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Development of An Online Platform for Streamlining Highway LiDAR Data Collection, Sharing, and Processing

FINAL REPORT
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16. Abstract
Lidar (a portmanteau of "light" and "radar.") is a remote sensing technology that measures distance by illuminating a target with a laser and analyzing the reflected light. Among other applications, lidar is particularly useful for detailed mapping of highway and bridges, highway surface deterioration monitoring, highway information modeling, highway safety analysis, and rapid post-disaster damage assessment. Current spatial resolution of lidar technology can be as precise as millimeter with static terrestrial laser scanning and centimeter with mobile terrestrial laser scanning. The field is rapidly maturing in capabilities, applications, and utility. With more and larger-scale applications of lidar technology happening each day in the transportation sector, effective management and utilization of the collected lidar data, often very large in size, has become a critical issue. Due to their size, lidar data are often delivered to state transportation agencies on hard drives along with other deliverables. A transportation agency often need to procure and set up expensive hardware and software to effectively use these data sets, not to mention the amount of training required for its employees. Because of these limitations, lidar data with the exception of specifically derived products such as bridge clearance, which are often acquired for a specific transportation program, are difficult to be effectively used across multiple divisions and programs. There is a great need for a data infrastructure that can minimize state agencies' investment in hardware and software but still would allow state agencies to store, stream, visualize, and analyze lidar data on demand. This study investigated methods and platforms for managing, sharing, visualizing, and processing of massive point cloud data sets. The study starts with synthesizing existing studies on point cloud data visualization. We systematically characterized point cloud data sets in terms of their data volume, variety, variability, and their processing needs in highway applications. A web-based platform was developed in this study to enable visualization of large-scale point cloud data sets in common web browsers. The web portal is tested using several types of lidar data, including data collected along a large segment of Route 1 in New Jersey. The test demonstrated the effectiveness of the developed portal. The outcome of this research provides a versatile tool for state DOTs to leverage various lidar data sets in their asset management programs as well as in future construction projects.

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INTRODUCTION

Description of the Problem

Lidar (a portmanteau of "light" and "radar.") is a remote sensing technology that measures distance by illuminating a target with a laser and analyzing the reflected light. Among other applications, lidar is particularly useful for detailed mapping of highway and bridges, highway surface deterioration monitoring, highway information modeling, highway safety analysis, and rapid post-disaster damage assessment. Current spatial resolution of lidar technology can be as precise as millimeter with static terrestrial laser scanning and centimeter with mobile terrestrial laser scanning. The field is rapidly maturing in capabilities, applications, and utility. With more and larger-scale applications of lidar technology happening each day in the transportation sector, effective management and utilization of the collected lidar data, often very large in size, has become a critical issue. Due to their size, lidar data are often delivered to state transportation agencies on hard drives along with other deliverables. A transportation agency often need to procure and set up expensive hardware and software to effectively use these data sets, not to mention the amount of training required for its employees. Because of these limitations, lidar data with the exception of specifically derived products such as bridge clearance, which are often acquired for a specific transportation program, are difficult to be effectively used across multiple divisions and programs. There is a great need for a data infrastructure that can minimize state agencies' investment in hardware and software but still would allow state agencies to store, stream, visualize, and analyze lidar data on demand.

Relevance to Strategic Goals

The primary and secondary USDOT Strategic Goals are supported by the proposed project. An effective data infrastructure for lidar technology offers potential to drastically improve state DOTs' design, operation, and maintenance practices. It is well-known that lidar data can be used to rapidly analyze road surface conditions and detect safety issues on roadways (such as sight distance, signage conditions, etc..). The envisioned tool in this research will significantly increase State DOTs' effectiveness and efficiency in exploiting the benefits of lidar data. Such a tool can be used to support and inform decisions and develop models.

Background

To efficiently manage highway systems, State DOTs often collect a variety of geospatial data to support their management programs. These programs include, but are not limited to, bridge clearance measurement, asset inventory and management surveys, as-built surveys, engineering topographic surveys, corridor study and planning surveys, Americans with Disabilities Act (ADA) compliance surveys, deformation surveys, environmental surveys, sight distance analysis surveys, earthwork surveys, coastal zone erosion analysis, crash prediction and response, and construction inspection. The collection of geospatial data to support these programs incurs costs of hundreds of millions of dollars. Crews are often exposed to dangerous road traffic during data collection. Considering the vital role of highway systems for the nation's economy, methods that can collect higher quality geospatial data in a safer manner and with lower cost are immediate needs. The recent rise of city-scale spatial mapping technologies such as airborne, UAV, and mobile lidar technologies has in part addressed these needs, but it also brings additional challenges in managing, sharing, and processing the growing volume of highway lidar data sets. These data sets are too massive to be managed with the traditional desktop computer based computing paradigm. Web-based platforms are potential solutions available to state DOTs to effectively manage the large lidar data sets. Yet, systematic studies on ways of improving state DOTs' capability in handling large lidar data sets are scarce, leading to wasted opportunities in improving the return of investment on lidar technologies.

Research Goals and Objectives

The goal of this project is to develop an online platform for sharing, visualizing, and analyzing lidar data to support typical DOT data needs. The project is based on existing data collection capabilities that have been developed at Rutgers University. These capabilities include static terrestrial laser scanning and mobile terrestrial laser scanning.

Specific objectives are:

(1) Evaluate lidar data characteristics and data analysis needs

(2) Identify ways and mechanisms to share and analyze lidar data

(3) Develop an open-source online platform for lidar data sharing and analysis

(4) Demonstrate lidar data collection, sharing, and analysis with the developed platform using several user cases

Overview of the Report

This report documents the research approach, methodology, findings, conclusions and recommendations of this collaborative research project. The following sections outline the approach and methodology. The next section presents the findings, followed by sections documenting the conclusions and making recommendations for future work and application in state Departments of Transportation.

APPROACH

The objective of this proposal is to investigate how lidar data can be most effectively utilized by state transportation agencies and to develop an open-source online platform for lidar data sharing and analytics. In the project, we will demonstrate how lidar data can be collected, shared, streamed, and processed over an online portal to support DOT design, operation, and maintenance needs. This research proposal involves Rutgers University and infrastructure stakeholders from the NJ region. Jie Gong from Rutgers University will lead the project and be responsible for the overall management of the project.

To set the stage, the researchers will first evaluate examples of lidar data used in state transportation applications. The purpose is to evaluate data quantity and quality, access, rate of change (frequency of data collection), access and longevity. These tasks will involve consultation with out partners in state DOTs.

The project will then explore ways and mechanisms of sharing and analyzing lidar data over the Internet based on literature reviews of applications in other fields associated with data intensive studies. The researchers will identify potential open-source projects that can be used as building blocks for the proposed online platform. As a complement. we will also identify environments to support data sharing.

The next step of the project is to develop the online platform that provides data streaming, visualization, and advanced analytics capabilities. We will set up a data server and develop and deploy a lidar data sharing and analysis software framework. The focus is on defining several data and analytic abstractions that can be expanded later on.

Finally, we will demonstrate the tool through a pilot study. The study will involve collecting lidar data on a road segment, sharing and streaming the lidar data over the Internet, and demonstrating several user cases, such as surface condition assessment, flooding vulnerability visualization, and virtual safety audits.

METHODOLOGY

The following tasks will be undertaken to complete the objectives of this project.

Task 1. Evaluate lidar data characteristics and data analysis needs (April 1, 2015 - May 31, 2015)

This task will require exploration of a wide variety of lidar data sets and analysis how these data sets are typically used in transportation applications. This task will make use of various databases, our research partners, and the literature in the field.

Task 2. Identify ways and mechanisms to share and analyze lidar data (May 1, 2015 - June 30, 2015)

This task will involve reviewing of existing literature and data infrastructure solutions for lidar data sharing and analysis. The findings will be synthesized to identify ways, mechanisms, and environment in which the proposed solution can be developed.

Task 3. Develop an online platform for lidar data sharing and analysis (May 1, 2015 - November 30, 2015)

In this task, we will develop a data infrastructure for sharing lidar data and conducting server-side lidar analytics. In particular, a server-client based lidar data service will be developed to allow users to stream lidar data, visualize lidar data, submit data analysis tasks, and retrieve data analysis results. A small-scale data cluster with GPU computing capabilities will be assembled for this task. On the cluster, we will develop several prototype lidar data analytics such as spatial measurement and change detection and optimize lidar data visualization through network communications. The online platform will provide a GIS interface for data selection and streaming. The overall goal of the task is to move most computational intensive tasks to the server side while offering flexible visualization capabilities on the client side. We will work closely with project partners at state DOTs on this task.

Task 4. Demonstrate lidar data collection, sharing, and analysis with the developed platform using several user cases (November 1, 2015 - December 31, 2015)

A pilot study with the developed tool will be conducted in this task. The pilot study will first collect mobile lidar data on US Route 1 and US 35 in the flood prone coastal area. Following data collection, we will demonstrate using the developed tool for remote sharing of lidar data and online visualization of lidar data based on user selection. Several user cases such as visualization of work zone setup and storm surge impacts and virtual field measurement will be conducted to evaluate the utility of the developed tool.

Task 6: Develop the final report (November 1, 2015 - December 31, 2015)

The following tasks will be undertaken to complete the objectives of this project.

Expected outcomes from this research are:

(1) A software framework for lidar data sharing and analysis over the Internet

(2) Catalog of environments and tools that support data sharing including costs, limitations, and strengths

(3) Data products for selected highway segments

(4) Final reporting documenting the process used to develop these products

FINDINGS

Highway LiDAR Mapping Applications

Modern Big spatial data acquisition technologies such as laser scanning from airborne, mobile, or static platforms are increasingly used for highway asset management, generating point clouds with millions, billions, or even trillions of 3D points with in many cases multiple attributes such as radiometric parameters attached. In the following, we provide a quick overview of various lidar technologies useful for highway mapping applications.

