance measurements, the total cost of surveying all bridge structures for Caltrans is about $1,500,000 per inspection cycle, which ideally spans every two to four years.

Option 2: Renting and Operating a Survey-Grade MTLS System

This option assumes that Caltrans rents and uses a survey-grade MTLS system to collect data. In this scenario, the data collection cost consists of equipment rental at $50,000 per month, a one-time training cost of $50,000, a vehicle cost of $0.56 per mile, and a personnel cost based on Caltrans rates. The weighted average rate of a Caltrans' surveyor is $135, which includes overhead. The overhead portion of the labor rate includes the cost of the computers, administrative support, and GNSS base station equipment for MTLS surveys. In this option, the breakdown of the total cost is calculated for both pavement surveys as well as for bridge clearance measurements. Table 2 and Table 3 show these cost breakdowns, respectively.

From Table 2, the rental costs represent the majority of the cost associated with this option of renting and using an MTLS system. The average project cost is calculated to approximately $14,000, where approximately $9,000 or 64%, is the rental cost. This means that the cost per project for the rental option is highly sensitive to the number of projects completed per month during the rental period. Therefore, careful planning and time coordination can result in a lower overall cost by completing more projects per month to increase the utilization rate or by reducing the rental duration.

Table 2. MTLS rental and operation cost estimates for pavement survey.

Description	**Year 1**	**Year 2 to 6**	**Total 6 Years**
Software and MTLS Rental Cost			
Data extraction software	$150,000	$0	$150,000
Data extraction software maintenance	$15,000	$75,000	$90,000
Survey-grade mobile LiDAR equipment rental cost for 12 months @ $50,000/month	$600,000	$3,000,000	$3,600,000
Training	$50,000	$0	$50,000
Total Fixed Cost	**$815,000**	**$3,075,000**	**$3,890,000**
Data Collection Cost			
Vehicle Mileage Cost ($0.56/mile, 6 projects/month, 10 miles/project on ave., 2 passes on ave. and 10x travel to work site mileage overhead. Total mileage per month = 220*6 =1,320 miles or 15,840 miles/year)	$8,870	$44,352	$53,222
Data Collection Personnel cost ($135/hr, 3 person crew, 1 day/project + 0.5 day driver cost per project)	$272,160	$1,360,800	$1,632,960
Office Georefencing (12 hrs/project)	$116,640	$583,200	$699,840
Total Labor and vehicle cost	**$397,670**	**$1,988,352**	**$2,386,022**
Total data collection cost	**$1,212,670**	**$5,063,352**	**$6,276,022**

Table 3. MTLS rental and operation cost estimate for bridge clearance measurement.

Total Number of Bridges / Structures in CA	12,000
Total Number of Bridge / Structure Highway Centerline Miles in CA	14,851
Number of Passes per Centerline Mile	2
Travel Miles Overhead (times)	1.5
Total Number of Travel Miles for Bridge Scanning	=(2+1.5)*14,851 = 74,255 miles
Vehicle Travel Cost	=$0.56*74,255 = $41,583
Travel Miles per Day (miles/day)	400
Total Bridge Scanning Days	=74,255/400 = 186 Days
Driver and Operator Labor Rate	$135/hr.
Data Collection Labor Cost	=2*8*186*$135=$401,760
Data Post-Processing Time per Bridge	0.5 hours
Data Post-Processing Labor Cost @ $135/hr.	=0.5*12,000*$135=$810,000
Total Cost (without equipment cost)	=$41,583+$401,760+$810,000 =$1,253,343
Cost per Bridge (without equipment cost)	=$1,253,343/12,000 = **$104 per bridge**
Equipment Cost per Day (50 weeks/yr., 5 days/wk.)	=$50,000*12/(50*5) = $2,400/day
Total Equipment Cost	=$2,400/day*186 days = $446,400
Total Cost with Equipment	=$1,253,343+$446,400 = $1,699,743
Cost per Bridge with Equipment Cost	=$1,699,743/12,000 = **$141 per bridge**

In the case of bridge clearance measurement, Table 3 provides the breakdown of the cost for the rental option, resulting in an approximate cost of $141 per bridge. Recently, the Division of Maintenance contracted with an MTLS service provider to collect and extract bridge clearance data throughout California. The cost was approximately $125 per bridge structure. Therefore, the renting option, for this purpose alone, is not cost effective when compared with using a service provider.

Option 3: Purchasing and Operating a Survey-Grade MTLS System

The cost of a survey-grade MTLS system currently varies from $550,000 to $850,000 depending on the LiDAR and camera configuration used in the system. This option assumes that Caltrans purchases and operates a survey-grade MTLS system for data collection with in-house personnel. The basic assumptions in this option are as follows:

- The MTLS system cost is $850,000 (the higher value in the cost range is used here to ensure the system will have high performance capabilities).
- The system will be utilized for the entire 12 months in a year.
- A three-person crew will be used for data collection.
- An average of six projects is completed in each month (72 projects per 12 months).

- A project consists of 10 highway miles and two passes are needed for each project, resulting in 20 highway miles per project.
- The overhead travel miles (going back and forth to the project site) are estimated as an average of 10 times the project travel miles (200 miles per project).

Based on the above assumptions, Table 4 displays the calculated and summarized MTLS operating and ownership costs for pavement surveys. The following cost basis criteria were used in the calculation of the cost breakdown depicted in Table 4:

- The data collection cost consists of equipment cost ($850,000), annual maintenance cost (10% of equipment cost), one-time training cost ($50,000), vehicle cost ($0.56 per mile), and personnel cost ($135 per hour).
- The first-time hardware installation cost ($6,000).
- The annual maintenance cost (10% or $85,000) includes firmware/software upgrades, calibration, and an extended warranty.
- Data processing costs consist of data-processing software ($150,000) and software maintenance costs (10%, or $15,000).

The vehicle cost described in the table is calculated based on the average of 220 total miles traveled per project (200 overhead travel miles plus 20 miles for two passes through a 10-mile project). Considering six projects per month and 12 months of operations in a year, the result is 15,840 miles per year, at a total vehicle cost of $8,870 per year.

Table 4 . MTLS ownership and operating costs for pavement survey.

Description	Year 1	Year 2 to 6	Total 6 Years
Fixed Cost			
Data Post-processing software	$150,000	$0	$150,000
Software maintenance (10%)	$15,000	$75,000	$90,000
Survey-grade mobile LiDAR Equipment cost	$850,000	$0	$850,000
Survey-grade mobile LiDAR equipment maintenance cost (10% equipment cost per year)	$85,000	$425,000	$510,000
Hardware Installation	$6,000	$0	$6,000
Total Fixed Cost	**$1,015,000**	**$500,000**	**$1,515,000**
Data Collection Operating Cost			
Vehicle Mileage Cost ($0.56/mile, 6 projects/month, 10 miles/project on ave., 2 passes on ave. and 10x travel to work site mileage overhead. Total mileage per month = 220*6 =1,320 miles or 15,840 miles/year)	$8,870	$44,352	$53,222
Data Collection Personnel cost ($135/hr, 3 person crew, 1 day/project + 0.5 day driver cost per project)	$272,160	$1,360,800	$1,632,960
Office Georefencing (12 hrs/project @ $135/hr)	$116,640	$583,200	$699,840
Total labor and vehicle cost	**$397,670**	**$1,988,352**	**$2,386,022**
Total data collection cost	**$1,412,670**	**$2,488,352**	**$3,901,022**

Based on the data in the table, the average cost per project is $9,030, and the average equipment cost per project is $3,507 (assuming MTLS is not used for other applications such as bridge clearance measurement or asset inventory). The average equipment cost per project depends highly on the equipment utilization rate (the average number of projects completed per month). The equipment cost per project doubles if the average number of projects is reduced to three per month.

This option is also considered for using MTLS for bridge clearance measurements. Table 5 includes a summary of the cost break down [3]. If one considers a typical life of six years for the MTLS equipment, then the cost per bridge structure calculates to approximately $118 per bridge structure, as shown in Table 5.

Table 5. MTLS ownership and operating costs for bridge clearance measurements.

Total Number of Bridges / Structures in CA	12,000
Total Number of Bridge / Structure Highway Centerline Miles in CA	14,851
Number of Passes per Centerline Mile	2
Travel Miles Overhead (times)	1.5
Total Number of Travel Miles for Bridge Scanning	=(2+1.5)*14,851 = 74,255 miles
Vehicle Travel Cost	=$0.56*74,255 = $41,583
Travel Miles per Day (miles/day)	400
Total Bridge Scanning Days	=74,255/400 = 186 Days
Driver and Operator Labor Rate	$135/hr.
Data Collection Labor Cost	=2*8*186*$135=$401,760
Data Post-Processing Time per Bridge	0.5 hours
Data Post-Processing Labor Cost @ $135/hr.	=0.5*12,000*$135=$810,000
Total Cost (without equipment cost)	=$41,583+$401,760+$810,000 =$1,253,343
Cost per Bridge (without equipment cost)	=$1,253,343/12,000 = **$104 per bridge**
Equipment Cost per Day (50 weeks/yr., 5 days/wk., 6 year life, $850,000 MTLS cost, 10%/yr. maintenance cost)	=$850,00*1.6/(50*5*6) = $907/day
Total Equipment Cost	=$907/day*186 days = $168,640
Total Cost with Equipment	=$1,253,343+$168,640 = $1,421,983
Cost per Bridge with Equipment Cost	=$1,421,983/12,000 = **$118 per bridge**

Option 4: Purchasing a Fractional Ownership of a Survey-Grade MTLS System

This option considers a 50% fractional ownership of a survey-grade MTLS system and then using the system in-house. The current costs of this type of ownership for up to 100 days of use per year and up to 25 times access to the system per year are as follows (please note that these values are based on data from some of the existing companies providing fractional ownerships):

- One-time capital cost: $403,000
- Monthly management and maintenance fee: $18,000
- Fixed per mile usage and data processing fee: $75/mile

Table 6 depicts the total cost breakdown for this system for up to its life expectancy of six years. For the calculations used in this table, the equipment purchase and maintenance costs remain fixed. The project cost is determined based on six pavement survey projects per month with each project consisting of 10 miles and requiring two passes as before for a total of 20 miles per project. Considering the assumed operational life of six years for the MTLS equipment, the per pavement survey project cost of this option is $9,366. These calculations show that fractional ownership can be a cost-effective solution if careful planning and time coordination is implemented to complete a large number of pavement-survey projects within the 100 days available. In the fractional ownership scenario, the service provider's fixed cost of $75/mile for data includes the costs of cost of usage as well as personnel for data collection and post-processing. Therefore, Caltrans does not need to use trained personnel of its own to operate the MTLS system. Shortcomings are limited access to the system and the need for advanced scheduling of its use.

Table 6. The cost breakdown for fractional ownership of a survey-grade MTLS system.

Description	**Year 1**	**Year 2 to 6**	**Total 6 Years**
Initial 50% survey-grade mobile LiDAR equipment purchase	$403,000	$0	$403,000
Mobile LiDAR equipment maintenance / management cost (@ $18,000/month)	$216,000	$1,080,000	$1,296,000
Data collection and processing cost ($75/mile) 6 Projects/month for 6 months/year at 20 miles per project	$54,000	$270,000	$324,000
Total Data collection cost	**$673,000**	**$1,350,000**	**$2,023,000**
Average cost per project			**$9,366**

The result of the fractional ownership option for bridge clearance measurements differs completely than that of pavement surveys. Table 7 depicts the breakdown of the costs for this option. As calculated in the table, the cost per bridge structure (assuming a six-year operational use of an MTLS system) is $291, which exceeds the service provider cost of $125. Therefore, based on current service provider rates, this method of ownership is not cost effective for Caltrans' bridge clearance inspection.

Table 7. Fractional Ownership of an MTLS system for use in bridge clearance measurement.

Total Number of Bridges / Structures in CA	12,000
Total Number of Bridge / Structure Highway Centerline Miles in CA	14,851
Number of Passes per Centerline Mile	2
Miles Travel Overhead (times)	1.5
Data Processing Cost ($75 per mile)	=14851*2*$75 =$2,227,650
Data Post-Processing Time per Bridge	0.5 hours
Data Post-Processing Labor Cost @ $135/hr.	=0.5*12,000*$135=$810,000
Total Cost (without equipment cost)	=$2,227,650+$810,000 = $3,037,650
Cost per Bridge (without equipment cost)	=$3,037,650/12,000 = **$253 per bridge**
Equipment Cost per Day (50 weeks/yr., 5 days/wk., 6 year life)	=($403,000+$14,851*12*6)/(100*6) =$2,454/day
Total Equipment Cost	=$2,454/day*186 days = $456,444
Total Cost with Equipment	=$3,037,650+$456,444= $3,494,094
Cost per Bridge with Equipment Cost	=$3,494,094/12,000 = **$291 per bridge**

Comparison of Different Options

Table 8 summarizes the cost breakdowns presented for the four options discussed in the previous subsection. Based on the six-year operational life of an MTLS system, the level of utilization, and the project specifications, option 3 (purchasing and operating a survey-grade MTLS system) is the most cost-effective method for pavement survey. Options 2 (renting a system) and 3 (purchasing a system) are the most cost-effective options for bridge clearance measurement.

Table 8. Comparative summary of the cost per project for various options.

Option Description	**Cost per project**	**Cost per bridge**
1: Contract for mobile LiDAR services **(survey-grade)** and Bridge clearance services	$13,255	$125
2: Rent and operate a **survey-grade** mobile LiDAR system	$14,528	$118
3: Purchase and operate a **survey-grade** mobile LiDAR system	$9,030	$118
4: 50% fractional ownership of a **survey-grade** mobile LiDAR system	$9,366	N/A

The utilization rate is a key factor in reducing the average cost per project of an MTLS system. Completing more projects will result in a lower cost per project. In order to illustrate this in Figure 4, the average cost per project is plotted as a function of utilization rate per month. The utilization rate per month is defined as the average number of projects that will be completed per month during the life cycle of the MTLS system.

