STATE OF CALIFORNIA • DEPARTMENT OF TRANSPORTATION

TECHNICAL REPORT DOCUMENTATION PAGE

TR0003 (REV 10/98)

ADA Notice

1. REPORT NUMBER	2. GOVERNMENT ASSOCIATION NUMBER	3. RECIPIENT'S CATALOG NUMBER
CA21-3179	N/A	N/A

4. TITLE AND SUBTITLE
Support for Caltrans Statewide Mobile Terrestrial Laser Scanning (MTLS) System Usage

5. REPORT DATE
August 28, 2020

6. PERFORMING ORGANIZATION CODE
AHMCT Research Center, UC Davis

7. AUTHOR
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8. PERFORMING ORGANIZATION REPORT NO.
UCD-ARR-20-08-31-01

9. PERFORMING ORGANIZATION NAME AND ADDRESS
AHMCT Research Center
UCD Dept. of Mechanical & Aerospace Engineering
Davis, California 95616-5294

10. WORK UNIT NUMBER
N/A

11. CONTRACT OR GRANT NUMBER
65A0560 / 65A0749, Task 3179

13. TYPE OF REPORT AND PERIOD COVERED
Final Report
January 2018 – August 2020

12. SPONSORING AGENCY AND ADDRESS
California Department of Transportation
P.O. Box 942873, MS #83
Sacramento, CA 94273-0001

14. SPONSORING AGENCY CODE
Caltrans

15. SUPPLEMENTARY NOTES
N/A

16. ABSTRACT

This research supported Caltrans Office of Land Surveys' (OLS) update of Chapter 15 of the *Caltrans Survey Manual* and creation of the *Caltrans MTLS Guidelines* document. In addition, the research contributed to firmware/software updates on both the Trimble MX8 and Riegl VMX-1HA MTLS systems, the integration of a Ladybug 5+ 360-degree camera to the MX8 system, establishment of the Geospatial Technology Proving Ground (GTPG) for MTLS target spacing experimentation, and MTLS target spacing research. The Advanced Highway Maintenance and Construction Technology (AHMCT) researchers worked closely with OLS as well as Caltrans districts on this project. OLS and district surveyors contributed the majority of the *Caltrans MTLS Guidelines* content. The GTPG provides a vital resource for evaluation of future mobile mapping technologies.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
MTLS, LiDAR, Mobile Terrestrial Laser Scanning, GTPG, GIS, Mobile Mapping	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. SECURITY CLASSIFICATION *(of this report)*	20. NUMBER OF PAGES	21. COST OF REPORT CHARGED
Unclassified	52	N/A

DISCLAIMER

Advanced Highway Maintenance and Construction Technology Research Center

Department of Mechanical and Aerospace Engineering
University of California at Davis

Support for Caltrans Statewide Mobile Terrestrial Laser Scanning (MTLS) System Usage

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Dr. Ty A. Lasky: Principal Investigator

Report Number: CA21-3179
AHMCT Research Report: UCD-ARR-20-08-31-01
Final Report of Contracts: 65A0560 / 65A0749, Task 3179

August 28, 2020

California Department of Transportation

Division of Research, Innovation and System Information

Executive Summary

Problem

The California Department of Transportation (Caltrans) owns and operates two Mobile Terrestrial Laser Scanning (MTLS) systems, the Trimble MX8 and Riegl VMX-1HA. Maintaining a pool of trained Caltrans professionals to manage two different MTLS systems and process the data for either system is an on-going challenge. MTLS operation and data processing are perishable skills, and keeping personnel proficient is essential for successful MTLS outcomes. The district surveyors' primary role is project delivery, so they must rely on others to coordinate peer support and systems management. Education and outreach is lacking to fully understand and exploit the full benefits and value of geospatial survey data as the foundation of the transportation system.

In addition, Caltrans does not have a Geospatial Technology Proving Ground (GTPG) or any baseline data to help verify mobile mapping data from vendors or other geospatial technology platforms elsewhere in the Department. Without a GTPG, Caltrans cannot validate system performance before system acceptance or after system component changes. Having a Caltrans-specific GTPG will aide with further research and development in using current MTLS standards and specifications and help to manage capabilities and capacities.

Need

Caltrans needs additional MTLS training and deployment support as current MTLS personnel retire or are promoted, including new resources and materials for in-house training, education and outreach, and updates to manuals and procedures on emerging applications of MTLS for virtual design construction, digital highways, and transportation asset management.

Documenting the cost and operational benefits of MTLS by way of emerging applications, standardizing new workflows and procedures, and sharing best practices and lessons learned throughout the industry are essential to further realize MTLS return on investment, ensure systems interoperability and data integration, and retain institutional knowledge as personnel retire or transition to other duties.

Caltrans does not have a Geospatial Technology Proving Ground (GTPG) to verify mobile mapping data from vendors or other geospatial technology platforms elsewhere in Caltrans. Without a GTPG, Caltrans cannot calibrate or verify current system performance before or after any component changes. Having a Caltrans-specific GTPG will aid with further research and development in using current MTLS and Stationary Terrestrial Laser Scanning standards and specifications as well as help to manage the capabilities and capacities of the Surveys Program. Caltrans also needs a GTPG for system validation and calibration of the two current Caltrans MTLS vehicles as well as for determining optimal control point spacing and quantifying and verifying vendor-acquired terrestrial, airborne Light Detection And Ranging, and remote sensing data.

Purpose

This task supported the Caltrans Geospatial Strategic Direction and the Caltrans Office of Land Surveys' (OLS) leading role in the creation, management, and visualization of geospatial data. It provided education and outreach, updated guidance documents, updated MTLS operator and post-processing training for new Caltrans personnel, and refresher training for existing personnel. Finally, it created the GTPG.

This task also provided support for integrating and combining geospatial platforms, tools, and systems. Coordinated use of geospatial technologies such as MTLS, GPR, and Photolog (for example) may yield amplified benefits and efficiencies for all of Caltrans.

This research task included:

- Supporting Caltrans with their updates to Chapter 15 of the *Caltrans Survey Manual*
- Supporting Caltrans with their creation of the *Caltrans MTLS Guidelines* document
- Integrating a Ladybug 5+ 360-degree camera to the MX8 MTLS system
- Establishing the GTPG
- Performing MTLS target spacing research

Recommendations

Recommendations for future work include:

- Expand other MTLS uses to
  - Asset data collection
  - Pavement marking reflectivity measurement
- Automate asset extraction with Machine Learning technologies
- Integrate point cloud and imagery with Geographic Information System

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List of Acronyms and Abbreviations

Acronym	Definition
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
CAD	Computer-Aided Design
CADD	Computer-Aided Design and Drafting
Caltrans	California Department of Transportation
DOT	Department of Transportation
DRISI	Caltrans Division of Research, Innovation and System Information
FHWA	Federal Highway Administration
GAMS	GPS Azimuth Measurement Subsystem
GIS	Geographic Information System
GLONASS	Globalnaya navigatsionnaya sputnikovaya sistema
GNSS	Global Navigation Satellite System
GPR	Ground-Penetrating Radar
GPS	Global Positioning System
GTPG	Geospatial Technology Proving Ground
HQ	Headquarters
IMU	Inertial Measurement Unit
IT	Information Technology
LiDAR	Light Detection And Ranging
MMS	Mobile Mapping Suite

Acronym	Definition
MTLS	Mobile Terrestrial Laser Scanning
OLS	Office of Land Surveys
POS	Position and Orientation System
POSPac	Position and Orientation System Post-processing Package
RFQ	Request for Quote
SMB	Surveys Management Board
STLS	Stationary Terrestrial Laser Scanning
SUE	Subsurface Utility Engineering
TAG	Technical Advisory Group
TRB	Transportation Research Board
UCD	University of California – Davis
USB	Universal Serial Bus
VDC	Virtual Design and Construction

Acknowledgments

The authors thank the California Department of Transportation (Caltrans) for their support, particularly Mark Turner, Ginger Congi, John Gilmore, Mark Counts, Eric Vance, and Molly Wollam with the Division of Right of Way and Land Surveys, and Arvern Lofton, Joe Horton, and Justin Unck with the Division of Research, Innovation and System Information. The authors thank Headquarters and Districts 1, 2, 3, 4, 5, 6, 8, 10, 11, and 12 surveyors and managers, Diego Alvarado, Ruben Aparicio, Benardino Armas, Jeff Ayer, Bruce Baker, Jeremiah Bean, Rebecca Boyer, John Crawford, Matthew Herbert, Oscar Huerta, Kuldip Hundal, David Karp, Jason Keblesh, Pegge Lum, Mike McCalligan, Stacey Meacham, Dave Olander, Aaron Ott, Robert Perez, Scott Reinhart, Andrew Robertson, Ned Salman, Scott Tikalsky, Khin Voong, and Randall Wigton for their valuable participation, support, and contributions. The authors thank Applanix, California Surveying and Drafting Supply, Riegl USA, Trimble, and R.E.Y. Engineers, Inc. for their support. The authors acknowledge the dedicated efforts of the AHMCT team who have made this work possible.

Chapter 1: Introduction

Background and Problem

Through the current and previous research projects, the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center at the University of California – Davis (UCD) has assisted the California Department of Transportation (DOT) (Caltrans) Surveys in the deployment, training, installation, maintenance, repair, upgrade, and use of Mobile Terrestrial Laser Scanning (MTLS) systems. MTLS is a transformative geospatial data collection tool. Developing and maintaining MTLS operational capability is key to satisfying geospatial data needs for all Caltrans divisions now and in the foreseeable future. As Caltrans expands MTLS use into transportation asset management, virtual design and construction (VDC), digital highways, and other areas, maintaining an effective group of MTLS personnel trained in multiple operational systems is essential to meeting Caltrans' geospatial data collection needs. The existing research with AHMCT providing support for the Trimble and Riegl MTLS systems is nearing its end, and the Trimble MX8 maintenance agreement with the vendor has expired. The skills and expertise offered by AHMCT are necessary to compensate for the loss of industry support in order to ensure the continued operation of the MX8 MTLS.

Caltrans owns and operates two MTLS systems, the Trimble MX8 and the Riegl VMX-1HA. Maintaining a pool of trained Caltrans professionals to manage two different MTLS systems and process the data for either system is an on-going challenge. MTLS operation and data processing are perishable skills, and keeping personnel modernized and proficient is essential for successful MTLS outcomes. The district surveyors' primary role is project delivery, so they have to rely on others to coordinate peer support and systems management.

Caltrans needs additional MTLS training and deployment support for escalating MTLS operations as current MTLS personnel retire or are promoted. Caltrans needs new resources and materials for in-house training, education, and outreach, and updates to manuals and procedures. Caltrans has accumulated years of institutional knowledge in MTLS workflows and procedures as well as best practices and lessons learned. This institutional knowledge must be documented in detail in order to pass it on to new generations of surveyors.

In addition, at the outset of the current research, Caltrans did not have a geospatial technology proving ground or any reference baseline to help verify geospatial mobile mapping data from vendors or other mobile mapping platforms. Without a proving ground, Caltrans cannot validate and verify system performance before systems are accepted or after system component changes, and there is no basis for new equipment evaluation to determine whether Caltrans' design specifications and requirements are met.

Caltrans has a need for a Geospatial Technology Proving Ground (GTPG). The two current Caltrans MTLS vehicles need a proving ground for software/hardware validation. There is a need to quantify and verify vendor mobile and aerial Light Detection And Ranging (LiDAR) data and for future research of other Departmental mobile mapping platforms. Future research may investigate use of a geospatial test track for system calibration and validation as well as investigate combining geospatial tools and developing new tools and techniques.

Objectives

This research supported the Caltrans Geospatial Strategic Direction and the Caltrans Office of Land Surveys' (OLS) leading role in the creation, management, and visualization of geospatial data. This research provided education and outreach, updated guidance documents, updated MTLS operator and post-processing training for new Caltrans personnel, and refresher training for existing personnel. At the end of this research, Caltrans will be able to maintain and provide training on the MTLS systems that it owns.

In addition, this research supported integrating and combining geospatial platforms, tools, and systems. Lastly, this research established the GTPG, located in Northern California, for MTLS research and validation.

Scope and Research Methodology

At the outset of this research, AHMCT worked with Caltrans to form a Technical Advisory Group (TAG) composed of representatives from Caltrans District Surveys, OLS, the AHMCT researchers, and Caltrans Division of Research, Innovation, and System Information (DRISI). Regular meetings were held with the Project Manager and/or the TAG. AHMCT and the TAG worked collaboratively during the research to best guide the effort. The TAG was consulted regularly throughout the project. To achieve the proposed objectives, we divided the research into the following tasks:

1. Perform an MTLS literature review and attend Caltrans MTLS users peer-to-peer meetings

This entailed a brief literature review of current MTLS research in private, educational, survey journals, trade publications, and government institutions. The AHMCT researchers attended MTLS-related webinars, Caltrans Surveys Management Board (SMB) meetings, and Caltrans MTLS user meetings. This task maintained national and international engagement with state-of-the-art MTLS research and best practices.

2. Deployment support for MTLS use in California

Under this task, AHMCT supported the two MTLS units including: systems maintenance services, system diagnostics, repair, and possible upgrades. The primary focus was on the MX8 unit since the Riegl VMX-1HA is currently supported by Riegl under their extended support and warranty program.