Lidar (also written LIDAR or LiDAR) is a remote sensing technology that measures distance by illuminating a target with a laser and analyzing the reflected light. A lidar system typically consists of several components:

- Laser transmitter and detector/receiver
- Deflection mechanism of the laser ray
- GPS/INS
- Computer, onboard software and storage devices, including precise timing device that synchronizes all sensors
- Optionally other optical sensors such as digital cameras

For a lidar system, 600–1000 nm lasers are most common used for non-scientific applications. They are inexpensive, but since they can be focused and easily absorbed by the eye, the maximum power is limited by the need to make them eye-safe. Eye-safety is often a requirement for most applications. A common alternative, 1550 nm lasers, are eye-safe at much higher power levels since this wavelength is not focused by the eye, but the detector technology is less advanced and so these wavelengths are generally used at longer ranges and lower accuracies. They are also used for military applications as 1550 nm is not visible in night vision goggles, unlike the shorter 1000 nm infrared laser

Other than the type of lasers used, a lidar system is also characterized by the following mechanical and performance factors:

- Pulse repetition frequency (PRF) or pulse rate: number of pulses sent per second
- Echoes: number of received pulse reflections recorded for one sent pulse
- Minimum vertical object separation: minimum distance between 2 separate echoes
- Scan rate: number of scan patterns (e.g. scan lines) per second

- Field of View (FOV) or scan angle: across-flight angle that laser beam can cover
- Beam divergence: the angle showing the deviation of the laser beam from parallelity
- Wavelength: important for measuring certain objects
- GPS/INS measurement frequency and accuracy
- Range resolution and accuracy

Lidar systems can be installed on a variety of platforms such as airborne or ground-based platforms. While there are occasionally other platforms such as satellites or waterborne vehicles which can be used, airborne and ground-based Lidar systems are the most commonly systems.

Airborne lidar systems

The typical platforms used for airborne lidar are fixed-wing airplanes, helicopters, and more recently unmanned airborne vehicles (UAVs). According to their applications, airborne lidar systems can be further divided into airborne topographic mapping and bathymetric mapping lidars.

Airborne topographic mapping lidars

Airborne topographic mapping lidars generally use 1064 nm diode pumped YAG lasers. Airborne lidar systems typically use scanning lasers at pulse rates that can exceed 100k/second to produce dense (>1/square meter), high accuracy (~0.1m vertical) point clouds along 300-600m-wide swaths at forward speeds around 100knots. Returns will include both canopy (trees, houses) and ground, often with multiple returns from a single lidar pulse, and often have co-located aerial photography.

Bathymetric mapping lidars

Designed for accurate sea-depth determination, bathymetric lidar systems are composed of two beams, one green (532 nm) and one infrared (1064 nm). The green beam traverses the air-water interface and propagates in the water until the sea bottom with the least attenuation. The infrared beam is reflected by the water and gives the range from the plane to the sea surface. Low-flying aircraft equipped with GPS/IMU and a pulsed laser scanner is the platform of choice for this application. The data are used to support navigation, military operations, and environmental and recreational needs.

Bathymetric lidar systems are often flown simultaneously with digital cameras and hyperspectral sensors to gather additional information about water quality and bottom composition.

UAV lidar

UAV lidar systems are amongst a technical breakthrough period. Compared to other systems, power source and payload weight are two major concerns with UAV lidar systems. Current UAV lidar systems have to balance between the weights of sensors and the performance of these sensors. Often the lidar sensors have to be light-weight, which inevitably sacrifices on range and/or weight. In many situations, UAV lidar faces fierce competitions from UAV-based photogrammetry systems.

The accuracy and resolution of airborne data is typically lower than many ground-based remote sensing technologies. Many building structure evaluation and environmental assessment tasks require high accuracy geospatial data. Many studies have dedicated to quantify the accuracy of airborne lidar systems. Table 1 provides a quick summary of findings from a variety studies. The airborne lidar data can be used to generate a relatively accurate terrain model, but falling short of detecting movement of infrastructures and assets. Because the 15 cm measure accuracy of lidar data is likely greater than the extent of erosion, in most cases erosion would not be reliably identifiable. In addition, airborne lidar data are sparse (1-10 points/m^2), therefore, they may have limited or no data return on infrastructure itself, leading to difficulty in detecting the displacement of infrastructures or nearby features. Third, the 15 cm vertical and 10-100 cm horizontal measure accuracies render airborne lidar impractical for accurately detecting movement of critical infrastructure.

Table 1 A Summary of previous literatures on the vertical accuracy of airborne system in different environment

Studies	Environment	Reference	Vertical Accuracy
(Krabill, Thomas et al. 1995)	Ice-surface elevations	Differential Global Positioning System	0.20m
(Kraus and Pfeifer 1998)	wooded area	photogrammetry with reference to a big pilot project	0.25 m

(Latypov 2002)	surface size and flatness	overlapping LIDAR datasets	0.21m
(Töyrä, Pietroniro et al. 2003)	wetlands, deltas, or other similar areas	in situ survey data	0.26 m
(Reutebuch, McGaughey et al. 2003)	heavily forested areas	Conventional ground survey methods	0.22 ± 0.24 m (mean ± SD)
(Hodgson and Bresnahan 2004)	Pavement, Low Grass, High Grass, Brush/ Low Trees, Evergreen Forest, Deciduous Forest	-	0.17-0.19m
(Hopkinson, Chasmer et al. 2005)	Utikuma boreal wetland area	kinematic GPS surveys	0.15 ± 0.22 m (mean ± SD)
(Pfeifer and Briese 2007)	-	analytical derivation of error formulas	0.225m
(Bowen and Waltermire 2002)	Western river corridor (variable terrain and large topographic relief.)	ground GPS surveys	0.43 m

For the purpose of bathymetric mapping, water clarity and depth are the most significant limiting factors; in the clearest water, penetration down to 50 meters can be achieved. Despite the limitations, lidar fills an important gap in collection of critical near-shore bathymetry. Ship-based sonars can collect depth data in deep water, but cannot operate in shallow, near-shore waters where lidar is most effective. Combining topographic and bathymetric lidars on the same platform makes it possible to collect this near-shore bathymetry, along with direct observation of the coastline, beaches, and dunes

Ground-based lidar systems

Ground-based lidar systems are either static (on a stationary platform such as a tripod or mast) or dynamic (on a moving vehicle). It has been incorporated into surveying and metrology instruments and is often employed in mobile lidar systems. In a static implementation, a GPS/INS geo-referencing system is not needed. The lidar is set up over a known point, and the scan angles for each point are recorded in the data set. Reference points on the target surface can also be surveyed to provide additional geo-referencing control. In a dynamic implementation of ground-based lidar, GPS/IMU is utilized to provide geo-referencing, just as it would be on an airborne platform. Using an infrared or green wavelength laser, ground-based lidars pulse at rates up to 1000 Hz, and can map objects from about 1 meter up to 1000 meters away with accuracies on the order of millimeters to a few centimeters. The accuracy of individual points can be affected by atmospheric conditions, distance to the target, angle of incidence of the laser pulse upon the target, and the reflectivity of the target surface. Very shiny, polished surfaces and very black surfaces that absorb nearly all incident light are difficult to image. Three types of scanning systems are employed in ground-based lidars:

- Panoramic scanners rotate 360 degrees around the mounting axis, and scan 180 degrees vertically to provide seamless and total coverage of the surroundings.
- Single axis scanners also rotate 360 degrees but are limited to a 50-60 vertical swath.
- Camera scanners point in a fixed direction with limited angular range both horizontally and vertically.

Ground-based lidars can also be classified according to operational range:

- Short-range systems operate at ranges of 50 - 100 meters with panoramic scanning, and are often used to map building interiors or small objects.
- Medium range systems operate at distances of 150 - 250 meters, also achieving millimeter accuracies in high definition surveying and 3D modeling applications, such as bridge and dam monitoring.
- Long range systems can measure at distances of up to one kilometer and are frequently used in open-pit mining and topographic survey applications

Commercially-available mobile lidar systems can be classified into two types of systems: mapping-grade and survey-grade systems. Mapping-grade systems are used for mapping and inventory applications, providing absolute and relative accuracy in the range of 1 foot and 0.1 foot respectively. Survey-grade systems can produce 0.1 foot absolute accuracy. The system's absolute accuracy refers to the position accuracy of a point in a point cloud in a global coordinate system such as elevation datum, and the relative accuracy refers to the position accuracy of a point relative to other neighbor points. Among the most common lidar sensors used in survey-grade MTLS systems are Optech Lynx, Riegl VMX-250, and Trimble MX8. The exact accuracy of lidar data varies from system to system. Most mobile lidar systems can generate very high density point cloud data: 100-1,000 pts/m^2. The typical accuracy standard for a survey-grade mobile mapping system without setting up control points is:

- Absolute accuracy of ± 10cm @ 1σ in good GPS coverage areas or areas accessible to set up control scans or points within 20 meters of the collected area (without control points)
- Absolute accuracy of ± 1m @ 1σ in poor GPS coverage areas or areas not accessible to set up control scans or points within 20 meters of the collected area (without control points)
- Absolute accuracy of ± 2cm @ 1σ (with control points)
- Relative accuracies of ± 5cm @ 1σ anywhere within the project area

Table 2 Mobile mapping system specifications

	Low-end	**Mid-range**	**High-end**
Scanner	DynaScan	ScanLook, Topcon, Mandli	Optech, Riegl, Trimble, Leica
Data Rate	36Khz	700Khz - 1333KHz	500Khz
Scan Freq	30 hz	10/15/20/100 hz	200 hz
Range	150m+	70-120m	200m+
Accuracy	5cm	2mm – 2cm	5 – 8mm
Lasers	Time of flight	Time of flight, phase	Time of flight
#Returns	Multiple	1/Multiple	Multiple
Price (US$K)	100 to 200	200 to 400	705+

The intrinsic meanings and interpretations of data are largely depending on its context. Similar as the natural language processing, this is especially true with LiDAR data. Essentially, LiDAR data are a clusters of points that contains information such as 3D coordinate, intensity and etc. If isolated, each point of LiDAR is meaningless. Meaningful features can be extracted from LiDAR only when certain amount of the point clouds work together. Point density, scanning pattern are features that is often determined by the sensor itself and the platform that carry the sensor. As a result, even targeting for the same locations, data collected using different platforms can express different prospect of information, and thus require varied processing algorithms.