Due to its large roadway network, Caltrans would have a high demand for MTLS pavement survey projects and bridges requiring constant, updated clearance measurements and therefore could maintain a high MTLS utilization. Thus, the average project cost for purchasing and operating an MTLS option could be lower or competitive with that of outside contractors or service providers. However, a single district with smaller roadway networks should examine the equipment rental, contractor, and partial ownership option for cost-effectiveness and viability. In addition factors that can reduce utilization such as setting ground control, planning logistics and poor weather should be considered.

The cost-benefit analysis presented here has also been extended to include the published results of data from the State of Washington (see [3]).

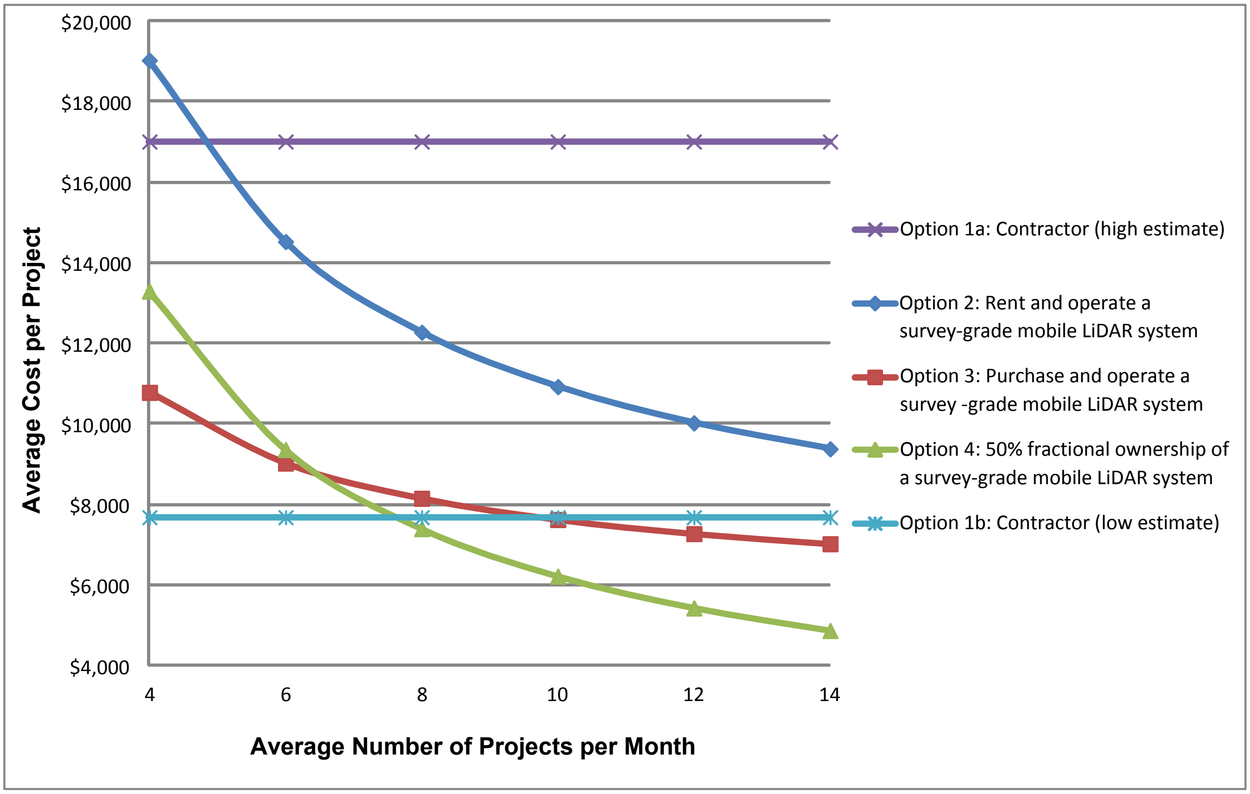

Figure 4. Average project cost vs. utilization rate per month.

MTLS GEO-REFERENCE REGISTRATION TARGET SPACING EXPERIMENT

Asset or resource-grade accuracy MTLS data may be collected and processed using only a GNSS base station without ground control targets. Engineering/survey-grade MTLS data collection, however, requires ground controls and targets for accuracy improvement and data validation. Multiple scan passes could provide some degree of data validation. Figure 5 depicts examples of ground targets painted on the shoulder of the road. Such ground controls and targets are vital means of improving accuracy and validity before and after the data adjustment. However, setting up ground control targets and surveying their precise locations is labor intensive, time consuming, and exposes workers to traffic hazards.

Figure 5. Sample ground control targets located on the road shoulder.

In addition, there are associated labor and material cost for the targets, surveying their precise locations, and traffic control. A cost estimate for ground control placement can be calculated based on the following assumptions:

- Caltrans' loaded rate per three-man crew hour is $350 for construction staking.
- Target spacing is 500 feet on both sides of a two-lane highway.

- The average time duration for the MTLS ground control target placement and coordinate survey is 15 crew hours per mile (this is based on data from Districts 1, 2, and 3).

The estimated average cost to place, coordinate (determine X, Y of target points), and elevate (determine Z of target point) MTLS targets is approximately $5,325 per mile, which can be a significant percentage of the $9,030 cost of a pavement survey project for the purchasing option discussed in the previous section. Setting the control targets is clearly the major cost to use MTLS and therefore optimizing the control setting operation can result in significant cost savings in MTLS utlization. Several other factors exist that can change this cost estimate such as:

- The type of road (two lane vs. four-plus lanes)
- The location of the road (metropolitan vs. rural)
- The type of target being set (painted, thermoplastic, shape of target)
- The density of the existing control (This estimate does not include any primary project control.)
- The desired accuracy (RTK vs. differential levels, single- or double-tie position)
- The safety considerations (lane closures)

Furthermore, one should keep in mind that every project presents its own unique challenges, which can influence the time to complete targeting. Reducing the required number (i.e., density) of ground control targets would have cost and safety benefits. This research study, therefore, undertook an experimental evaluation to determine the relationship between target spacing and the resulting point cloud accuracy. The aim was to develop target spacing recommendations for a given accuracy requirement in order to optimize the density of target spacing and thus leaner and safer operations by reducing the costs of target placement and workers' exposure to traffic.

Experiment Setup

The experimental set up for determining the relationship between the registration/ground control target spacing and the accuracy of the resulting point cloud for MTLS consisted of placing Chevron shaped targets (as shown in Figure 6) on a section of a test roadway. These targets were made with two pieces of 4"x18" reflective adhesive tape and placed on a 1.7-mile section of Hutchison Drive in Davis, California near the University of California, Davis. The targets were placed on the shoulders/bike lanes between Celadon Street and Country Road 98. Figures 7 and 8, respectively, depict the location and the ground view of the targets. This section of the roadway was chosen because of its relatively flat and open sky view in the majority of the test section. A group of trees was present only on the south side of the road near the middle of the test section.

A target spacing of 75 meters resulted in 33 targets on the north shoulder and 33 targets on the south shoulder for a total of 66 targets. Targets were laid down on both eastbound and westbound portions of the bike lane.

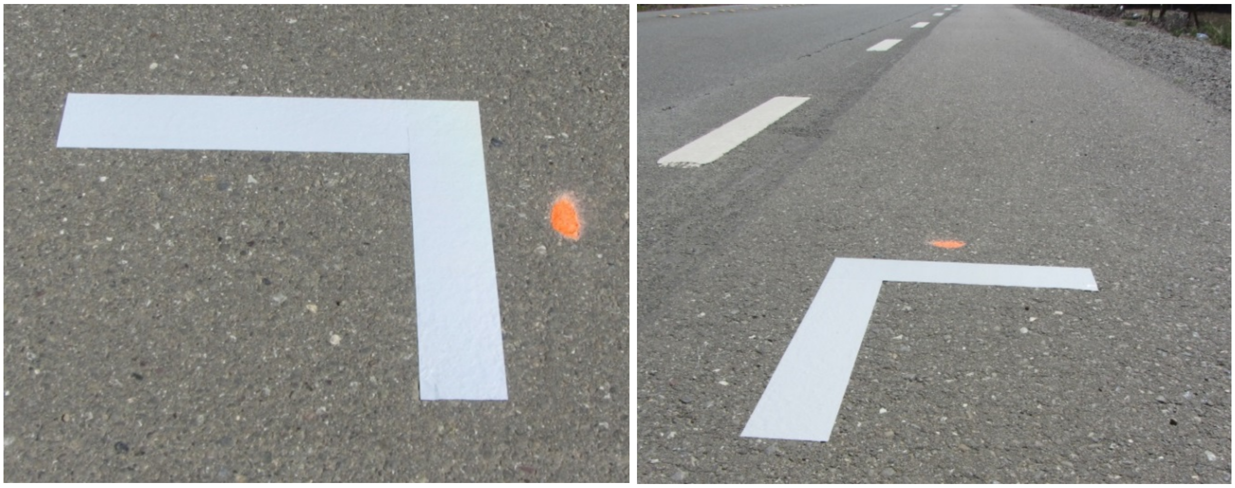

Figure 6. Chevron-shaped target using reflective adhesive tape.

Figure 7. An aerial photo of the test site on Hutchison Drive (courtesy of Google Earth).

Figure 8. Ground view of the test site traveling westbound on Hutchison Drive.

In one experiment, the Caltrans' MX8 MTLS system repeatedly and continuously scanned the test site for one hour, starting in the westbound direction from the eastern end of the test site. Two laser scanners were mounted on the vehicle one on the right (passenger) side and one on the left (driver) side of the vehicle. Ten passes at 35 miles per hour were made during this hour of experimental data collection. In a second experiment, the test site was scanned every 1.5 hours over a 24-hour period. Three repeated passes at 35 miles per hour were made for every scan session, which took 30 minutes. The first scan session started at 6:00 am (06:00). The subsequent 15 scan sessions started at 07:30, 09:00, 10:30, 12:00, 13:30, 15:00, 16:30, 18:00, 19:30, 21:00, 22:30, 00:00 (midnight), 01:30, 03:00, and 04:30 local time. Four total passes were made at the 12:00 and 03:00 scan sessions instead of the three passes of the other scan sessions. The data collection for each scan session was broken down into individual "runs" for every westbound and eastbound scan. In other words, there were typically six runs for each scan session. The first run traveled westbound from the eastern end of the test site (run 0). The even numbered (0, 2, and 4) runs collected scan data while traveling westbound, and the odd numbered (1, 3, and 5) runs collected scan data while traveling eastbound from the western end of the test site. Both the 12:00 and 03:00 o'clock scan sets have a total of eight runs due to the one extra pass.

MTLS Data Post-Processing

To produce the high-accuracy point cloud from the raw data, the Applanix GNSS/IMU data were first processed with Applanix software and with Continuously Operating Reference Station (CORS) base station data, using Applanix SmartBase methods with GAMS enabled. CORS stations PLSB, P265, VCVL, DIXN, P268, and UCD1 were used in the GNSS/IMU data post-processing to calculate the best estimated vehicle trajectory. CORS stations P265, VCVL, DIXN, P268, and UCD1 provided GPS-only data once every 15 seconds, while CORS station PLSB provided GPS and GLONASS data once every 15 seconds. After all sixteen data collection sessions were processed; the solution results were checked for any anomalies. The solution error estimates were checked for any large errors or long GNSS signal outages. The estimated X and Y errors near the trees in the mid-section of the test site were found to be generally larger than other areas.

After the raw data was generated in the experiments, the Trimble Trident GPS and LAS files (from the raw capture data) were updated using the GNSS/IMU post-processed vehicle trajectory solutions and Trident software. The MTLS point cloud data were then exported to LAS 1.1 format in UTM Zone 10N WGS84 with no geo-reference-id. Manually using Cyclone determined the approximate location of each target. The target approximate locations were used as a "seed" to crop out the point cloud surrounding the target. Las2txt, from LAStools, was used to crop a neighborhood of points (0.6 meters in radius) around the "seed" point, and the points were saved to a text file for each target and run of the right laser scanner data. Each target text file contained points with X, Y, Z, Intensity, and GPS time.

Target Extraction and Validation

The target point cloud text files from all runs were processed using custom Matlab code to extract the chevron target vertex coordinates (X, Y, Z). The right laser data was used because it is closer to the targets and provides a dense point cloud of the target as shown in Figure 9. In this figure, the L-shaped targets shown on the top right and lower left corners represent points with high reflectivity due to the reflective tapes used.

