Best Practices for Surveying and Mapping Roadways and Intersections for Connected Vehicle Applications

Final Report

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Executive Summary

Connected Vehicle applications require established methods of roadway feature representation and reference in the form of a map. Numerous mapping methods exist to acquire and record geospatial data that represent roadway relevant objects and terrain. Based on our extensive analysis carried out in this research project, the preferred existing acquisition method for roadway mapping will likely utilize GPS/IMU-integrated LIDAR sensing that generates a three dimensional georectified point cloud data set. When data acquisition is conducted with multiple integrated sensors at a high frequency, the resulting dataset will be sufficiently large to require automated application specific data processing for roadway relevant feature mapping. This is particularly true when mapping at the national or global scales is necessary for commercial success.

This report entitled "Best Practices for Surveying and Mapping Roadways and Intersections for Connected Vehicle Applications" presents a technology and methodology review of current mapping methods and technologies. The main body of the report is divided into six main chapters:

1. Mapping Methodology Assessment;
2. Mobile Mapping System Enhancement;
3. Map Representations;
4. Map Representation Updating;
5. Feature Extraction Methods, and;
6. Intersection Mapping Experimental Results.

Subsequent chapters discuss best practices, conclusions, and future work. The report also includes a list of references and three appendices.

Connected vehicles require accurate and up-to-date maps both to allow coordination between vehicles and with the infrastructure. Such maps may also have utility for application aspects such as vehicle position estimation or control. In Chapter 1, Mapping Methodology Assessment, we describe several ways that maps can be acquired. Based on the analysis, it was found that mobile terrestrial laser scanning (MTLS) methods work best for connected vehicles purposes. The research team has previously participated in the development and operation of a Mobile Positioning and Mapping System (MPMS) deployed and tested at Turner Fairbanks Highway Research Center. This system meets a number of key criteria including accuracy, robustness, efficiency, cost, safety, and usability. Chapter 1 reviews the MTLS approach and examines the mapping and positioning accuracy requirements of a large number of CV applications, particularly those applications listed in the Connected Vehicle Reference Implementation Architecture (CVRIA).

MPMS's are mounted on a vehicle platform which collects positioning and mapping data from a variety of sensors and combines them to provide accurate, and continuously available information about both the trajectory of the MPMS and the surrounding areas, yielding more accurate and precise location detail and associated feature maps. This is achieved through a combination of global positioning satellite (GPS) technology, feature-based aiding sensors (vision, RADAR, LIDAR) and high-rate kinematic sensors (wheel encoders or inertial measurement units (IMU)) to capture and process multiple location and feature-based signals and to bridge data gaps whenever

sensor reception is interrupted. The improvement to the UCR MPMS hardware and software is the focus of Chapter 2.

For successful collaboration with automakers, it is expected that some entities (government or commercial) will develop and maintain continent-scale roadway map databases, and eventually global scale. Maintenance of this master map will result in differences between the master map and the maps stored on user vehicles. The master map is too large to be convenient for wireless communication to users in its entirety; therefore, mechanisms have been defined for communication of application relevant pieces of the map to connected vehicles. Chapter 3 discusses the processes, general standards, and the SAE J2735 standard, which along with its modifications for demonstration purposes is the dominant standard for connected vehicle applications.

It is certain that the infrastructure and roadway features will change over time, particularly for corridors that are heavily utilizing connected vehicle technology. Therefore, once a map database is established (as described in Chapters 2 and 3), a key issues is how it can be updated to accommodate changes in the infrastructure, the introduction of new mapping techniques, or the desire to map additional features. Chapter 4 briefly describes different possible update technologies and approaches.

Chapter 5 presents an automated feature extraction approach explaining the data processing steps utilized to transform a georectified point cloud representation of the roadway environment to relevant intersection features represented in a SAE J2725 map message. SAE J2735 is the dominant communication media and associated map message format intended to represent intersection geometry and features appropriate for connected vehicle applications. The feature extraction methodology presented is intended to exemplify a uniform approach applicable to standardized intersections meeting accepted roadway design criteria. As such, the feature extraction methodology can serve as a template for feature extraction beyond the scope of J2735 based applications.

The roadway feature extraction process consists of the following primary steps:

- Preprocessing to extract the georectified point cloud and associated MPMS trajectory portions relevant to an intersection that is of interest;
- Identification and extraction of the road surface point cloud, road edge curves, and median edge curves;
- Conversion of the intersection road surface point cloud to an image to enable feature extraction using image processing techniques;
- Image-based roadway feature extraction; and
- Translation to a J2735 intersections feature map output format.

The feature extraction and map representation methodology are described with a detailed explanation of data processing and integration, including examples. This detailed approach allows for future feature extraction of relevant roadway features in a connected vehicle environment. The performance of the semi-automated feature extraction approach is demonstrated using eleven example intersections along El Camino Real in Palo Alto California. Separate lists of recommended best practices are included in Section 7 for equipment, data collection, and data post-processing.

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1. MAPPING METHODOLOGY OVERVIEW

1.1 Introduction

This research project focuses on best practices for sensor-based surveying and mapping of roadways and intersections relative to the needs of Connected Vehicle (CV) applications. CV applications will put new demands on transportation surveying and mapping given that detailed roadway feature maps will need to be developed, maintained, and communicated consistently to connected vehicles. To enable these applications, within the U.S. alone, hundreds of thousands of intersections and other roadway locations will need to be surveyed, with application-relevant roadway features mapped to application-specific accuracies. This chapter documents the results of a sensor-based mapping methodology assessment. The assessment methodology included interviews with persons listed in Appendix B and a literature survey of the documents in the Bibliography.

There are several alternative methodologies for roadway mapping. For CV applications, the methods must be capable of creating and maintaining maps of roadway features such as lane edges, road edges, and stop bars. Maps could be extracted from design and as-built construction documents. The advantage is that these documents are often already available in computer-aided design files. The disadvantage is that the current reality on the ground, especially regarding lane and stop bar striping, may diverge significantly from the design documents over time, necessitating map updating by other means. Other methods include photogrammetry, laser scanning, probe vehicles, and crowd sourcing, all of which will be referred to as sensor-based.

This chapter focuses on sensor-based mapping and is organized as follows. Sections 1.2 provides an introduction to sensor-based mapping, introduces stationary, mobile and aerial laser scanning approaches, and discusses related tradeoffs. Section 1.3 discusses the mobile terrestrial laser scanning (MTLS) map production process. The discussion includes current practices, expected improvements, and issues affecting attainable accuracy. Section 1.4 discusses selected CV applications (based on the Connected Vehicle Reference Implementation Architecture or CVRIA, version 1, see http://www.iteris.com/cvria/) along with necessary feature and required mapping accuracy. It also discusses the effect that the map accuracy specification has on real-time vehicle position estimation specifications. Section 1.6 discusses various map production business models.

1.2 Sensor Based Mapping

For existing CV testbeds, the surveying/mapping work has been accomplished using whatever means were readily available. Manual surveying can achieve high accuracy, but with a high cost per intersection. Manual extraction of roadway features from satellite (e.g., Google Earth)[1] imagery yields relative accuracy at the decimeter level with absolute accuracy at the meter level, but is a slow human-involved process. Such non-automated processes have been feasible to date, because the number of locations to be mapped has been small. In the future, however, many more locations will need to be completed. Some examples of map information required by connected vehicle applications include: lane edges, road edges, location of intersection center, number of

[1] Manual CV testbed data feature extraction from DOT geo-rectified photo logs should also be feasible, but to the authors' knowledge, this has not been implemented.

approaches, number of lanes on each approach, lane widths, location of stop bars, and length of storage space in left turn lanes.

Commercial success of CV applications requires buy-in from automobile manufacturers. Auto manufacturers become interested when there is a uniform and global scale solution. Numerous local solutions are infeasible from their production, marketing, and maintenance perspectives. In the future, when maps for roadways and intersections across a variety of nations must be developed maintained, and distributed, in addition to cost and accuracy, several technical issues become important:

- Initialization of the map;
- Detection of changes to or obsolescence of regions within existing maps;
- Adaptation or replacement of regions within existing maps; and
- Continuity of maps across jurisdictional or geographic boundaries.

The following sections discuss the use of various sensor technologies to automate such processes. The required sensors are currently available. Both the sensors and the processes discussed below are being used at present in manual and semi-automated processes. Due to the vast quantities of data that are involved, further automation of the mapping construction and updating processes are required for these technologies to move from testbeds to global realities.

Sensor Based Mapping Overview

The high-level steps of the sensor based mapping process are illustrated in Fig. 1.1 [1, 2].

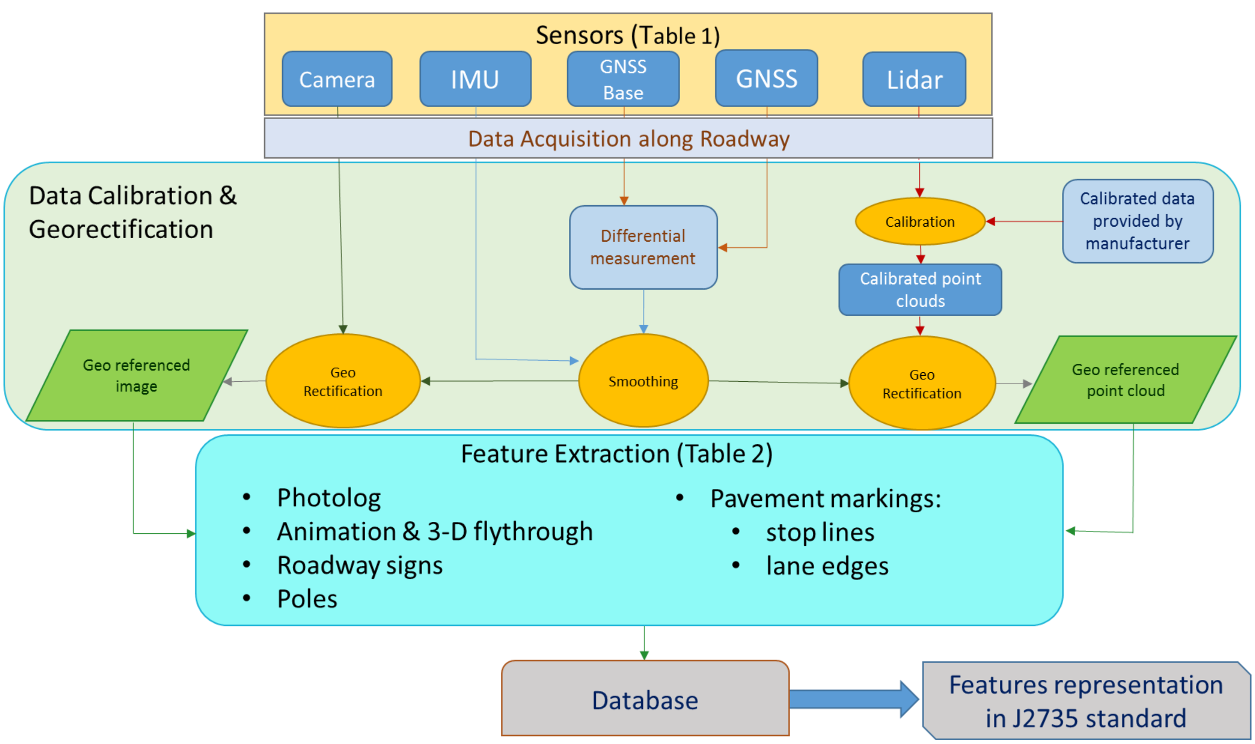


Figure 1.1 Sensor Based Mapping Process

A rigid platform containing a suite of sensors is placed in or moved through an environment for which a digital map is to be constructed. Sensor data are acquired and processed (see Section 1.3) to produce a map of roadway features.

A variety of databases may be involved in the above steps:

1. The raw uncalibrated sensor data that are the output of the upper gray box, prior to the georectification process, are usually not distributed publicly, except by special request. Instead, it is maintained in a variety of formats within the databases of the entity that acquires the data. The database formats may be proprietary to the instrument manufacturer or converted to standard formats such as Rinex for Global Navigation Satellite System (GNSS) [3] or LAS for LIDAR (Light Detection and Ranging) [4].
2. The calibrated and georectified imagery and point cloud data are the output of the green box and is potentially available for distribution. Photologs and LIDAR calibrated photologs (colorized point clouds) are two of the most common types of mapping database distributions at the present time. State Departments of Transportation (DOT's) use photologs for a variety of purposes, such as for roadway assessment, roadway inventory management, accident analysis, and safety analysis. Software products are available that allow the user to "fly through" and make position related calculations using the calibrated imagery.
3. After manual or automated processing of the calibrated imagery and point cloud data, certain roadway features can then be extracted along with their locations and metadata descriptors. These are the output of the Cyan box. Distribution of such feature maps is still in its infancy, especially over large regions. Effective distribution and use will require specifications for feature descriptors. Examples include the Navigation Data Standard (NDS) [5] and the SAE J2735 [6]

To enable CV applications, within the limited communication constraints, subsets of the roadway feature database are communicated to the end-users (connected vehicles and infrastructure) using communication standards such as SAE J2735 [6].

Typical Sensor Packages

Typical sensors include Global Navigation Satellite System (GNSS) receivers, an inertial measurement unit (IMU), cameras, and LIDARs [1, 2, 7]. The purpose of the cameras and LIDAR sensors is to sense the roadway environment to enable analysis of that environment, including feature detection and mapping. The camera and LIDAR sense the roadway feature locations relative to the sensor platform. The georectification process requires knowledge of the platform orientation and location (i.e. the platform pose) to compute the feature locations in an Earth Centered Earth Fixed reference frame suitable for a map. The purpose of the GNSS and IMU data is to compute the sensor platform pose with high accuracy at a high rate.

A few examples of sensor packages that are currently available are summarized in Table 1.1. Each contains at least 6 cameras, providing a nearly 360 degree field-of-view, and at least two LIDAR sensors. Each contains at least one dual frequency GNSS receiver and an IMU. Multiple cameras are useful to help ensure that visual imagery is available of the roadway, features, and overhead structures in spite of occlusions. Multiple LIDAR sensors help to ensure a sufficiently dense set of reflections from features to enable feature detection. Also, multiple views of features from different locations and aspect angles facilitates accurate estimation of feature location. One GNSS receiver is sufficient for determining platform location. The GNSS combined with the IMU allows accurate estimation of the time history of the pose at the high sampling rate of the IMU [1]. Sometimes two GNSS antennae are used to directly measure platform attitude [8].