3. Update Caltrans documents and assist Caltrans in training staff on MTLS operations

Under this task, AHMCT researchers supported Caltrans' update of the following documents developed in previous MTLS projects:

- *Caltrans MTLS Guidelines* (see Chapter 3 for details)
- Chapter 15 of the *Caltrans Surveys Manual*

In addition, AHMCT assisted Caltrans in training Caltrans staff on MTLS operations on an as-needed basis due to personnel retirement or promotion. This included on-site and remote support for Caltrans MTLS surveyors.

4. Support of MTLS data management and related IT deployment

Under this task, AHMCT researchers supported Caltrans OLS' statewide MTLS data management effort and its associated Information Technology (IT) infrastructure deployment. MTLS post-processing places significant demands on computing resources. AHMCT worked with OLS and district surveyors to prepare the participating districts to update requirements for MTLS IT resources, such as data storage and data transfer.

5. External sensor integration on the MX8

This task resulted in the integration of a Ladybug 5+ 360-degree camera into the MX8 system. Coordinated use of geospatial technologies, such as MTLS and 360-degree imagery, may yield amplified benefits and efficiencies for all of Caltrans.

6. Establish a GTPG and perform target spacing research

The objective of this task was to establish the Caltrans GTPG for MTLS validation of the two current Caltrans MTLS vehicles, quantify and verify vendor mobile mapping systems, and begin future research on other Caltrans mobile mapping platforms. Future research may also investigate combining data from other geospatial tools, such as Ground-Penetrating Radar (GPR).

AHMCT also designed and performed experiments to determine optimal target spacing for MTLS survey using the GTPG mobile mapping validation site. The experiment results will be used to update Chapter 15 of the *Caltrans Surveys Manual*.

7. Document and manage the project

The overall project was documented in this final report. In addition, the research results will be published on our website and possibly in selected journals and conferences.

Overview of Research Results and Benefits

Prior research, along with Caltrans' operational experience utilizing MTLS technology, has shown that MTLS can improve safety and efficiency for multiple Caltrans application areas. MTLS collects geospatial data at or close to highway speeds. This data is used to produce 3D models. MTLS has been effectively used in pavement condition surveys; however, the data's application is broader with the potential to lead to enhanced safety, lean maintenance operations, lean construction, rapid project delivery, and enhanced asset management by providing accurate geospatial data to connected vehicles and autonomous vehicles. Management and staff are gaining a full understanding of the benefits and value of geospatial survey data as the foundation of the transportation system. The availability and utility of the geospatial data created from MTLS needs to be promoted along with the full range of products and services it provides. Due to the current research, Caltrans now has a GTPG that will enable Caltrans to improve its capabilities and capacities of geospatial data. In particular, the GTPG may allow Caltrans to increase the spacing of MTLS control points, which would enhance personnel and traveling public safety.

The key deliverables of this project include:

1. Updated Chapter 15 of the *Caltrans Surveys Manual*
2. Presentation files for SMB meetings and Transportation Research Board (TRB) AFB80 committee presentation
3. Input for and review of the *Caltrans MTLS Guidelines* (see Chapter 3 for details)
4. Documented MTLS data management plan (included in *Caltrans MTLS Guidelines*)
5. Documentation of the process and result of 360-degree camera integration with MX8
6. GTPG implementation and documentation
7. MTLS target spacing experiment design, results, and recommendations
8. GTPG reference point cloud

Chapter 2: Provide Deployment Support for MTLS use in California

This task included:

- General technical support
- MX8 front center camera repair
- MX8 Applanix Position and Orientation System (POS) LV520 firmware upgrade
- VMX-1HA software upgrade
- VMX-1HA camera repair support

General Technical Support

General technical support included:

- Webinar and telephone support for:
    - MTLS software—Trimble Trident and Applanix POS Post-processing Package (POSPac) Mobile Mapping Suite (MMS)—installation and configuration
    - MTLS post-processing using Trimble Trident and Applanix POSPac MMS. Common errors in Applanix POSPac MMS were related to the corrupted Global Navigation Satellite System (GNSS) base station file(s) and errors in base station coordinates.
    - MTLS data collection support using the updated Trimble Trident Capture 7 data collection software with Ladybug Camera
    - Laser scanners overheating due to high ambient temperature
    - MX8 vehicle high power alternator failure
- Biannual Inertial Measurement Unit (IMU) health checks
- System diagnostics to identify hardware failures and make corresponding repairs
- MX8 MTLS data collection training for MTLS users
- MX8 MTLS system and vehicle storage as well as moving the MX8 vehicle for maintenance

Trimble MX8 Front Center Camera Repair

In late June 2018, the MX8 front center camera did not respond to the Trident data collection software. In addition, MTLS users reported that the MX8 back down camera responded only intermittently. An AHMCT researcher performed diagnosis on the MX8 front center and back down cameras and determined that cabling was not the cause of the malfunctions. The broken front center camera was removed from the MX8 front camera pod and shipped for repair to FLIR Systems, Inc., the camera maker, without the lens. The front center camera repair cost $200. Figure 2.1 shows the front camera pod under the front sensor pod cover. Figure 2.2 shows the interior view of the front camera pod with the silica gel desiccant removed.

FLIR completed the front center camera repair. The repaired front center camera was reinstalled into the front camera pod with new silica gel desiccant in July 2018. System verification tests were performed to verify that all sensors functioned properly, including the front center camera. The MX8 was put back into operation in July 2018.

The back down camera now works consistently. The back down camera failure could not be duplicated in the controlled environment of the shop. The cause of the back down camera failure was unknown and undetermined.

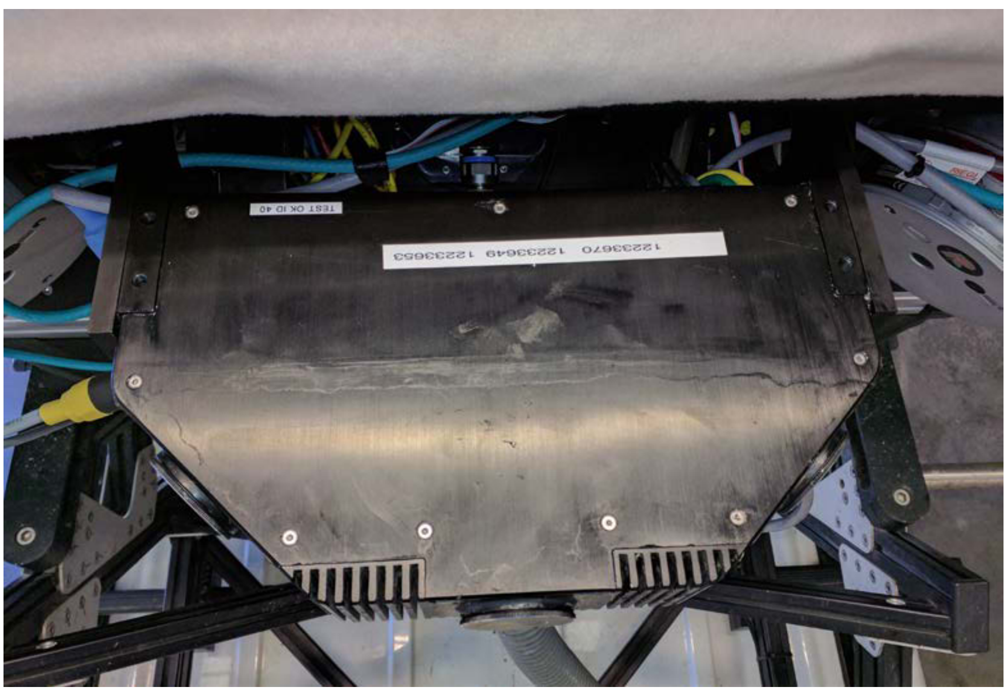

Figure 2.1: Housing for three MX8 front cameras

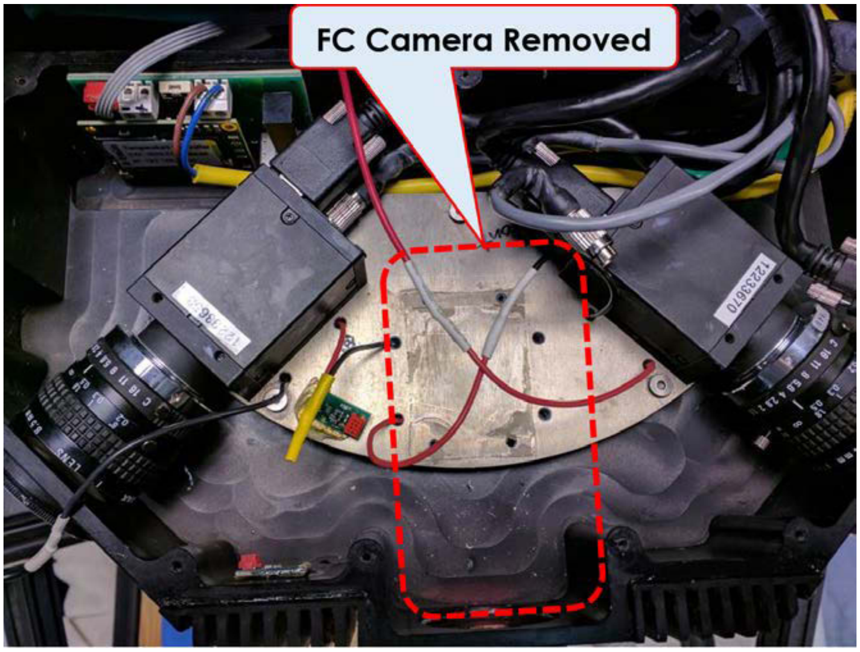

Figure 2.2: Inside view of the MX8 front camera housing with FC camera removed

Trimble MX8 Applanix Firmware Upgrade

The Applanix POS LV520 GNSS/IMU system firmware was updated from version 5.2 to 9.6 in January 2018. The firmware update also included GNSS receiver firmware update. In order to update to the latest version of the GNSS firmware, a few complete update cycles were performed through intermediate firmware versions as the update to the latest version could not be done directly. This may be pertinent for future updates.

The Applanix POS LV520 GNSS/IMU system firmware was updated from version 9.6 to10.11 in December 2018. The latest firmware supports all four major GNSS constellations—the US Global Positioning System (GPS), the Russian Globalnaya navigatsionnaya sputnikovaya sistema (GLONASS), the European Galileo, and the Chinese BeiDou. The MX8 system was tested after the firmware update. The latest Applanix POSPac MMS GNSS/IMU post-processing software supports GPS, GLONASS, and Galileo signals.

VMX-1HA Software Upgrade

Riegl released a new firmware/software that enhanced the integration of the Ladybug 360-degree camera with their system. Previously, the Ladybug 360-degree camera was controlled by a laptop. The Ladybug 360-degree camera data was stored on the laptop, requiring additional steps to transfer the data. The new firmware/software enhancement allows the on-board computer to control the Ladybug camera and store its data, eliminating the need for an additional laptop. The software update reduces setup and data transfer steps and complexity.

The Riegl computing unit consists of two on-board computers. One computer runs the Windows 10 operating system. The other computer runs the Linux operating system and controls all the cameras. In order to run the new camera control software, the Linux computer's operating system must be upgraded to Ubuntu 16.04. Riegl provided detailed upgrade procedures. After reviewing Riegl documents on the VMX-1HA software upgrade, a bootable Universal Serial Bus (USB) drive with the new VMX-1HA computer embedded Linux operating system was created.

The software update was performed in District 12 in September 2018. Before the software update, the Ladybug camera USB-3 cable was re-routed in order to reach and plug into the Riegl computing unit. After that, the Linux computer operating system was upgraded to Ubuntu 16.04. The enhanced Riegl camera control software was installed onto the Linux computer using the Windows 10 computer. The installation process requires clearing the Putty key on the Windows 10 computer before running the installation software. The system was tested with District 12 surveyors after the software upgrade to ensure the system was working properly. The entire process was completed in one day.

VMX-1HA Camera Repair

During the VMX-1HA testing after the software update, the image output from Camera 2 was found to be blurred or unfocused as shown in Figure 2.3. Camera 2 is the Riegl VMX-1HA back right camera. Sample data was collected and sent to Riegl for diagnosis. Photographs of the broken camera lens, shown in Figure 2.4, were also sent to Riegl. Eventually, the back right camera was returned to Riegl for repair. The repaired camera was returned to District 12. District 12 surveyors completed the camera installation and performed system verification testing.