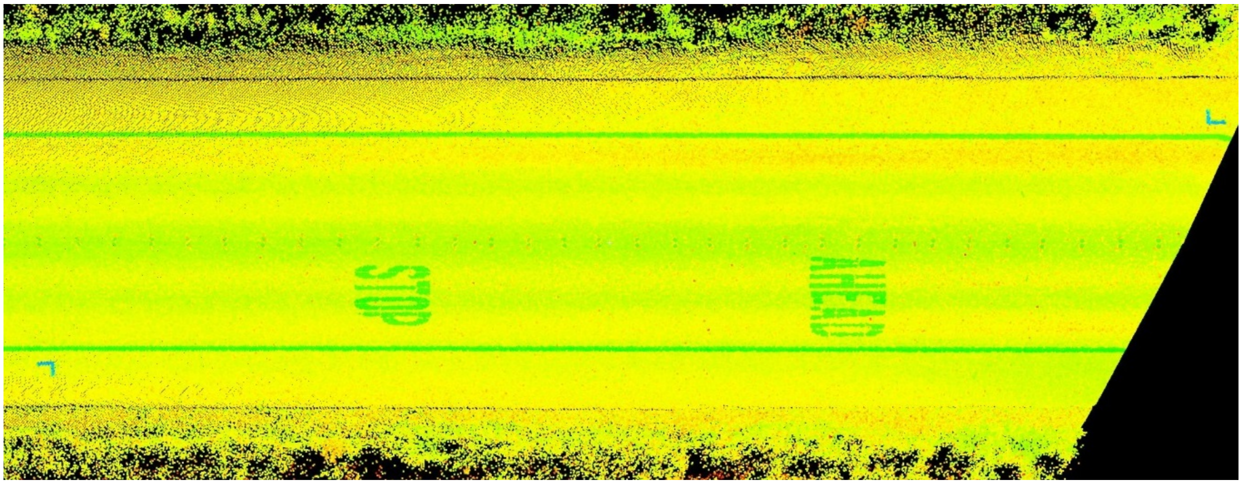

Figure 9. Resulting point cloud from the right laser scanner.

Figure 10 depicts the overhead view of the target L shapes. The points returned from the reflective tape had higher intensity readings, represented by the points with blue color. The amber points represent the points returned from the black asphalt pavement with low reflectivity. The larger white point represents the chevron target vertex extracted using custom Matlab code.

The X and Y target vertex coordinate is determined by the intersection of two best fit lines of the outer most blue points of the reflective target. The target Z coordinate is calculated by averaging the Z elevations of the nearest 10 points from the target vertex.

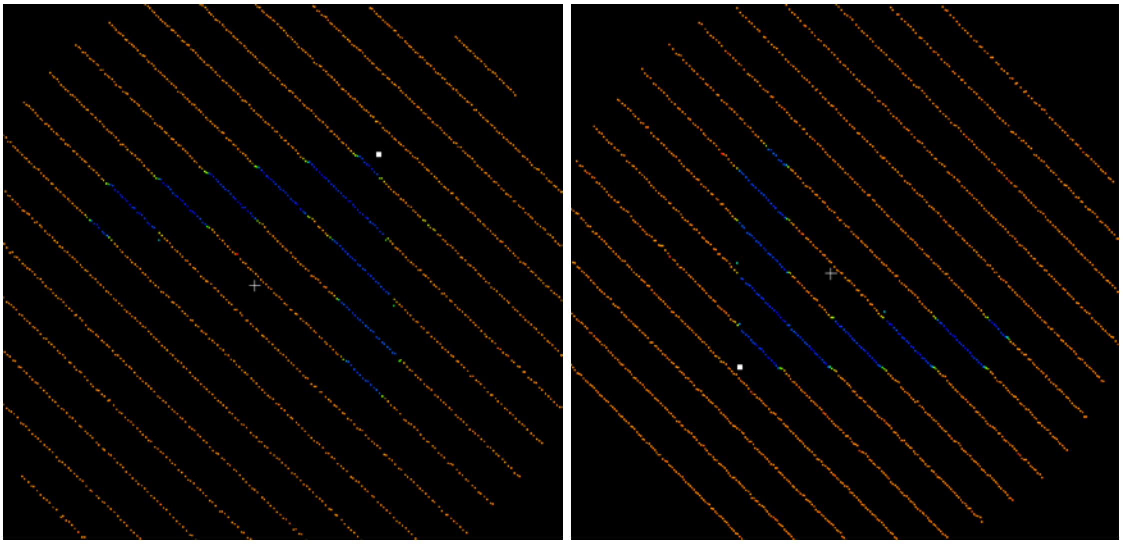

Figure 10. Overhead view of the point cloud of a target.

Each of the north shoulder targets is assigned with Target ID # of 1xx. Target ID #101 is located at the easternmost target on the north shoulder, and Target ID #133 is located at the westernmost target on the north shoulder. Similarly, each of the south shoulder targets is assigned with Target ID # of 2xx. Target ID #201 is located at the westernmost target on the south shoulder, and Target ID #233 is located at the easternmost target on the south shoulder. Target ID #114 was blocked by bicycle traffic in 9:00 am run number 4, and its coordinates could not be extracted. Target ID #101 was missing from the data set of run 0 of 18:00, 19:30, 00:00, and 04:30 due to late start of laser data collection. A total of 3263 targets were extracted from all the data sets. Due to the five missing targets and extra runs from the 12:00 and 03:00 data sets, the weighted average of the control point coordinates (X, Y, and Z) were calculated for each Target ID in order to weight each session equally. After that, each target's coordinate deviation from the weighted average Target ID coordinate (delta X, Y, Z, and XY) was calculated.

The data were then examined for any outliers due to target recognition error. Targets with a large error (delta X, Y, and Z) from the weighted target average or session average were examined manually for any target recognition error. The extracted target coordinates and the target point cloud were visually examined using CloudCompare software. Thirty-three extracted target points were examined manually, and four target extraction points were found to have large errors due to a target recognition algorithm error. The target recognition algorithm was revised, and the revised code was re-run on the entire data set. Figure 11 displays the plot of each target's X and Y deviation error relative to the average and shows that most targets' X and Y deviation errors are smaller than 0.02 meters.

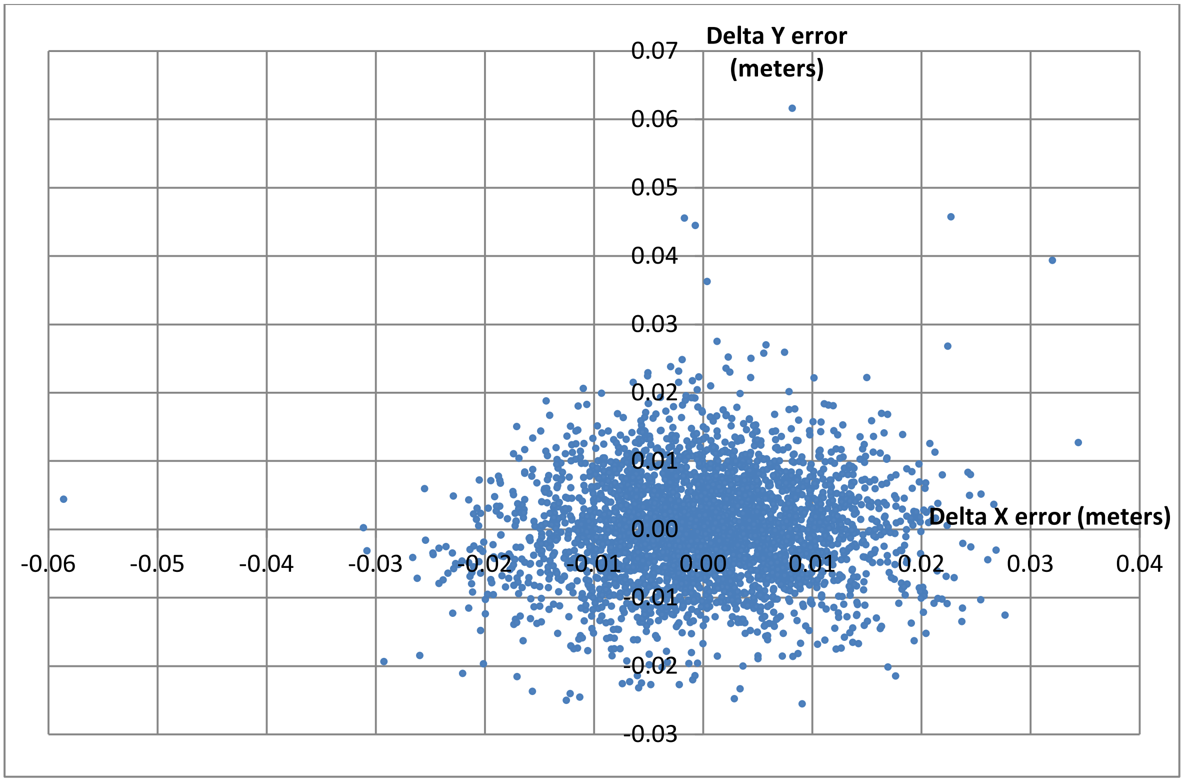

Figure 11. Delta X vs. Delta Y of every target.

Targets with X and Y deviations larger than 0.03 meters were examined manually. Figure 12 and Figure 13 show the X and Y error distribution of all targets from the weighted average target coordinates. Figure 14 and Figure 15 depict plots of each target's Z deviation error for the north and south shoulders, respectively. The data in these two figures show that most target Z deviation errors are within 0.05 meters. Figure 16 shows the Z error distribution of all targets from the weighted average target coordinates. The Z error distribution shown in this figure is skewed due to the use of the session weighted average value for the target coordinate. The standard deviations of the errors X, Y, and Z are 0.09, 0.08, and 0.24 meters, respectively. The vertical Z error is about 3 times that of the horizontal X and Y error.

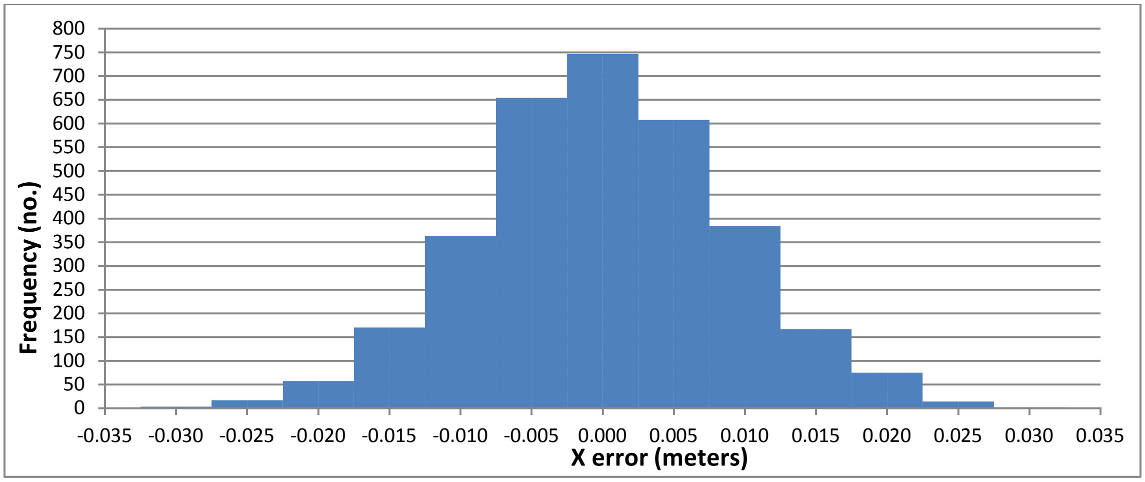

Figure 12. Delta X error distribution.

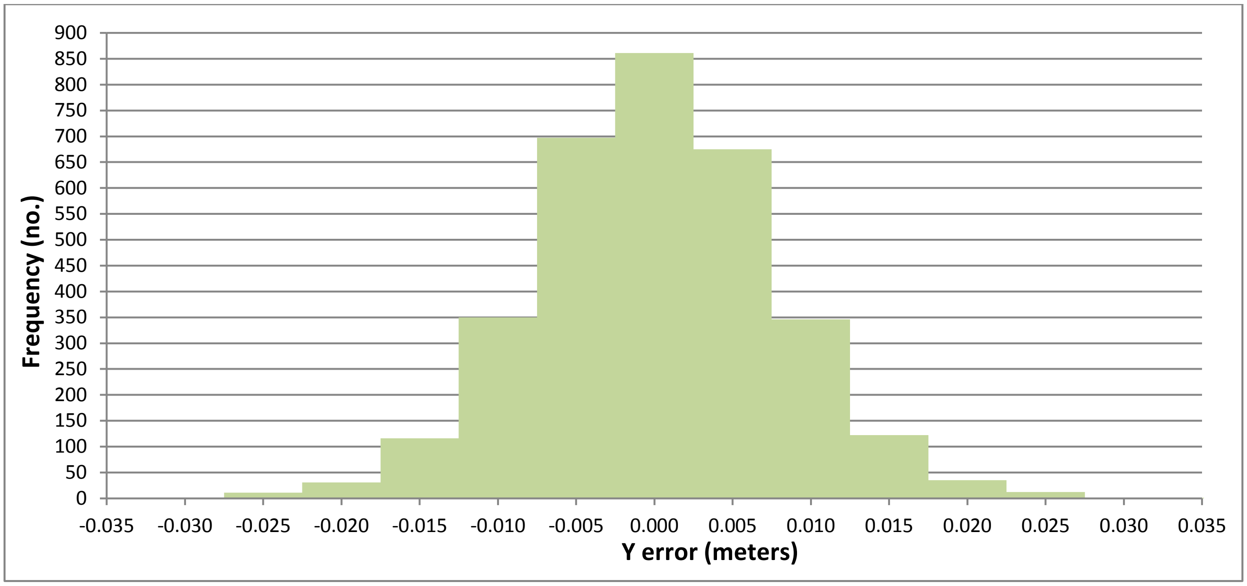

Figure 13. Delta Y error distribution.