Table 3 Summary of different variations in the characteristics of different scanning platform

	Static Terrestrial LiDAR (STL)	Mobile LiDAR System (MLS)	Airborne LiDAR System (ALS)
Pattern	Point density diminishes along with the range	Significant Line pattern, Gaps between lines	Resolution higher in the direction prependicular than along the motion
Range	Scanner (30 to 300 meters)	Scanner x Travel Speed	Scanner x Travel Speed
Ground Surface Density	1million pts/m^2	1000 pts/m^2	1 pts/m^2
Limitation	Obstruction, missing back-side information , too high the point density for rapid procssing	Obstruction, missing back-side information	Obstruction such as cloud coverage, not sufficient point density to show details
Level of detail	Neat componet edges that can be used for dimension measuremnt	Roughly represntation of component	Roughly representation of the Structure

Lidar scanning from air, mobile, and static platforms produce point cloud data with different patterns. Static terrestrial laser scanners are often combining a shaft scanner with azimuth rotation. The scanner performs scanning at a fixed location, thus resulting in two characteristics: high resolution and limit range. Among all scanning platforms, static terrestrial scanner has the highest resolution of point clouds and ground surface point density reach approximately at the level of 1 million pts/sq.m. The resolution diminishes gradually along the range of the scanner. The range of the terrestrial scanners varies from 30 to 300 meters depending on the manufacture design. Different from the terrestrial scanner, Mobile LiDAR systems is equipped with one-dimensional scanner. The second dimension is accomplished by the forward motion of a vehicle. The rotation head will produce a distinct line pattern when it scans This pattern will generate point clouds that the resolution point clouds in parallel to the rotation head direction significant higher than that in perpendicular direction. The resolution and range of data MLS is not only determined by the scanner, but also the speed of the vehicle. At normal driving speed (30-50 mph), the surface point density for MLS is at the level of a thousand points per square meter. MLS has a much higher scanning efficiency which will cover a large area equaling to the scanner range multiplies by the speed of the vehicle. The LiDAR sensor used by airborne systems share the same principle with the MLS but with a much lower resolution (1 pts/sq m). Depending on the scanner mirrors, the data varies in pattern such as oscillating, flipping zig-zag (Li et al 2008). ALS has the capability of capture the hundreds of mile of terrain information within one hour, however, this capability is infected by weather conditions such as cloud coverage. The outcome data sets from these three technologies vary in resolution, detail, spatial coverage, accuracy, and range. Figure 2 shows example data sets from these three types of lidar systems.

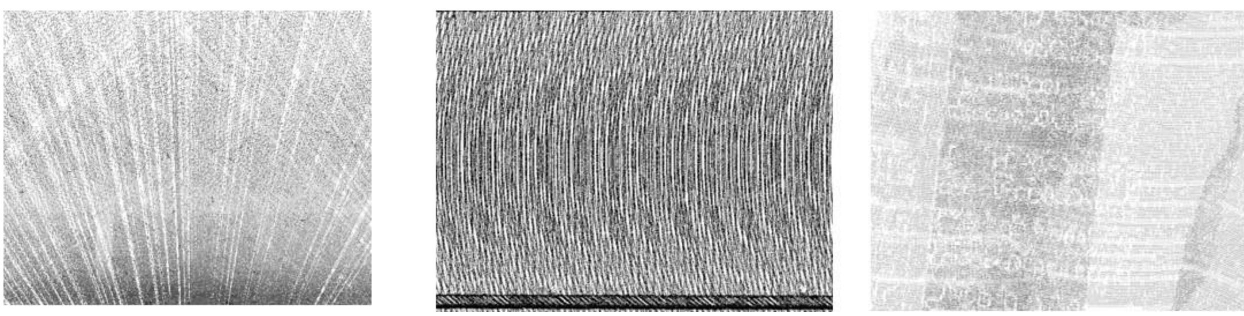

Figure 1 Scan pattern comparison: (left) static terrestrial lidar; (middle) mobile lidar; (right) airborne lidar

Figure 2 Lidar data comparison: (left) airborne lidar; (middle) mobile lidar; (right) static terrestrial lidar

Collectively, these spatial sensing technologies have been applied in numerous applications. Table 4 provides a quick summary of some of these applications.

Table 4 Current application status

	Mapping Capabilities	**Applications**
Airborne lidar	Terrain mapping Bathymetric mapping Chemical sensing	Flood mapping Damage assessment Crime and accident scene analysis Methane detection Forest monitoring Beach and dune monitoring Landslide and erosion mapping Corridor mapping Infrastructure network monitoring
Ground-based lidar	Terrain mapping Building mapping Infrastructure mapping	Architectural restoration Facilities inventory Crime and accident scene analysis Landslide and erosion mapping Building and infrastructure design and retrofitting City modeling Infrastructure inventory Damage assessment Construction monitoring Critical infrastructure protection Autonomous Driving Virtual manufacturing Entertainment

One of the most important application areas for lidar technologies is in the transportation sector. In the following, we provide a list of common use cases to demonstrate its utility in highway asset management.