Table 1.1. Examples of commercially available Mobile Terrestrial Laser Scanners (MTLS).

Product Features	Product Name			
	Trimble MX2	Trimble MX8	Topcon	Mandli
360° LIDAR	72 K pps	1 M pps	120 K pps	1.4 M pps
Number of LIDARs	2	2	5	2
LIDAR name	SLM-251 Class 1	VQ-250	Velodyne HDL-32E	Velodyne HDL-64E
Number/Resolution of digital cameras	6/12 MP	8/5 MP	6/30 MP	8/8 MP
Dual frequency GNSS receiver	Yes	Yes	Yes	Yes
IMU Positioning & orientation rate		200 Hz	100 Hz	200 Hz
IMU/GNSS Brand	Applanix POSPac MMS	Applanix POS LV 220	Honeywell HG1700	Applanix POS LV 220
Wheel Encoder DMI		Yes	Yes	Yes

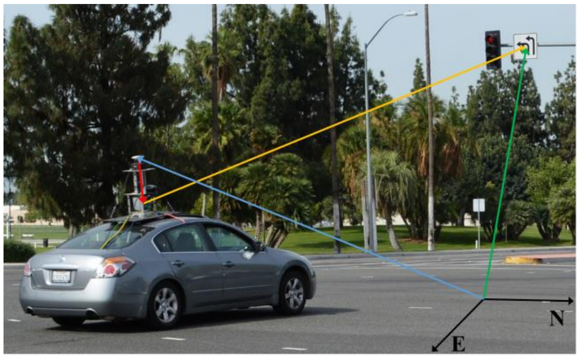
An example of sensor data rates are summarized in Table 1.2. For different sensor combinations, the specific amounts of data will change, but the overall conclusion is the same. The database containing the raw sensor data grows very quickly. Due to the size of the data sets and the time varying nature of the roadway infrastructure, the database must be managed and curated with care.

Table 1.2. Example rates of data accumulation for an MTLS.

Sensor	Bytes/Msg.	Msgs./sec	Bytes/Sec	GB/Hr	GB/Hr (with timestamp overhead)
IMU	19	200	3800	0.013	0.232
LIDAR	1206	3473	4,188,438	15.08	15.278
Camera	35,836,416	7.5	268,773,120	967.583232	967.583
GPS measurement data	612	1	612	0.002	0.0374
GPS Ephemeris data	256	.002	.512	1.8432e-6	3.13344e-5
DGPS data	1071	1	1071	0.0038	0.0039
		Total:	273 MB /sec	982 GB/Hr	983 GB/Hr
		Hrs. of collection per TB:			≈1 Hr.
		Miles of coverage per TB (assuming a speed of 30 mph):			≈30 miles

Georectification

Fig. 1.2 illustrates the *GeoRectification* process. The goal is to estimate and store the position of feature points within a specified world frame of reference. In this figure, the desired feature is the



$$P_F^W = R_{WP}\left(R_{PL}P_F^L + T_{PL}^P\right) + T_{WP}^W$$

Figure 1.2 Georectification Process

center of the left hand turn sign. The frame of reference has its origin at the center of the intersection. This feature position is depicted by the green arrow, which is indicated by the symbol P_F^W for the position of the feature F relative to the World. There is no single sensor that can efficiently provide P_F^W, so the vector is instead measured indirectly through the various quantities shown in the right hand side of the equation at the bottom of the figure. GNSS and IMU data can be processed to determine the position and rotation (i.e., the pose) of the sensor platform relative to the world. This vector is represented by the purple arrow in the figure. The position and orientation are represented by the purple symbols T_{WP}^W and R_{WP} in the equation at the bottom of the figure. The translation and orientation of the LIDAR and Camera frames relative to the IMU are known and fixed when the platform is designed. These quantities a represented by the red arrow and the red symbols T_{PL}^P and R_{PL} in the equation at the bottom of the figure. Finally, the yellow arrow represents the LIDAR measurement of the feature location relative to the LIDAR frame, which is represented by P_F^L. Because all the quantities on the right hand side of the equation can be computed from the sensor data, the desired position of the feature in the world frame P_F^W, as necessary for a map, can be computed.

Various factors affect the accuracy and success of sensor based mapping. The right-hand side of the georectification equation in Fig. 1.2 contains five quantities that are estimated from the data. Any inaccuracies in the determination of these five quantities accumulates into the overall inaccuracy of P_F^W. The quality of the IMU, GNSS and processing algorithms determine the accuracy of T_{WP}^W and R_{WP}, which are computed at high-rates. Processing algorithms typically smooth IMU and GNSS data optimally in a post-processing mode [1,9,10,11]. While the quantities T_{PL}^P and R_{PL} are accurately initialized based on design calculations, their values may also be refined in the post-processing optimization process. The reliability of detecting features and the accuracy of estimation of P_F^L are determined by various LIDAR and operational issues, predominantly the distribution and density of LIDAR reflections from the feature's surface. Various articles discuss the processing of LIDAR point clouds to detect roadway relative features [12-20].

Laser Scanning and Photogrammetry: STLS, MTLS, ALS

The principles underlying Laser Scanning and Photogrammetry are similar and will be treated together in three different scenarios [21]: Stationary Terrestrial Laser Scanning (STLS), Mobile Terrestrial Laser Scanning (MTLS), and Aerial Laser Scanning (ALS).

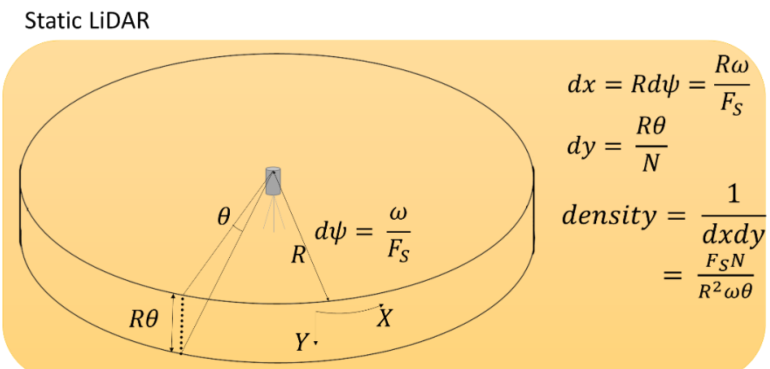


Figure 1.3 Stationary Terrestrial Laser Scanner Performance

The georectification process for STLS is simplified by the fact that the stationary instrument location serves as the reference point and is stable throughout the data collection procedure. This enables all measurements in a single survey to be referenced relative to a single point. The georectification transformation procedure from the LIDAR instrument relative measurement to the earth frame (e.g., latitude, longitude, elevation) is greatly simplified. The relative spatial errors generated in the measurement process are solely attributed to the accuracy of the LIDAR measurements. An inaccuracy of the resulting georectified survey is a combination of the LIDAR measurement error and instrument location error (usually via GNSS). The GNSS survey of the instrument location is greatly enhanced due to extended GNSS measurement duration at a single stationary location.

Fig. 1.3 depicts a typical STLS configuration wherein a LIDAR rotates at an angular rate ω, emitting a vertical line containing *N* laser pulses distributed across a field-of-view (FOV) with angle θ. For each pulse, the return intensity and round-trip time-of-flight are measured at a rate F_S. When the LIDAR reflects from an object at a distance *R*, the density of reflected points is approximately $\frac{F_S N}{R^2\omega\theta}$ points per square meter. For example, if an STLS rotates at 15 Hz with 1000 vertical scans per second ($F_S = 15kHz$), each containing *N*=64 laser pulses with a 30 degree FOV, then a reflecting surface *R*=20 meters from the LIDAR would reflect approximately 49 points per meter (PPM) squared per second. The number of points per stationary reflecting object accumulates as the STLS remains running at a fixed location. The STLS includes a GNSS receiver so that its location can be precisely determined. Knowledge of the LIDAR frame cylindrical coordinates (*R*, θ, ψ) together with the STLS pose allows estimation of the ECEF position of each reflected LIDAR point. The main drawback of the STLS is that the region that is mapped is small, as determined by the LIDAR range. The STLS could be moved to multiple (stationary) locations to extend its range.

The migration from stationary surveys to mobile surveys has allowed an increased rate of data collection with the development of new methods to manage the accuracy of the resulting survey in spite of the motion of the instruments. Each individual LIDAR measurement must be time aligned with a specific *pose* of instrumentation. Each pose describes both the position and attitude (i.e., orientation) of the LIDAR at a specific time. While STLS only requires accurate determination of one pose, MTLS and ALS require determination of a time history (or trajectory) of poses. This trajectory estimation process can be solved by various methods [1,9-11] and introduces various opportunities for estimation errors that are not relevant in a static survey. The trajectory estimation methods may incorporate GNSS receivers, Inertial Measurement Units (IMU), and cameras. Time alignment associated with integrating measurements from various sensors introduces errors that become more significant as the speed of the moving platform increases. The speed of the survey platform transitioning through the environment also affects the quantity of data collected for a specific region. The point density in a mobile survey will become sparser as the velocity of the measurement platform increases.

ALS mounts the sensor platform on either a piloted or autonomous aerial vehicles (UAVs). The mapping error in an ALS approach is strongly influenced by two factors: the speed of the platform and the distance of the LIDAR reflections. Traditional ALS vehicles are fixed wing vehicles that move at high speeds and cannot hover. The high speed lowers the point density per pass over a given area and makes time alignment more critical. Long range due to high altitude makes platform attitude estimation more critical. Imaging of surveyed control points on the ground or incorporating an IMU provides additional measurements to calibrate these error sources.

For fixed wing aircraft the ALS survey accuracy is typically reduced relative to MTLS and STLS. This issue is overcome in some ALS implementations where the aerial vehicle (e.g., a quadrotor) is capable of travelling at slow speeds, hovering, and flight at low altitudes.

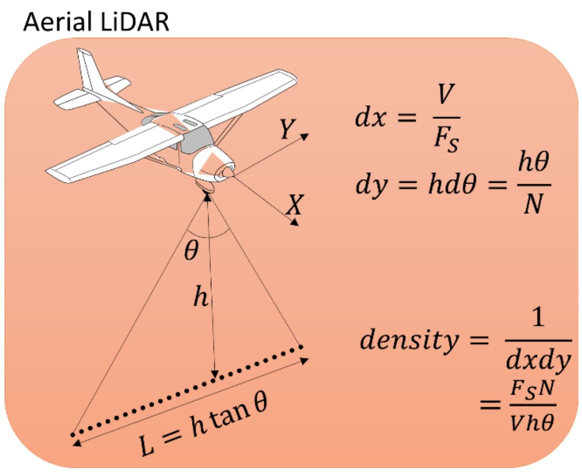


Figure 1.4. Aerial Laser Scanner Performance

Fig. 1.4 depicts a traditional ALS configuration wherein a LIDAR emits a line containing N laser pulses distributed across a FOV with angle θ. The LIDAR line scanner is rigidly mounted so that straight and level flight results in a scan on the Earth surface, below the plane, perpendicular to the direction of travel. The lines are generated and the return intensity and round-trip time-of-flight are measured at a rate F_S. When the LIDAR reflects from an object at a vertical distance h, the density of reflected points is approximately $\frac{F_S}{Vh\tan\left(\frac{\theta}{N}\right)}$ points per square meter. For example, if an ALS at traveling at V=100 m/s emits pulses at a line rate of F_S =15 kHz, with N=64 laser pulses per line over a 30 degree FOV, then a reflecting surface h=5000m below the LIDAR would reflect approximately 4 PPM. The number of points per reflecting object does not accumulate, unless the aircraft traverses the airspace above the reflecting object multiple times. Because the aircraft is moving, it typically is instrumented with at least one GNSS antenna and receiver and an IMU. These instruments allow accurate determination of the LIDAR attitude and position at the high LIDAR sampling rate. The aircraft is typically also instrumented with cameras allowing the detection of known survey points on the earth for calibration and cross-checking. A main advantage of ALS is that it can cover a large geographic area much faster that is possible with an STLS. The main disadvantages are the lower density and position accuracy of the reflected points.

An MTLS mounts one or more rotating LIDARs onboard a land vehicle that can be driven through the environment to be mapped. The MTLS is more mobile than an STLS allowing it to acquire data more rapidly for mapping a roadway network. However, reflecting objects may be occluded from the LIDAR by interfering entities such as other vehicles. The density of the point cloud along the roadway is approximately $\frac{F_S N}{R^2 \omega \theta}$ points per meter. The number of points reflected per object does accumulate as the MTLS drives by, but only over a short time-window determined by the speed of travel of the vehicle. Multiple transits within a given section of roadway, although not required, may have several benefits: increased point cloud density, decreasing the likelihood of occluded sections, and acquiring surface reflections from various aspect angles.

Tables 1.3 and 1.4 compare the accuracy, collection speed and range of STLS, MTLS, and ALS. Table 1.3 is qualitative, while Table 1.4 gives example numbers based on assumed experimental conditions [21]. The point density is critical to the performance of automated feature (e.g., lane stripe) detection.

Table 1.3. Qualitative comparison of STLS, MTLS, and ALS.

Laser Scanner	Stationary	Mobile	Aerial
Collection Range/ Speed	Small	Large	Very Large
Point Density	High	Medium	Low

Table 1.4. Example quantitative comparison of MTLS and ALS [21].

Laser Scanner	Mobile	Aerial
Point Density (ppm)	100 - 3000	10-50
Field of View (degree)	360	45-60
Measurement Rate (pps)	160,000 – 400,000	200,000
Relative Accuracy (ft)	0.023	0.065
Absolute Accuracy (ft)	Submeter	0.25 – 0.5

The ALS and MTLS instrument suite includes GNSS and IMU to enhance the accuracy of the platform trajectory (pose history) estimation. The IMU also enhances that ability to accurately time align the instrument measurements with the appropriate vehicle pose. Commercial trajectory estimation approaches reliably achieve meter level trajectory estimation with the MTLS system moving at highway speeds. Use of advanced estimation methods has demonstrated decimeter level (or better) automated survey results [1]. When accuracies equivalent to a stationary survey are required with a mobile application, individual control points can be surveyed and used to improve the accuracy of the MTLS survey.