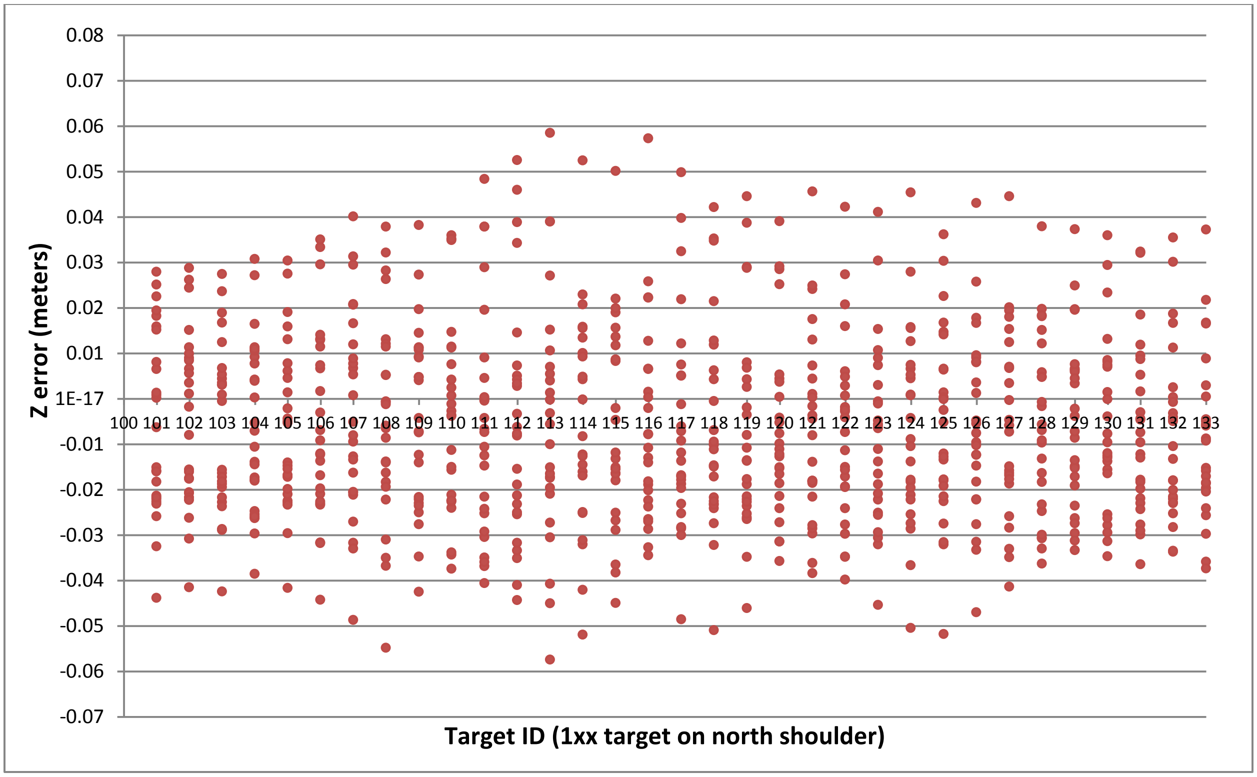

Figure 14. Delta Z error for target ID 1xx on the north shoulder.

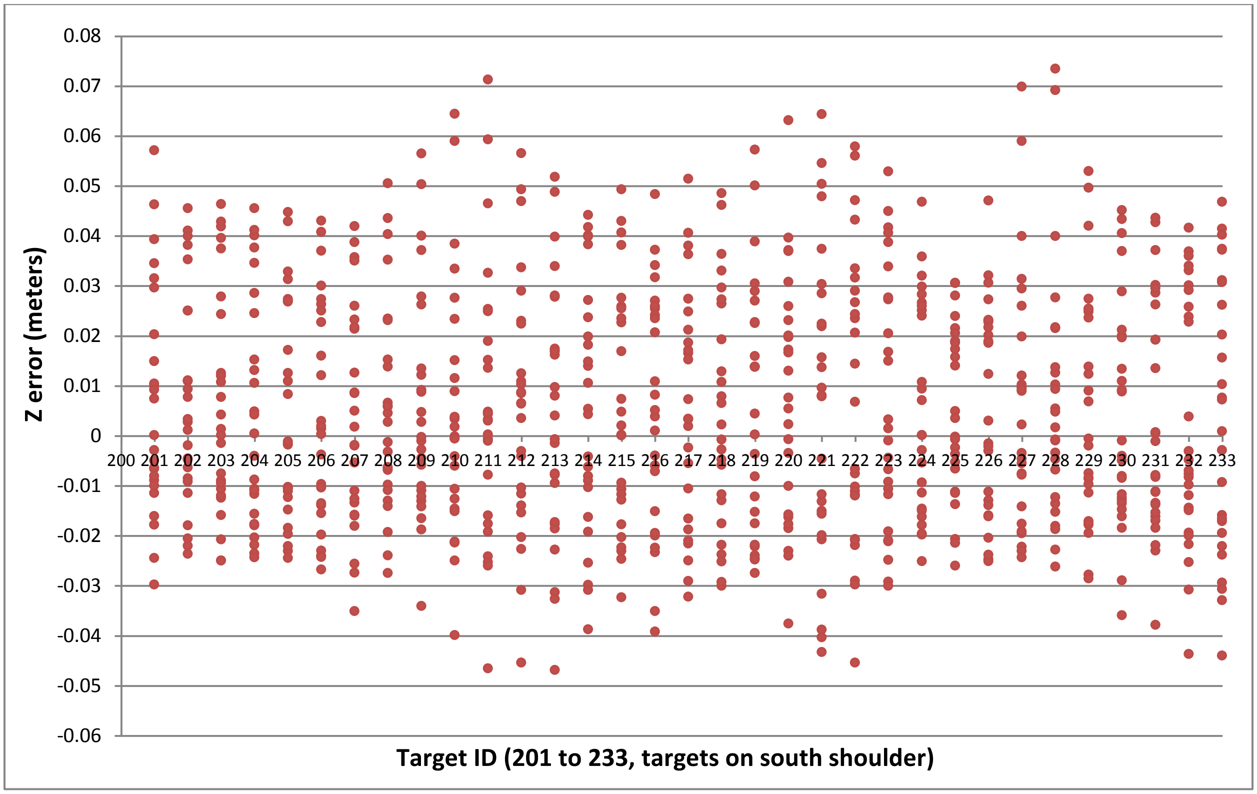

Figure 15. Delta Z error for target ID 2xx on the south shoulder.

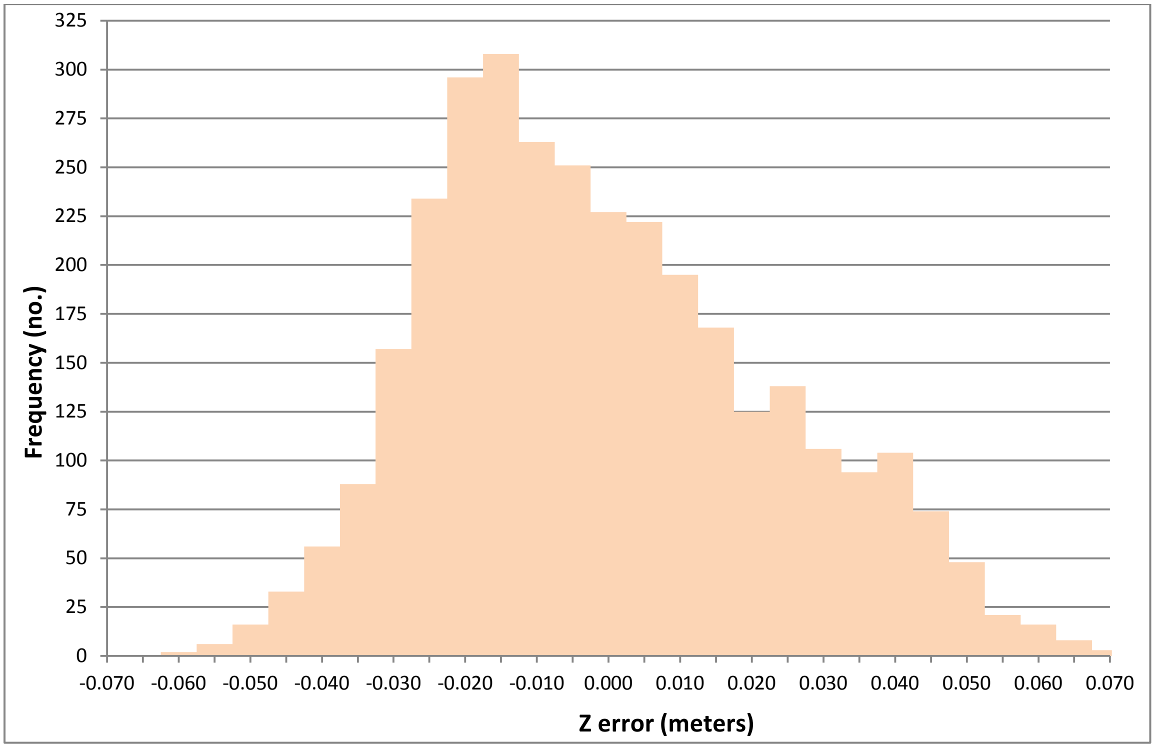

Figure 16. Delta Z error distribution.

Data Analysis

In order to perform the data analysis, the X, Y and Z errors need to be plotted as a function of time. Figure 17 plots the vertical (Z) error versus time. In this figure, zero seconds represents the experiment start time; each red "x" represents the Z error from the target mean Z coordinate. The blue dot represents the average error of a single "run" (~ 3 minutes / 1.7 miles). Figure 17 also displays a vertical (Z) error bias/offset at any given short period of time. In other words, the average error for a given short half-hour data collection session is non-zero. The average Z error offset for a single run ranges from -0.04 m to 0.05 m.

The data for X and Y errors are plotted in Figure 18 and Figure 19. In these two figures, again zero seconds represents the experiment start time, and each red "x" represents the X or Y error from the target mean X or Y coordinates, respectively. The target error data are clustered in half-hour durations of a typical data collection session. The data gaps between the clusters of points are due to the time gaps between data collections. The blue dot represents the average error of a single "run." Comparing the data in these two figures with the data in Figure 17 shows that the X and Y errors exhibit similar behavior to that of the Z error but with a much smaller error offset. The data shows that correcting for the error offset can improve point cloud data accuracy, particularly that of the vertical or Z error.

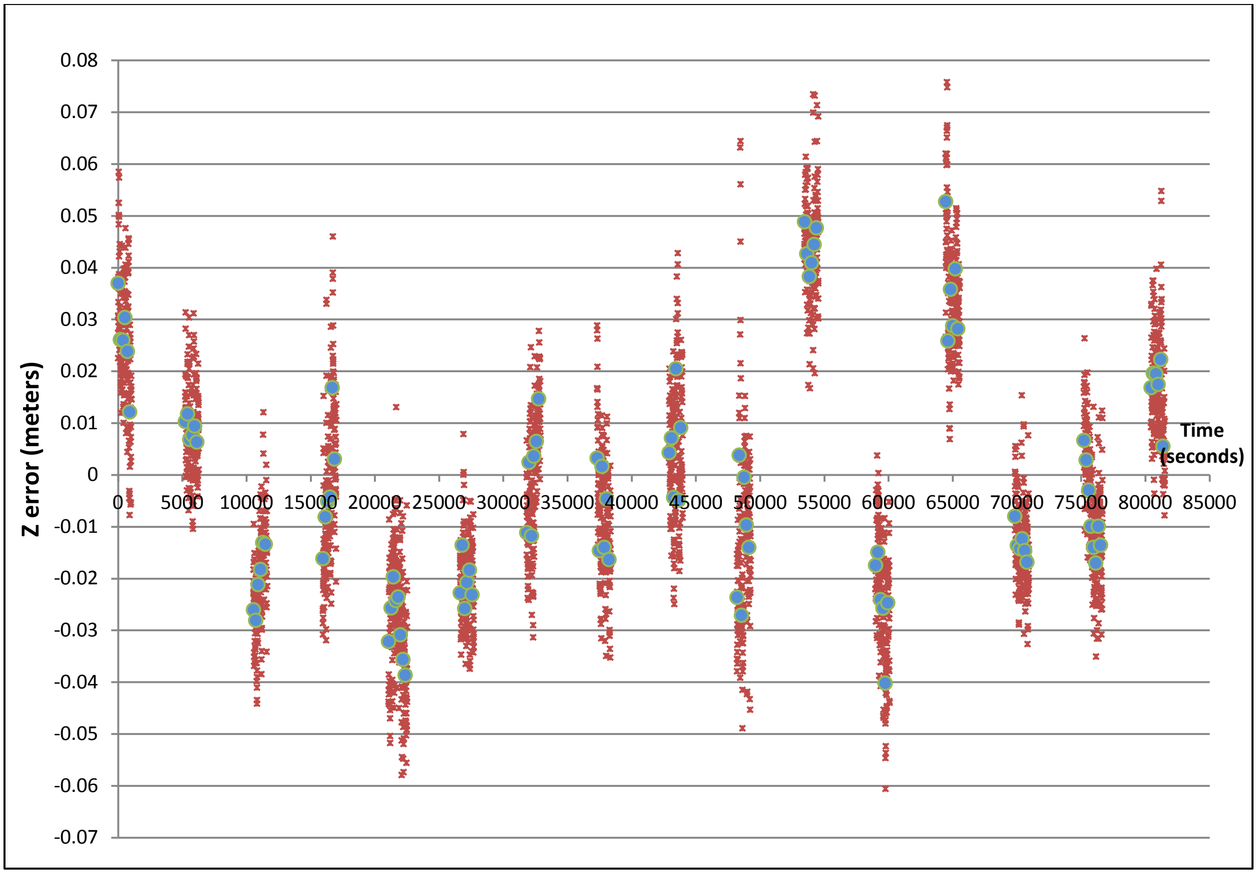

Figure 17. Z error vs. time.