Extraction of roadside slopes from mobile lidar data

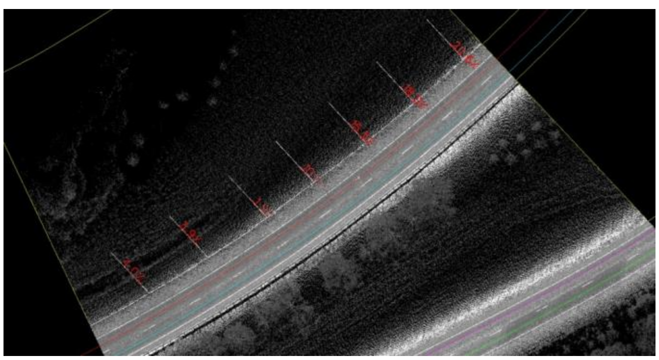

Figure 3 Extraction Roadside Slope

Road geometry modeling

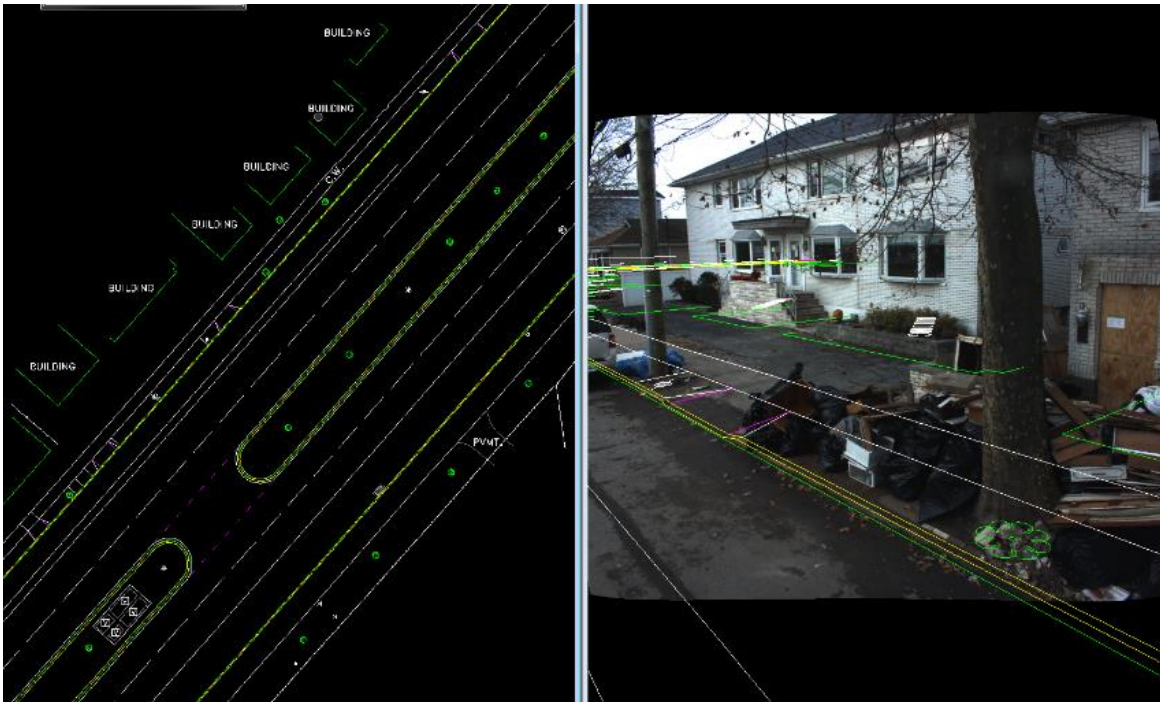

Figure 4. Extraction of Planimetric Features

As-built modeling of highway structures

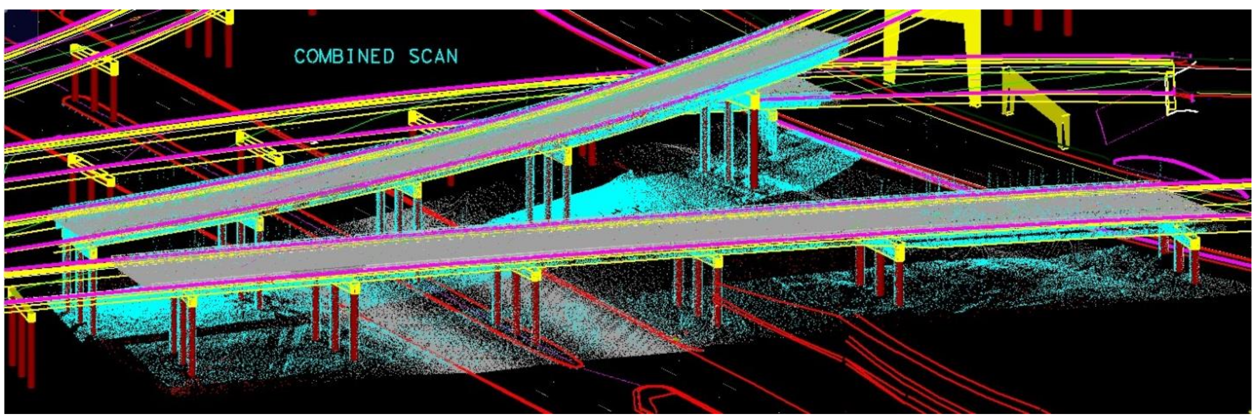

Figure 5. Overpass As-Built Modeling

Clearance measurement

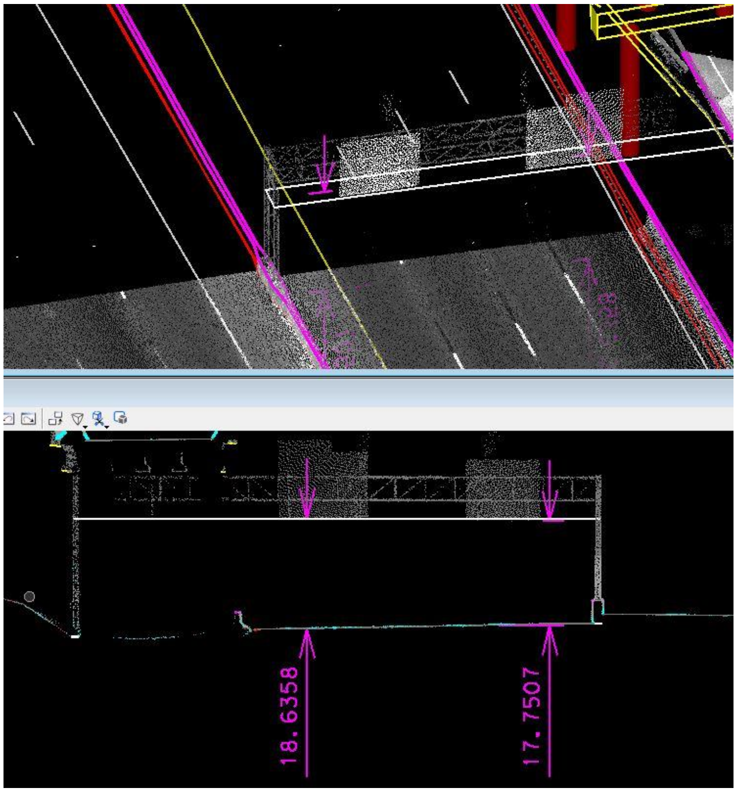

Figure 6 Clearance measurement for sign structures

Inventory of traffic signs

Figure 7 Traffic sign inventory

Construction quality control

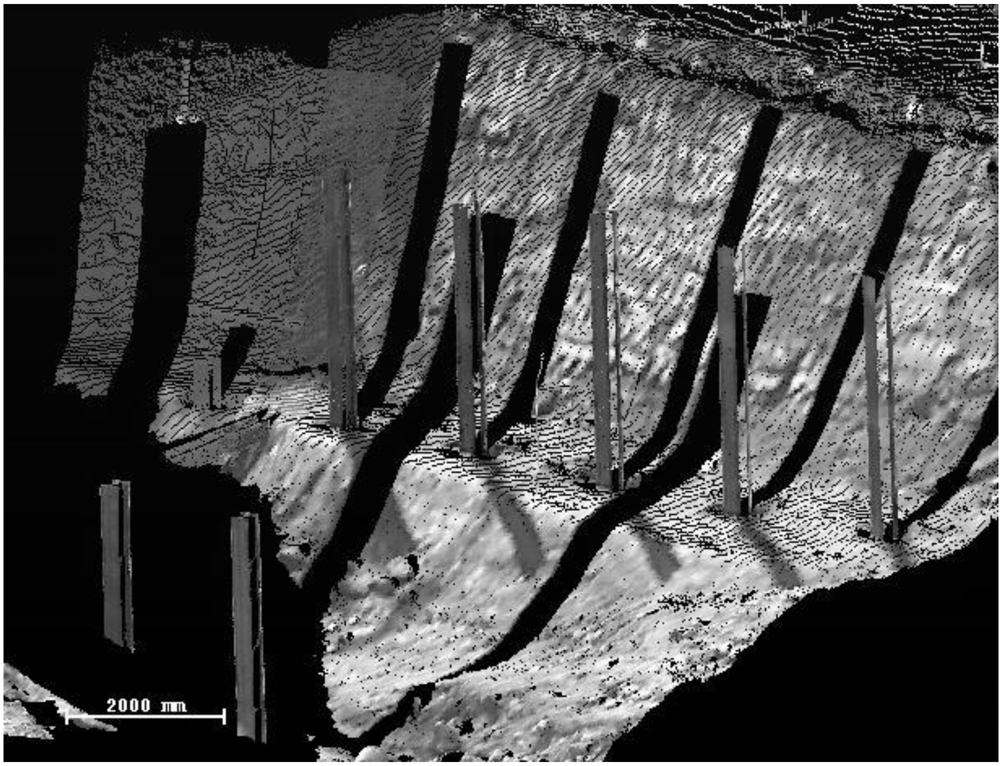

Figure 8 Static lidar for pile driving quality control

Superelevation measurement

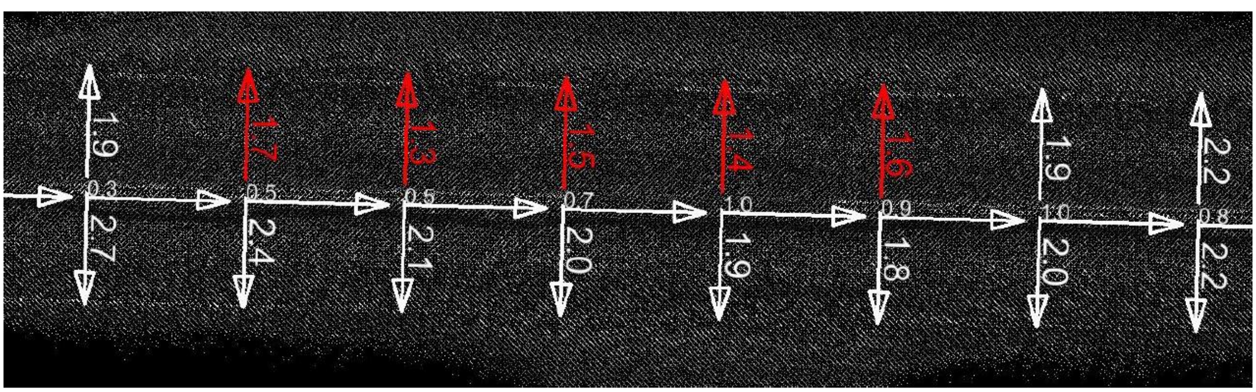

Figure 9 Superelevation measurement

Pavement surface distress detection

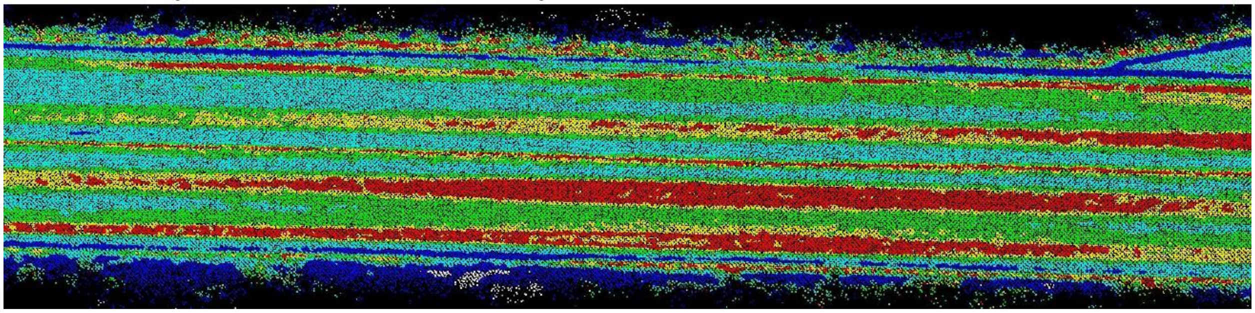

Figure 10 Identification of rutting areas

Most lidar systems today are capable of collecting large volumes of detailed highway inventory data in a short amount of time. Collecting a 20-mile highway corridor with traditional survey methods usually requires a field survey crew to work 10 days in good weather conditions. A most lidar system can collect such data in 30 minutes, and all the data processing tasks can be completed in the home office. Nevertheless, an increasingly pronounced issue with these systems is the requirement of significant computer resources and significant amount of data reduction effort to extract required highway data. A recent study by the Washington State DOT investigated the cost of mobile LiDAR system-based highway inventory data collection. The mobile LiDAR systems evaluated in this study include both mobile photogrammetry and mobile terrestrial laser scanning systems (Yen et al. 2011b). They estimated the cost of seven operation options for a 6-year program with three cycles of data collection and processing. These options include: 1) Contract for mapping-grade mobile LiDAR services; 2) Contract for bridge clearance measurement services; 3) Rent and operate a mapping-grade mobile LiDAR system; 4) Purchase and operate a mapping-grade mobile LiDAR system; 5) Rent and operate a survey-grade mobile LiDAR system; 6) Purchase and operate a survey-grade mobile LiDAR system; and 7) Purchase fractional ownership of a survey-grade mobile LiDAR system. The study found that the costs of these options are in the range of $5,779,500 to $10,730,588. A significant part of the cost is related to data extraction, more precisely the data post-processing part, as shown in Figure 11. This is clearly reflected in Figure 11, as it shows the proportion of cost associated with data extraction in the total cost ranges from 42%-59% with an average of 51%. The cost of option 2 (contract for bridge clearance measurement services) is not considered since it only concerns a specific DOT program.