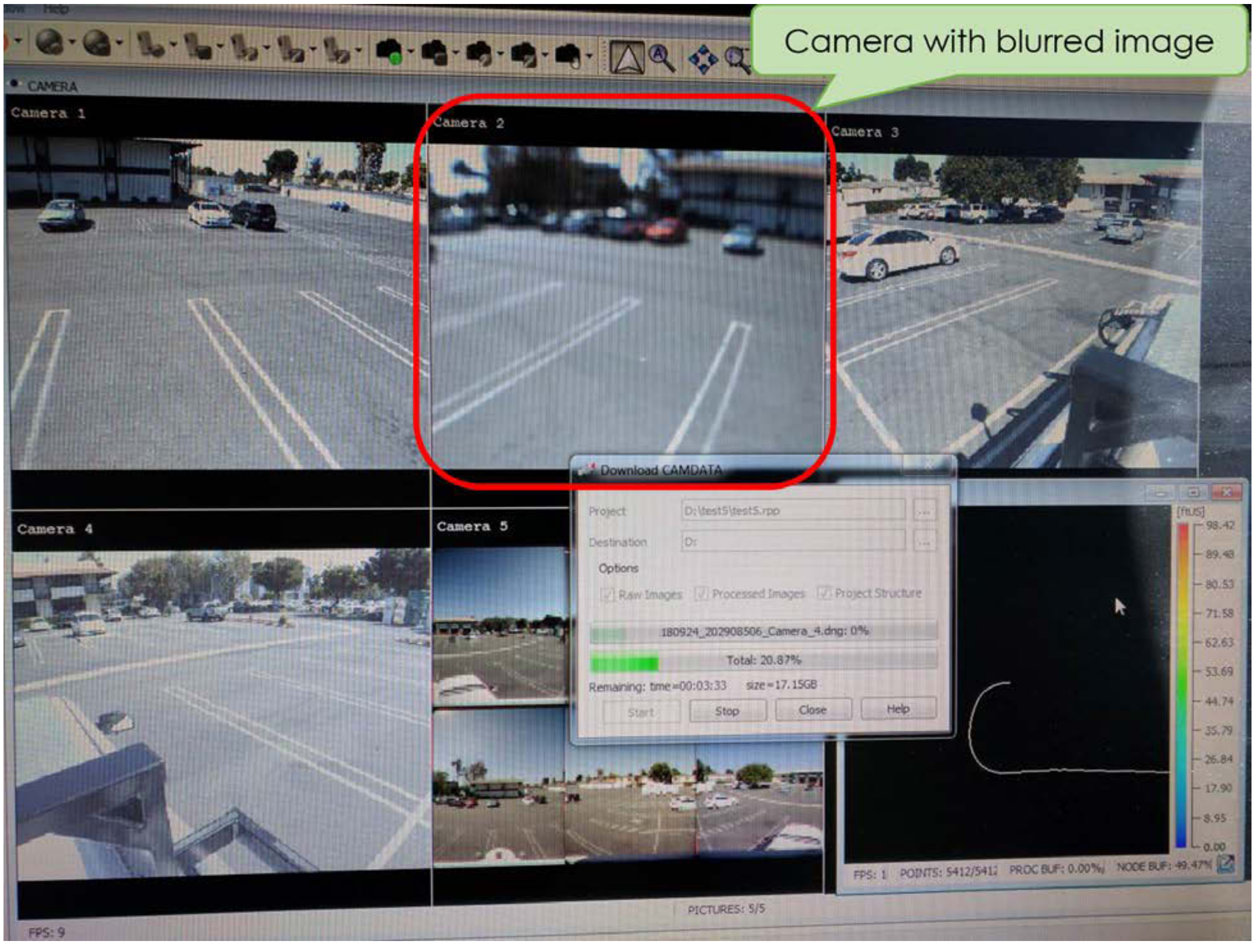

Figure 2.3: Screenshot showing blurry image from VMX-1HA Camera 2

Figure 2.4: VMX-1HA Camera 2 mounted on the rear passenger side of the vehicle

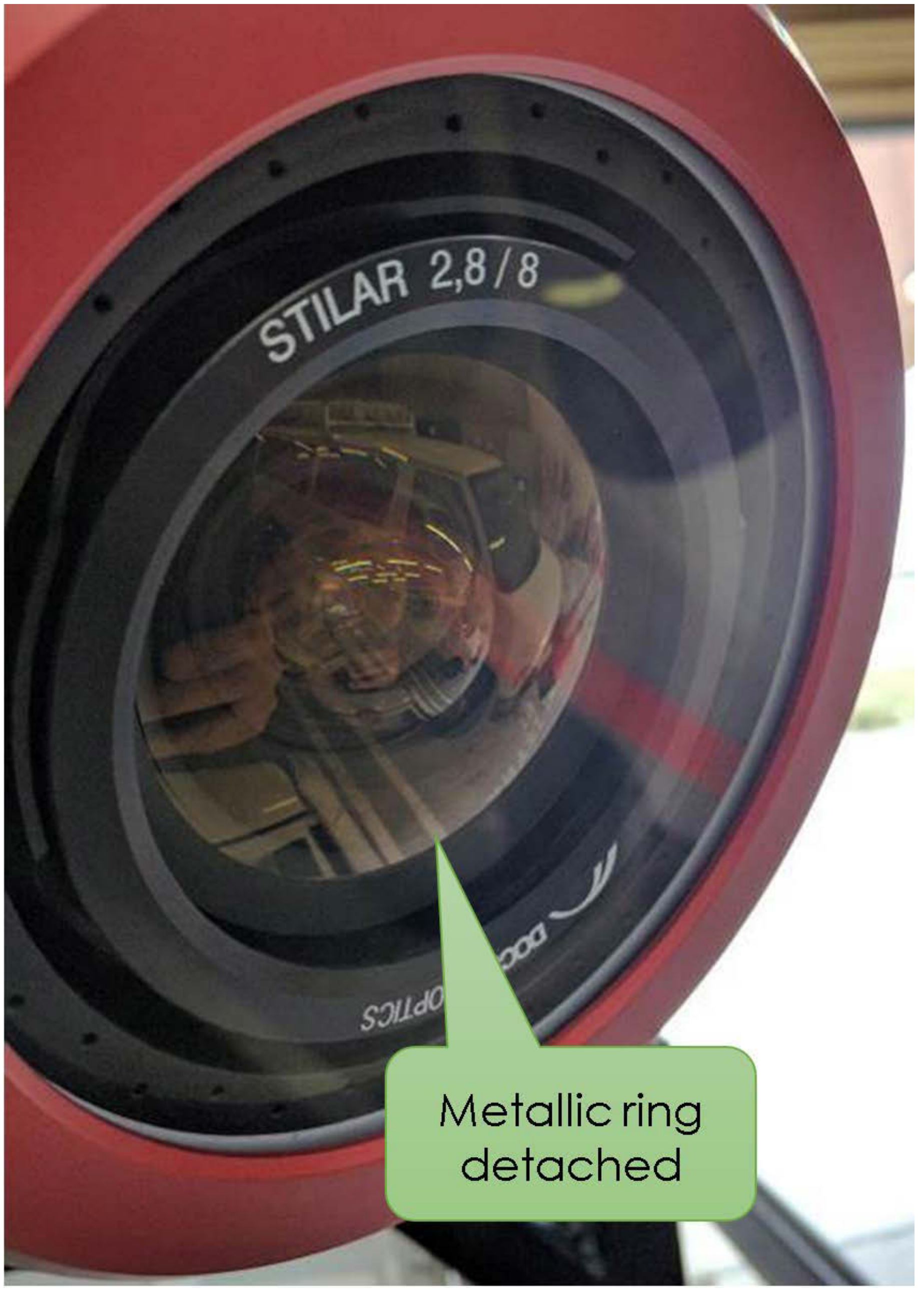

Figure 2.5: Close-up view of VMX-1HA Camera 2 lens. The metallic ring detached from the lens and contacted the camera housing glass cover.

External Outreach

Caltrans hosted the TRB AFB 80 meeting in July 2018. AHMCT assisted Caltrans OLS in showcasing the two Caltrans MTLS systems to the national AFB 80 meeting attendees. AHMCT and OLS also presented Caltrans' experiences and status in MTLS deployment to the attendees, which included Federal Highway Administration (FHWA) and State DOTs personnel as well as AFB 80 committee members.

AHMCT and OLS held a webinar meeting with Florida DOT and Riegl and a teleconference with Oregon DOT to exchange ideas, best practices, and lessons learned on MTLS deployment. The exchanges were very valuable to all participants. Additional webinar meetings with Florida DOT and Oregon DOT were planned for the future.

AHMCT reviewed Caltrans' Asset Collection Scope of Work from the Office of Roadway Engineering and provided feedback.

Chapter 3: Assist Caltrans in Updating Documents and in Training Staff on MTLS Operations

Under this task, the AHMCT researcher supported Caltrans surveyors in creating *Caltrans MTLS Guidelines* and updating Chapter 15 of the *Caltrans Surveys Manual*.

AHMCT also assisted Caltrans in training Caltrans staff on MTLS operations on an as-needed basis due to personnel retirement or promotion. This task included providing on-site and remote support for Caltrans MTLS surveyors.

Update of Chapter 15 of the *Caltrans Surveys Manual*

AHMCT supported OLS in updating Chapter 15 of the *Caltrans Surveys Manual*. *Caltrans Surveys Manual* Chapter 15 addresses Caltrans standards related to stationary Terrestrial LiDAR and MTLS. A workshop was held with OLS personnel and district surveyors in July 2017 to gather input and feedback on the updated draft of the *Caltrans Surveys Manual* Chapter 15. In addition, the draft of the *Caltrans Surveys Manual* Chapter 15 was provided to other OLS and district surveyors for review and feedback. The *Caltrans Surveys Manual*, including the Chapter 15 updates, was published on Caltrans' website in June 2018.

Caltrans MTLS Guidelines Document

Background and Objectives

In its growing use of MTLS, Caltrans OLS has recognized the need for a guidelines document to document and preserve the institutional knowledge in MTLS workflows and procedures as well as best practices and lessons learned. Surveys has gained significant knowledge regarding workflows, procedures, practices, and lessons learned. However, Caltrans experiences typical turnover of staff at both the district and Headquarters (HQ) levels. Turnover is typically due to rotation to a new position, promotion, or retirement. Caltrans has been experiencing a large wave of retirement in the past few years, which will continue on into the near future. All of these factors introduce the need for guidelines to document and preserve institutional knowledge of MTLS as well as support remaining personnel in passing on this critical knowledge. As this need was recognized, Caltrans OLS decided to develop the *Caltrans MTLS Guidelines* document.

The objective of the *Caltrans MTLS Guidelines* is to document and preserve the institutional knowledge in MTLS workflows and procedures as well as best practices and lessons learned. These guidelines document MTLS institutional knowledge in written form to be passed on to the new generation of surveyors as current MTLS personnel are promoted or retire.

Caltrans MTLS Guidelines *Development Process*

Two one-week long workshops were held in February 2019 and March 2019 with main MTLS users from different Caltrans districts. The first MTLS workshop focused on training Caltrans MTLS users in project planning, execution, and data collection. The second MTLS workshop focused on training Caltrans MTLS users in MTLS data post-processing and feature extraction. The active participation of Caltrans MTLS users was vital to the resulting *Caltrans MTLS Guidelines* document.

Information gathered from Caltrans MTLS users was organized, and several draft guidelines documents were circulated for review by OLS and district MTLS users. The 381-page *Caltrans MTLS Guidelines* document consists of nine chapters and twelve appendices as listed below. The document was completed in January 2020.

Caltrans MTLS Guidelines *Contents*

Chapter 1 Introduction (Overview of MTLS surveys and MTLS workflow)

Chapter 2 MTLS Staff, Roles, & Responsibilities

Chapter 3 MTLS Planning

Chapter 4 GNSS/IMU Data Post-Processing

Chapter 5 MTLS Data Post-Processing

Chapter 6 Feature Extraction and Delivery

Chapter 7 Transferring Extracted Data to Civil 3D

Chapter 8 MTLS Data Management and IT Resources

Chapter 9 MTLS Support

APPENDIX A MTLS Charging Code

APPENDIX B MTLS Workload Priority Guideline

APPENDIX C MX8 – Maintenance

APPENDIX D Trident Capture Ver. 7 Workflow with Ladybug 5+ Camera

APPENDIX E VMX-1HA – Dispatch & Receiving Checklist

Chapter 4: Support MTLS Data Management and Related IT Deployment

Caltrans has completed over 300 MTLS projects and scanned over 1,700 centerline miles. Currently, Caltrans stores about 220 Terabytes of MTLS data across different district servers, external drives, and office workstations. AHMCT worked with OLS and district surveyors to initiate MTLS data management efforts. The *Caltrans MTLS Guidelines* document includes the resulting work documented in Chapter 8: MTLS Data Management Plan and IT Resources, which contains the following:

- 8.1 MTLS Data Management Plan
  - 8.1.1 Background
  - 8.1.2 Objectives
  - 8.1.3 Roles and Responsibilities
  - 8.1.4 MTLS Data Backup
  - 8.1.5 Data Retention and Formats
  - 8.1.6 Data Organization
  - 8.1.7 Data Directory Structure and Naming Convention in the MTLS Project Folder
  - 8.1.8 Data Transfer Procedures
  - 8.1.9 Standards for Data and Metadata
  - 8.1.10 Access, Sharing and Security
- 8.2 IT Resource Requirements
  - 8.2.1 MTLS Software
  - 8.2.2 Number of Workstations Required
- 8.3 Handling Large Data
  - 8.3.1 Windows 10 File Explorer Crashes when opening MTLS Folders
  - 8.3.2 Civil 3D Performance Enhancement

In addition, OLS worked with IT to provide MTLS data storage for backup purposes. A district-to-OLS data transfer instruction document was completed as part of this task. Caltrans districts have started to transfer data to the OLS data storage, which is managed by Caltrans IT.