Crowd Sourced Data

Crowd sourced-based mapping data consist of vehicle trajectories from connected vehicles themselves, or ordinary from drivers that have navigation software running either through their cellular phone or through on-board devices typically used for general navigational purposes. These anonymized trajectories provide very large datasets that explicitly contain potentially useful information about traffic conditions. The datasets do not contain explicit information about roadway features such as stop bars or lane edges; however, bundles of closely spaced trajectories provide useful information about number of lanes, lane centerlines, lane and route connectivity, road conditions, and other items. The individual trajectory data are not highly accurate, because the location of the data recording device in the vehicle is typically not known and cellphone or on-vehicle position determination is currently not accurate to more than a few meters. Enhanced processing algorithms may be able to improve accuracy. Most importantly, the data are timely and low cost, and can serve complementary purposes to accurate surveyed data sets, as described in Chapter 4. The data can, for example, detect accidents, pot holes, obstacles, road closures, or newly opened streets or roadway connections, which could trigger a request for mapping by more accurate means. The use of crowd-sourced trajectory data for various mapping purposes is a subject of a separate technical report outside the scope of this project (see [37]).

Summary

The capabilities of STLS, MTLS, ALS, and crowd sourcing have been evaluated relative to the requirements for Connected Vehicle application mapping requirements. The conclusions are summarized in Table 1.5. While the accuracy obtained through STLS implementations is sufficient for CV applications, the time investment involved in widespread STLS surveys for roadway applications is prohibitive. ALS by fixed-wing aircraft is the best option for regional surveys, but currently lacks the accuracy and road surface reflection point density needed for reliable roadway feature detection, especially those requiring sub-meter mapping accuracy. For intersection mapping, ALS by quadrotor could achieve suitably dense point clouds, without roadway vehicles occluding the view; however, current quadrotors (with flight times less than one hour) would require recharging between each intersection survey. *The most suitable mapping approach for Connected Vehicle applications is MTLS.*

After the sensor suite acquires the data, the GNSS and IMU data are combine to optimally estimate the sensor platform trajectory for georectification, to enable feature extraction and mapping. At present, feature extraction is largely a manual process. Over the next several years, these processes are expected to migrate from manual through human-assisted toward automatic processing. Crowd sourced data is expected to be useful for detecting changes to the roadway infrastructure that will later be surveyed by more accurate methods. Further details associated with MTLS hardware, software, configuration, and methodology are discussed below.

	Technology	Purpose for Inclusion in Sensor Suite	ECEF Accuracy	Feature Detection Capability	Coverage		Point Density
					Volume of Data	Utility for Roadway Map Development	
Individual sensor technologies	INS	Bandwidth, Sample Rate, Continuity	N/A	No			
	GNSS	ECEF accuracy	cm	No			
	Camera	Feature detection and photolog	N/A	Yes			
	LiDAR	Feature detection, accurate feature georectification	N/A	Yes			
Sensor Suites	STLS	GPS, Camera, Lidar	cm	Yes	75m × 75m	No	High
	MTLS	INS, GPS, Camera, Lidar	cm	Yes	100m × Trajectory length	Yes	High
	ALS	INS, GPS, Camera, Lidar	submeter	Yes	150m × Trajectory length	Yes	Low
	Crowd Source Data		m	Inferred	Full road	Detecting Map Updates	N/A

Table 1.5: Comparison of different mapping technologies.

1.3 MTLS Process, Instruments, Software

Due to the conclusion of the prior section that MTLS is currently the most appropriate approach for automated intersection mapping, this section expands on the MTLS process, instruments, and software processing. MTLS's are composed of numerous individual sensors mounted upon a single platform, as summarized in Table 1.5.

The common sensors and components comprising an MTLS include:

- LIDAR(s) – either planar or rotating LIDAR sensor(s)
- Camera(s) – one or more cameras
- GNSS – Real Time Kinematic (RTK) capable GNSS receiver
- IMU – Inertial measurement
- Processors – Data logging with precisely time aligned data streams
- Data Storage – repository for partially processed data onboard the vehicle
- Power support – energy storage and/or generation to handle additional power loads

The physical construction of the MTLS requires significant consideration to physical layout, occlusions, signal processing, calibration, and configuration. Each individual sensor possesses specific operational constraints and considerations. When properly integrated and configured the system provides accurate and robust system for mapping roadway infrastructure effectively and efficiently [2, 22]. The overall process is depicted in Fig. 1.1.

The physical layout attempts to provide a rigid structure, so that the pose variables T_{PL}^{P} and R_{PL} defined relative to Fig. 2.1 are constant. The camera(s) and LIDAR(s) are mounted to not be occluded by the mounting structure and the other instruments, while also having a clear view of the roadway and its environment. It is critical that the LIDAR(s) are able to acquire a high density of roadway reflections to allow detection and recognition of roadway features.

While the sensor data may be processed in real-time for quality assurance, all the data is saved to the disk with precise time stamps for post-processing. Accurate time alignment is necessary because the platform is moving. The georectification process sums three vectors to construct the desired vector P_F^W. Three of the quantities in the georectification formula change with the pose of the vehicle. Accurate time alignment ensures that the correct set of quantities is estimated and summed.

The first step of the georectification process is determination of the platform trajectory by use of the GNSS and IMU data. The (differential) GNSS measurements provide constraints on the vehicle location at the measurement time instants at a low rate (i.e., 1 Hz). The IMU measurements provide constraints on the platform motion between the GNSS measurement epochs at very high rates (i.e., >200 Hz). Optimal nonlinear smoothing algorithms [1,9,19] combine these data in a post-processing operation to estimate the platform trajectory. These algorithms can also incorporate the LIDAR and Camera measurements. For example reflectors easily detectable by either the LIDAR or Camera may be placed at surveyed locations to serve as control points. This GNSS/IMU smoothed result provides the time history of the platform pose at the IMU sample rate which is necessary to perform LIDAR and camera georectification.

The LIDAR data and camera data are stored onboard. The translation of camera data and LIDAR data into a georectified point cloud and photolog requires extensive post processing, filtering, and manipulation. The photolog and colorized point cloud are direct outputs of the georectification process. Commercial companies (e.g., HERE) will soon stitch the photolog images together into a continuous panoramic image. In either case, the user can fly though this database seeing and analyzing the roadway environment.

The georectified LIDAR point cloud data are useful for feature detection and mapping. After data reduction to a small specific region, the first task is to identify the individual points within the point cloud subset that are expected to belong to the same surface (e.g., high intensity points lying on a near horizontal surface). These individual points are processed to remove outliers and used to estimate the desired characteristics to describe the feature (e.g., location).

The designated features such as lane markings, road edges, stop bars, and intersections can be identified, characterized and defined. This feature extraction process is specific to the attribute and requires very specific programming. A high density of LIDAR reflections on the surface of interest greatly facilitates feature detection and mapping.

The process of creating a georectified photolog is similar to processing the LIDAR data but entails special image processing steps when transitioning from one survey frame to the next. Each image will possess a small amount of location measurement error. When two or more images are being merged the images must be processed and aligned to avoid visual blurring and distortion. This process is well-documented (see, e.g., [23]) but requires significant processing power as the size of the images increase. Due to the extensive processing requirements the integrated and georectified photolog (or panoramic image) is created as a post-processing step.

1.4 Applications: Features and accuracy requirements

Numerous ITS applications have been identified with the potential to improve mobility, safety, and the environment [24-26]. Connected vehicle technology has been identified as an enabling technology for many of the identified applications. The V2V and V2I connected vehicle implementations often require accurate positional information relative to a reference map. The reference map contains road features, such as, lane markings, stop bars, road edges, turn pockets and intersection geometry. The goal of this section is to discuss mapping and real-time positioning tradeoffs and to characterize the accuracy requirements of a variety of connected vehicle applications. For a common list of connected vehicle applications, we reference the CVRIA (http://www.iteris.com/cvria/). The CVRIA CV application list is based on the results of an extensive connected vehicle research program carried out by the USDOT over the last decade.

Mapping and Real-time Positioning Tradeoffs

The Fig. 1.5 illustrates a connected vehicle maneuvering within a lane near an intersection. Various quantities of interest for the application – forward distance s_F, left distance s_L, and right distance s_R – are illustrated. Each of these quantities is computed in real-time at a high rate by differencing the vehicle position p_V with a quantity computed from the map information: p_L, p_F, or p_R. For example, $s_F = p_F - p_V$, each of which is uncertain, with uncertainty indicated in the figure by the size of the concentric circles around the point. Therefore, the uncertainty in the computed quantity is related to the uncertainty in the positions. If we characterize the uncertainty by a standard deviation, then the equation is

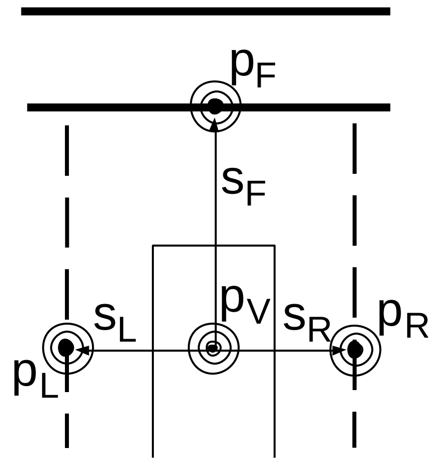


Figure 1.5 CV application variable definitions

$$\sigma_{s_F} = \sqrt{\left(\sigma_{p_V}\right)^2 + \left(\sigma_{p_F}\right)^2}.$$

This equation is important as it shows the tradeoff between the accuracy specifications of the map features denoted by σ_{p_F} and the implied accuracy requirements for real-time positioning (i.e., navigation) denoted by σ_{p_V}.

Fig. 1.6 illustrates this tradeoff. Assume that for a given application, the distance to the stop bar $||s_F||$ must be computed with a standard deviation of less than one meter. The outermost curve in the figure shows the locus of points that satisfy this specification. If for example, the map is accurate to 10 cm, then real-time vehicle position estimated to 0.99 meter accuracy is sufficient. However, if the map is only accurate to 0.9m, then the vehicle position must be estimated in real-time to an accuracy of approximately 40 cm.

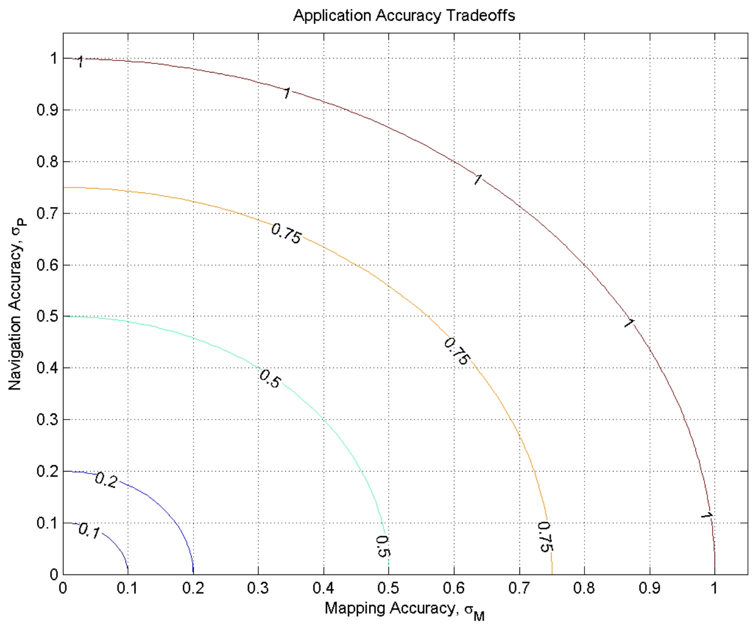


Figure 1.6 CV Mapping and positioning

Connected Vehicle (CV) Application Accuracy Requirements

The CV applications from the CVRIA version 1 are presented in three tables (Table 1.6a-1.6c) segregated as either a mobility, environmental, or safety application[2]. In these tables, we also describe to the best of our analysis the mapping accuracy requirements. Vehicles possessing CV technology will typically possess a GNSS receiver capable of 2 to 3 meters accuracy in many road environments. This level of GNSS technology will likely provide sufficient accuracy for applications requiring "Coarse Positioning" in the following tables. The mobility applications requiring "Lane Level Positioning" or "Where in Lane Positioning" will require improved positioning technology (e.g., a GNSS receiver capable of receiving differential corrections, perhaps processing the carrier phase information) and likely require an accurate reference map of the roadway.

The CV safety applications, as shown in Table 1.6a, identify numerous applications requiring positioning better than 3 meters. The pure V2V applications that are independent of lane arrangement do not require a detailed map representation. Alternately the V2V applications such as Intersection Movement Assist requires detailed knowledge of the intersection geometry and the position of vehicles within the intersection. This example clearly requires a detailed intersection reference map as well as accurate vehicle positioning.

The CV mobility applications, as outlined in Table 1.6b, have several V2I implementations that required accurate knowledge of a vehicle's position within the roadway, both from a lateral point-of-view (e.g., lane markings) and a longitudinal point-of-view (e.g., stop bars at intersections). Examples include: Traffic Signal Priority, Speed Harmonization, and Intermittent Bus Lanes.

[2] Please note that the initial mapping and positioning accuracy analysis was carried out on CVRIA version 1; as of August 3, 2015 CVRIA version 2 has been released, describing an expanded list of CV applications..

These applications must coordinate specific vehicle movements within a lane and require detailed reference maps in conjunction with accurate vehicle positioning.

Several CV environmental applications, as shown in Table 1.6c, also require accurate map relative positioning. Eco Approach and Departure, Eco Speed Harmonization, and Eco Transit Signal Priority all require detailed knowledge of vehicle position within the roadway. It is important to note that the required positional accuracy for a specific application must consider the additive errors of vehicle positioning error and map errors. A two meter vehicle positioning error and two meter map error leads to a potential four meter error in the CV application deployment. Since errors are more easily controlled during a mapping survey it is important to reduce map errors whenever feasible.