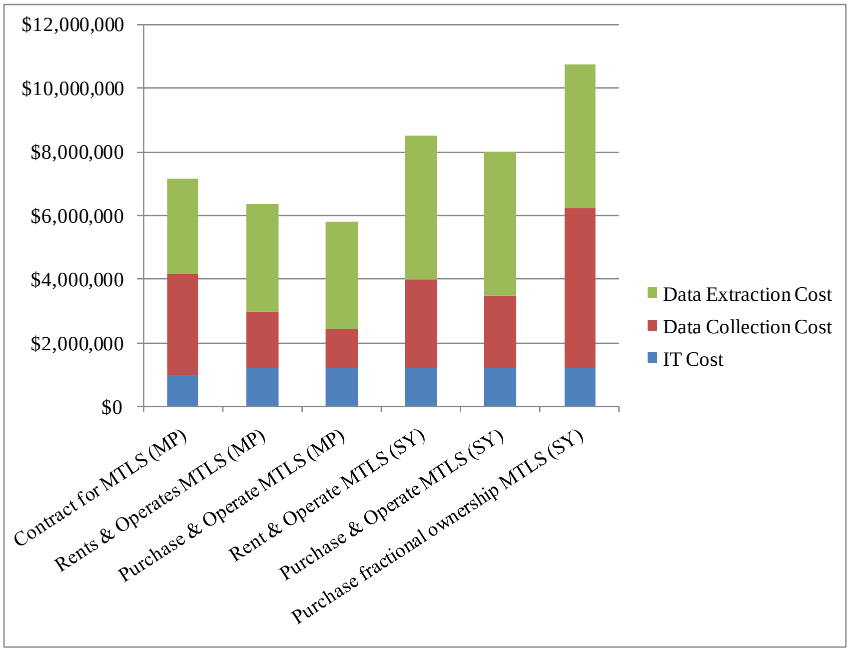

Figure 11 The Cost Scenarios of MTLS based Highway System Data Collection (Data source: Yen et al. 2011b)

The central question investigated in this research is whether the rising of web technologies can provide a web-based platform to allow convenient sharing of large lidar data sets across multiple departments within a state DOT such that computer infrastructure investment can be minimized and whether such platform can allow rapid visualization of lidar data and convenient extraction of interested features.

Ways and Mechanisms for Sharing and Analyzing Lidar Data

Many of existing lidar data analytics software are programs installed on local computers. Some of the popular programs include Terrasolid, QT Modeler, Virtual Geomatics, VR Mesh, Leica Cyclone, and Lastools (Fernandez, Singhania et al. 2007). All of these programs except for Lastools which offers limited open-sourced processing capabilities require fairly expensive licenses. Lidar data sets used in these programs are often organized in some sorts of indexing schema and stored locally on computer. Therefore, use of these software program inevitably requires painful transfer of large lidar data sets if the data need to be processed on multiple computers in different locations. This means additional copies of large lidar data sets have to be created, causing unnecessary data movement which can be quite costly.

To this end, storing large lidar data sets at central locations while allowing users to stream data of need over the Internet and to interactively explore the streamed data sets is an attractive solution. Since the birth of WebGL, a number of renderers have recently become available for the visualization of point cloud data over the web. These renderers include Plasio and Potree. Most of these renders have explored level-of-detail (LoD) to realize real-time streaming and visualization of large lidar data sets.

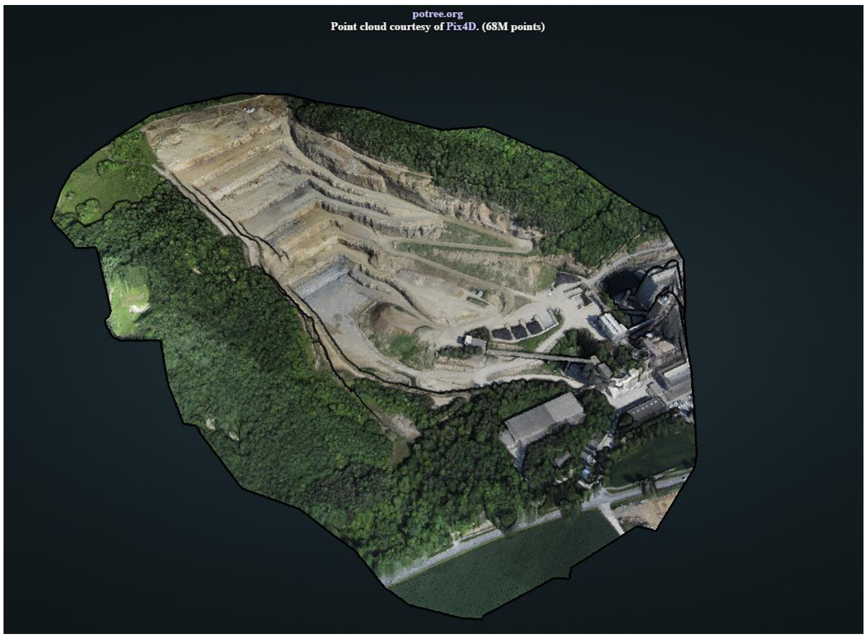

Figure 12 Example Potree based Point Cloud Visualization

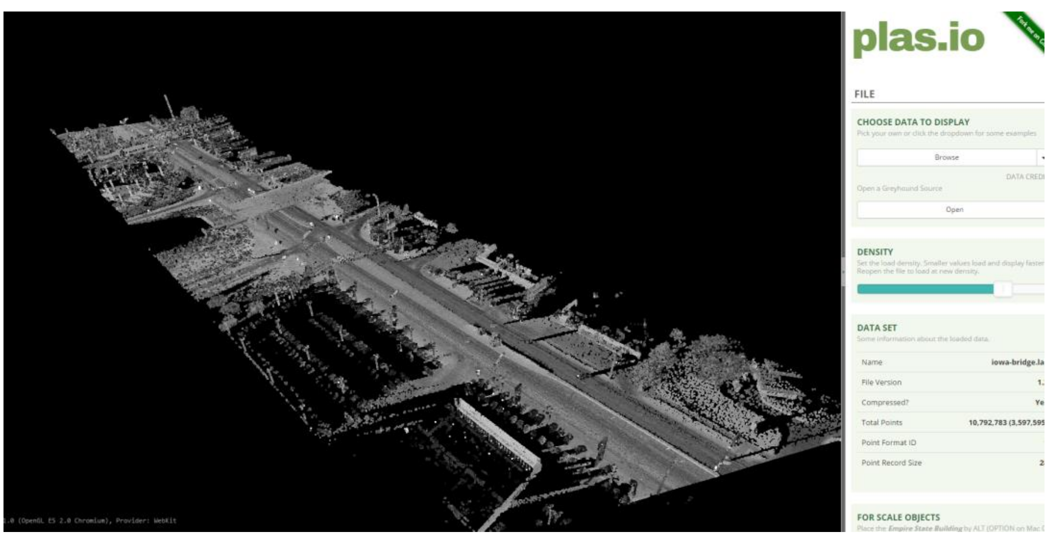

Figure 13 Plasio based Point Cloud Visualization

Use of LoD to realize fast visualization of large point cloud data has been extensively studied in the past. QSplat is a solution to render large point sampled models that do not fit in main memory, and it builds a hierarchical point-per-node data structure with level-of-detail (LoD) selection capabilities (Rusinkiewicz and Levoy 2000). Layered Point Clouds (LPC) designed a schema to allow several points stored per node which allows to use GPU's to boost the performance (Gobbetti and Marton 2004). The limitation of LPC is that it assumes uniform sampling density. Instant Points is the first point renderer that did not assume any sampling distribution and did not require normal computations or other pre-processing steps (Wimmer and Scheiblauer 2006). In essence, it uses an octree data structure where the hierarchical nodes also contain multiple points. Similarly, a multi-way (balanced) kd-tree has been proposed to realize LoD based visualization (Goswami, Erol et al. 2013). Other researchers have explored techniques on how to further boost the GPU capabilities for point rendering (Günther, Kanzok et al. 2013). Albeit these studies have shown carefully design point cloud data structure can dramatically accelerate visualization of large point cloud data sets, these studies have primarily focused on desktop based applications.

Potree in essence is a multi-resolution octree built with the goal of streaming point cloud data over the Internet (Martinez-Rubi, Verhoeven et al. 2015). It is built upon Instant Points, which was further extended to render point clouds in web browsers. At the current stage, Potree can convert an input set of point cloud files (in LAS, LAZ, PTX or PLY format) to the required multi-resolution octree data structure for the Potree renderer. In the octree data structure, each node of the octree is stored in LAS or LAZ binary files file. The whole octree hierarchy is stored in multiple auxiliary files to reduce initial load times.

In Potree, the multi-resolution octree data structure allows for efficient view frustum culling and level of detail calculations. This means that nodes outside the visible region are not rendered at all and nodes close to the viewer are favored over nodes that are far away. Potree is developed based on standard web technologies such as WebGL, three.js50 and Javascript. Because of this, it does not require additional plugins, and it is flexible enough to combine it with other web applications. Based on the above literature analysis, we have chosen Potree as the foundation for developing our online platform for lidar data sharing and analysis.

Development of An Online Platform for Lidar Data Sharing and Analysis

We developed a lightweight web-based 3D data visualization and exploration framework that provides capabilities to visualize, explore, and interact with city-scale point cloud data. The platform extends the Potree open source program by adding various new capabilities. All development are done in Javascript and PHP. The platform has server-side and client-side components. For the server side, the platform provides capabilities for:

- Raw data pre-processing:
  - Massive Point clouds data cleaning;
  - Massive Point clouds meta data (point cloud bounding box, spacing, etc.) extraction and organization;
  - Multiple Geo-tagged data GPS information extraction and organization
- Point Cloud Database Generation:
  - Generate massive web links linking mobile point clouds and their paired geo-tagged data (digital images, infrared images, etc.) base on GPS location
- User Search Engine Generation
  - Generate a search engine that help users locate target building/path in the database

On the client side, the platform provides capabilities including:

- Web-based visualization of point cloud data
- Distance, area, and volume measurement
- Point cloud clipping
- Integration with street-level photo data
- Integration with infrared thermography data

The system user interface and user workflow are shown in Figure 14.