In a previous research project with Caltrans District 4, AHMCT developed LiDARCrawl software [1]. LiDARCrawl automates the MTLS data cataloging process and provides users with a PostGIS database of Caltrans' current MTLS data coverage on any given data storage device. The system supports Geographic Information System (GIS)-based visualization of data availability and properties. AHMCT has discussed the use of LiDARCrawl software to catalog MTLS data with Caltrans Computer-Aided Design (CAD) and Drafting (CADD) and OLS. However, more work remains to develop the best approach for integrating MTLS data with a GIS.

Chapter 5:
External Sensor Integration with the MX8

FLIR Ladybug 5+ Camera Integration

The 360-degree images from the Ladybug 5 camera on the VMX-1HA MTLS system was well received by Surveys' customers. The image quality is much better than the on-board camera without any custom processing. The 360-degree image viewer is easy to use for general users without extensive training. Thus, the Ladybug 5+ camera was purchased and integrated to the MX8 system.

The integration tasks included:

- Determining the best Ladybug 5+ camera placement location
- Designing, fabricating, and installing the Ladybug 5+ camera mount and cover (see Figures 5.1, 5.4, 5.5, and 5.8)
- Designing, fabricating, and installing the standing platform with traction tape (see Figures 5.2, 5.4, and 5.5)
- Integrating the image capture triggering with the MX8 system. A new cable was added to the Trimble MX8 sensor pod to connect the existing camera digital triggering signal to the Ladybug 5+ camera.
- Adding a new computer to control the Ladybug 5+ camera as well as storing its image output data (see Figure 5.6). The Ladybug camera software is not compatible with existing MX8 data collection software. Thus, an additional computer and display were required.
- Integrating the geolocation data with the Ladybug 5+ camera data capture software
- Revising the Trimble Trident Capture 7 workflow document to include instructions for Ladybug camera data collection procedures
- Providing training and technical support to MTLS users for using the Ladybug 5+ 360-degree camera
- Relocating the front GNSS antenna and performing GPS Azimuth Measurement Subsystem (GAMS) calibration of the POS LV520 system

The Ladybug 5+ camera integration tasks were completed in February 2019. The MX8 with Ladybug 5+ camera was used for the Camp Fire survey and several subsequent MTLS projects.

AHMCT has experimented with the use of ArcGIS Pro and an AHMCT web server to share Ladybug Camera 360-degree images on the ArcGIS online web portal, which provides a Google Street View™-like user interface. The initial end user experience from OLS and CADD was positive. However, automating the process requires more work.

Based on the successful integration of the Ladybug 5+ camera with the MX8, it is worthwhile to consider integration of the MX8 or the Riegl VMX-1HA system with other external sensors, such as 3D-GPR and thermal-imaging cameras.

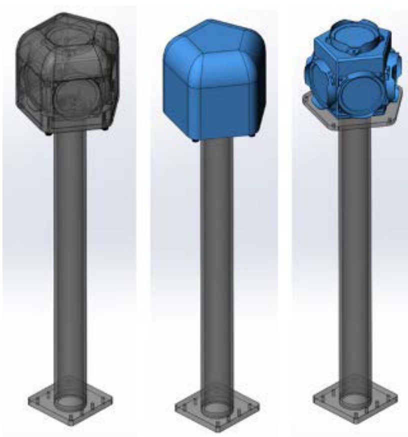

Figure 5.1: CAD model of the Ladybug 5+ camera mount and cover

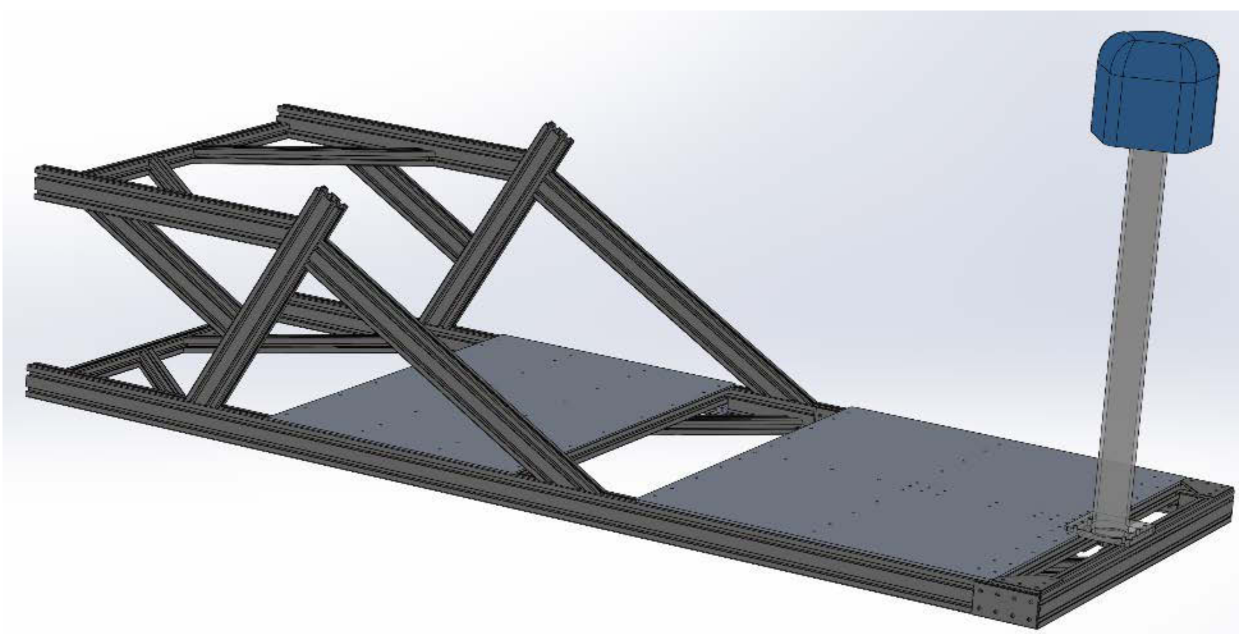

Figure 5.2: CAD model of the standing platform with Ladybug 5+ camera mount and cover

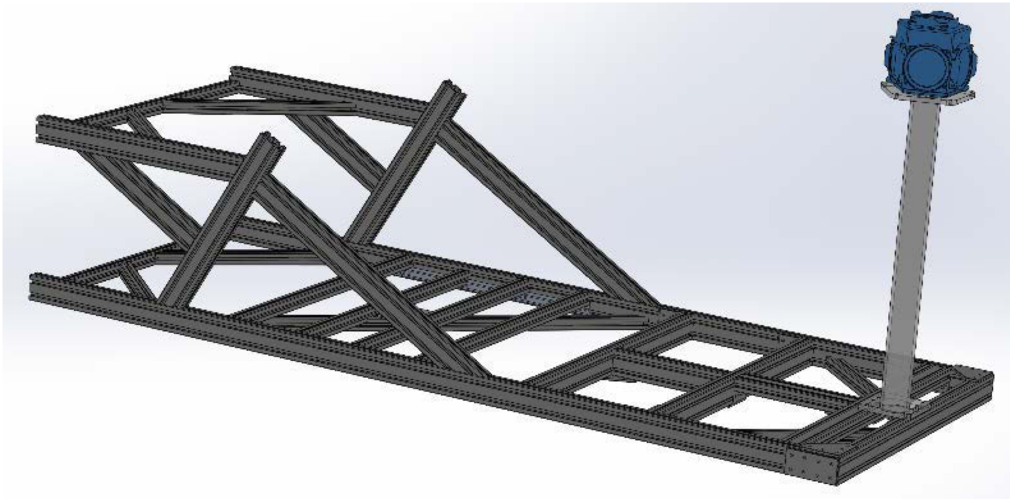

Figure 5.3: CAD model of the standing platform and Ladybug 5+ camera mount with standing plate and camera cover removed

Figure 5.4: MX8 roof-mounted sensor pod with standing platform and Ladybug 5+ camera mount with camera cover

Figure 5.5: MX8 roof-mounted sensor pod with standing platform and Ladybug 5+ camera mount with camera cover removed

Figure 5.6: Ladybug 5+ data collection computer setup

Figure 5.7: Ladybug 5+ camera data collection computer display location

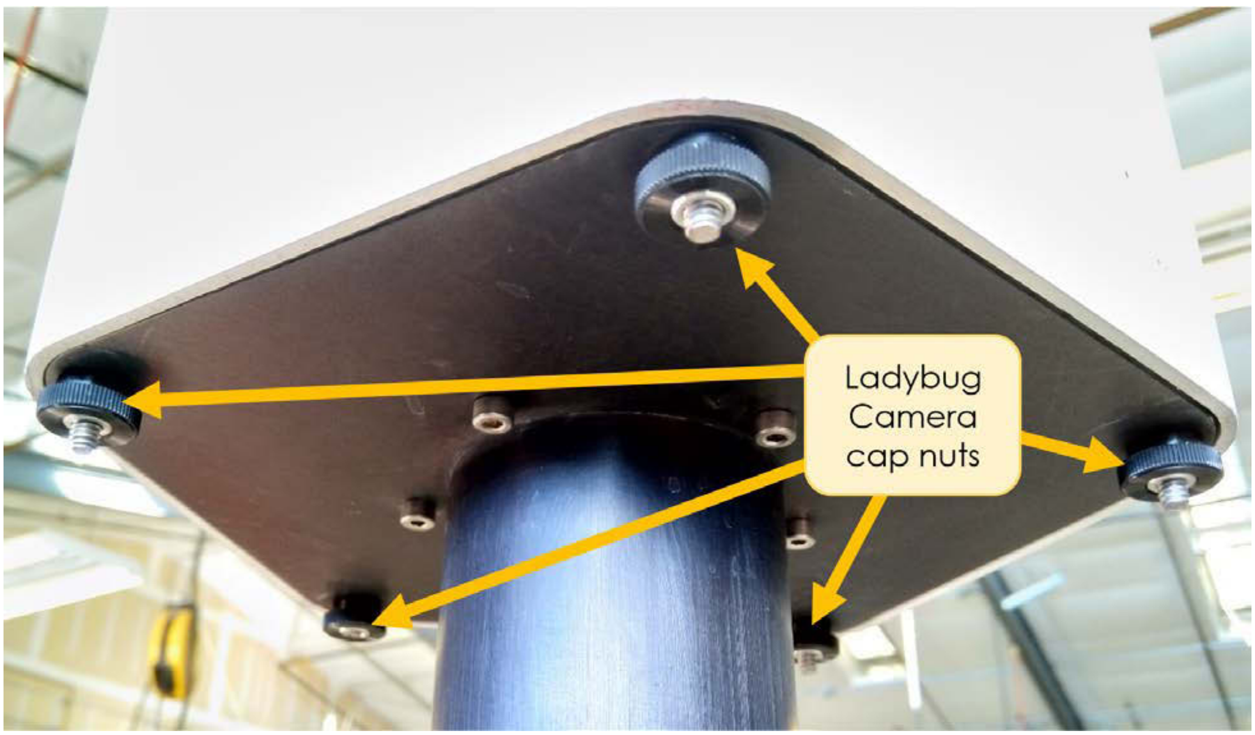

Figure 5.8: Ladybug 5+ camera cap nut locations

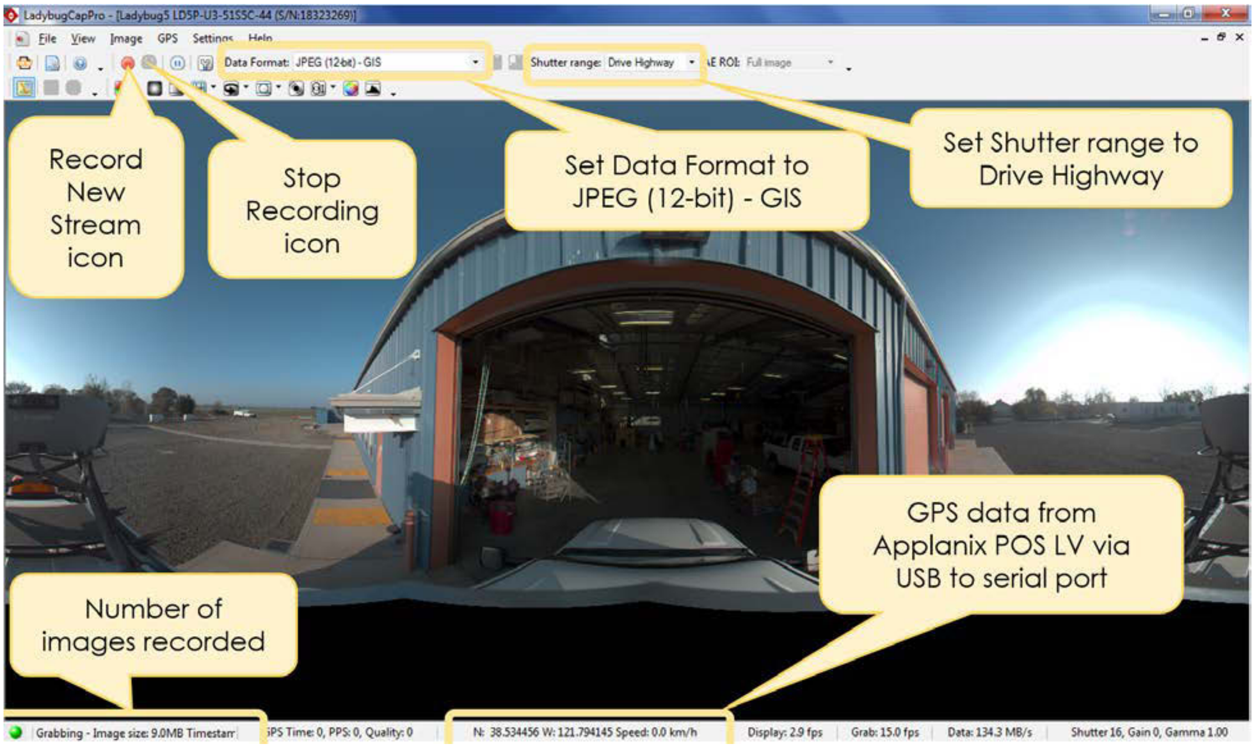

Figure 5.9: LadybugCapPro user interface

Figure 5.10: Example of a Ladybug 5+ camera 360-degree image

Chapter 6: Establish a Geospatial Technology Proving Ground (GTPG) and Perform Target Spacing Research