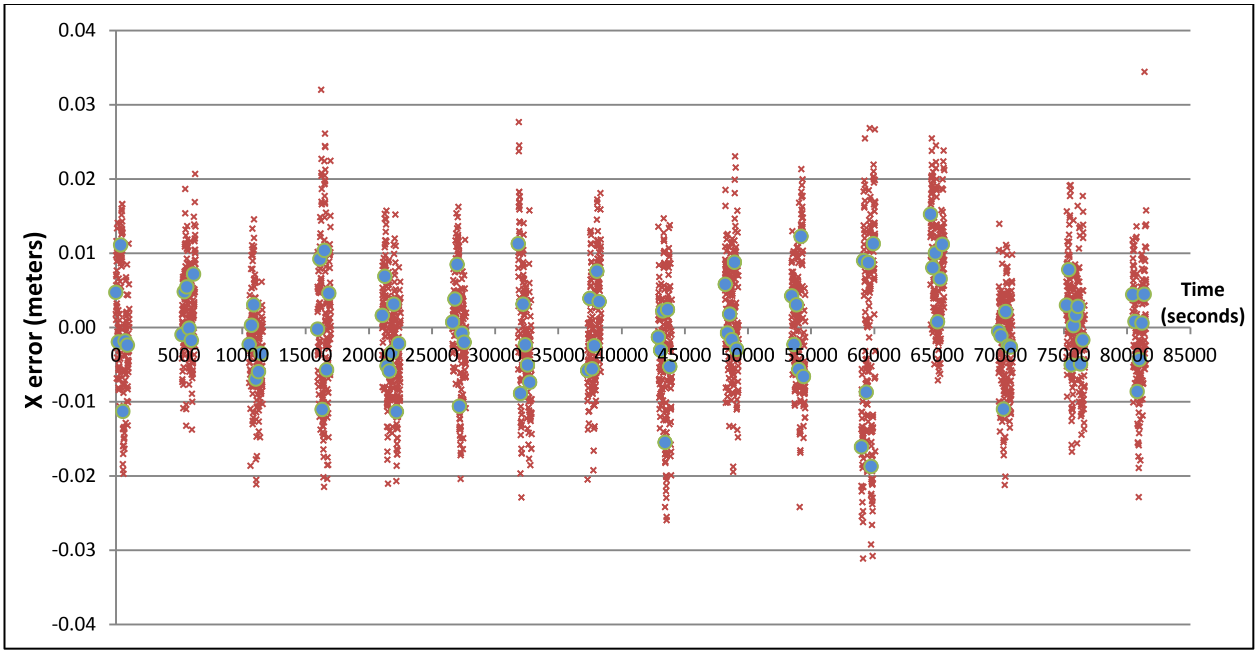

Figure 18. X error vs. time.

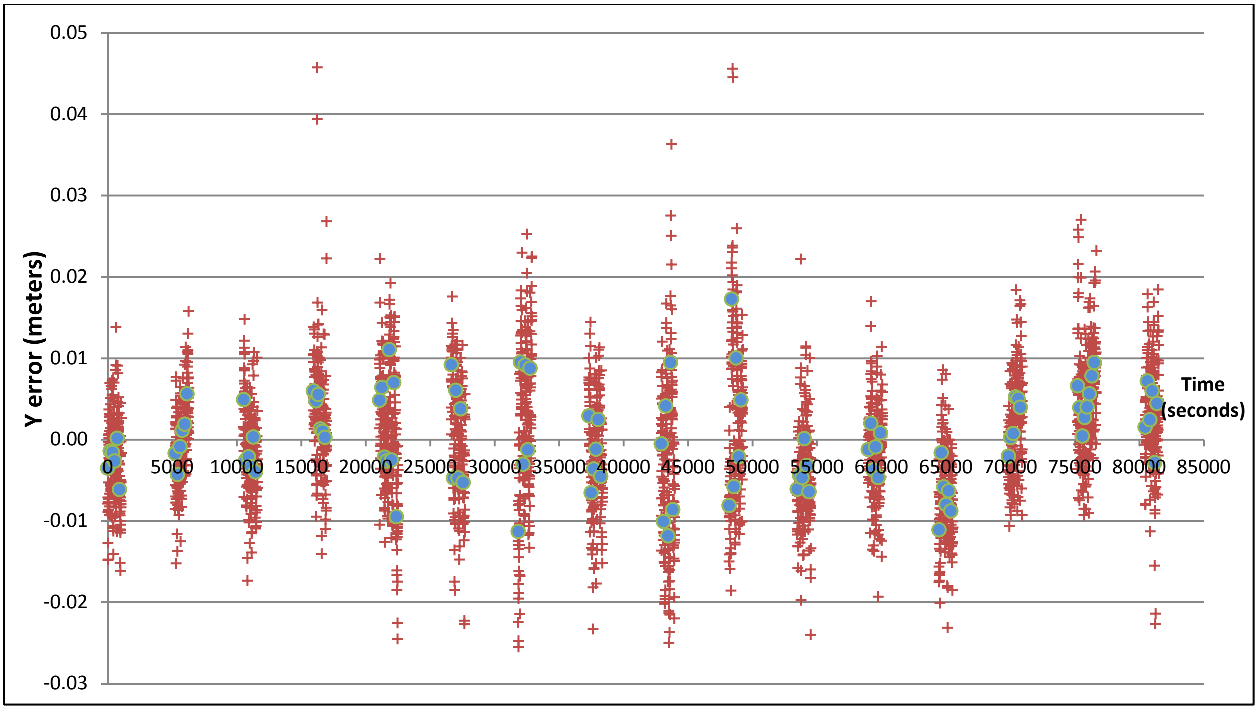

Figure 19. Y error vs. time.

XYZ Adjustment Method

Different methods can be used for adjusting the point cloud using a given set of adjustment control targets. The simplest way is to take an average of the control targets in a segment to determine the single error offsets in X, Y, and Z. Then, the entire point cloud segment will be shifted by the average offset in each direction. This method works well for small projects; however, if the project is broken up into segments for adjustment, the approach can introduce disjointed surfaces at their boundaries since each segment's offset may be different. Alternatively, other adjustment methods can be devised using line fit or curve fit adjustment targets to determine the adjustment/correction value for each point in the point cloud segment. The advantage of this method is eliminating discrete discontinuity at the segment boundaries.

In this research study, a simple straight line fit was applied to determine the adjustment target spacing and position error relationship. Two adjustment target error offsets and times are used to determine the X, Y, and Z adjustment values for each point in the point cloud. The validation targets in-between the adjustment targets helped determine the errors after adjustment. This process is illustrated in Figure 20 and mathematically represented by Equation (1).

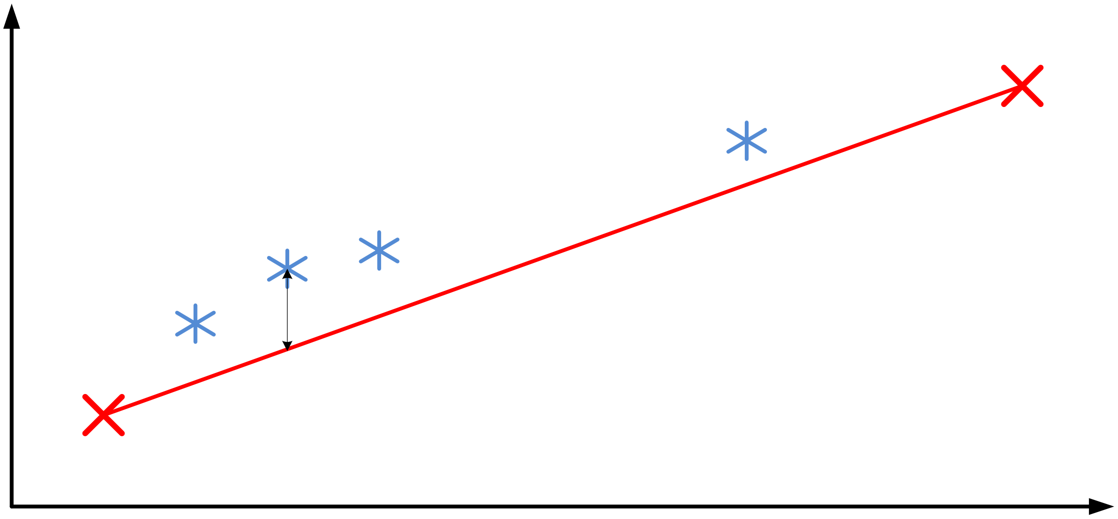

Figure 20. Straight line adjustment method and the corresponding error.

$$E_{adj_i} = Err_i - \left(\left(\frac{E_e - E_f}{T_e - T_f}\right)(T_i - T_f) + E_f\right) \tag{1}$$

In this equation, E_{adj_i} is the error after adjustment in the (X, Y, or Z) direction of the i^{th} validation target and Err_i represents the error before the adjustment in the (X, Y, or Z) direction of the i^{th} validation target between the adjustment target. The time duration for validation of a target being scanned by the scanner is T_i. In this equation, the range of i is from 1 to n, where n is the number of validation targets between the two adjustment targets at both ends and it is given by:

$$n = \frac{\text{Target Spacing}}{75} - 1.$$

The Target ID of the i^{th} validation target is FID + i, where FID is the first adjustment Target ID number. E_f is the error of the first adjustment target in the (X, Y, or Z) direction. The first adjustment Target ID number ranges from 101 to ($133 - n - 1$) or 201 to ($233 - n - 1$) in increments of 1. T_f denotes the time that the first adjustment target was scanned by the scanner. E_e is the error of the end adjustment target in the (X, Y, or Z) direction, and its Target ID # is equal to (FID+$n + 1$). T_e represents the time that the end adjustment target was scanned by the scanner.

Since the ground target spacing is 75 meters in the experimental setup, the number of validation target points depends on the adjustment target spacing. The validation target errors after adjustment were calculated for every run in every session using adjustment target spacing from 150 to 2250 meters in 150-meter increments. Run number 4 at 9:00 am was not used because bicycle traffic blocked one of the targets. The standard deviations of the errors in X, Y, and Z after and before adjustment are plotted for a 24-hour period in Figure 21. Noteworthy from this figure the Y error over 24 hours is very close to the X error for the same time period. The same adjustment method and error calculation were applied to the ten 1-hour passes of continuous data collected. Figure 22 displays a plot of the results over a 1-hour period. This figure shows that the Y error over one hour is very close to the X error over the same time period.

Both Figure 21 and Figure 22 show that the standard deviation of the error increases as the target spacing increases. Both 1-hour and 24-hour data sets show a similar trend: the standard deviation of the error becomes relatively constant when target spacing increases beyond 1200 meters. In addition, the 24-hour experimental data set results reveal significant vertical error reduction (51% or more) using ground control targets, even at very large target spacing.

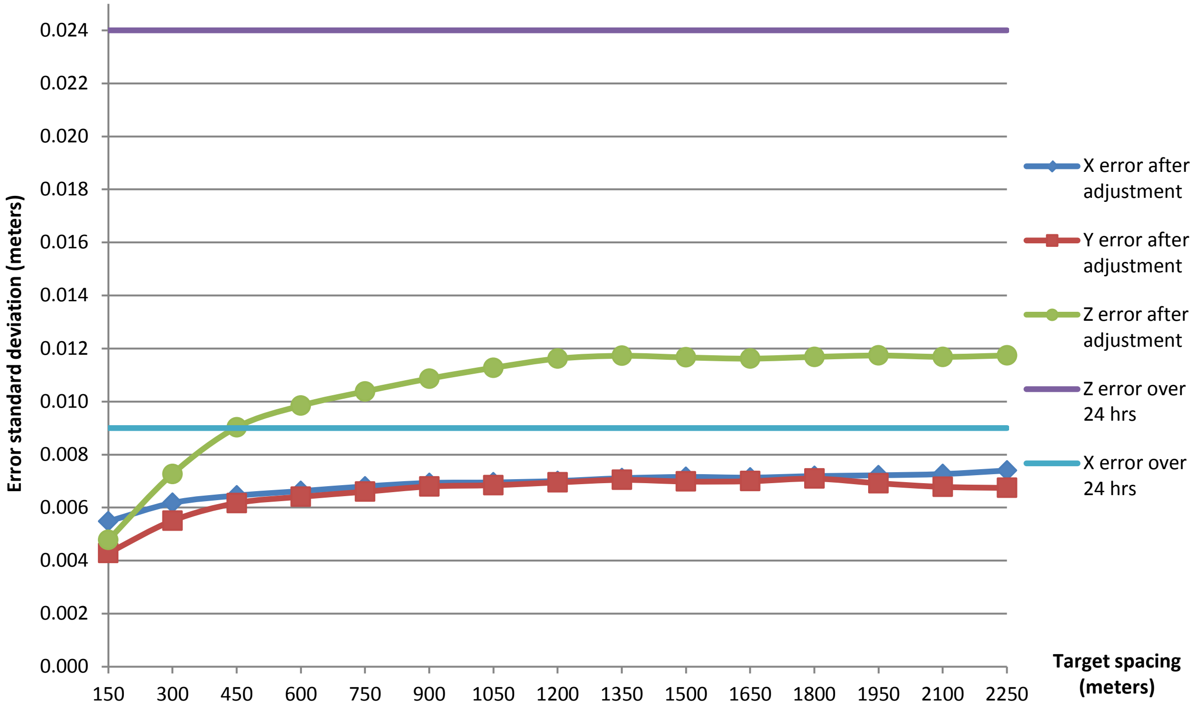

Figure 21. Standard deviations of X, Y, and Z errors after and before adjustment vs. target spacing over 24 hours.