1.5 Applications: Examples

Rather than report explicitly on each application in Table 1.6, we discuss three example applications below to provide background on the positioning and mapping needs from the areas of safety, mobility, and the environment.

Safety Application Example – Emergency Electronic Brake Light (EEBL)

The EEBL application enables a vehicle to broadcast a self-generated emergency brake event to surrounding vehicles. The receiving vehicle determines the relevance of the event and if appropriate provides a warning to the driver in order to avoid a crash. This application improves driver safety for both the host vehicle and the remote vehicle as seen in Fig. 1.7. The EEBL equipped braking vehicle (RV) and the EEBL vehicle receiving the message (HV) can interact in numerous beneficial scenarios. The most beneficial situation in Fig. 1.7 is scenario 4 when a heavy braking event occurs and the equipped HV can not only avoid impacting the RV but can moderate is own deceleration rate. The moderation of deceleration by the HV reduces the risk of additional collisions of non-equipped vehicle following the HV. Many potential scenarios exist for the potential deployment of EEBL with varying levels of technology implementation.

At the simplest EEBL technology level a vehicle can be equipped to sense the distance and deceleration rate of a vehicle directly in front of a host vehicle. This can be accomplished without the need of absolute vehicle position and only requires proximity (e.g. radar, LIDAR, stereo vision camera) sensing. EEBL applications which only utilize on-board proximity sensors will be limited to responding only to vehicles directly in front of a host vehicle. Any obstructions will reduce the effectiveness of the application.

EEBL applications utilizing CV technology will integrate the equipped vehicles' absolute position into the EEBL algorithm. When a vehicle's positional accuracy is "coarse positioning", the benefits are limited by approximation relative vehicle positioning between equipped vehicles. A hard braking event can be broadcast to nearby vehicle as a warning, but countermeasures cannot be fully deployed since vehicle proximity is unknown and the vehicle may be in different lanes.

EEBL applications utilizing "lane level positioning" can improve the fidelity of the application by limiting warnings to vehicles in the same lane. This greatly improves the effectiveness of the application. Finally, "where in lane" positioning provides the greatest benefit to equipped vehicles. The scenarios shown in Fig. 1.7 can be fully optimized with where in lane positioning. The relative position between equipped vehicles will be accurately determined even when line-of-sight doesn't exist. The EEBL application is particularly useful when there is line of sight obstruction by other vehicles or poor weather conditions (e.g., fog, heavy rain). Various automotive OEMs have experimented with the EEBL concept.

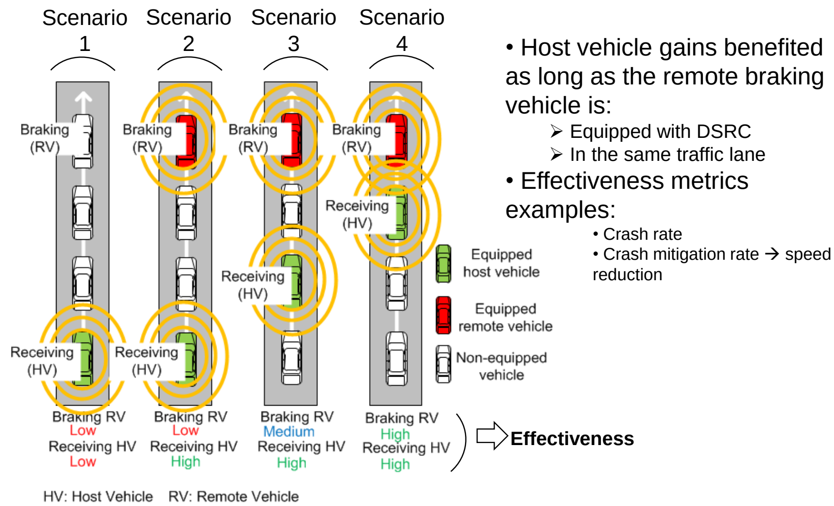


Figure 1.7 EEBL Safety CVRIA application as envisioned by OEM (Honda).

Mobility Application Example – Cooperative Adaptive Cruise Control (CACC)

The goal of CACC is through partial automation to coordinate the longitudinal motion of a string of vehicles by utilizing V2V communications in addition to traditional adaptive cruise control (ACC) systems. There are a wide variety of CACC implementations, but in general CACC implementations employ the following conditions:

- V2V messages are communicated between leading and following vehicles, and the application performs calculations to determine how and if a string can be formed;
- The CACC system provides speed and lane information of surrounding vehicles in order to efficiently and safely form or decouple platoons of vehicles; and,
- the “groups” of vehicles that are formed are referred to as “strings” rather than “platoons” of vehicles (strings are sometimes called loosely coupled platoons).

The simplest CACC technology can be deployed with only proximity (e.g. radar, LIDAR, stereo vision camera) sensing and with significant gaps between the vehicles. This “no-positioning” version would not be able to coordinate platoon formation or decoupling. The application would only be able to loosely keep a group of vehicles traveling a constant speed. More meaningful implementations of CACC require some level of absolute vehicle positioning.

When a vehicle’s positional accuracy is at “coarse positioning”, the benefits are limited by approximating relative vehicle positions between equipped vehicles. Lateral maneuvers would not be feasible without the addition of on-board sensors to determine lane markings and nearby vehicle proximity. When at “Lane Level” positioning accuracy, it is possible to have the application coordinate vehicle strings with formation and de-coupling maneuvers. But to maximize CACC potential, “where in lane” accuracy is required to manage complex merge and split maneuvers and minimize headway within a string. The additional integration of lane keeping can be assisted by onboard proximity sensing and sub-meter relative position accuracy. Fig. 1.8 depicts a CACC application with relevant gap, headway, and vehicle roles.

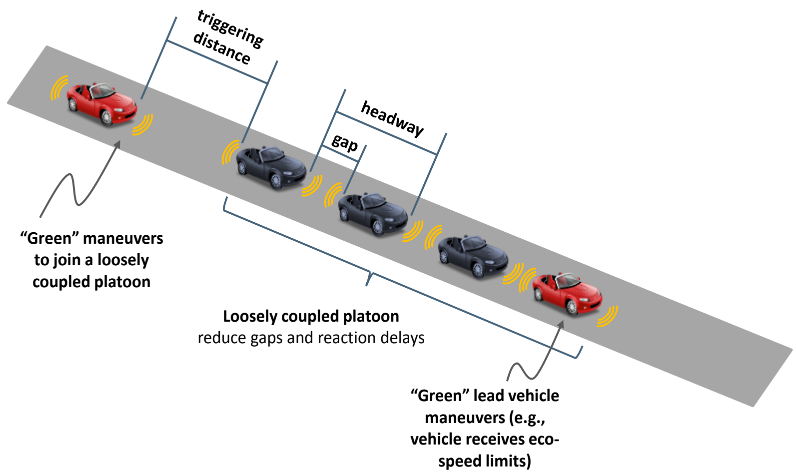


Figure 1.8 CACC Mobility CVRIA application as deployed in pilot demonstrations.

Environmental Application Example – Eco Approach and Departure (EAD)

An EAD implementation at signalized intersections provides speed advice to the driver of the vehicle traveling through the intersection. Longitudinal control can be carried out by driver using driver vehicle interface or the longitudinal control can be automated (e.g., see the GlidePath program). The speed of the vehicle is managed to pass the next traffic signal on green or to decelerate to a stop in the most eco-friendly manner. The application also considers a vehicle's acceleration as it departs from a signalized intersection. An EAD equipped vehicle will be advised to follow a speed trajectory based on: SPaT data sent from a roadside equipment (RSE) unit to connected vehicles via V2I communications; Intersection geometry information; signal phase movement information; and, potential data from nearby vehicles can also be utilized using V2V communications. Fig. 1.9 shows the current pilot deployment architecture of EAD at signalized intersections.

At the simplest EAD technology can be deployed with "coarse positioning" and serve as a loose advisory to the driver. The coarse positioning application would lack precision and only provide limited environmental or fuel improvements. To improve the potential for EAD, a minimum of "Lane-level" positioning is required with some level of on-board proximity sensors. The proximity sensors determine the presence of forward vehicles relative to the equipped vehicle. To fully maximize the EAD application potential, "where in lane" accuracy is required to manage maneuvers during congestion and brief signal opportunities. Careful coordination of SPaT, vehicle position, vehicle speed, and frontal vehicle's provide the greatest environmental improvements. Fig. 1.10 depicts a EAD application with signal timing scenarios.

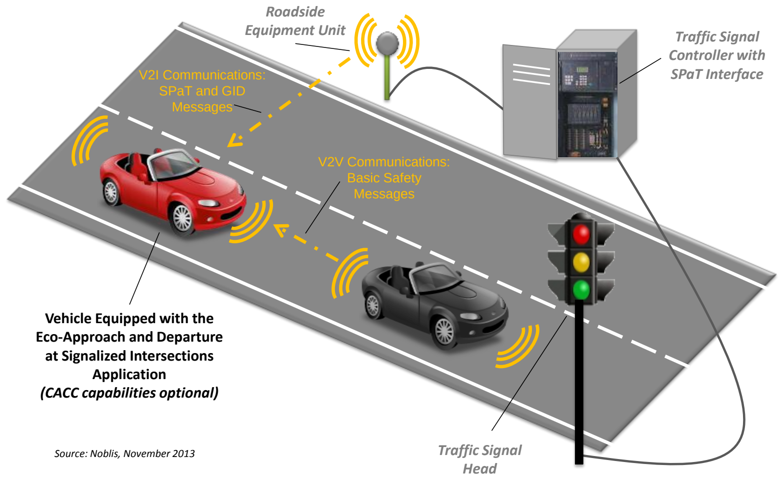


Figure 1.9 EAD Environmental CVRIA application as deployed in pilot demonstrations.

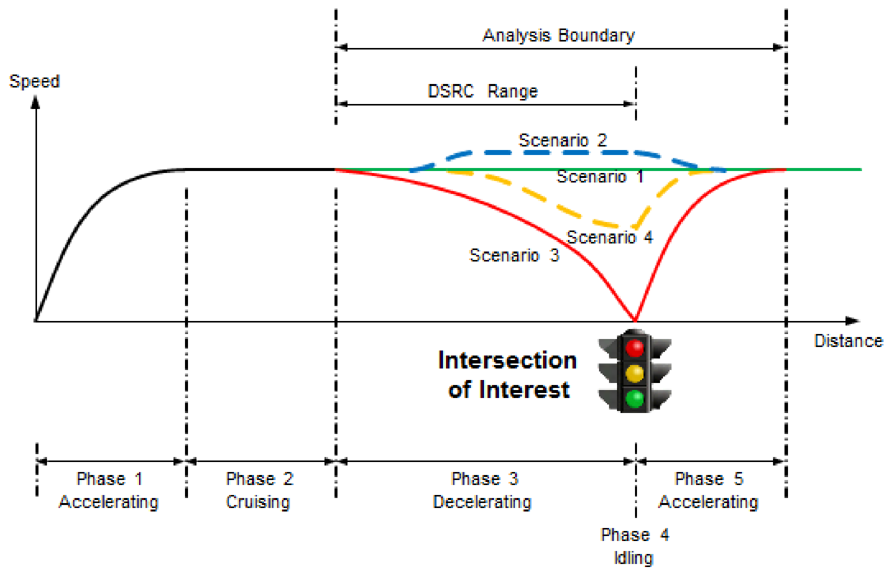


Figure 1.10 EAD signalized intersection timing scenarios.

			No Positioning	Coarse Positioning $\sigma_S > 3m$	Lane Level Positioning $3m > \sigma_S > 1m$	Where in Lane Positioning $0.5m > \sigma_S$
Safety	**Transit Safety**	Transit Pedestrian Indication		Coarse positioning is sufficient to inform the pedestrians about the (future) presence of a transit vehicle		
		Transit vehicle at Station/Stop/Stop Warnings		Coarse positioning is sufficient to inform nearby vehicles of the presence of a transit vehicle in near future	Enhanced accuracy and bandwidth will enable prediction of vehicle motion	
		Vehicle Turning Right in Front of a Transit Vehicle			Lane-level positioning is sufficient to activate driver warnings	Better positioning accuracy and bandwidth will help to predict the vehicle trajectory motion
	V2I Safety	Curve Speed Warning		Coarse positioning is sufficient for general speed warnings	Lane-level positioning allows warnings specific to vehicles about a curve as well as recommended speed	
		In-Vehicle Signage		Coarse positioning is sufficient to provide all the regulatory warning and informational signs and signals(stop, curve warning, guide signs, service signs, and directional signs)	Lane-level positioning will improve the selectivity of vehicle for the presented information	
		Oversize Vehicle Warning		Coarse positioning will help unequipped vehicles to display warnings or reroute information when the vehicle does not have adequate height or width clearance	Lane-level positioning will allow lane specific vehicle warnings and guidance	
		Pedestrian in Signalized Crosswalk Warning		Coarse positioning is sufficient to warn local vehicles regarding presence of known pedestrians in the crosswalk and also inform the pedestrians about potential vehicle in the area	Lane-level positioning will enable prediction of vehicle crosswalk infringement.	
		Railroad Crossing Warning		Coarse positioning is sufficient to provide selected vehicles with warning about approaching train	Lane-level positioning will enable prediction of unsafe situations	
		Red Light Violation Warning		Coarse positioning is sufficient to provide selected vehicles with signal information	Lane-level positioning is the least requirement to predict the likelihood of vehicle signal violation	Better positioning efficacy will provide warning about possible signal violation beforehand and also give instructions to prevent the situation

Table 1.6a: Safety Connected Vehicle Applications (part 1 of 3)