Background and Need

Caltrans does not have a GTPG or any baseline data to help verify mobile mapping data from vendors or other geospatial technology platforms elsewhere in Caltrans. Without a GTPG, Caltrans cannot calibrate or verify current system performance before or after any component changes. There is no baseline data available to determine whether any new equipment or third-party data would meet Caltrans' design specifications and requirements. The nearest potential proving ground in Northern California is impractical and not designed to support Caltrans' needs and research efforts at UCD. Having a Caltrans-specific GTPG will aid with further research and development in using current MTLS and Stationary Terrestrial Laser Scanning (STLS) standards and specifications as well as help to manage the capabilities and capacities of the Surveys Program.

Caltrans also needs a GTPG for system validation of the two current Caltrans MTLS vehicles as well as for determining optimal control point spacing and quantifying and verifying vendor-acquired terrestrial, airborne LiDAR, and remote sensing data. The GTPG baseline data will be available for the integration of other current Caltrans geospatial technology platforms, such as photolog, pavement assessment, asset management, Subsurface Utility Engineering (SUE), and connected autonomous vehicles. Additional research may make use of a GTPG for investigation into combining geospatial tools and developing new tools and techniques.

Objectives

The objective of this task was to design and survey a GTPG for the MTLS calibration validation of the two current Caltrans MTLS vehicles, for quantifying and verifying vendor MTLS data, and for future research of other Caltrans mobile mapping platforms.

AHMCT also designed and performed experiments to determine optimal target spacing for MTLS surveys using the GTPG site. The experimental data provided the relationship between desired vertical accuracy vs. target spacing.

The experiment’s results will be used to update Chapter 15 of the *Caltrans Surveys Manual*.

The GTPG mobile and static scan reference point cloud will be used to verify vendor-acquired terrestrial, airborne LiDAR, and remote sensing data as well as integration with other Caltrans geospatial technology platforms such as photolog, pavement assessment, asset management, and connected autonomous vehicles. In the future, the reference point cloud may also be used to investigate the combination of other geospatial tools such as GPR.

The GTPG site point cloud may also be used to:

- Experiment with various methods of performing uncontrolled MTLS point cloud registration without painted targets
- Support MTLS system evaluation and validation as well as validation of third-party data
- Support third-party use of point cloud data for autonomous vehicle experimentation

Establish the GTPG

The first task was GTPG site selection. In consultation with OLS, the GTPG site was selected based on proximity to Sacramento, traffic volume, and median and shoulder width. The GTPG is located at Yolo County State Route 113 southbound from postmiles 3.5 to 7.14, including on-ramps and off-ramps at County Road 29 and County Road 27. The MTLS targets are located on both the median and shoulder.

Working with OLS, a GTPG implementation plan was created to document and plan for the GTPG deployment. The GTPG plan, which was revised as needed, included an estimated schedule, GTPG control network design, and MTLS control target layout design as shown in Figure 6.1. GTPG site reconnaissance was conducted with OLS personnel to determine primary control locations and complete the GPS survey plan. The primary control and MTLS target locations are shown in Figure 6.2. The MTLS target nominal spacing is 500 ft. The MTLS target spacing on the shoulder is not uniform near the on-ramp and off-ramp due to physical constraints of available space.

A request for quote (RFQ) for GTPG control and MTLS target survey was sent to professional survey firms. Two quotes were received. R.E.Y. Engineers, Inc., was selected to perform the survey work. A kickoff meeting was held with R.E.Y. Engineers before work was initiated. R.E.Y. Engineers completed the GTPG control and MTLS target survey in July 2019 and provided the required deliverables stated in the RFQ, including a detailed survey report.

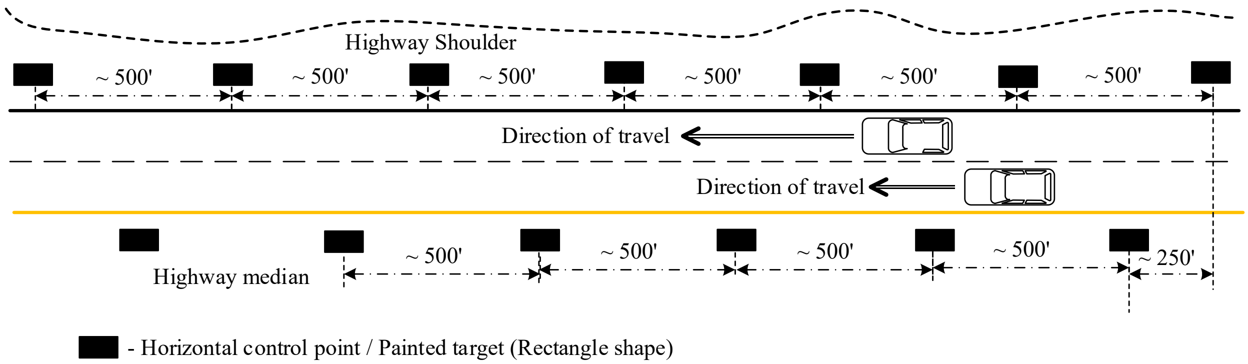

Figure 6.1: GTPG MTLS control target layout design

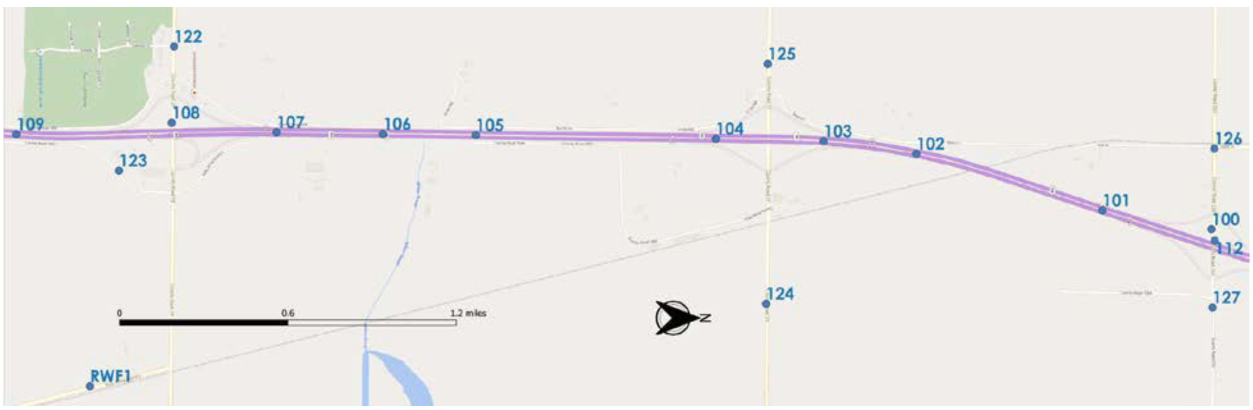

Figure 6.2: Aerial view of GTPG site overlaid on Microsoft Bing Maps. The blue round dots, numbered from 100 to 125, mark the locations of the primary control.

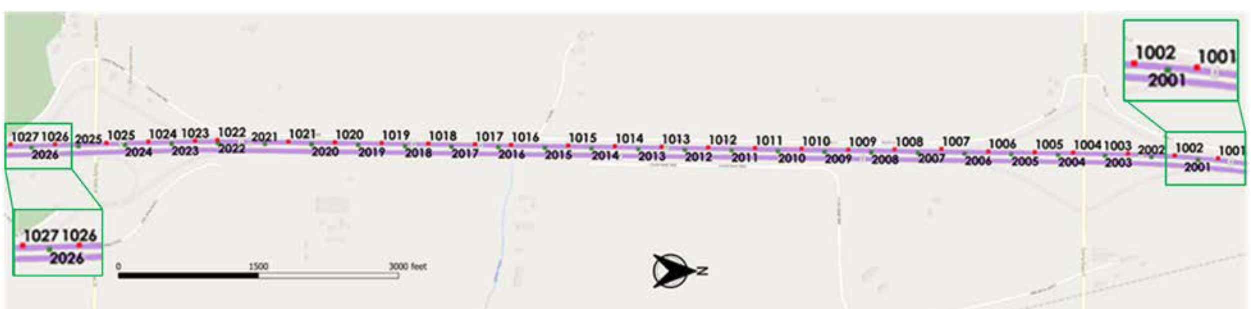

Figure 6.3: Aerial view of GTPG site MTLS targets overlaid on Microsoft Bing Maps. The red squares with numbers 10xx mark the location of MTLS targets on the shoulder. The green squares with numbers 20xx mark the location of MTLS targets on the median.

The MTLS targets are 8" x 18" white thermoplastic pavement marking material. There are 27 MTLS targets on the shoulder numbered from 1001 to 1027 and 26 MTLS targets on the median numbered from 2001 to 2026 as shown in Figure 6.3. The GTPG may be extended along State Route 113 northbound in the future based on funding availability.

Target Spacing Experiment

Setup

The target spacing experiment was designed and carried out to collect data to explore the relationship between desired vertical accuracy vs. registration control spacing. The registration control spacing experiment data was collected in June 2019. The data consisted of four sessions collected on four different days at different times of day (06/05/2019 10:00 AM, 06/06/2019 1:30 PM, 06/12/2019 9:00 PM, and 06/13/2019 1:00 AM). Each session consisted of three passes on the number 1 (left, fast) lane and number 2 (right) lane. The GNSS base station was set at primary control point 106 near the middle of the project as shown in Figure 6.3. Both GPS and GLONASS data were collected for each session except during the 06/05/2019 session. Due to a user error, only GPS base station data was logged during the 06/05/2019 session. The maximum baseline length is less than 2.8 miles.

Caltrans OLS and AHMCT personnel post-processed MTLS data at various registration control spacings. Since the MTLS control targets on the median are uniform in spacing and distance from the fog line as opposed to the MTLS targets on the shoulder, the left laser data from the number 1 lane passes were selected for error statistical analysis. There was a total of twelve passes traveling on the number 1 lane from all four sessions. All MTLS target point cloud points were first manually classified to the target layer. The classification results were then checked manually. The auto target detection function in Trimble Trident was used to determine the MTLS target position within the point cloud.

In the case of 500' spacing registration, all the median MTLS targets (point numbers 2001 to 2026) were used for XYZ registration. The MTLS targets on the shoulder (point numbers 1002 to 1026) were used to determine the vertical errors. Point numbers 1001 and 1027 were excluded in the error statistics since they are outside of the registration area. Point 1001 is the most northern MTLS target located north of point 2001 as shown by the first red point from the right edge of Figure 6.3. Point 1027 is the most southern MTLS target located south of point 2026 as shown by the first red point from the left edge of Figure 6.3. However, since targets 1002 to 1026 were relatively far from the Trimble MX8 MTLS vehicle's left laser scanner (average laser beam distance of 38'), there were not enough laser points on the targets to accurately determine the horizontal error (X- and Y-directions) for 500' control registration spacing. Therefore, there is no data on the horizontal error at 500' registration control spacing. For registration control spacing above 500', the MTLS targets on the median between the registration control points were used to determine the registration error statistics in X, Y, and Z-directions. Table 6.1 shows the MTLS registration points used in the various registration control spacings in this evaluation.

Table 6.1 MTLS targets used for registration

Registration spacing	MTLS target point number	Number of control points for error determination per pass
500'	2001 to 2026	23
1000'	2001, 2003, 2005, 2007, 2009, 2011, 2013, 2015, 2017, 2019, 2021, 2025, and 2026	12
1500'	2001, 2004, 2007, 2010, 2013, 2016, 2019, 2022, 2025, and 2026	16
2000'	2001, 2005, 2009, 2013, 2017, 2021, 2025, and 2026	18
2500'	2001, 2006, 2011, 2021, and 2026	20

Results

Error Characteristics before Registration

Figures 6.4 and 6.5 show two examples of XYZ errors before registration vs. MTLS targets. Since the scanning vehicle was traveling at a constant speed from target numbers 2001 to 2016, both Figures 6.4 and 6.5 can also be viewed as XYZ errors before registration vs. time. In general, the vertical errors (Z-direction) are bigger than the horizontal errors(X- and Y-direction). The XYZ errors of other passes exhibited similar behavior.