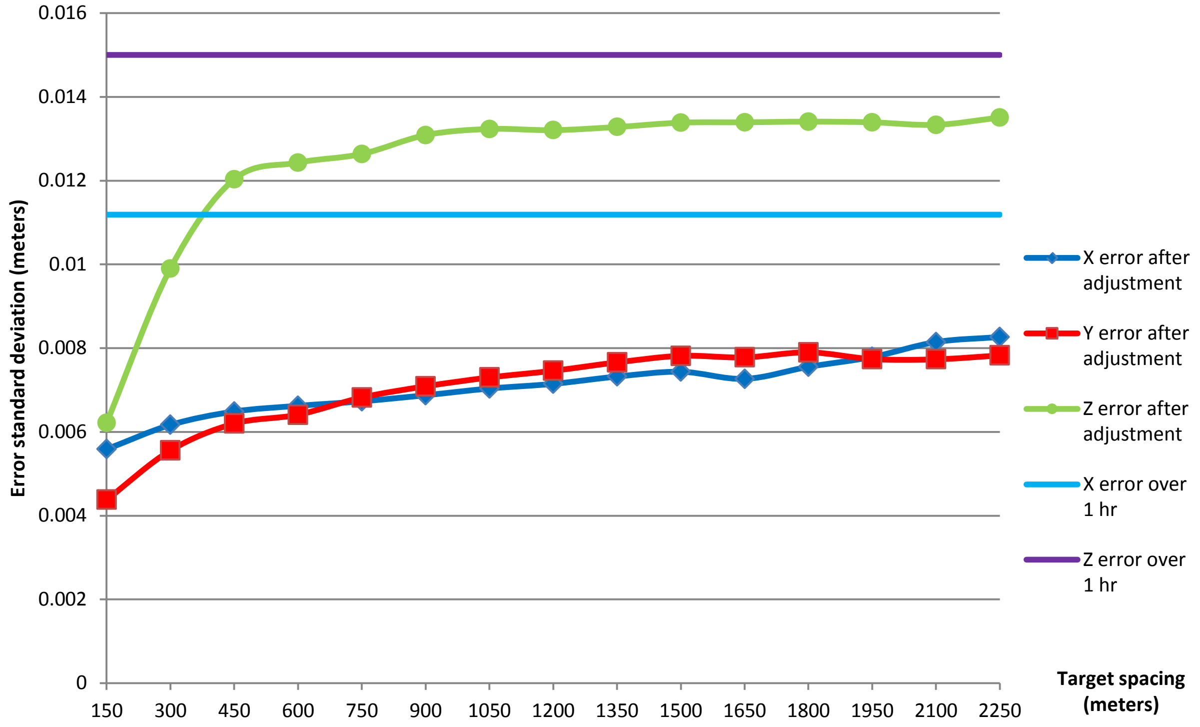

Figure 22. Standard deviations of X, Y, and Z errors with and without adjustment vs. target spacing over one hour.

Future Work

The GPS-only CORS station data is only available for GNSS/IMU post-processing. The CORS station data are updated once every 15 seconds. A GNSS base station logging at 1 Hz could improve the accuracy of the GNSS/IMU solution. The test should be repeated with a dedicated GNSS base station to compare the accuracy performance of the post-processed solution vs. when using CORS stations. Alternatively, real project data can be utilized to compare the accuracy of the post-processed solution when using a dedicated GNSS base station and a CORS base station. Ideally, the ground targets should be surveyed using the traditional method rather than by deriving coordinates through averaging. The target vertical coordinates should be surveyed with a digital level. The data can be used to test different adjustment methods and their effects on the resulting accuracy of the overall point cloud data.

The error statistics from real MTLS projects should be collected and examined to determine if the experimental and the actual results agree.

KINEMATIC REGISTRATION

This section deals with kinematic registration of point cloud data, which involves the basic research component of this study. Compared with the more immediate impacts of the last sections of this report, the material presented in this section will have a longer-term impact upon the utilization of MTLS. Kinematic registration for roadway applications is defined as merging two sets of point cloud data such that they are similarly geo-referenced rather than described by different coordinate systems. MTLS systems are typically used for projects devoted to relatively small sections of a highway. When point cloud data is generated by these systems over adjacent patches of the highway with some overlapping sections, then the data can be merged using kinematic registration. Kinematic registration also allows the point cloud data from different service providers about the adjacent sections of a highway infrastructure to be merged, providing a more complete digital model of the highway system. Broader, digital models of the highway infrastructure can then be utilized in operational planning, construction, maintenance, asset management, and a variety of other applications to promote leaner operations.

One of the popular approaches to solving the kinematic registration problem for point cloud data is to use the Iterative Closest Point (ICP) method. This method was initially developed by Besl and McKay [4] and has been extended by many researchers including Bergevin, et al. [5], Bae and Lichti [6] and Minguez, et al. [7]. The registration problem between a source point cloud and a target point cloud using the ICP algorithm involves finding the closest points in the two point clouds and estimating the rotation and translation that would move one into the other in rigid body motion by minimizing the mean squared error distance between the two point clouds. The drawback of ICP is the required use of an accurate initial estimate of the rigid body transformation matrix. In most situations, the raw scan data cannot provide an accurate enough initial estimate of the transformation matrix to start the ICP algorithm.

This study developed a new point cloud registration method for point clouds generated by an MTLS system for highway applications. The approach utilizes a concept from Distance Geometry and combines it with methods from computer vision. The theoretical basis of Distance Geometry and its use in kinematic registration are discussed in the PhD thesis of one of the AHMCT researchers [8]. This method is extended and applied here to actual point cloud data generated by MTLS in highway applications. Point cloud registration methods require the knowledge of point correspondence, namely which control points from one point cloud correspond to the control points in the other point cloud. In overcoming this problem, manual methods are typically practiced. However, these methods are inefficient and sometimes difficult due to ambiguities in point cloud data control points or their lack of clear features.

Other developed methods involve placing markers in the scene that eliminate ambiguities and provide clear corresponding features, as demonstrated by Akca [9] and Franaszek [10]. Yet, such methods both require some level of uniformity in marker use in generating point clouds for adjacent highway patches and introduce unnecessary objects into the point cloud data that require removal at the post-processing stage.

The approach developed, in this study, determines the correspondence between the source and the target point clouds by finding congruent tetrahedrons. The steps involved in finding such tetrahedrons are as follows:

1. Use four key points from the target point cloud to construct a tetrahedron ABCD.

2. Start with one of the vertices of a tetrahedron, and project it to the plane formed by the rest of the three vertices. In this case, the vertex D is projected onto the plane formed by the remaining three vertices (Figure 23).

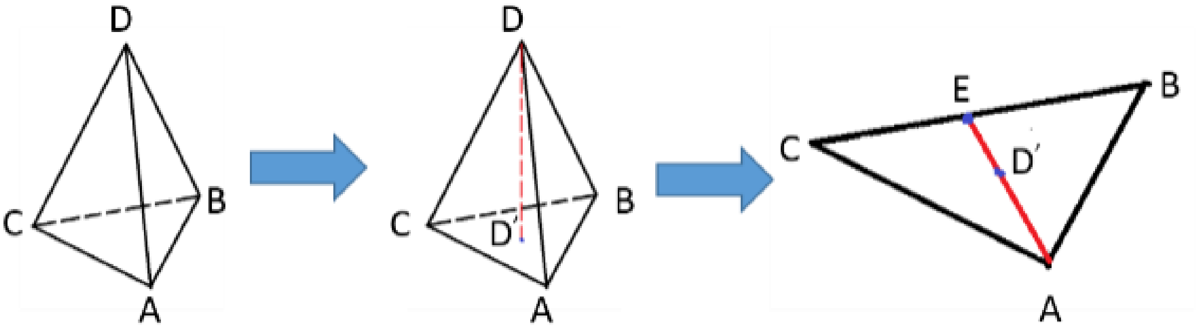

Figure 23. Projected point inside the base triangle.

3. Determine whether the projected vertex is inside the triangle formed by the rest of the three vertices. If this is the case, then form two ratios as follows:

$$r_1 = \frac{|AD'|}{|AE|} \quad (2)$$

$$r_2 = \frac{|BE|}{|BC|} \quad (3)$$

4. If the projected vertex is a point D’ outside the triangle formed by the rest of the other three vertices (as shown in Figure 24), and the quadrangle ABCD’ is convex, create the following ratios:

$$r_1 = \frac{|AE|}{|AD'|} \quad (4)$$

$$r_2 = \frac{|BE|}{|BC|} \quad (5)$$

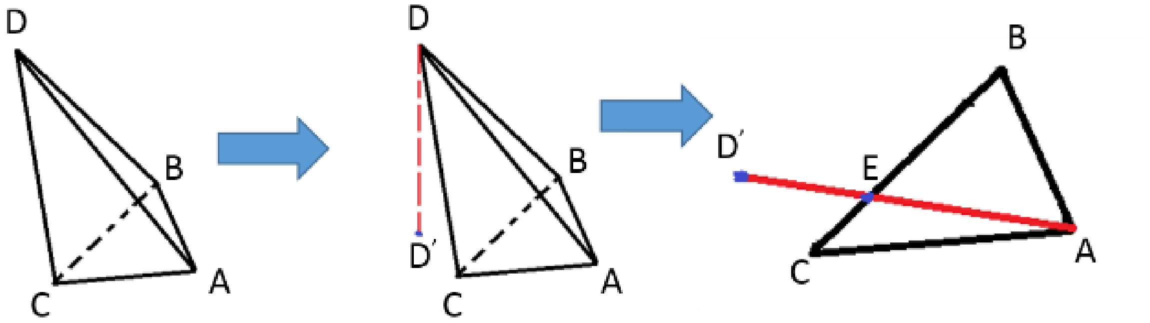

Figure 24. Projected point outside the base triangle

5. If the projected point is outside the triangle, but ABCD’ is a concave quadrangle (as shown in Figure 25), the case is ignored.

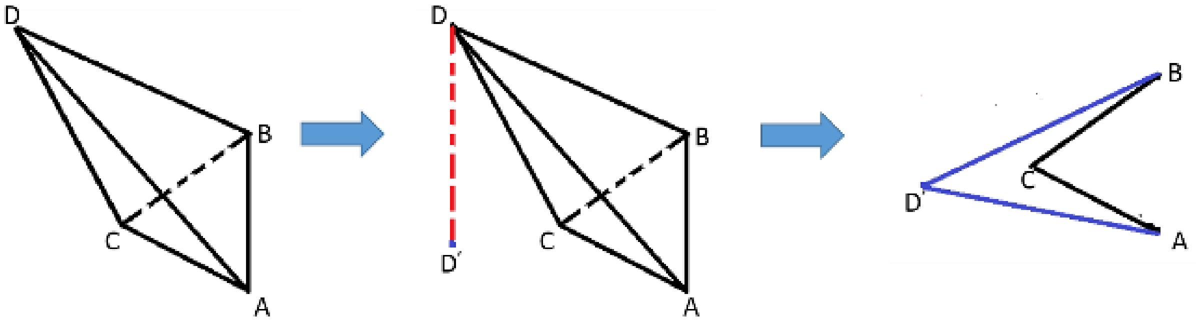

Figure 25. The Projected point is outside the base triangle

6. Steps 2 to 5 are then repeated for all vertices of the tetrahedron, and the ratios are stored.

7. In source point cloud data, steps 2 to 6 are repeated for all the tetrahedrons constructed by the key points from the associated clusters.

8. The ratios from the target point cloud and the source point cloud are then compared. Any two tetrahedrons whose ratios are close within a threshold are corresponding or congruent within the two point clouds and can be used for point correspondence.

The points defining the vertices of the tetrahedrons in the source and the target point clouds can be determined using clustering techniques or methods from the field of computer vision or interactively by the user. Once the point correspondence is established, any methods of kinematic registration with known correspondence can be used. This study used the method developed by AHMCT researcher Tabib [8] and applied the results to the point cloud data of a highway section collected by the Trimble MX-8 mobile laser scanner system. The data represents a 4-lane roadway, signs, trees and vehicles. The scan area is about 2,400m^2 with approximately one million points. There is about a 30% overlap region between the two point clouds. Figure 26 shows the point clouds for the two roadway sections with the 30% overlap.

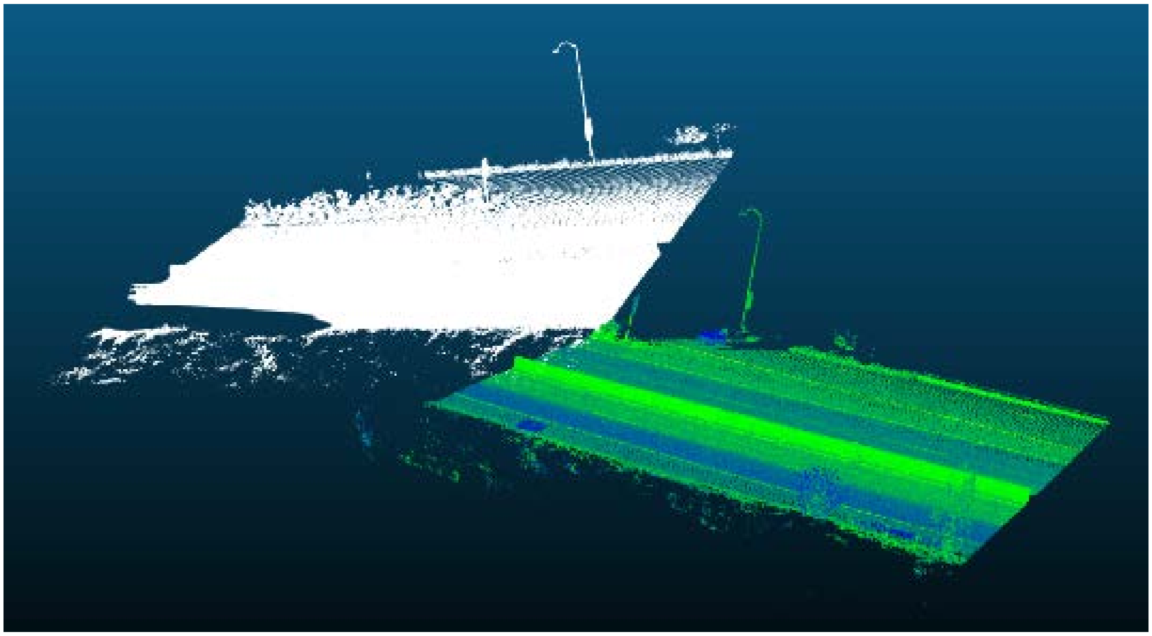

Figure 26. Point clouds for two overlapping roadway sections.