		Reduced Speed Zone Warning		Coarse positioning is sufficient	Lane-level positioning allows per lane guidance	
		Restricted Lane Warnings		Coarse positioning allows identical communication to all vehicles	Lane-level positioning allows vehicle specific restriction warnings and alternative route advice specific to each lane	
		Spot Weather Impact Warning		Coarse positioning is necessary to alert drivers about unsafe and blocked road conditions	Lane specific warning is possible along with substitute route advice	Automated driver assistance is feasible for local road conditions
		Stop Sign Gap Assist			Lane-level positioning enables warning drivers on minor roads about unsafe gaps on the major road	Enhance accuracy improves prediction about possible collision, especially for multiple vehicles on minor roads
		Stop Sign Violation Warning			Lane-level positioning is sufficient to warn drivers about predicted stop sign violations	Enhanced accuracy enables automated assistance for better prediction or prevention
		Warnings about Hazards in a Work Zone		Coarse positioning enables warnings about general hazards (vehicle approaching at high speed) to maintenance personnel within a work zone	Lane-level accuracy significantly enhances accuracy of predictions (giving warnings to more specific vehicles), reducing false alarms.	
		Warnings about Upcoming Work Zone		Coarse positioning is sufficient to provide information about an approaching work zone condition	Lane-level allows per vehicle alternate routing suggestions.	
	V2V Safety	Blind Spot Warning	Relative vehicle position is sufficient for applying currently			Where in lane positioning is necessary when absolute positioning is used in both vehicles
		Control Loss Warning	Internal vehicle detection of loss of traction control enables broadcast to all vehicles within range	Absolute positioning allows far away vehicles to ignore the message	Allows nearby vehicles to display driver warnings	Allows automatic vehicle reaction
		Do Not Pass Warning			Lane level positioning is necessary to warn about passing zone which is occupied by vehicles in the opposite direction of travel	Where in lane will assist drivers regarding when to pass
		Emergency Electronic Brake Light	No positioning is necessary to broadcast a self-generated emergency brake event to surrounding vehicles	Absolute positioning allows far away vehicles to ignore the message	Allows nearby vehicles to display driver warnings	

Table 1.6a: Safety Connected Vehicle Applications (part 2 of3)

		Emergency Vehicle Alert	No positioning is necessary to alert the driver about the location of and the movement of public safety vehicles responding to an incident	Absolute positioning allows far away vehicles to ignore the message	Allows nearby vehicles to display driver warnings	
		Forward Collision Warning	Relative positioning is sufficient to implement in current technology			Where in lane positioning is necessary when absolute positioning is used on both vehicles, plus V2V communications
		Motorcycle Approaching Indication	Relative positioning can be implemented in today's technology to give warnings	Coarse positioning is sufficient for providing warnings to all the vehicles in specific region	More accurate positioning will provide more vehicle specific warnings	More accurate positioning will help vehicles to predict any future collision or accident
		Intersection Movement Assist			Lane level positioning is necessary to warn about potential conflicts	Where in lane positioning will improve prediction
		Pre-crash Actions			Lane level positioning is necessary to mitigate the injuries in a crash by activating pre-crash actions	Where in lane positioning enables faster predictions with more warning time
		Situational Awareness		Coarse positioning is sufficient to broadcast a general warning to all vehicles about road conditions measured by other vehicles	Lane level positioning allows more lane specific warnings, plus vehicles can determine warning relevance	
		Slow Vehicle Warning		Coarse positioning is sufficient to warn the driver about approaching a slow vehicle	Lane level positioning will help providing warnings to vehicles in specified lane	
		Stationary Vehicle Warning		Coarse positioning is sufficient to warn the driver about an approaching stationary vehicle	Lane specific warnings can be implemented	
		Tailgating Advisory	Relative positioning can be used to provide tailgating warning with no positioning requirement		Lane level positioning on both vehicles is necessary in case of absolute positioning	Where in lane will help provide more accurate warnings and discard the false alarms
		Vehicle Emergency Response		Coarse positioning is needed for public safety vehicles to get information from connected vehicles involved in a crash	Improved positioning will help to gather more information	Allows diagnosis of how the accident happened

Table 1.6a: Safety Connected Vehicle Applications (part 3 of 3)

			No Positioning	Coarse Positioning $\sigma_S > 3m$	Lane Level Positioning $3m > \sigma_S > 1m$	Where in Lane Positioning $0.5m > \sigma_S$
Mobility	**Border**	Border Management Systems	No positioning is necessary for electronic interactions if RF transponder is used		Lane level positioning is necessary when the use of RF transponder is limited or absent	
	Commercial Vehicle Fleet Operations	Container Security	No positioning is necessary for container security operation			
		Container/Chassis Operating Data	No positioning is necessary for this application	Coarse positioning can include more operating data like route log		
		Electronic Work Diaries		Coarse positioning is necessary to collect information relevant to the activity of a commercial vehicle	Better positioning will collect more detailed work information (routing, log activity, driving pattern etc.) in future	
		Intelligent Access Program		Coarse positioning is necessary for remote compliance monitoring	Better positioning will enable more detailed monitoring	
		Intelligent Access Program – Mass Monitoring				
	Commercial Vehicle Roadside Operations	Intelligent Speed Compliance		Coarse positioning is necessary for monitoring speed	Lane level positioning will provide more information about the driving pattern	
		Smart Roadside Initiative		Coarse positioning is necessary to activate the application	Lane level positioning will provide more detailed information	
	Electronic Payment	Electronic Toll Collection	No positioning is required when RF transponder is used to collect tolls electronically and detect and process violation		Lane level positioning of vehicle is necessary when the use of RF transponder is limited or absent	
		Road Use Charging				
	Freight Advanced Traveler Information Systems	Freight Drayage Optimization		Coarse positioning of the vehicle is necessary for information exchanges		
		Freight Specific Dynamic Travel Planning		Coarse positioning is necessary to have pre-trip and enroute travel planning, routing, and other traveler information such as truck parking locations and current status	Better positioning will help by providing more detailed route and nearby facility information in future	

Table 1.6b: Mobility Connected Vehicle Applications (part 1 of 4)

	Planning and Performance Monitoring	Performance Monitoring and Planning		Coarse positioning is necessary to monitor and collect data including transportation planning, condition monitoring, safety analyses, and research and predict speed and travel times	Lane level positioning will predict lane level speed and travel times and thus improve the application efficiency	
	Public Safety	Advanced Automatic Crash Notification Relay		Coarse positioning is necessary to automatically transmit an emergency message in times of crash or other distress situation	Lane level positioning will enable the vehicle to broadcast messages to nearby vehicles only	
		Emergency Communications and Evacuation		Coarse positioning is sufficient to activate the application		
		Incident Scene Pre-Arrival Staging Guidance for Emergency Responders		Coarse positioning is necessary to activate the application		
		Incident Scene Work Zone Alerts for Drivers and Workers		Coarse positioning is necessary to activate the application		
	Traffic Network	Cooperative Adaptive Cruise Control			Lane level positioning is sufficient for automatically synchronizing the movements of many vehicles within a platoon	Where in lane positioning will improve the applications efficiency and reduce the occurrences of wanted circumstance
		Queue Warning			Lane level positioning is sufficient to broadcast the queued status information (rapid deceleration, disabled status, lane location) give warnings to vehicles in times of potential crash situation	
		Speed Harmonization		Coarse positioning is necessary speed recommendations based on weather information	Lane level positioning is suitable for speed recommendations based on traffic conditions	

Table 1.6b: Mobility Connected Vehicle Applications (part 2 of 4)

		Vehicle Data for Traffic Operations		Coarse positioning helps pointing out the changes in vehicle speeds indicating the disruption of traffic flow as well as the location of potential incidents	Lane level positioning will help detecting the incident location more efficiently and accurately	
	Traffic Signals	Emergency Vehicle Preemption		Coarse positioning is necessary to activate the application	Lane level positioning is necessary to plan travelling route and facilitate safe and efficient movement through intersections for high priority emergency vehicle	
		Freight Signal Priority			Lane level positioning of freight and commercial vehicles is necessary to provide traffic signal priority for traveling in a signalized network	
		Intelligent Traffic Signal System			Lane level positioning of vehicle is necessary to get vehicle location and movement information to improve the operations of traffic signal control systems	
		Transit Signal Priority				Where in lane positioning of transit vehicle is necessary to respond to a transit vehicle request for a priority at one or a series of intersection
	Transit	Dynamic Ridesharing		Coarse positioning is a necessity to gather information from both passengers and drivers to provide them with convenient route by arranging carpool trips	Better positioning will improve the dynamic ridesharing application	
		Dynamic Transit Operations		Coarse positioning is necessary to plan, schedule, modify and dispatch users trips and itinerary by using automated vehicle location	Better positioning will improve the efficiency of the application in future	
		Integrated Multi-Modal Electronic Payment	No positioning is necessary for electronic interactions if RF transponder is used		Lane level positioning is necessary when the use of RF transponder is limited or absent	

Table 1.6b: Mobility Connected Vehicle Applications (part 3 of 4)

		Intermittent Bus Lanes	No positioning is necessary to create and remove a bus lane during peak demand times to enhance transit operation mobility		Lane level positioning will help maintaining the lanes	
		Road ID for the Visually Impaired		Coarse positioning is necessary to assist visibly impaired travelers to identify the appropriate bus and route options to their intended destination.	Better positioning will help the traveler in times of distress (road accident, weather hazard etc.)	
		Smart Park and Ride System		Coarse positioning is sufficient to provide travelers with real-time information on Park and Ride capacity	Lane level positioning will provide travelers with the location of the park and ride capacity	
		Transit Connection Protection		Coarse positioning is necessary to help the passenger with the information of approximate arrival time, vehicle transfer to reach safely to the destination	Better positioning will improve the applications efficiency	
		Transit Stop Requested		Coarse positioning allows a transit passenger to send a stop request to an approaching transit vehicle		
	Traveler Information	Advanced Traveler Information Systems		Coarse positioning is sufficient for the collection of information including traffic, transit, road weather, work zone, and connected vehicle related data		
		Receive Parking Space Availability and Service Information		Coarse positioning is necessary for providing pre-trip and enroute traveler information such as truck parking locations	Better positioning will improve the applications efficiency	
		Traveler Information-Smart Parking			Lane level positioning of the vehicle is suitable to provide real-time location, availability, type (e.g., street, garage, AFV only), and the price of parking	

Table 1.6b: Mobility Connected Vehicle Applications (part 4 of 4)

			No Positioning	Coarse Positioning $\sigma_S > 3m$	Lane Level Positioning $3m > \sigma_S > 1m$	Where in Lane Positioning $0.5m > \sigma_S$
Environmental	AERIS/ Sustainable Travel	Connected Eco-Driving		Coarse positioning is required for longitudinal actions such as following speed advice	Could be necessary to differentiate between lane-based eco-driving advice	
		Dynamic Eco-Routing		Coarse positioning is necessary to enable the application		
		Eco- Approach and Departure at Signalized Intersections		Required for longitudinal speed trajectory planning	Required for differentiating lane-based SPaT	Required for scenario 3 where vehicle has to stop precisely at stop bar
		Eco-Cooperative Adaptive Cruise Control			Required for lateral and longitudinal control, with sensor assist	Sensor-based relative positioning is required
		Eco-Freight Signal Priority		Required for longitudinal speed trajectory planning	Required for differentiating lane-based SPaT	
		Eco-Integrated Corridor Management Decision Support System	No positioning is necessary to enable the application	Coarse positioning provides advanced functions		
		Eco-lanes Management		Coarse positioning is necessary to enable the application	Lane level positioning will improve the application's efficiency in future	
		Eco-Multimodal Real-Time Traveler Information	No positioning is necessary to enable the application	Coarse positioning provides advanced functions		
		Eco-Ramp Metering			Lane Level positioning is necessary to differentiate lane speeds	
		Eco-Smart Parking		Coarse positioning is necessary to enable the application		
		Eco-Speed Harmonization		Coarse positioning is necessary to enable the application	Lane level positioning is necessary to differentiate lane-based speed advice	
		Eco-Traffic Signal Timing	No positioning is necessary to enable the application			
		Eco-Transit Signal Priority		Required for longitudinal speed trajectory planning	Required for differentiating lane-based SPaT	
		Electric Charging Stations Management		Coarse positioning is necessary to enable the application		
		Low Emissions Zone Management		Coarse positioning is necessary to enable the application		

Table 1.6c: Environmental Connected Vehicle Applications (part 1 of 2)

		Roadside Lighting		Coarse positioning is necessary to enable the application		
	Road Weather	Enhanced Maintenance Decision Support System		Coarse positioning is necessary to enable the application		
		Road Weather Advisories and Warning for Motorists		Coarse positioning is necessary to enable the application	Possible lane differentiation required for hazards	
		Road Weather Information and Routing Support for Emergency Responders		Coarse positioning is necessary to enable the application		
		Road Weather Information for Freight Carriers		Coarse positioning is necessary to enable the application		
		Road Weather Information for Maintenance and Fleet Management Systems		Coarse positioning is necessary to enable the application		
		Variable Speed Limits for Weather-Responsive Traffic Management		Coarse positioning is necessary to enable the application		

Table 1.6c: Environmental Connected Vehicle Applications (part 2 of 2)

In addition to this CVRIA applications mapping requirements analysis, we also provide an analysis of the requirements of the three recently initiated Connected Vehicle Pilot Deployment projects in Appendix C.

1.6 Business Models

The main focus of this Task 1 effort was sensor based mapping approaches and requirements related to CV applications. Accurate roadway digital databases are also important to other roadway applications, for example: roadway planning, construction documentation, accident investigation, roadway inventory assessment, pavement characterization, and vertical clearances. Numerous sources and methodologies exist to acquire digital roadway infrastructure maps and representations. The focus thus far has been to explain and analyze the existing technologies, requirements, and applications. Telephone interviews make clear that the FHWA, state DOT's and commercial enterprises are all at various stages of constructing roadway digital data bases.

Before summarizing existing business models, it is useful to consider the issues, tradeoffs, and desired characteristics related to digital roadway data bases:

- **Huge data sets:** The raw data produced by the instruments is huge. To illustrate the order of magnitude of data consider the data in Table 1.2: given 4.1 million miles of US public roads, driven at 50 mph, with 1 TB/hr of data generation, yields about $82x10^3$ TB of raw data. Much of the data may be irrelevant or redundant. Which raw data should be stored? How and where should it be stored? Who should have access to it?
- **Time variation:** The roadways, the plates on which they sit, the roadway environment, and the coordinate systems in which they are defined are all time varying. How often should the data sets be reacquired? How can obsolete data be detected and removed or replaced?
- **Database spatial continuity:** Connected vehicle commercial success will require uniformity of database contents, accuracy, and behavior across geographic boundaries.
- **Automaker uniformity:** Market success will require uniform vehicle behavioral expectations across auto manufacturers.