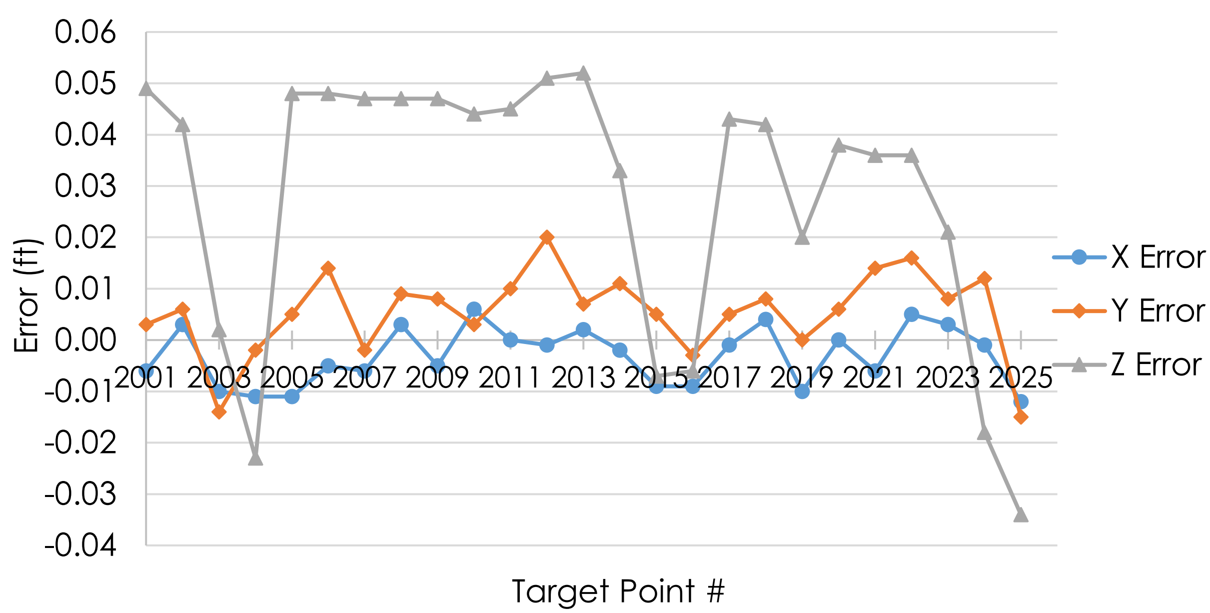

Figure 6.4: Example of position errors vs. MTLS targets before registration (06/06/2019 pass #4)

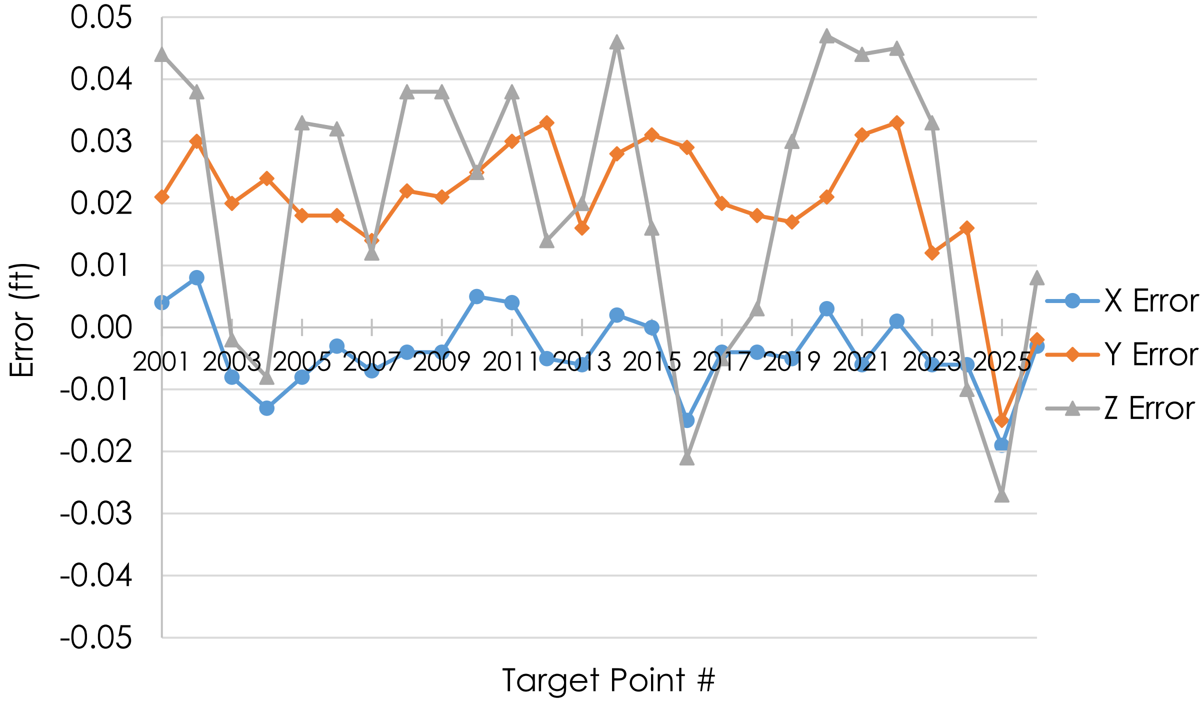

Figure 6.5: Example of position errors vs. MTLS targets before registration (06/12/2019 pass #5)

Each blue dot in Figure 6.6 represents an average (mean) Easting (X) direction error and Easting error standard deviation (σ) for a single pass of single laser data (either left or right). Similarly, each orange diamond in Figure 6.6 represents an average Northing (Y) direction error and Northing error standard deviation for a single pass of single laser data (either left or right). There are 48 blue dots and 48 orange diamonds (6 passes x 2 lasers x 4 sessions = 48 points) in Figure 6.6. Figure 6.6 shows a consistent average error bias over zero, illustrating that there is a systematic offset in the X- and Y-directions. The error standard deviation measures the variability or dispersion of the error from the mean error. The change in GNSS constellation at the data collection time contributed to some of the changes in error variation (error standard deviation value). All data were collected traveling southbound. The horizontal systematic offset could be dependent on travel direction.

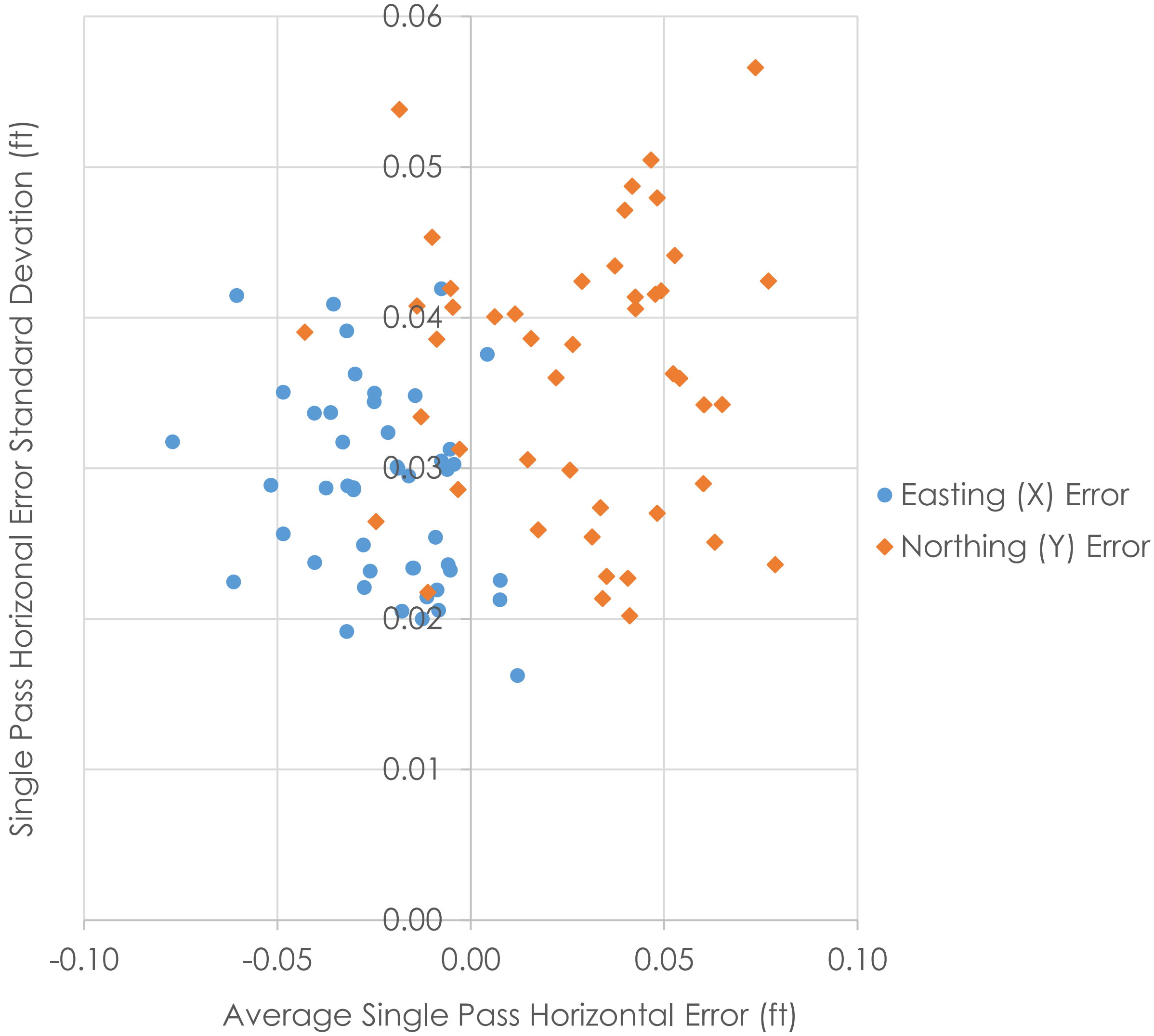

Figure 6.6: Average horizontal (Easting X- and Northing Y-direction) error vs. horizontal error standard devation for left and right laser data of each pass in all four sessions

Each grey triangle in Figure 6.7 represents an average vertical (Z) direction error and vertical error standard deviation for a single pass of single laser data (either left or right). Figure 6.7 shows that both the average vertical (Z) error and the vertical error standard deviation are generally greater than that of the horizontal directions.

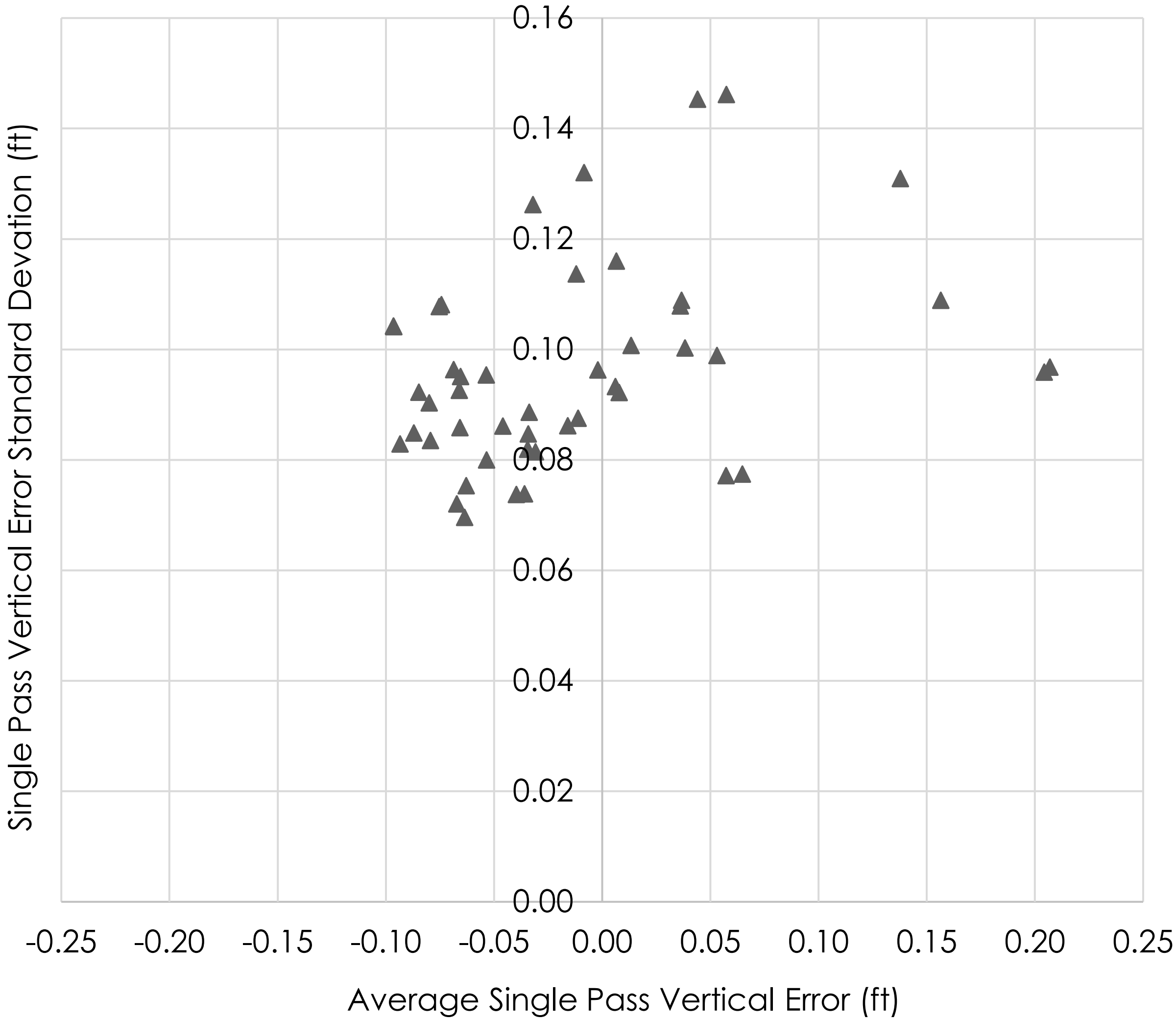

Figure 6.7: Average vertical (Z-direction) error vs. vertical error standard devation for left and right laser data of each pass in all four sessions