These two point clouds, as shown in Figure 26, are not registered. Using the method developed in this research when the point correspondence is unknown, kinematic registration was performed on the two point clouds. Figure 27 depicts the resulting two point clouds.

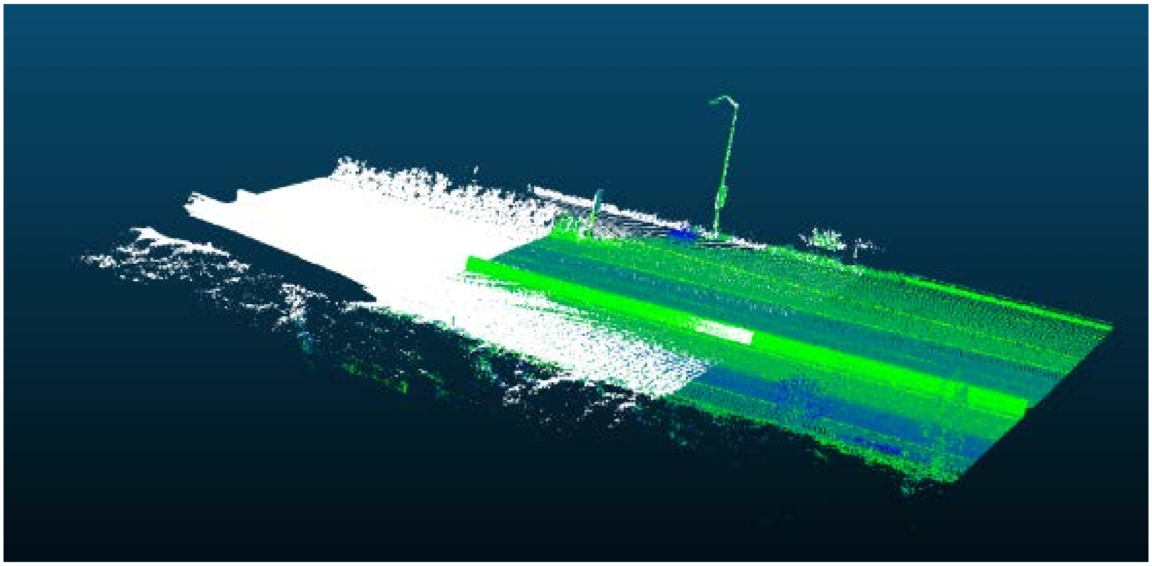

Figure 27. Two point clouds after registration.

For accuracy comparison, a few homologous points from each point cloud were manually selected before registration. After registration, the average distance between these homologous points was about 0.12m.

FEATURE EXTRACTION

Material presented in this section also relates to the basic research component of this study. Feature extraction involves searching for and extracting lines, planes, surfaces and objects from point cloud data. In 1985, Canny [11] proposed a computational approach to edge detection. He used the derivative of the Gaussian of an image to derive a family of convolution filters. An edge was detected by placing the operator at a point in the signal, multiplying each value of the signal by the corresponding weight of the filter, and determining their sum. This method works for images with continuous pixels but does not directly apply to point cloud data due to its sparsity. Fischler and Bolles [12] proposed Random Sample Consensus (RANSAC) as a method to segment the point cloud data. This method selects random points in the data, fits a geometric model to the selected data, and finds out the number of points fitted to the model within some tolerance. RANSAC is able to segment a point cloud when the point cloud consists of two distinct features but no more. Yang, et al. [13] generated a geo-referenced feature image from point cloud data and used it to separate road mark points from the rest of the point cloud based on intensity. The resulting image did not show the solid lane lines at their locations. El-Halawany, et al. [14] developed a methodology for road curb detection. Ground points and non-ground points were separated by calculating eigenvalues and the surface normal of each point. Then, elevation gradients in the local neighborhood, surface normal direction, and three normalized eigenvalues are used to isolate roadway curbs from other features. The drawback of this method is that the point cloud density affects the accuracy of the elevation gradient, surface normal, and eigenvalues. McElhinney, et al. [15] detected the roadway edge by fitting a spline to the cross-section of the roadway, calculating its slope, and finding the locations where rapid changes in the slopes occurred. The accuracy of road edge detection of Elhinney's method depends on the accuracy of the spline fitting and the accuracy of detecting the rapid changes of the slope.

This study evaluated the extraction of the following roadway features: lane lines, roadway edges, road signs, k-rails, and guard-rails. The remainder of this section of the report describes each of these feature extractions.

Lane Line Extraction

During laser scanning, bright-colored objects or features return higher intensity, while dark-colored objects or features return lower intensity images. In general, lane lines are brighter than the surface of the road, and points on lane lines can therefore be distinguished from the rest of the road based on intensity. In addition to their difference in intensity, lane lines usually follow the direction of the roadway. Combining these two pieces of information, the algorithm developed for lane line extraction is as follows:

1. Select three initial seed points on the lane line to start the algorithm. Two of the seed points are used for starting points, and the third point is used as the end point.
2. Based on the two starting points, select points near the second seed point.
3. Apply an intensity filter to obtain likely points to be considered as the next set of seed points. If the numbers of likely seed points are not enough, go back to Step 2 to increase the search radius.
4. Apply both intensity and directional filters to choose the next seed point.

5. Iterate the above process until the seed point is close to the ending point.
6. Based on each seed point, search for nearby points with similar intensities, and list them as points for the lane line.

The algorithm was applied to a section of a roadway and the lane lines were extracted. Figure 28 depicts the results. The lower portion of this figure displays an enlarged image of a smaller section of the roadway illustrated in the upper portion of the same figure. The grey points depict the roadway, and the red points depict the lane line.

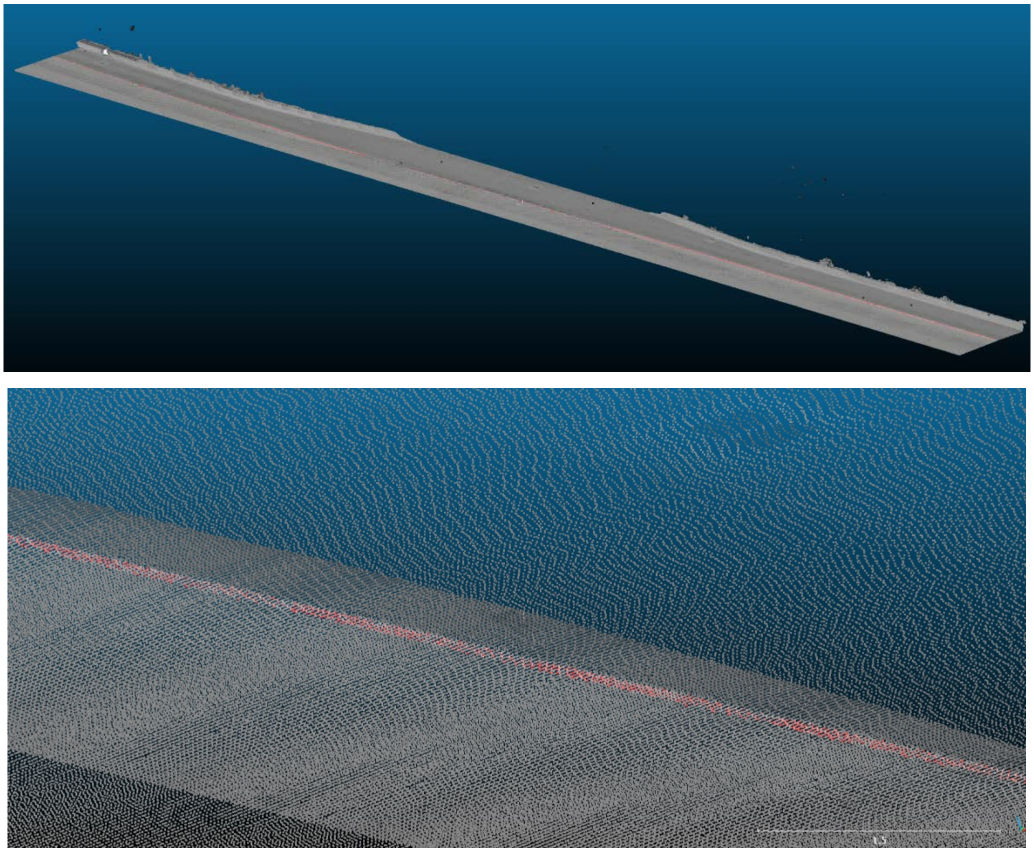

Figure 28. Lane line extraction results.

Extraction of the Edge of the Roadway, K-Rails, and Guardrails

The edge of the roadway represents another feature to be extracted because the actual width of the road can be obtained and compared with the original planning width of the road. The K-Rails and guardrails are easier to detect because of their heights and can also help in identifying the roadway edge when placed there. The algorithm developed for identifying these roadway features is basically a smaller portion of the algorithm used for finding point correspondence in registration. The developed algorithm uses a segmentation method based on the differences of the normal vectors to each point in the point cloud combined with Principal Component Analysis and the Euclidean Distance Clustering. This algorithm is described in more detail in [16] and has been used effectively to separate buildings, cars, vegetation, poles, and pedestrians in the point cloud of a scene.

The differences between normal vectors, $\Delta_{\hat{n}}$, to a surface can be used to filter out orientable surfaces or edges. Figure 29 depicts the point cloud data for a road section with K-rails and a light pole. A segmentation algorithm was applied to this point cloud, and Figure 30 displays the results. The segmented point cloud data was processed again using Euclidean Distance Clustering. The results are depicted in Figure 31. The roadway features, including the K-Rails, are clearly identified in the final data as shown in Figure 31.

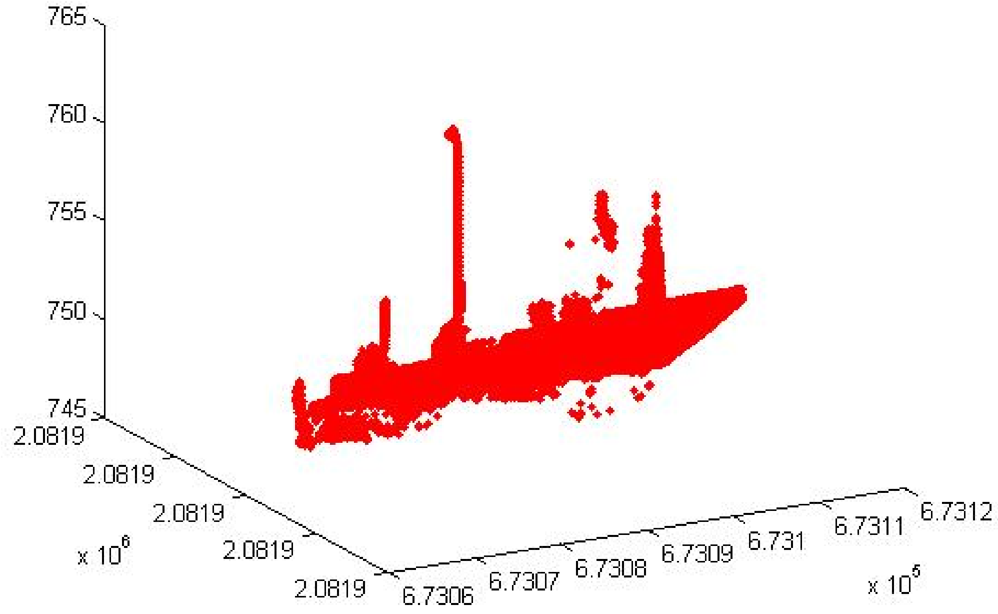

Figure 29. A point cloud before segmentation in terms of differences between normal vectors.

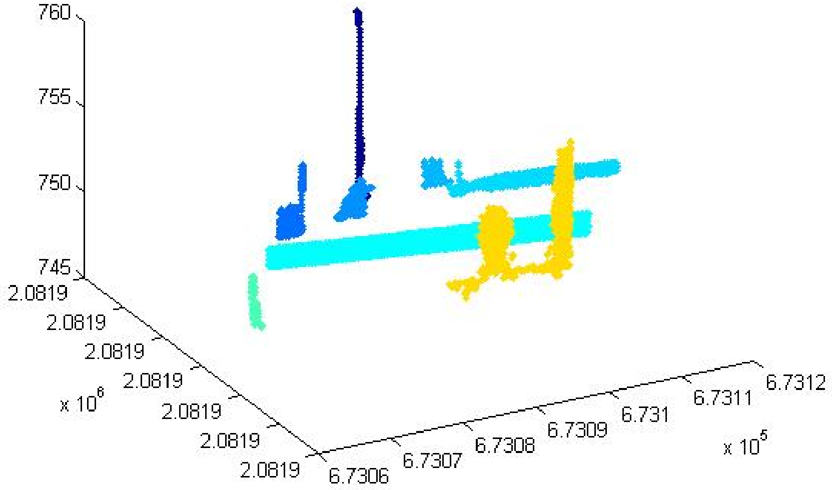

Figure 30. A point cloud after segmentation in terms of differences between normal vectors.