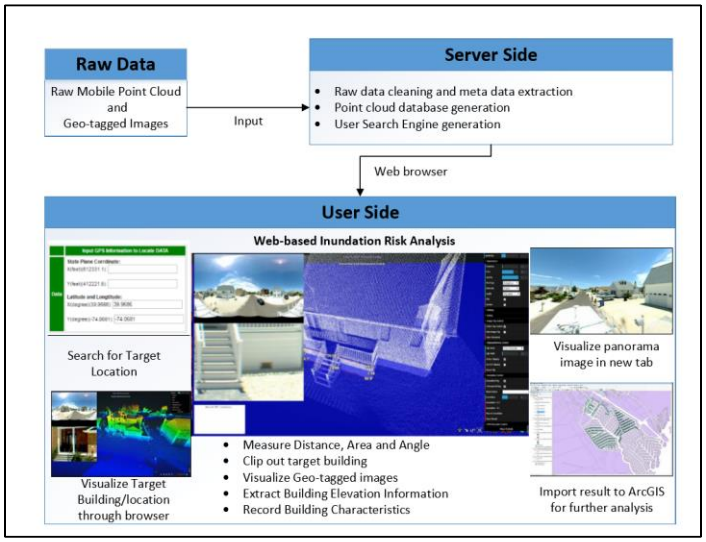

Figure 14 System User Interface and Workflow

The integration with other sources of visual data is achieved through a projective mapping process.

Calibration between Image and Point Cloud:

Denote a point as $C = [X, Y,\ Z, 1]^T$, and a pixel as $c = [u, v, 1]^T$. The projection from a 3D point on to a 2D pixel could be expressed as:

$$c = \boldsymbol{A}[\boldsymbol{R}|\boldsymbol{t}]C \qquad (1)$$

Where

$$A = \begin{bmatrix} \alpha & \gamma & u_0 \\ 0 & \beta & v_0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$R = R_x(roll) \cdot R_y(pitch) \cdot R_z(yaw)$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(roll) & \sin(roll) \\ 0 & -\sin(roll) & \cos(roll) \end{bmatrix} \begin{bmatrix} \cos(pitch) & 0 & -\sin(pitch) \\ 0 & 1 & 0 \\ \sin(pitch) & 0 & \cos(pitch) \end{bmatrix} \begin{bmatrix} \cos(yaw) & \sin(yaw) & 0 \\ -\sin(yaw) & \cos(yaw) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$t = [x, y, z]^T$$

Denote the projection matrix as $\boldsymbol{P} = \boldsymbol{A}[\boldsymbol{R}|\boldsymbol{t}]$, for each pair of points $C_i = [X_i, Y_i, Z_i, 1]^T$, and $c_i = [u_i, v_i, 1]^T$, equation (1) could be rewritten as:

$$\underbrace{\begin{bmatrix} X_i & Y_i & Z_i & 1 & 0 & 0 & 0 & 0 & u_iX_i & u_iY_i & u_iZ_i & u_i \\ 0 & 0 & 0 & 0 & X_i & Y_i & Z_i & 1 & v_iX_i & v_iY_i & v_iZ_i & v_i \end{bmatrix}}_{G_i} \begin{bmatrix} P_{11} \\ P_{12} \\ P_{13} \\ P_{14} \\ P_{21} \\ P_{22} \\ P_{23} \\ P_{24} \\ P_{31} \\ P_{32} \\ P_{33} \\ P_{34} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (2)$$

The projection matrix $\boldsymbol{p} = [P_{11}, P_{12}, \dots, P_{43}]^T$ then could be solved by

$$\min_P \|\boldsymbol{Gp}\|^2 \;\; s.t. \|\boldsymbol{p}\| = 1 \quad (3)$$

After the projection matrix $\boldsymbol{P}$ has been estimated, the intrinsic parameters and extrinsic parameters could be retrieved as follow:

Denote $\boldsymbol{P} = \boldsymbol{A}[\boldsymbol{R}|\boldsymbol{t}] = [\boldsymbol{B}\ \boldsymbol{b}]$, therefore $\boldsymbol{B} = \boldsymbol{AR}, \boldsymbol{b} = \boldsymbol{At}$. Since rotation matrix is orthogonal, we have

$$K = BB^T = \boldsymbol{AR} \cdot (\boldsymbol{AR})^{\boldsymbol{T}} = \boldsymbol{ARR^TA^T} = \boldsymbol{AA^T} = \begin{bmatrix} \alpha^2 + \beta^2 + u_0^2 & u_0v_0 + \beta\gamma & u_0 \\ u_0v_0 + \beta\gamma & \beta^2 + v_0^2 & v_0 \\ u_0 & v_0 & 1 \end{bmatrix} = \begin{bmatrix} k_u & k_c & u_0 \\ k_c & k_v & v_0 \\ u_0 & v_0 & 1 \end{bmatrix} (4)$$

Therefore, the intrinsic parameters are computed as:

$$u_0 = K_{13}, v_0 = K_{23}, \beta = \sqrt{k_v - v_0^2}, \gamma = \frac{k_c - u_0v_0}{\beta}, \alpha = \sqrt{k_u - u_0^2 - \gamma^2}$$

And the rotation matrix and translation vector could be computed as:

$$\boldsymbol{R} = \boldsymbol{A}^{-1}\boldsymbol{B}, \boldsymbol{t} = \boldsymbol{A}^{-1}\boldsymbol{b} \quad (5)$$

Since one characteristic of rotation matrix is $\det(\boldsymbol{R}) = 1$. However, a rotation matrix estimated by equation (5) does not necessarily satisfy $\det(\boldsymbol{R}) = 1$, which will give incorrect rotation angles. To deal with this, a nonlinear optimization procedure is used to estimate the best calibration parameters. Denote a function $\tilde{c}_i = f(C_i, roll, pitch, yaw, x, y, z, \alpha, \beta, \gamma, u_0, v_0)$ that projects a 3D point onto a 2D image plane. The objective function could be defined as

$$\|c_i - \tilde{c}_i\| = \|c_i - f(C_i, roll, pitch, yaw, x, y, z, \alpha, \beta, \gamma, u_0, v_0)\| \qquad (6)$$

The best parameters are then estimated by solving the non-linear optimization problem defined as

$$\left[\widetilde{roll}, \widetilde{pitch}, \widetilde{yaw}, \tilde{x}, \tilde{y}, \tilde{z}, \tilde{\alpha}, \tilde{\beta}, \tilde{\gamma}, \widetilde{u_0}, \widetilde{v_0}\right] = \min_P \sum_i \|c_i - f(C_i, roll, pitch, yaw, x, y, z, \alpha, \beta, \gamma, u_0, v_0)\| \qquad (7)$$

As shown in Figure 1, 11 pairs of corresponding points are manually extracted, these points are used to estimate the calibration parameters. The initial calibration parameters are estimated using equation (3), and the re-projection error is shown in Figure 2(a). It is observed that the initial calibration parameters are not accurate enough to obtain a small re-projection error. Figure 2 (b) shows the re-projection error using the calibration parameters estimated using a non-linear optimization procedure described in equation (7). Compared with Figure 2 (a), it is easily observed that the re-projection error is significantly reduced. Figure 3 shows the result of colored point cloud using this approach.