Error Characteristics after Registration

Each blue dot in Figure 6.8 represents an Easting (X) error standard deviation of a single pass left laser data on the left lane after registration at registration control spacings of 1000', 1500', 2000', and 2500'. Similarly, each orange diamond in Figure 6.9 represents a Northing (Y) error standard deviation of a single pass left laser data on the left lane after registration at these control spacings. There are twelve blue dots and twelve orange diamonds (3 passes/session x 4 sessions = 12 points). Figures 6.8 and 6.9 illustrate that some passes exhibited smaller error variation after registration than others. The change in GNSS constellation at the data collection time contributed to some of the changes in error variation (error standard deviation value) between different passes.

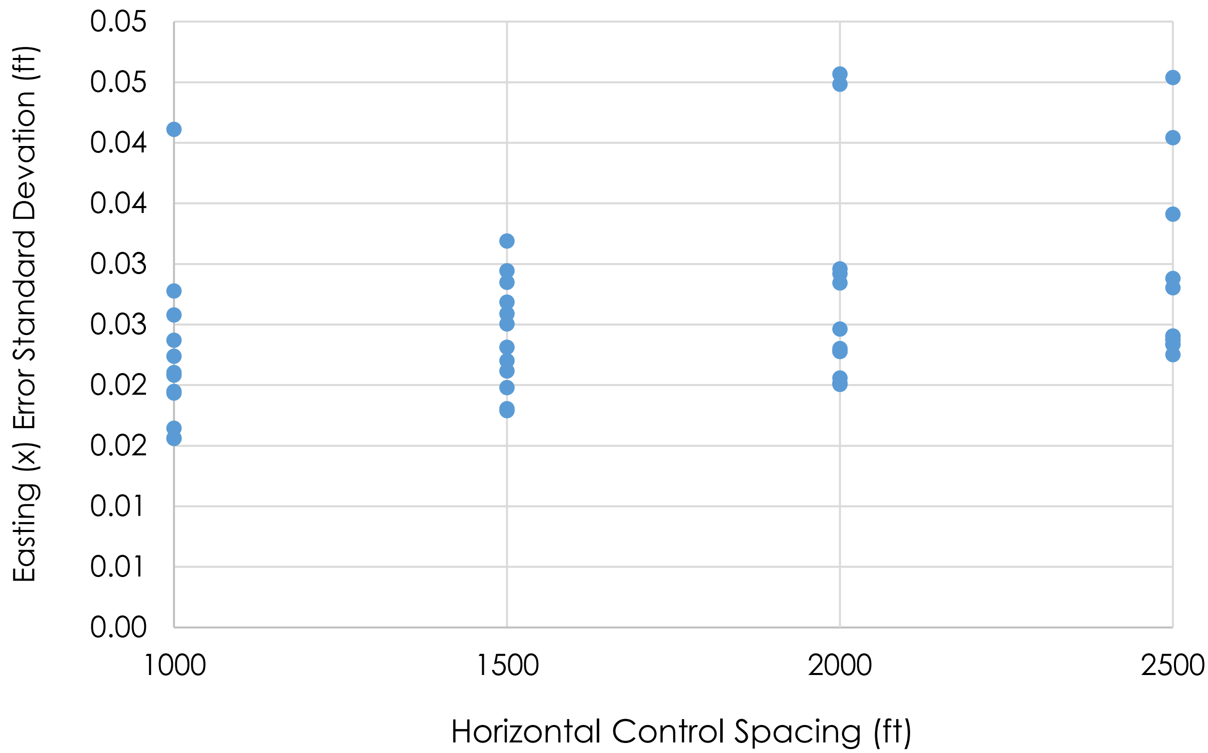

Figure 6.8: Left laser Easting (X) error standard devation of each pass traveling on number 1 lane at various registration control spacings

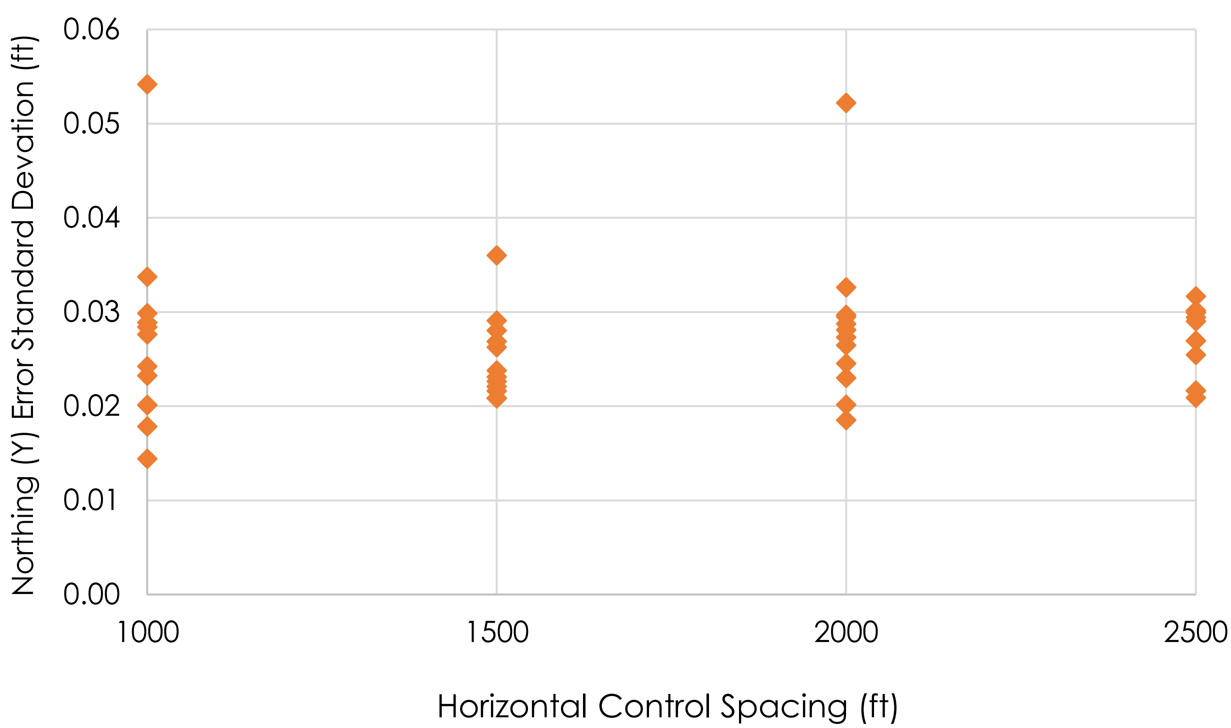

Figure 6.9: Left laser Northing (Y) standard devation of each pass traveling on number 1 lane at various registration control spacings

The horizontal error standard deviations (σ) using various control spacings were calculated combining all twelve passes' horizontal error statistics. Assuming the horizontal errors are normally distributed, the combined horizontal error standard deviations (σ) provide an estimate of the expected MTLS point cloud horizontal accuracy with different control spacings. Figure 6.10 shows X and Y error standard deviations (1σ and 2σ) vs. horizontal control spacing. Sixty-eight percent of the horizontal error in this experiment is smaller than the 1σ line, and 95% of the horizontal error in this experiment is smaller than the 2σ line, assuming the horizontal (X and Y) errors are normally distributed. Even though Figure 6.10 shows small differences between the horizontal accuracy between 1000' to 2500' control spacing, the differences are not statistically significant. Ninety-five percent of horizontal errors are less than 0.07' with horizontal control spacing of 2500' or less.

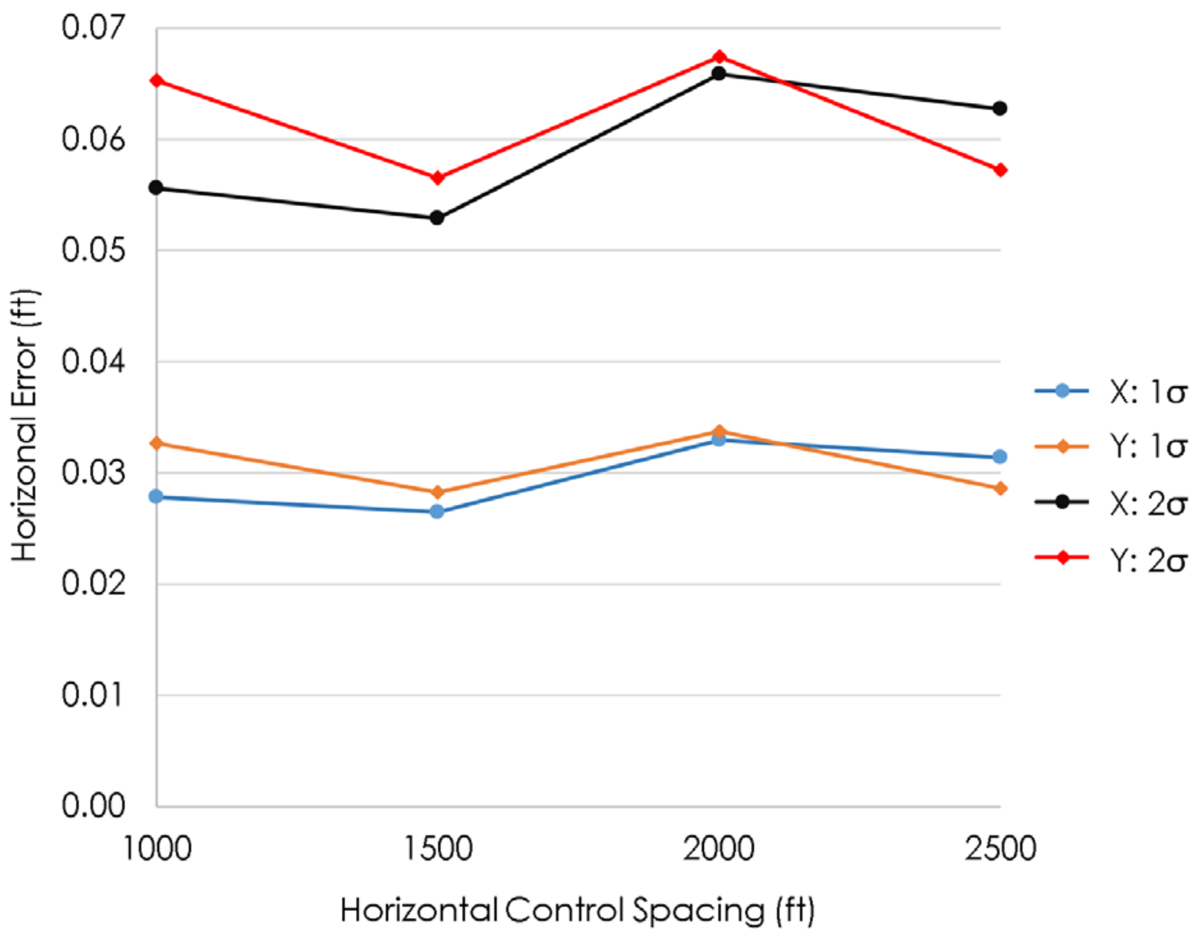

Figure 6.10: Horizontal (X and Y) accuracy estimate with various registration control spacings

Each black triangle in Figure 6.11 represents a vertical error standard deviation (σ) of a single pass for left laser data traveling on the left lane using different control spacings for registration. The vertical error distribution, quantified by σ, varies from pass to pass as shown in Figure 6.11. Moreover, the vertical error σ variation or spread increases as the registration control spacing increases.