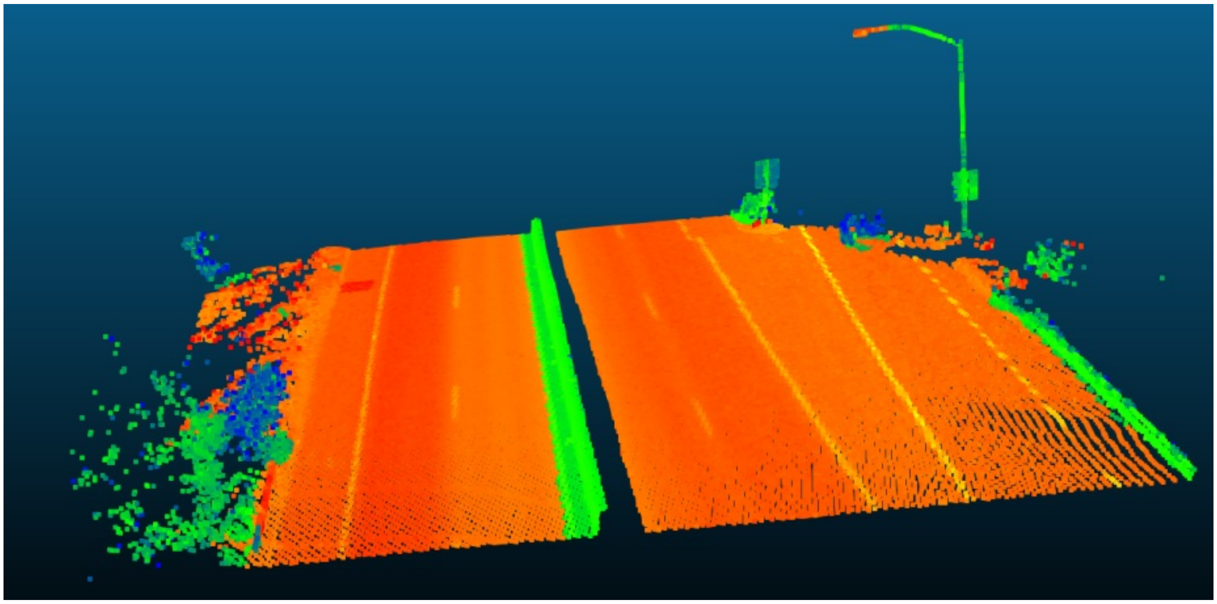

Figure 31. Point cloud data with features clearly identified.

As part of this study, several commercially available software packages for point cloud processing were evaluated. These packages are discussed in the next section. For each of these software packages, workflows were developed for Caltrans in terms of feature extraction and other useful attributes of these products. Based on the data and the methods presented in this section, for highway applications, existing methods in open literature can be used without the need for proprietary techniques.

WORKFLOW DEVELOPMENTS AND MTLS DATA MANAGEMENT

The workflow development portion of this research study was a component of the applied section. It evaluated commercially available software packages of interest to Caltrans districts and developed the workflow for its integration into Caltrans' operations. These software packages were all related to point cloud processing and included: Polyworks from InnovMetric Software Inc., Virtual Geomatics from SmartLiDAR^{TM} Solutions, and Navisworks from Autodesk®. Figure 32 graphically illustrates this development effort. The details of workflows for each of these commercially available software packages are described in separate reports [17-19] and are not repeated here.

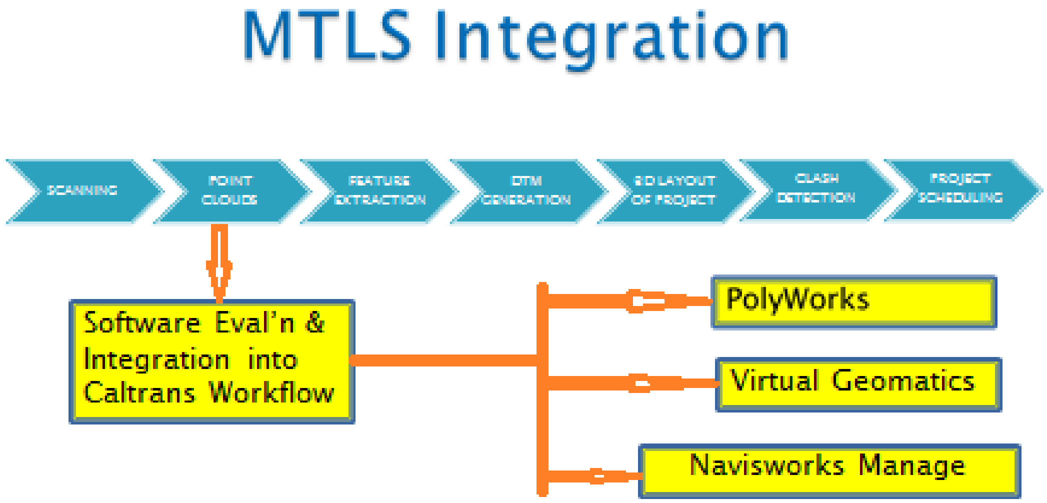

Figure 32. Software evaluation for workflow integration.

The three software packages evaluated all had feature extraction capabilities for highway applications as well as methods for assessing bridge heights from point cloud data. None had any practical algorithm that would allow kinematic registration without the knowledge of point correspondence. Therefore, the method presented in this research for kinematic registration without the knowledge of point correspondence enhances the capabilities for Caltrans or any other user of point cloud data to develop a data repository of integrated digital models of complete highway sections.

In evaluating the commercially available software packages and developing the workflow for their integration into Caltrans' operations, the need for the development of plans, standards, and requirements for MTLS data management became evident. Such data management plans should integrate input from Caltrans Information Technology (IT), Land Surveys, Caltrans districts, and other partners and stake holders.

The following research questions should be considered:

- How should data be best organized and stored statewide?
- How should the districts' data be integrated with a GIS Data Clearinghouse?

- How much can Caltrans push towards model-based design?
- For the range of internal and external customers:
    - What do they want?
    - What can be automated?
    - What can be distributed?
    - What search and visualization methods should be used?
- What control methods should be used to secure data, define various access levels, determine various accuracy levels, and bandwidth decimation?

Accessing the necessary requirements to respond to these questions was outside the scope of the present study and would require a separate research project. There is also a need to explore and evaluate the use of MTLS data in Tekla Software for the Bridge Information Management system (BrIM). This type of activity can enhance the workflow in design, construction, and maintenance operations.

CONCLUSIONS, RECOMMENDATIONS, AND LIMITATIONS

Cost-Benefit Analysis

Conclusions

The conclusions from the cost-benefit analysis revealed that the cost effectiveness of an option for a survey-grade project depends on the work capacity in terms of the number of projects that a unit would have per month. For bridge clearance measurements, the analysis indicated a cost of \$125 per bridge structure for option 1 and higher costs for options 2 (\$141 per bridge structure) and 4 (\$291 per bridge structure), but declined to \$118 per bridge structure for option 3 when the MTLS system was purchased and used for six years.

Recommendations

The following recommendations can be made based on the cost-benefit analysis:

- For bridge clearance measurements, option 1, which involves contracting out the work to a service contractor, is the most cost-effective option unless an MTLS system is purchased and operated for six or more years and also used in other projects. Even in the latter scenario, contracting with a service provider (option 1) for such a task is very competitive.

- For pavement survey applications:
    - If the number of projects to be completed is less than eight per month, then option 1 (using a service contractor) is the most cost effective if the contractor is at the low end of the cost structure, but not cost effective if the contractor is at the higher end of the cost structure.
    - If the number of projects to be completed is eight or higher per month, then option 4 (50% fractional ownership) is the most cost effective, assuming such an ownership contract can be worked out.
    - If the number of projects to be completed is ten or higher and option 4 is not considered, then option 3 (purchasing and operating an MTLS system) is the most cost-effective option.

Limitations

The conclusions and the recommendations discussed for the cost-benefit analysis need to be used carefully since they are based on certain assumptions and are subject to the following limitations:

- Hourly rates for surveyors, data processing, and other staff used in the calculations are based on data available at the time of writing of this report. They need to be adjusted as yearly rates change.

- Cost estimates for pavement surveys were calculated based on 72 projects per year (6 per month).

- Historical and current expenditures for the Caltrans Office of Land Surveys and Structure Maintenance were used. Therefore, data for other operations may lead to different conclusions.

- The equipment cost for MTLS systems can change over the years, leading to changes in the cost basis of the different options discussed herein.

- Mileage and vehicle utilization costs can change over time and may need to be adjusted.

- Service contractor costs and fees can change over time and need to be adjusted.

- All options discussed herein may not always be available, such as fractional equipment ownership or equipment rental.

Control Point Spacing and Accuracy

Engineering and survey-grade MTLS data collection requires ground controls and targets for accuracy improvement and data validation. The spacing requirements for the control points can greatly influence the accuracy of data collection. At present, no standard guidelines dictate the control point spacing that correlates to an expected level of accuracy in collected data. In this work, experimentation on an actual roadway surface was used to understand the effect of control point spacing on the accuracy of collected point cloud data.

Conclusions

The following conclusions were drawn from the experimental study and the analysis related to target spacing in this study:

- The data showed that the vertical error ($1\sigma = 0.024$ meters) is about three times that of the horizontal error ($1\sigma = 0.009$ meters), without using any adjustment targets.

- The experimental results confirmed that the use of ground control targets can be effective for vertical and horizontal error reduction. It can reduce the vertical error by half or more, but the reduction in horizontal error (18%) is much less in both percentage and absolute value.

- Vertical, or Z error, is the most significant error in point cloud data collection in roadway applications.

- Distance errors stop increasing and become relatively static when target spacing gets large. At a target spacing of 1200 meters or greater, vertical error is approximately 13 to 14 millimeters and horizontal error is approximately 8 millimeters.

Recommendations

Table 9 summarizes the recommendations on target spacing for a given data accuracy derived from this research:

Table 9. Target spacing recommendations.

Adjustment Target Spacing	Estimated Vertical Error
150 m	6.5 mm
300 m	10 mm
450 m	12 mm
1200 m	13.5 mm

Furthermore, the following additional recommendations are made:

- Figure 21 can be used as an alternative to Table 9 as a basis for determining the target spacing necessary to achieve the desirable accuracy in a specific project.

- Extra ground control targets will be needed for validation in addition to the adjustment targets.

- A minimum of one validation target between each pair of adjustment targets is recommended.

- If a contractor performs the work, the research study recommends that the survey crew consider having one extra set of validation target coordinates withheld from the contractor to check the accuracy of the delivered point cloud. This means that the contractor will use one set of validation targets for their internal quality control and that the survey crew will use the other set of validation targets to check the accuracy of the delivered point cloud.

Limitations

The limitations of the results presented herein are based on the following assumptions used in evaluating the experiments:

- The experiments assumed that the average of the 16 sessions over the 24-hour period yields an accurate measurement of the target positions.
- The researchers conducted the experiments in an area with relatively open sky and good GNSS signal reception and assumed this type of region represents a good area for a pavement survey project.

Kinematic Registration, Feature Extraction, and Point Cloud Processing Workflow Development

In patching MTLS point cloud data from different surveys or for surveys of adjacent sections of highway, one has to use the process of kinematic registration. Methods for this purpose within commercially available point cloud processing software are typically tedious and require a substantial amount of human interactions, making them error prone and inefficient. The three commercial software systems for which workflows were developed for Caltrans District 4 suffer from such problems.

Conclusions

Registration of point cloud data is necessary when integrating point cloud data from two adjacent sections of a highway. As part of the basic research component of this study, a method was developed for this process using correspondence between tetrahedrons in the source and target point clouds.

In terms of extractions for features that are useful for highway applications such as roadway edges, K-rails, and guard rails, this study showed that existing algorithms developed in the field of computer vision can be directly adopted for point cloud processing.

While evaluating and developing Caltrans District 4's workflows for the three commercially available software packages, this study identified the fact that the industry lags incorporating algorithms that can enhance the efficiency and utility of point cloud processing. Furthermore, the proprietary nature of some of the commercial systems limits their interoperability with different MTLS hardware. This problem, however, is diminished or eliminated by utilizing open source software and systems. At the present time, open source point cloud processing software has limited availability, but since the industry also lags in incorporating advanced kinematic registration and feature extraction techniques in their proprietary systems, developing and making the transition to open source software is needed.

Recommendations

The following recommendations are made based on the basic research component of this study:

- The use of open source software and systems is highly recommended to improve compatibility between different service providers, MTLS systems, and MTLS point cloud data.

- Additional research is needed to incorporate automated methods for kinematic registration and feature extraction into open source, point cloud processing software.

- Efforts should be made to develop a comprehensive and unifying frame work for MTLS data management that would be consistent, be incorporated into the Caltrans' geo-spatial strategic direction, and cause improved Caltrans' geo-spatial data collaborations.

- Methods for the data storage and distribution of MTLS data should include:
    - Automated data cataloging
    - Tools to "crawl" over data directory structures to catalog data
    - Open common file formats for the extraction of metadata
    - The creation of databases to store metadata
    - Web-based data selection and distribution
    - Intuitive web application with data collection boundaries overlaid on a map
    - The user selection of files by data collection boundary, area, or layer
    - Selected files delivered to the user via Internet download

Limitations

The methods developed in this part of the study could not be implemented in any commercially available point cloud processing software due to the proprietary nature of such software. The methods developed here, however, can be easily incorporated into open source point cloud processing software; as such systems are becoming more available through the efforts of various university and industry groups.

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