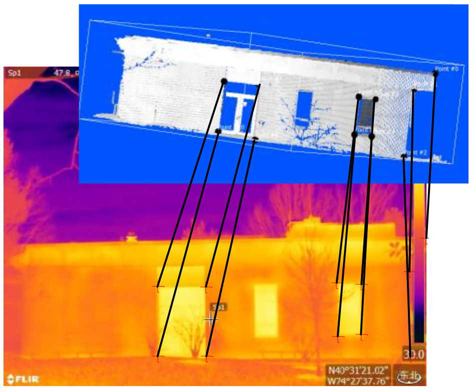

Figure 15 Key Point Matching

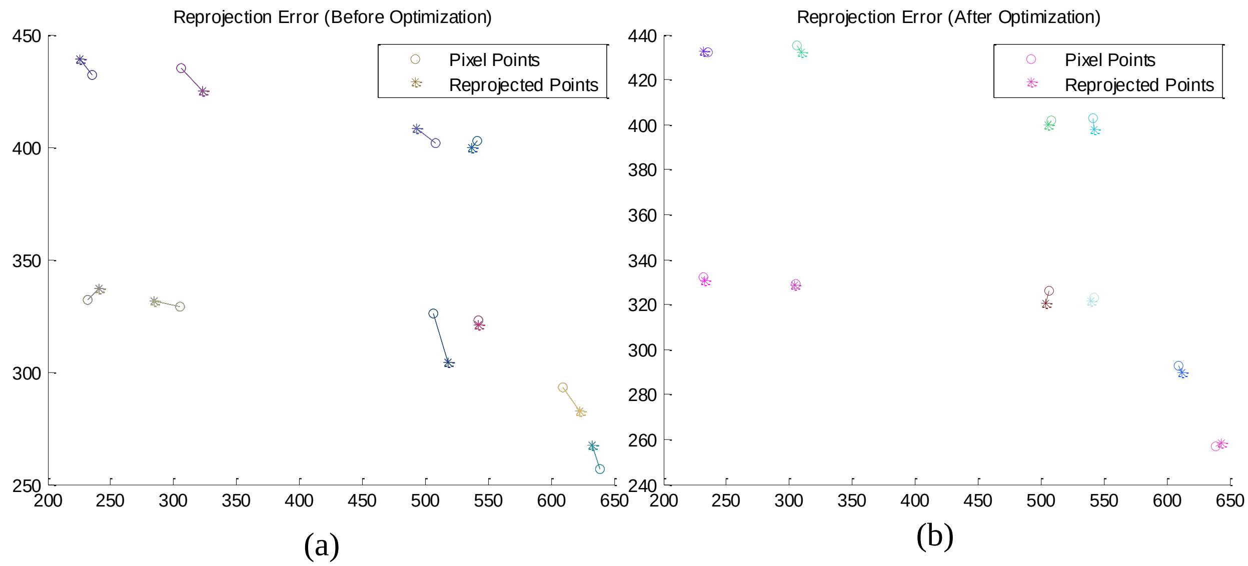

Figure 16 Reprojection Error

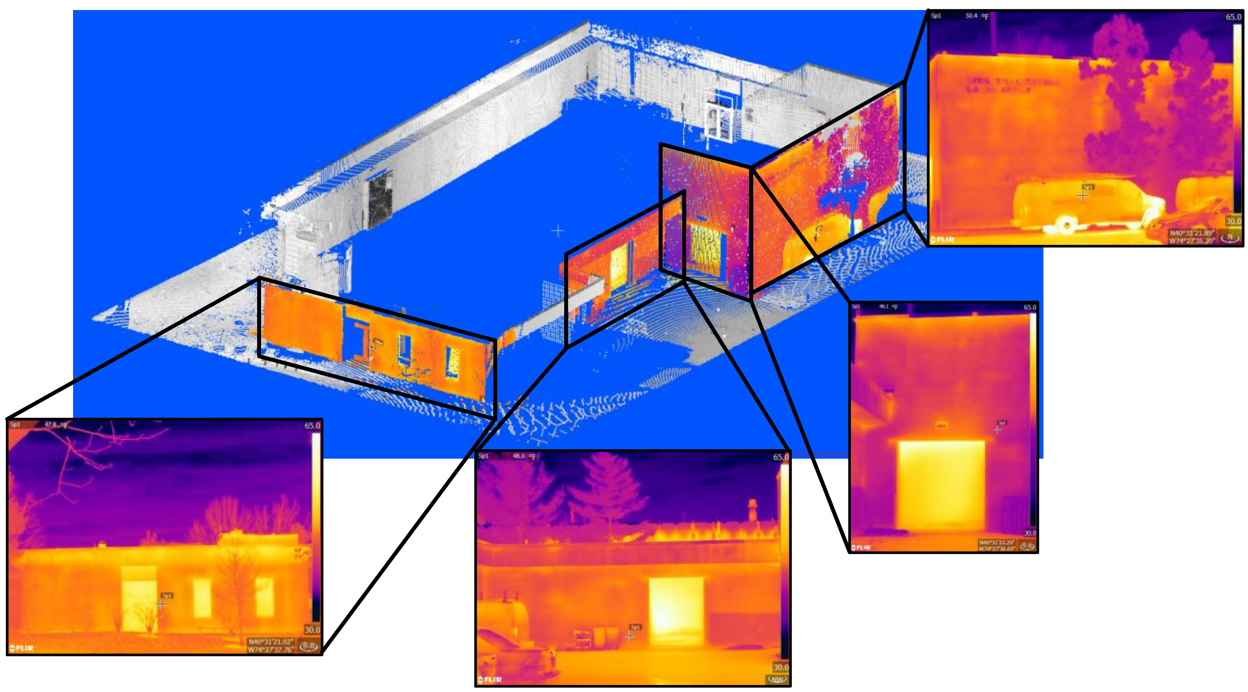

Figure 17 Projection Results

In addition to fusion with other source of data, we also provided a flood mapping tool that allows users to visualize flooding scenarios and measure the elevation of transportation infrastructures such as roads and bridges (Figure 18).

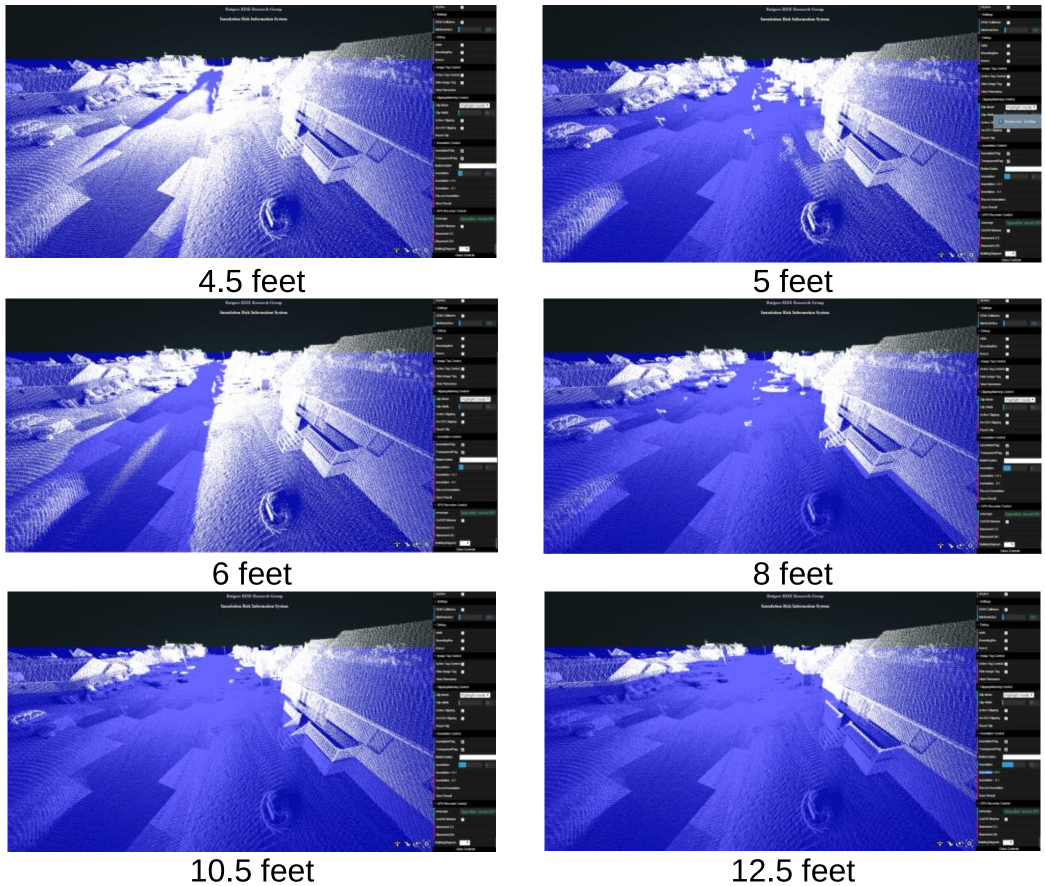

Figure 18 Flood mapping with different elevations (Unit: U.S. Survey Feet)

Case Studies

To test the capability of the online highway lidar data sharing and analysis platform, we conducted several case studies to evaluate its capabilities. The first case study is related to online visualization of highway lidar data collected on Route 1 in New Jersey. The second study is related to visualization of bridge lidar data and extraction of bridge geometrical data. The last study is to test the capability of the program to visualize very large lidar data sets.

Case study 1: Collection and Visualization of Highway Route 1 Data

We deployed our mobile lidar system along the Route 1 Highway in the State of New Jersey. The collected paths are shown in Figure 19. The system used for data collection is shown in Figure 20.

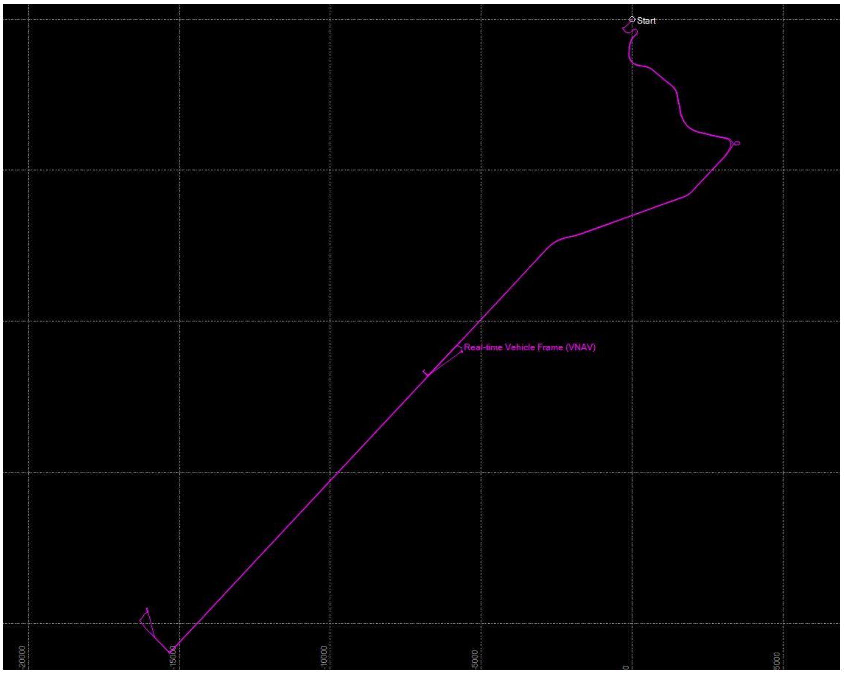

Figure 19 Data Collection Paths along Route 1 in New Jersey

Figure 20 Mobile lidar system

Figure 21 Panoramic images collected with lidar data

The data collection speed is roughly at 30 mile per hour. The mobile LiDAR data, once collected, can be processed according to the following steps:

(1) Extract POS file
(2) Extract las file
(3) Extract jpg images
(4) Review las file for completeness
(5) Boresight
(6) Match Strips
(7) Verify point cloud to control

Since accuracy is not a primary concern of this case study, control points are not used in this study. The data collection yielded around 40GB of point cloud files for a 20-mile segment. Sample data are shown in Figure 21.

Figure 21 Route 1. Highway Lidar Data

We converted the lidar data into data organized according to an octree structure. The converted data can be streamed in real-time and visualized in different kinds of browsers (Figure 22).