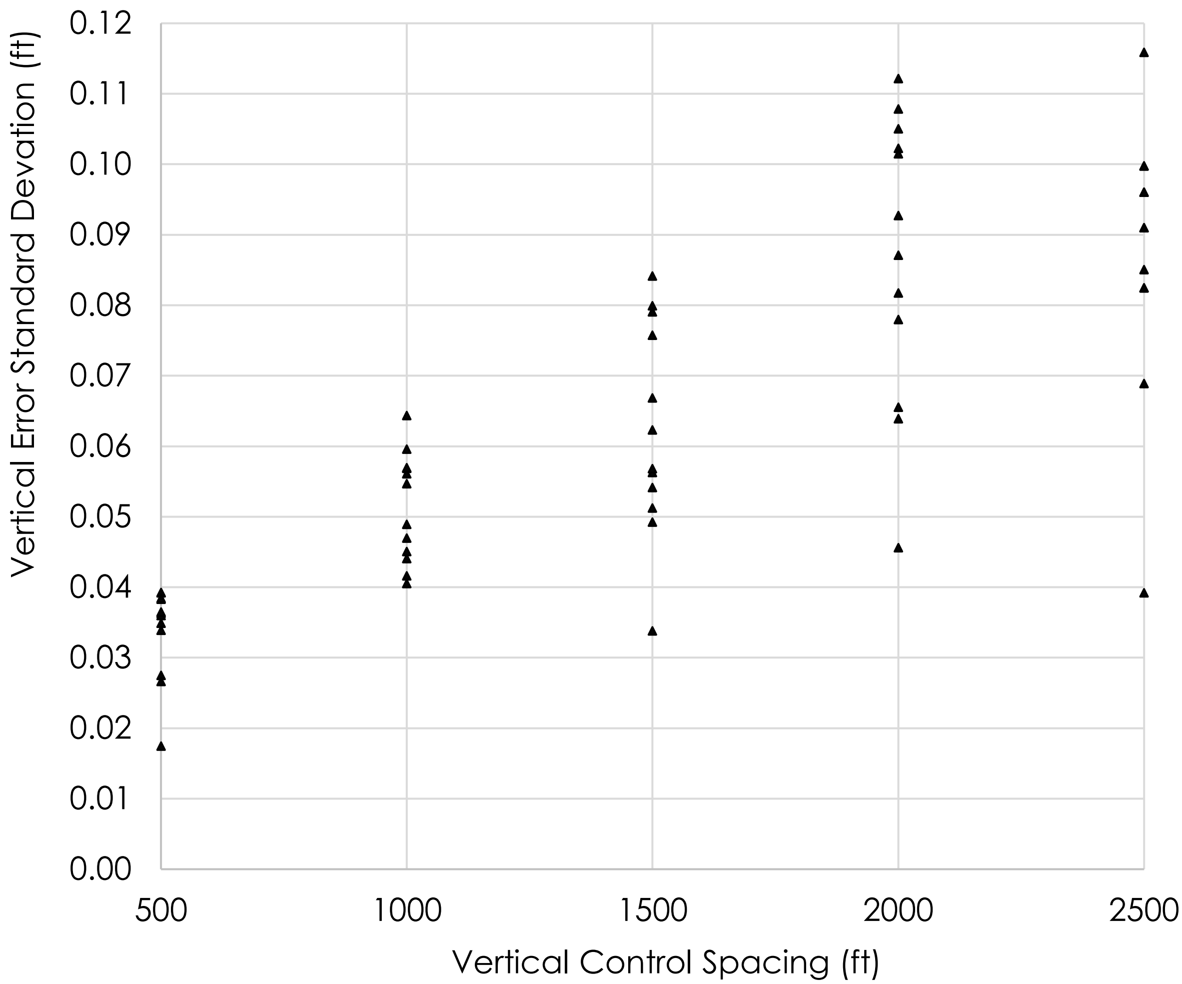

Figure 6.11: Left laser vertical (Z-direction) error standard devation of each pass traveling on left lane at various vertical control registration spacings

The vertical error standard deviation (σ) is calculated using all the error points from all twelve passes with various control spacings. Assuming the vertical errors are normally distributed, the vertical error standard deviations (σ) provide an estimate of the expected MTLS point cloud vertical accuracy with different control spacings. Figure 6.12 shows a plot of vertical error standard deviations (1σ and 2σ) vs. vertical control spacing. Sixty-eight percent of the vertical error in this experiment is below the 1σ line (blue dashed line), and 95% of the vertical error in this experiment is smaller than the 2σ line (orange solid line).

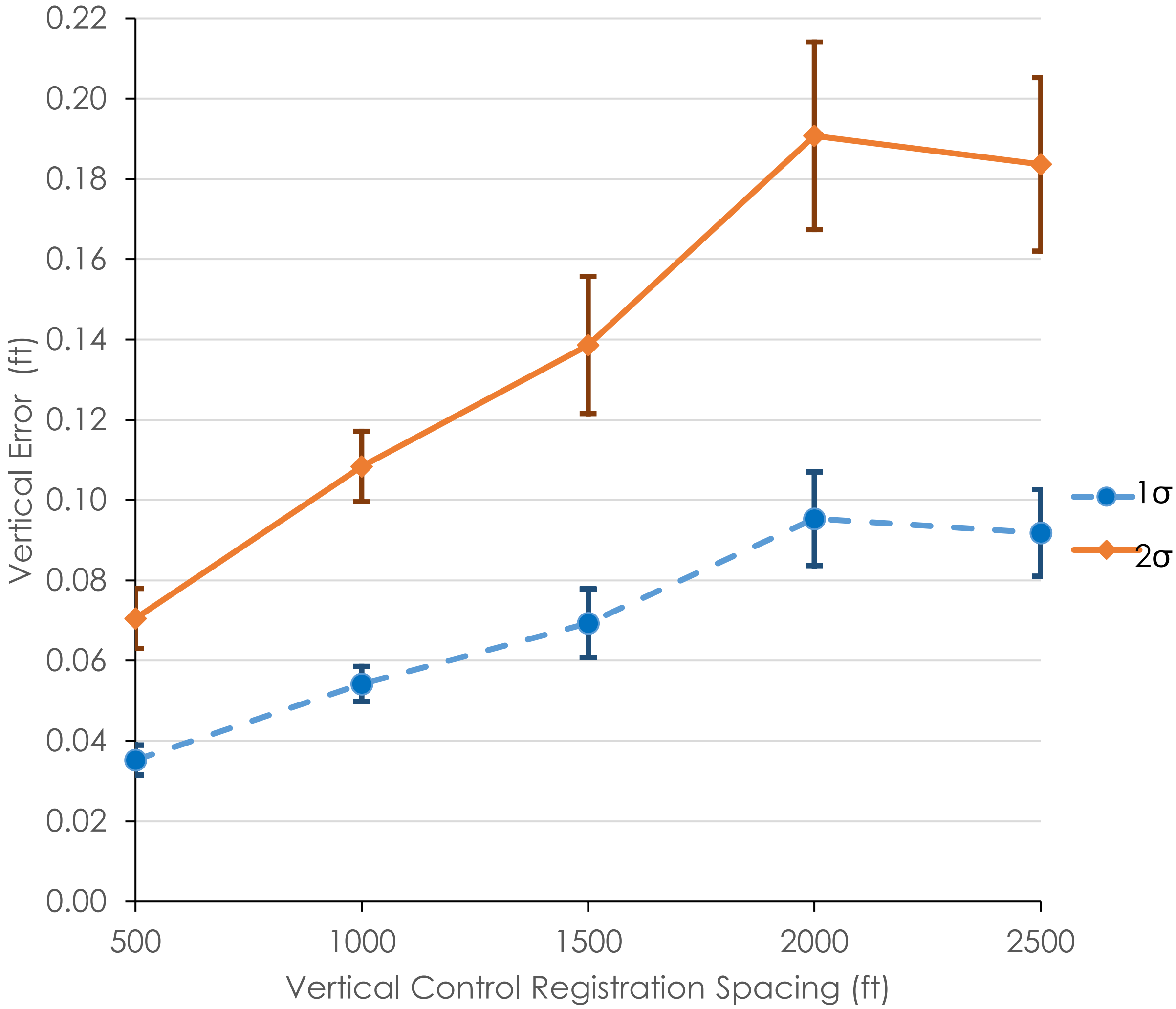

Figure 6.12: Vertical error estimate and 95% confidence intervals with various registration control spacings

The 95% confident interval error estimates are calculated based on the twelve pass standard deviations. The 95% confident intervals are plotted as error bars shown in Figure 6.12. The 95% confident interval valve depends on the sample size and the spread of the error standard deviation shown in Figure 6.11. Figure 6.12 shows that there is no significant change in the vertical accuracy from 2000' to 2500' registration control spacing. The orange line in Figure 6.12 shows that users should expect 95% of vertical error to be under 0.08' when using 500' vertical registration control spacing and 95% of vertical error to be under 0.12' when using 1000' vertical registration control spacing. Users can refer to Figure 6.12 to select the appropriate vertical control spacing to meet a project's vertical accuracy requirement.

Target Spacing Experiment Findings Summary

- The MTLS data was collected under ideal GNSS conditions with very short baseline length. Users should expect a larger standard deviation of the non-registered point cloud error with longer baseline length.
- Figure 6.10 shows that there is no significant change in the horizontal accuracy between 1000' to 2500' control spacing. Users should expect that 95% of horizontal errors are less than 0.07' with horizontal control spacing of 2500' or less. The MTLS horizontal control target spacing ("painted" targets) was recently changed from 500' to 1500' in Chapter 15 of the *Caltrans Surveys Manual*. However, horizontal control targets should be added in GNSS-challenged conditions as well as before and after overhead structures. Caltrans surveyors should refer to the *Caltrans MTLS Guidelines* document for detailed recommendations for MTLS target placement.
- Figure 6.12 may be used as a reference to select the appropriate vertical control spacing in order to meet or exceed a project's vertical accuracy requirement.

Chapter 7: Conclusions and Future Research

Lessons Learned

Documenting best practices, workflow, and lessons learned is vital in the deployment of any technology to maintain institutional knowledge as personnel retire or are promoted. The *Caltrans MTLS Guidelines* will be used for future on-the-job training. This extensive document provides the best repository of lessons learned to date with respect to MTLS by both AHMCT and Caltrans.

Problems and Issues that Affected Product Deployment

MTLS data storage and data management requires more work to find an optimal solution for Caltrans in consultation with Caltrans IT. MTLS data storage and data management must take GIS integration and data sharing (point clouds and georeferenced images) solution(s) into consideration. Other stakeholders will have to be involved in the discussion.

Solutions to Noted Problems and Issues

Long-term MTLS data storage and data management solutions are not available at this time. The solutions require more work, research, and discussions with stakeholders.

Other Considerations for Reaching Full Product Deployment

MTLS can be used for asset management as well as pavement marking and sign reflectivity measurements [2]. However, more research is necessary to improve feature extraction automation to make statewide asset management data extraction viable and cost effective.

The current *Caltrans MTLS Guidelines* do not address GIS data integration and pavement analysis workflow. The GIS data integration must also integrate the georeferenced images from other data sources such as historical photolog images and advanced pavement survey images.

Equipment Issues

The MX8 system is near the end of its lifespan. System replacement funding and procurement will be required soon. The MX8 was procured in 2011, and is thus approximately nine years old.

Conclusions

This research has achieved the project objectives. Some tasks were scaled back due to re-focused funding to support GTPG site survey and deployment.

Key contributions of this research project included:

1. Updated Chapter 15 of the *Caltrans Surveys Manual*
2. Presentation files for SMB meetings and TRB AFB80 committee presentation
3. *Caltrans MTLS Guidelines* containing all the Caltrans institutional knowledge on MTLS usage for the past several years
4. MTLS data management plan
5. Integration of 360-degree camera to MX8 MTLS
6. GTPG design, documentation, and implementation
7. MTLS target spacing experiment design, results, and recommendations
8. GTPG reference point cloud

Future Work and Research

MTLS has much potential to exploit that will benefit Caltrans. A limited number of trained personnel and lack of automation currently limit wider-scale MTLS deployment for other Caltrans customers. Future work includes:

- Expanding other MTLS uses to:
    - Planning phase
    - As-built survey for post-construction
    - Asset data collection
    - Pavement marking reflectivity measurement
- Asset extraction automation with Machine Learning technologies
- Point clouds and images integration with GIS
- Point cloud web portal with basic measurement
- Data integration with other remote sensing systems such as 3D-GPR and thermal-imaging camera

- Expansion of LiDARCrawl software for statewide MTLS data management. AHMCT has discussed the use of LiDARCrawl software to catalog MTLS data with Caltrans CADD and OLS. However, more work remains to develop the best approach for integrating MTLS data with a GIS.
- Use of ArcGIS Pro and a web server to share Ladybug Camera 360-degree images on the ArcGIS online web portal, which provides a Google Street View™- like user interface. The initial end user experience from OLS and CADD for such a system was positive. However, automating this process requires more work.

References

[1] T. Swanston, K. Yen, S. Donecker, R. Bahram, and T. Lasky, “Research and Support for MTLS Data Management and Visualization,” CA17-2996, Sep. 2016.

[2] E. Che, M. J. Olsen, C. E. Parrish, and J. Jung, “Pavement Marking Retroreflectivity Estimation and Evaluation using Mobile Lidar Data,” *Photogrammetric Engineering & Remote Sensing*, vol. 85, no. 8, pp. 573–583, 2019.