State DOTs are required to perform maintenance, management, construction, and oversight of a state owned roads and highways. This responsibility requires detailed knowledge of the road network, features, attributes, condition, and geometry. The traditional survey methods and photologs are rapidly being updated with georeferenced GIS databases. When the DOT desires data along an extensive network, GIS databases are frequently created with data collected through STLS, MTLS, and ALS. Since the primary interest of state DOTs is the road network, the predominate method of georeferenced data collection is transitioning toward MTLS mounted on a vehicle and driven on the state owned roads. The MTLS data collection for state DOTs is either contracted to third party service providers of MTLS data or state DOTS purchase MTLS equipment and perform their own georeferenced data collection.

State DOTs that purchase their own hardware and software have the upfront cost for hardware, software, training, and integration. Once the equipment and methods have been integrated within the institution there is the incremental cost of performing MTLS based surveys. Software packages are available to help with data management, georectification, and construction of photologs. This approach requires highly trained data processing personnel within the DOT are available as consultants. An advantage is that the DOT has complete control of the MTLS equipment and its schedule, plus direct access to the raw and processed to use as is needed. A disadvantage is that the high quantities of data must be managed and curated. Also, in states where MTLS is performed separately by each district, special attention must be paid to combining maps across district boundaries.

Other states contract to third parties (e.g., Mandli) to collect and process the MTLS data. This shifts the costs of equipment purchase and maintenance, data curation and management, and training of data processing personnel from the states to the third parties; however, the DOT may be limited in its access to some forms of data. The third parties try may be able to present the state DOT's with a cost savings by more fully utilizing their equipment and expertise, so that their fixed costs are spread over more projects. Some third parties are working towards automated feature detection. While the third party is responsible for managing and curating all data from a given contract period, it may be difficult to combine map information if the state DOT switches between third party vendors at the end of a contract.

The MTLS generated data is most useful if it can be accessed and used by all knowledgeable employees of the DOT. Some states and third party providers have developed the expertise to make this possible through web interfaces.

Finally, if the state DOT's will be generating the maps for CV applications, those states would need to specify methods at an early stage to ensure full coverage of all roads, nationwide (or global) coverage, uniform accuracy, and common interface standards. Without these characteristics, the automobile manufacturers will not be able to utilize the resulting map databases.

Certain corporate entities are also developing maps intended to have global coverage. Certain corporations (e.g., Apple, Bing, Google) are developing maps intended to be used in consumer applications (routing, advertising, context based search, autonomous taxi service). Such maps do not require high-accuracy and do not contain roadway relative features.

Other corporations (HERE, CivilMaps, QUANERGY) are developing highly accurate maps with global coverage, intending to use a "data as a service" business model.

HERE will have a fleet of over 300 MTLS vehicle allowing them to guarantee a maximum time between surveys of three years for any road in the U.S., with higher frequency surveys in urban areas, or surveys on demand in areas that are thought to have changed. Changes are detected using crowd sourced data or through authorized persons (e.g., DOT employees). They are developing at least two products of interest:

- HERE Reality Lens provides calibrated street-level panoramic views. The user can fly thorough the roadway environment and perform various types of measurements to support analysis. This product builds on the EarthMine technology. The database can be accessed via an internet user interface or downloaded (regionally) to the user computer.
- HERE HD Live Map provides a lane-level map with lane edges and centerline. This product is intended for connected vehicle and autonomous vehicle type of applications. Point features can be stored along the lanes. Both real-time and historical traffic information is expected to be included on a per lane basis.

Both of these products are still under development. HERE is open to discussions about map content and features, along with contracting options. If they succeed, it would be the first global roadway map.

There have also been discussions on how the federal government could assist in organizing datasets. Several discussions have been carried out as part of the CVRIA development, and the role it should play in terms of defining map features and databases.

1.7 Concluding Statement

Connected vehicle applications will continue to improve in performance and feasibility as roadway feature maps become more accurate and available. The methods and procedures implemented in the early stages will help define the future needs and requirements. This review and analysis has characterized the current and existing methods utilized by state DOTs, vendors, and corporations for collecting and mapping relevant road features and attributes. While most feature extraction and mapping is currently performed manually, globally applicable feature maps will necessitate that the processes progress toward human-assisted and eventually to automated processes.

2. MOBILE MAPPING SYSTEM ENHANCEMENTS

2.1 Introduction

Detailed roadway feature maps will need to be developed, maintained, and communicated consistently to support Connected Vehicle (CV) applications. As a result, within the U.S. alone, hundreds of thousands of intersections and millions of miles of roadway will need to be surveyed, with application-relevant roadway features mapped to application-specific accuracies. The UC Riverside research team developed a Mobile Positioning and Mapping System (MPMS) platform that provides an accurate geometric representation of the roadway and relevant roadway features. The associated data processing interprets the relevant data and provides properties of the roadway and features in and digitally transmittable map message. Most mapping solutions relevant to the connected vehicle program involve the use of some combination of sensors and equipment, platforms, processes, and software.

The MMPS is a vehicle mounted technology involving the use of positioning and sensor Global Position System (GPS) technology, Inertial Measurement Units (IMU), Light Detection and Ranging (LIDAR), and video cameras mounted on vehicles to capture data required for characterizing roadway geometries as well as the features associated with each roadway. The map data integration involves the use of input sensor data from multiple sources and the subsequent manipulation, transformation, and integration of the data sources to create new map data that are more accurate, complete, detailed, and current than the individual data sources.

Although certain functions of connected vehicle applications may be performed without requiring the use of roadway maps, mapping provides some distinct advantages in that it can facilitate the improvement of positioning accuracy and provide details on roadway features. Connected vehicle applications use map data to establish vehicle location relative to a map, facilitate positional accuracy, and provide data on roadway features over a specified time frame with a level of reliability. The MPMS is part of a mobile test-bed platform which collects positioning and mapping data from a variety of sensors and combines them to provide accurate, available and continuous intelligence on the state of the MPMS moving vehicle and on the surrounding areas, yielding more accurate and precise location detail and associated feature maps. This current task addresses and details hardware, software, and configuration enhancements associated with the MMPS to achieve operational improvements for subsequent tasks.

2.2 Mobile Positioning and Mapping System

The University of California-Riverside's MPMS mobile test-bed platform collects positioning and mapping data from a variety of sensors and combines them to provide accurate, continuously available intelligence about the state of the MPMS and its environment. The system allows centimeter accurate feature maps. The sensor suite includes the following technologies:

- LIDAR, Panoramic camera, RADAR: to enable detection of features in platform frame;
- GNSS (e.g., GPS): to enable the centimeter accurate estimation of absolute (e.g., ECEF or state plane) platform position;
- High-rate kinematic sensors (e.g., INS): to enable continuous availability and high time resolution.

This system is mounted on a roadway vehicle which is driven through the environment to capture roadway data. The UCR MPMS at the start of the project is shown in Fig. 2.1a. The UCR MPMS at the end of the project is shown in Fig. 2.1b. The purpose of the reconfiguration was to decrease the extent to which the feature sensors occluded each other. The reconfiguration also included improvement of the signal and power wiring for the system.

Data captured through the MPMS integrated vehicle telematics is utilized to create a coordinate-based map of features accurately surveyed down to the decimeter level. Such maps are needed both for CV applications and enabling feature-based sensors to be effectively used as navigation aids. This mobile mapping can be performed at normal arterial roadway speeds, enabling much faster data collection than what would be possible with conventional surveying techniques. Integration of data from high-rate and aiding sensors increase the accuracy and reliability of sensor fusion algorithms to accommodate asynchronous and latent sensor measurements. This Chapter provides details on the hardware and software improvements implemented to benefit the subsequent tasks.

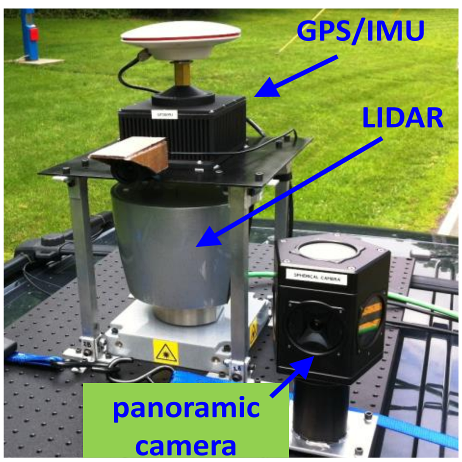


Figure 2.1a: Initial Configuration of UCR MPMS Platform

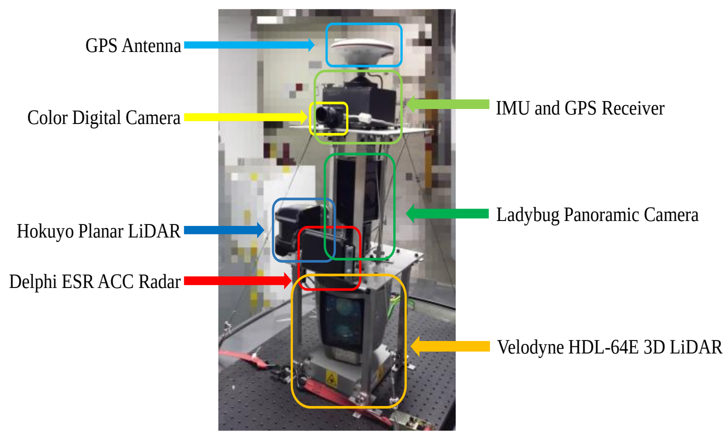


Figure 2.1b: Final Platform Configuration of UCR MPMS Platform

2.3 Data Collection Procedure Enhancement

The high-level steps sensor based mapping process is summarized in the Fig. 2.2. The MPMS platform containing a suite of sensors is placed on the vehicle and moved through the environment for which a digital map is to be constructed. Sensor data are acquired and processed to produce a map of roadway features.

A variety of databases are involved in the above steps:

- The raw point cloud data set obtained from the LIDAR sensor is usually not distributed publicly prior to the georectification process, except by special request. Instead, it is maintained in a variety of formats within the databases of the entity that acquires the data. The database formats have been optimized to reduce size and improve handling in post-processing steps.

- The raw data from the LIDAR sensor goes through a calibration and georectification process which creates a point cloud containing all necessary information for map creation with high accuracy. The accuracy of the final map representation is highly dependent on the accuracy of georectification process. Subsequent feature extraction techniques are improved as a result of enhanced calibration and georectification during the data collection and data processing steps.
- A georectified point cloud contains a large amount of redundant information which makes its use and maintenance difficult and costly. Hence, after manual or automated processing of the georectified point could data, specific roadway features are extracted along with their locations and metadata descriptors (these steps are further detailed in Chapter 5) which remove a large part of redundant information and makes the map representation manageable.

Additional details regarding data calibration and processing are provided below.

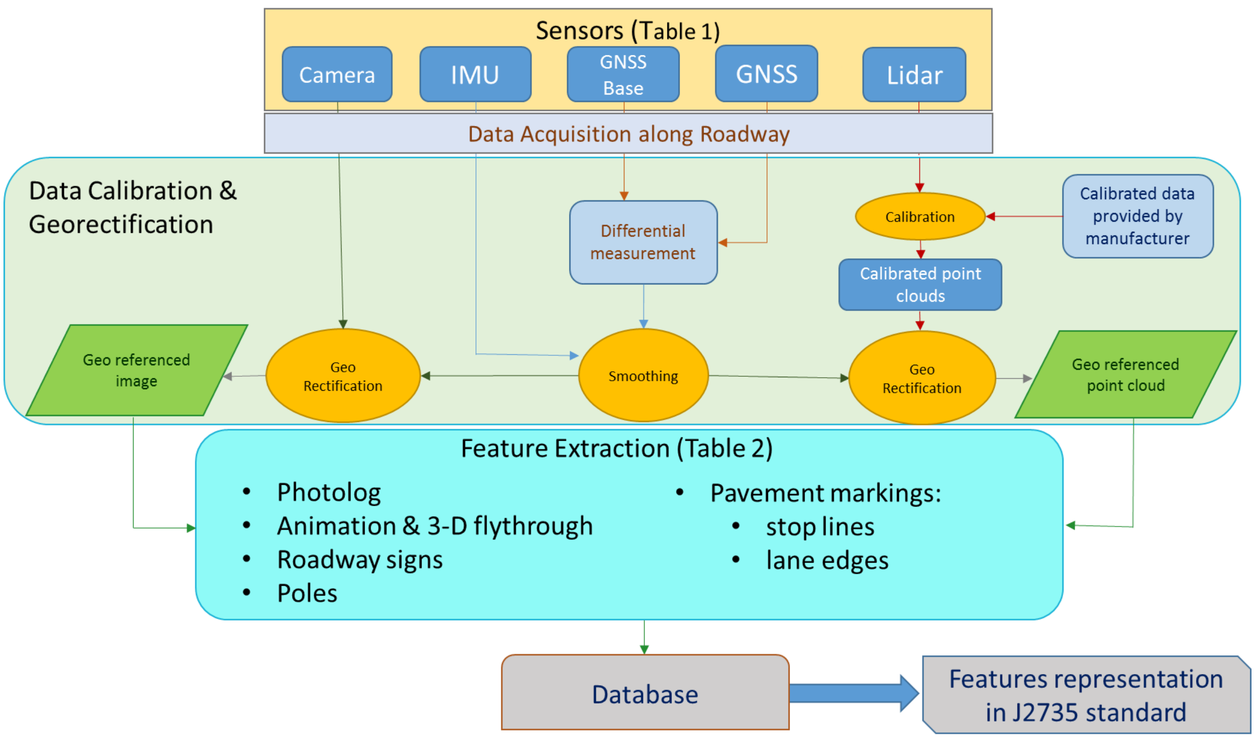


Figure 2.2: Data collection and processing flow chart Mobile Positioning Mapping System

Calibration

Prior to the data collection in the field, the MPMS undergoes setup and calibration. The preparation involves two types of calibration, specifically intrinsic and extrinsic sensor parameter calibration. Intrinsic sensor parameter calibration involves calibrating the final output according to internal configuration of the sensor system. Extrinsic sensor calibration involves calibrating the final output based on the configuration of different sensors relative to each other on the same platform. To guarantee the accuracy of the final map attributes, the entire system calibration methodology has been refined, improving sensor alignment and providing measurement parameters established in a real-world setting.