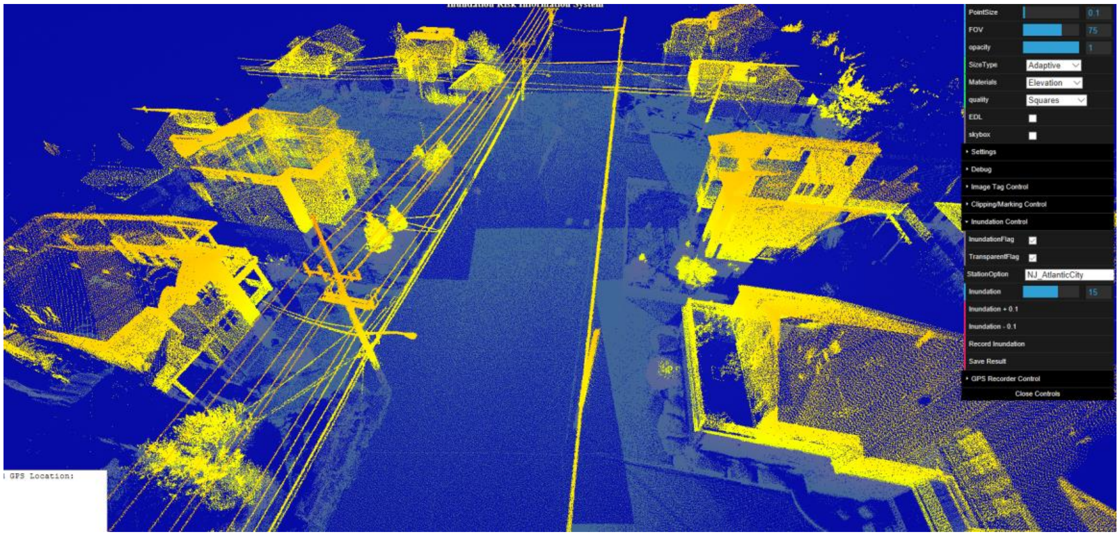

Figure 22 Highway lidar data in a web browser

Case study 2: Collection, Visualization, and Analysis of Bridge Data

In this case study, we used a static terrestrial laser scanner to acquire detailed point cloud data about a bridge structure. Six scans from different angles are conducted to ensure good coverage of the bridge structure. The registered point cloud data are converted into las files, which are further converted into an octree structure as specified in Potree. The resulting point cloud data can be streamed and visualized in Potree with ease. The following figure shows a snap of point cloud data of this bridge. Various dimension measurement tasks can be accomplished in the web browser, and these dimensions can be eventually converted into CAD drawings.

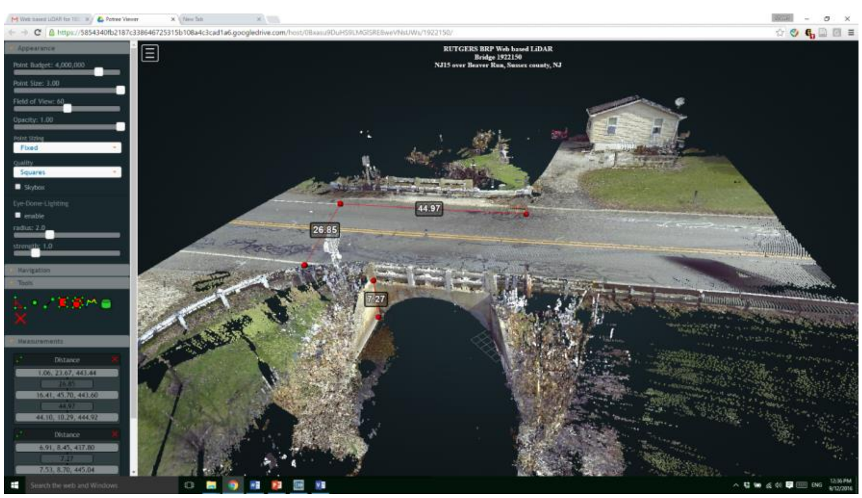

Figure 23 Bridge Lidar Data in a Web Browser

One additional capability we tested in this case study is to fuse lidar data with photographs and visualize the integrated data sets (Figure 24). This capability is useful for a variety of reasons. First, it provides multi-mode visualization of multi-sourced data. Second, it facilitates user interpretation of bridge condition data. Last, it provides a tool to examine bridge condition through different lens but in the same portal. One last test we conducted with this bridge is test the feasibility of visualizing data in mobile devices. Our test results show that lidar data can be conveniently visualized in smart phones (Figure 25).

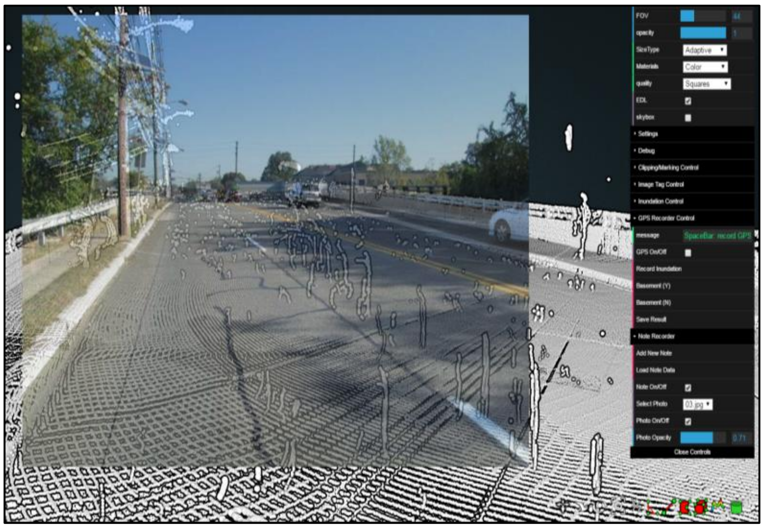

Figure 24 Fusion of Street View Photos with Lidar Data in an Online Portal

Figure 25 Visualization of Point Cloud Data using Mobile Devices

Case study 3: Hosting and Visualization of Very Large Lidar Data

In this case study, we evaluated the feasibility of using the web-based platform to manage very large point cloud data sets. We leveraged a 40 TB point cloud data set collected for a coastal county, and converted all the point cloud files into octree structure based LOD schema (Figure 26). Our experiment shows our web-based platform can deliver reliable visualization of these large data sets in web browsers and also provide convenient mechanisms for elevation data extraction and flood visualization.

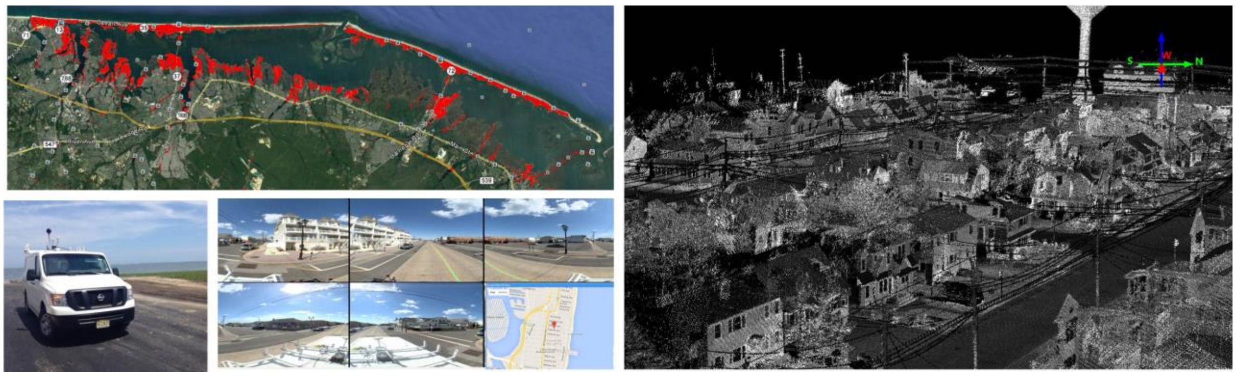

Figure 26 County-Scale Lidar Data Sets

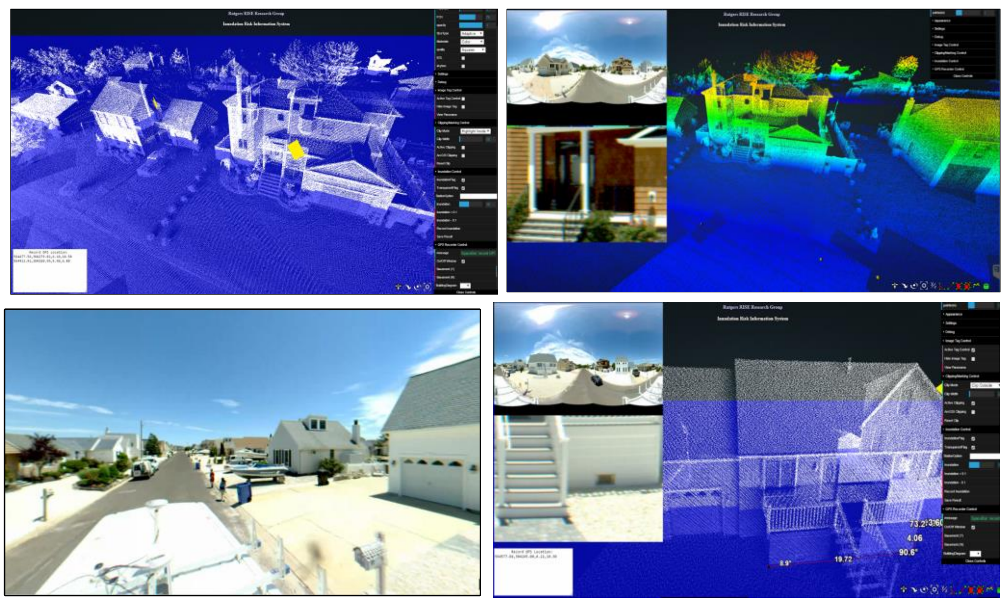

Figure 27 Flood Visualization in a Web-based Portal

CONCLUSIONS

This study investigated alternative methods to share and visualize lidar data sets, a growing type of remotely sensed data that have many use cases in transportation asset management. However, due to their size, lidar data are often delivered to state transportation agencies on hard drives along with other deliverables. A transportation agency often need to procure and set up expensive hardware and software to effectively use these data sets, not to mention the amount of training required for its employees. The research team conducted literature analysis on existing technique and platforms for managing, sharing, visualizing, and processing of massive point cloud data sets. As the outcome of the literature analysis, Potree, a web browser based visualization program, was selected as the foundational block for developing dedicated lidar data sharing and visualization services for state DOTs. We extended Potree by providing additional capabilities in fusing with other source of visual data and in conducting elevation measurement and visualizing flooding scenarios. The extended platform was tested with three case studies. The test demonstrated the effectiveness of the developed portal. The outcome of this research provides a versatile tool for state DOTs to leverage various lidar data sets in their asset management programs as well as in future construction projects. State DOTs can leverage such a platform to conduct remote field inspection work and other types of audit task. Future research studies in providing further technical capabilities such as point cloud classification and automated 3D modeling are of great need.

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