The MPMS has been transported to a variety of test sites, mounted on a test vehicle, and recalibrated for procedural validation. Several data collections are then performed in a controlled environment with known objects to refine the calibration parameters. Following the improved calibration process, data are collected for comparison purposes. The vehicle with the system is then driven repeatedly over the test site at different times of the day, with varying levels of congestion. At the end of each data run, the raw data are examined to determine the data validity which guides the subsequent data collection process. Once enough data are gathered for a test site, the raw data collection is complete.

Data Handling

The logged raw data processing has been refined as shown by three major blocks in Fig. 2.3. Raw GPS, IMU, LIDAR and/or camera measurements are input to the offline processing system. The data preparation block is the common step for all road feature extraction algorithms. In this block, the sensor platform trajectory is estimated by smoothing the whole log of GPS and IMU measurements. Subsequently, the raw LIDAR data are calibrated with the factory parameters and converted to global coordinate frame using the optimized vehicle trajectory and extrinsic parameters with respect to IMU, known as the georectification process. Finally, the LIDAR point cloud is stored into a GIS database. The second block generates the bird's eye view intensity image of selected intersection regions and then enhances the intensity image using morphological operations. In the third block, image processing algorithms are utilized on the intensity image to extract lane edges and stop bars.

Data Preparation

The LIDAR point cloud is recorded in the reference frame of the LIDAR. The first fundamental step for all mobile mapping systems is the georectification process, which relies on an accurate estimate of the position and attitude of the platform trajectory as a function of time. Because the LIDAR is recording thousands of scans per second and is moving, the platform trajectory is needed at very high rates. This platform trajectory estimate is obtained by combining the IMU and GPS data in a post-processing operation referred to as *smoothing*. The initial condition of the smoothing process may be the real-time trajectory as obtained from an Extended Kalman Filter (EKF); however, the post-processed smoothed trajectory will be much more accurate and reliable. An example smoothed trajectory with accuracy characterization from [1] is shown in Fig. 2.4.

In the LIDAR preprocessing block of Fig. 2.3, the raw LIDAR measurements are converted to 3D Cartesian coordinates with reference to the LIDAR frame using the calibration parameters and methods provided by the manufacturer. The 3D coordinates are then passed into the next block to be transformed to global coordinate frames (i.e., georectification).

The LIDAR points in LIDAR coordinate frame are stored as a list with the time reference when the laser point detection took place. To convert the LIDAR measurement to global coordinate frame, we need to find the corresponding vehicle pose at the specific laser detection time.

The pose is obtained by interpolation of the two states in the smoothed trajectory whose times are closest to the given LIDAR time step. The extrinsic calibration parameters between LIDAR and body frame must be applied to every data point prior to subsequent processing steps.

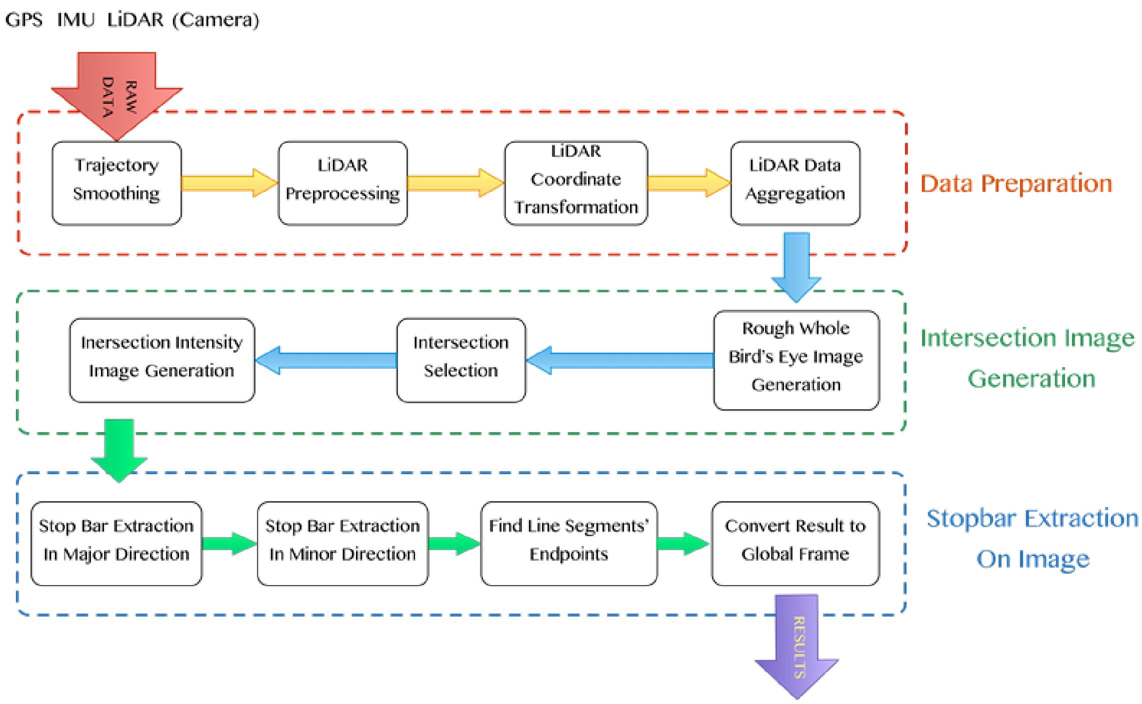


Figure 2.3: Data processing flow chart of our LIDAR based Mobile Mapping System

The size of preprocessed data for the 1000 second experiment shown in Fig. 2.4 is about 4 gigabytes. Such datasets hardly fit within standard computer memory. For processing, it is partitioned into 40 megabytes pieces. Each partition is converted to global frame separately, and then passed into the next processing step. The UCR data storage methodology onboard has been improved to allow for extended data collection events.

The LIDAR dataset in global frame from the previous block is stored in a GIS database. Later portions of it may be extracted as simple data files, because different applications could implement different algorithms on these preprocessed data. Instead of using the whole point cloud database, the feature extraction algorithms usually process only small sections of data to fit within limited computer memory. The improved partitioning procedure allows for advanced feature extraction as detailed in following tasks.

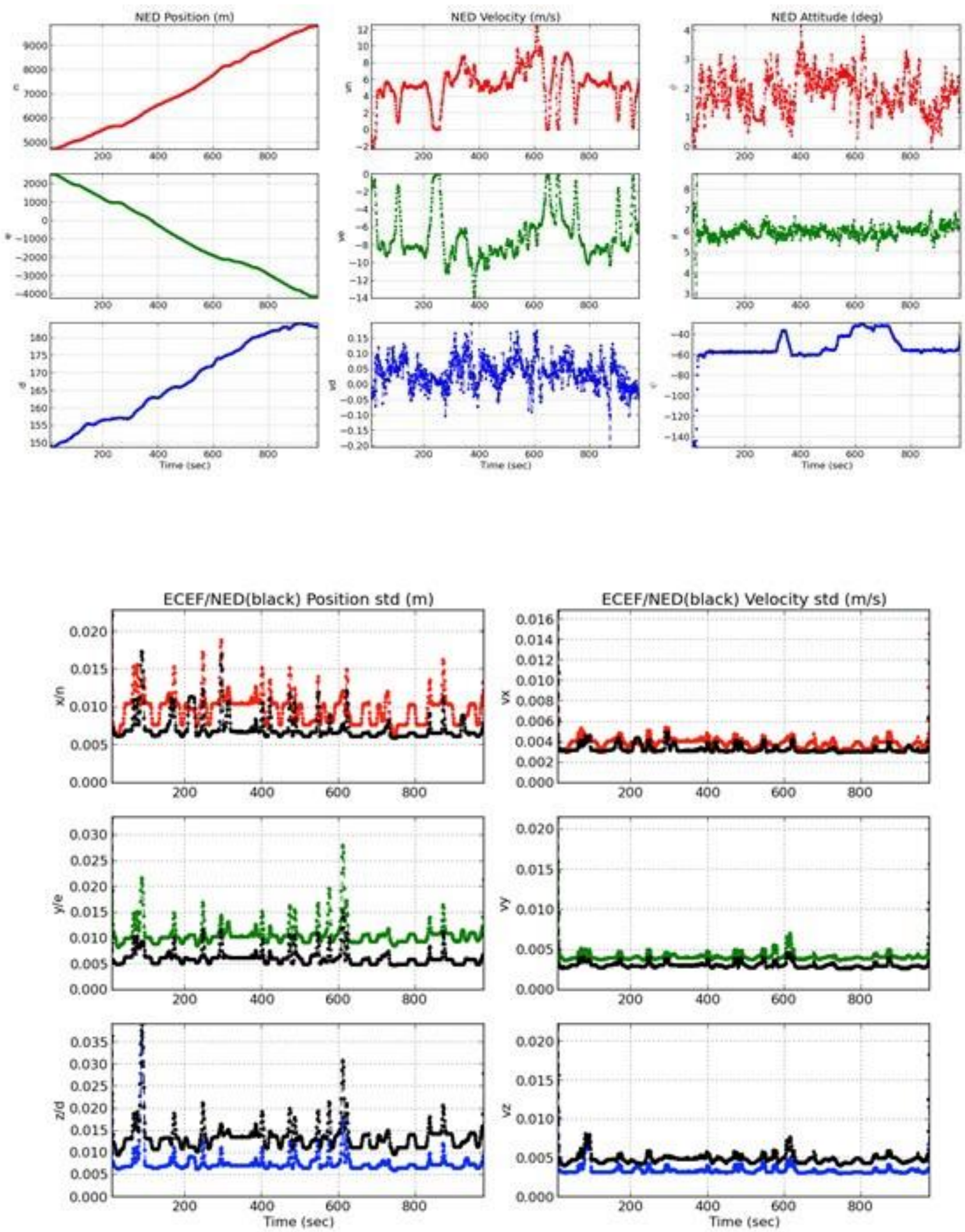


Figure 2.4: The first three rows are the smoothing results of the position, velocity and attitude in NED frame. The bottom three rows show the standard deviations of the position and velocity estimates. In general, the overall positioning standard deviation is below 2cm.

3. MAP REPRESENTATIONS

Detailed roadway feature maps will need to be developed, maintained, and communicated consistently to support Connected Vehicle (CV) applications. As a result, within the U.S. alone, hundreds of thousands of intersections and millions of miles of roadway will need to be surveyed, with application-relevant roadway features mapped to application-specific accuracies. Besides connected vehicle applications, accurate roadway digital databases are also important to other roadway applications such as: roadway planning, construction documentation, accident investigation, roadway inventory assessment, pavement characterization, and vertical clearances. While many of these applications have been of interest to Departments of Transportation (DOT's) for decades, connected and autonomous vehicles are now bringing these high accuracy maps within the interests of entities with commercial ambitions, such as auto manufacturers. Successful global commercialization of products incorporating high-accuracy digital maps has created a need for a standard digital map representation of the road way features and attributes. The digital map representation should possess the following important characteristics:

- **Spatial continuity:** Connected vehicle commercial success will require uniformity of database contents, accuracy, and behavior across geographic boundaries.
- **Automaker uniformity:** Connected vehicle market success will require uniform vehicle behavioral interactions with infrastructure and other vehicles across auto manufacturers.
- **Concise and transmittable**: Map information should be efficiently and reliably transmittable as certain roadway and intersection features must be shared in real-time with vehicles supporting CV applications.
- **Updatable:** The roadways, the continental plates on which they sit, the roadway environment, and the coordinate systems in which they are defined are all time varying. Hence, roadway maps should be readily updatable.

The automated sensor-based precision mapping process is discussed in Chapter 1. Map updating will be discussed in Chapter 4.

3.1 Map Representation Approaches

This section reviews various map representations currently known to be available. For successful collaboration with automakers, it is expected that some entities (government or commercial) will develop and maintain a continent scale map database, eventually global scale, in some implementation of a GIS. That GIS maintenance will result in differences between the master GIS and the maps stored on user vehicles. The master GIS is too large to be convenient for wireless communication to users in its entirety; therefore, mechanisms have been defined for communication of application relevant pieces of the map to connected vehicles.

Geographic Information Systems (GIS)

Geographic information system (GIS) is a system designed to capture, store, manipulate, analyze, manage, and present all types of spatial or geographical data. ESRI is the dominant supplier of GIS database, display, management, and analysis tools (e.g., ArcGIS). Such GIS store related data in layers each of which contains one type of attribute data: street-level data (highways, major roads, minor roads, one-way arrow indicators, railways), water features, landmarks, building footprints, administrative boundaries and shaded relief imagery. Even within a single jurisdiction, there may be many different GIS databases or one combined GIS data base. The GIS itself does not impose any standardized set of layers nor requirements for accuracy or data representation format for any given layer. Such standards are determined by outside professional organizations (e.g., SAE, ISO).

As an example, the National Map is a collaborative effort of the United States Geological Survey (USGS) and other federal, state, and local agencies to improve and deliver topographic information for the United States. The National Map is part of the USGS National Geospatial Program. The geographic information available includes orthoimagery (aerial photographs), elevation, geographic names, hydrography, boundaries, transportation, structures and land cover. The National Map is accessible via the Web, as products and services, and as downloadable data. Its applications range from recreation to scientific analysis to emergency response.

Related to transportation, various entities (e.g., federal, state, and regional DOT's; commercial entities) maintain their own internal GIS roadway and roadway feature databases. These may be in unique or proprietary formats, with unique data representations, and entity and geographically dependent accuracies.

The GIS master roadway map of any of these entities is typically very large, containing the roadway map for a large region, possibly with underlying raw sensor data, and many features and attributes necessary for other current and potential applications; therefore, this master GIS is not concise and transmittable as required for CV applications. Instead, certain portions of the master GIS are extracted and converted into other formats (e.g., SAE J2735, ISO 14825) that are designed to be concise and transmittable.

Proprietary Corporate Approaches

There are efforts to develop digital maps with global coverage. Certain corporations (e.g., Apple, Bing, Google) are developing maps intended to be used in consumer applications (routing, advertising, context based search, autonomous taxi service). Such maps do not require high-accuracy and do not contain roadway relative features.

Other corporations are developing highly accurate maps specifically intended for consumer and commercial transportation applications, see Section 1.7.

Corporate entities define proprietary GIS data structures convenient for their internal use and management. Selected portions of their internal GIS can be export in the pieces and formats (e.g., SAE J2735) defined by DOT's and automobile manufacturers for specific applications such as CV's.

Navigation Data Standard (NDS)

The effort and cost required to maintain proprietary internal GIS formats and convert them to various customer and application specific standards led a consortium of entities to form of the Navigation Data Standard (NDS) Association[3] in 2006. The Navigation Data Standard (NDS)

[3] The members of the NDS consortium as of January 2016 includes at least: Auto Navi, BMW, Bosch, Daimler, Denso, Garmin, HERE, Hyundai, Mitsubishi Electric, Mxnavi, Nav Info, Panasonic, Tom Tom, Volkswagen, Volvo.

specifies the content (e.g., which items), structure (e.g., how stored), and precision of the physical format (e.g., SD card) of a map database suitable for automotive applications [5].

The NDS specification includes in its HD model various items useful for Advanced Driver Assistance Systems (ADAS), Connected Vehicles (CV), and Autonomous Vehicles (AV):

- High-definition lane models: Store the centerline, boundaries, number of lanes, and attributes (e.g., stop bar, speed limit).
  - May be stored as vectors or splines. Current accuracy is at the meter level. Decimeter level (5-10 cm) accuracy is desired, as it is expected to be required and sufficient for such advanced applications. Items are stored with centimeter precision.
  - Lane connectivity is included, even across intersections, merged lanes, turning pockets, and stopping lanes.
- 3d positioning objects: These are items with locations that may be useful for estimating the position (and state) of a vehicle.
- Grade is accounted for as suitable for Eco-driving and EV range conscious routing.

The standard was originally designed for map databases physically stored on the vehicle.

At present, the on-vehicle physical format map is the main approach on which the system will rely. When there is a communication link, two way communications are possible. Cars could sense the infrastructure and communicate to a server roadway features that are detected. The cars do not communicate to each other. The server (i.e. the cloud), after accumulating sufficient confidence, may alter the map database with such crowd sourced information. The server may communicate map updates to the vehicles. At present, the methods in this paragraph are not standardized, but under consideration.

The standard does discuss methods and means for incremental updates. The communication medium is outside the scope of the specification. Whether or not to include a specification for communication of mapping messages is currently under discussion.

Connected Vehicle Standard

Connected vehicle applications expect to communicate map representations for smaller sections of roadway, via wireless mechanisms, either between vehicles or from the infrastructure to vehicles. This need for transmit-ability, reliability, and accuracy yields a very different set of requirements from those for the large internal roadway GIS's used either statically (without real-time updates) on a vehicle or within government and commercial entities. These specialized needs for communicable roadway map pieces have resulted in the SAE J2735 standard that is reviewed next. At present, the SAE J2735 is the dominant standard intended to CV applications.

BMW, Volkswagen and Daimler (Mercedes) are already offering their infotainment systems with NDS. TomTom and Nav Info also have NDS products.

Note that the NDS Association is a separate entity from either Society of Automotive Engineers (SAE) or the International Standards Organization (ISO).

3.2 SAE J2735

The SAE J2735 standard [6, 28] was designed to enable the mapping needs of CV applications, within limited communication constraints. SAE J2735 specifies the format by which selected elements of a larger roadway feature database are communicated between end-users (connected vehicles and infrastructure).

SAE J2735 Message Set Overview

SAE J2735 supports communication of roadway feature and attribute information between vehicles and infrastructure. Typically, the Map GIS is stored on the infrastructure and communicated to the vehicles, where it is stored and used for some short period of time in support of a CV application. For example, in signal, phase, and timing applications, the intersection controller might broadcast a description of the intersection to all vehicles in the vicinity of the intersection. The vehicles would maintain that intersection map in their local memory at least until they leave the vicinity of the intersection.

SAE J2735 Standard specifies a message set, data frames and data elements and is specifically designed to support applications intended to utilize the 5.9 GHz Dedicated Short Range Communications for Wireless Access in Vehicular Environments (DSRC/WAVE, referred in this document simply as "DSRC"), communications systems [28]. As an example, one of the message sets that is transmitted from roadway to vehicle includes: current operational status, signal phase and timing information, intersection geometry, surface conditions, warnings of potential violations or hazardous conditions, and approaching vehicle information.

The MapData message is used to convey many types of geographic information used in the message set. At present, its primary use is to convey one or more intersection lane geometry maps in a single message. The map message content can include such items as complex intersection descriptions, road segment descriptions, high speed curve outlines (used in curve safety alerts), and segments of roadway (used in platoon applications).

The MapData message can contain information for up to 32 intersections and 32 roadway segments. It contains information regarding intersection geometry such as, total number of lanes in the intersection, lane width, position of the nodes that make up the lanes, position of the stop bar, crown angle of the road etc. It also contains other attributes like direction of a lane, permitted maneuvers in a lane, connection to other lanes, lane sharing attributes etc.

The Signal Phase and Timing (SPAT) message communicates dynamic information related to the map. The SPAT message sends the current movement state of each active phase in the system as needed (values of what lights are active and values for the current status of the light is expected to continue). The state of un-active movements (typically all red) is not normally transmitted. Movements are mapped to specific lanes and approaches by use of lane identifiers present in the message. These lane identifiers correspond to the specific lanes described in the MAP message for that intersection. The current signal preemption and priority status values (when present or active) are also sent.

SAE J2735 Message Set Status

Distribution of such feature maps is still in its infancy. To date, it has not been implemented and tested over large regions (i.e., states, countries).

To date, various CV testbeds, on increasing size scales have been implemented. As these demonstrations have progressed recommended changes (e.g., larger sized messages to allow accurate descriptions of large intersections, additional features) to SAE J2735 have been one of the demonstration outcomes.

SAE J2735 Data Structure and Example

Fig. 3.1 illustrates the J2735 data structure and an example drawn on an image of an intersection. The J2735 is hierarchical. The description of each intersection would contain all of the portions indicted with colors. The green block describes high-level intersection information: ID, origin and default lane-width. Lower-level blocks specify the number of lanes followed by descriptions of each lane, including a lane identifier and a list of nodes along the lane centerline with the first node on the stopbar. Meta information about the lane can indicate its purpose: ingress, egress, left turn, etc.

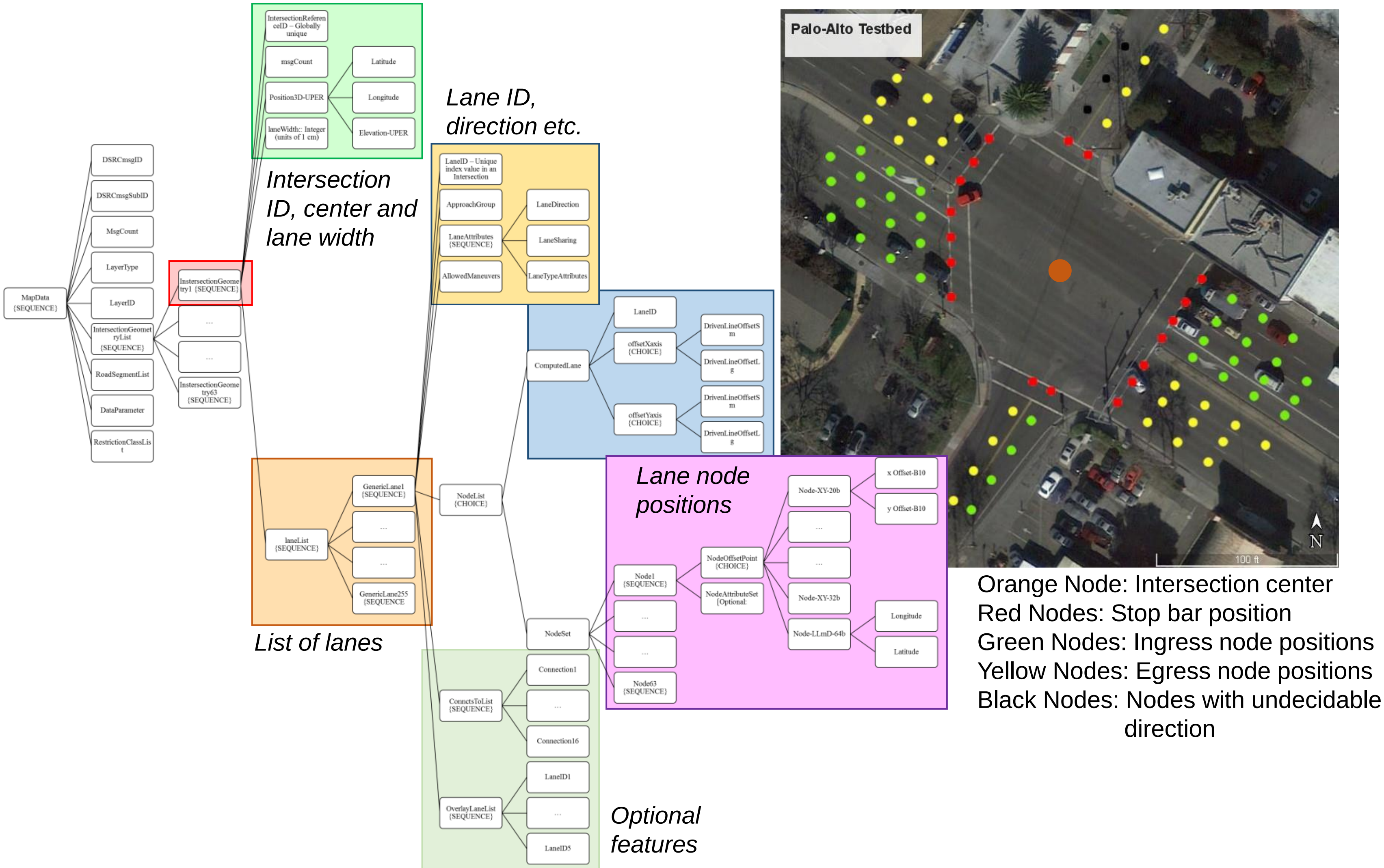


Figure 3.1: J2735 Data Structure and Example.

4. MAP REPRESENTATION UPDATING

As described in Chapter 3, roadway feature maps are necessary to enable collaboration between vehicles and with the infrastructure in Connected Vehicle (CV) applications. Therefore, detailed roadway feature maps will need to be developed, maintained, and communicated consistently. Successful global commercialization of products incorporating high-accuracy digital maps will require a standard digital map representation of the roadway features and attributes. The roadway environment is constantly changing based on many factors; in addition, the roadways themselves, along with the continental plates on which they sit, are also moving. Therefore, in addition to having spatial continuity across large areas, uniformity between developers/users, and an efficient data representation, high-accuracy maps databases will need to be updatable. Given the need for the maps to be updateable, various interesting questions arise:

1) How will the need for local map updates be detected or communicated to the map manager?

2) How will local map updates be integrated into the map database efficiently while maintaining spatial continuity?

3) How can data integrity be assured if map updates are obtained from different sources?

This section discusses the considerations and methods to address these questions and maintain maps for utilization in a connected vehicle environment. A suitable approach and methodology is presented that utilizes data and methodologies currently available.

4.1 Different Methods of Data Collection for Updating

For roadway map-building there are two main methods of information data collection:

- ***Direct*** **–** Examples of direct methods include: human surveys, photogrammetry, stationary terrestrial laser scanning, mobile terrestrial laser scanning, and aerial terrestrial laser scanning. Each of these involves direct detection and calibration of roadway feature locations. For further detail, see Chapter 1 of this project. Direct methods are performed by trusted entities either as employees or contractors; therefore, their data have a high-level of integrity and accuracy. These direct methods typically provide the best data, however the data collection can be expensive and time consuming. Scheduling is either periodic or by request. These direct methods are typically used by governmental entities and various companies (e.g., Mandli, HERE, CivilMaps).

- ***Indirect (or inferred)*** **–** The main example of an indirect method of map data collection is *crowd-sourced* data, which for roadway mapping applications refers to the accumulation of sensor trajectory data from the millions of connected vehicles and/or users driving on the nations roadways. The "sensors" in this case could be cell phones, navigation sensors within the vehicle, or standardized Basic Safety Messages (BSMs). This crowd-sourced method supplies huge quantities of sensor trajectory data from which it may be possible to mine different types of information about the roadways, such as lane centerlines and intersection stop bars. Of particular importance, these crowd-sourced methods can provide data useful for the *prompt* detection of changes to the roadway infrastructure. It is important to note that any map information extracted from crowd-sourcing is inferred, because there is no direct measurement of the sensor location relative to the roadway features. For example, tight bundles of similar trajectories might be inferred to represent lanes. Frequent stopping locations nearest to an intersection ingress point for such a bundle could be inferred to be a stop bar location. Frequent paths through intersections could be processed to infer ingress-egress lane connectivity. Indirect methods can accumulate data rapidly at very low cost. While the data integrity of each sensor may be suspect, the expectation is that statistics of the huge data set are very difficult for a small number of users to affect. The potential limiting factors are that the accuracy of the measured data by the inexpensive user sensors and validity of the various inferences are uncertain. Crowd-sourced methods have been investigated by various university research groups and commercial entities, such as, TomTom Inc.

4.2 Proposed Updating Technique

Experience has demonstrated that these direct and indirect methods are complementary, with each having a role to play, as depicted in Fig. 4.1. In this figure, the red arrows depict unprocessed sensor data. When compared to the master roadway GIS database (via the gold arrows), the sensor data are processed to detect, calibrate and map roadway features and information that can serve as map updates. These suggested map updates (blue arrows) are recommended to a decision processor that may make comparisons between the direct and indirect data sources and the master roadway GIS to determine whether or not to accept the recommendations for incorporation or to schedule a local survey using direct methods (green arrow). One example is the crowd source data indicating a connection between two roadways that is not represented in the database, which could automatically trigger a direct survey for that location.

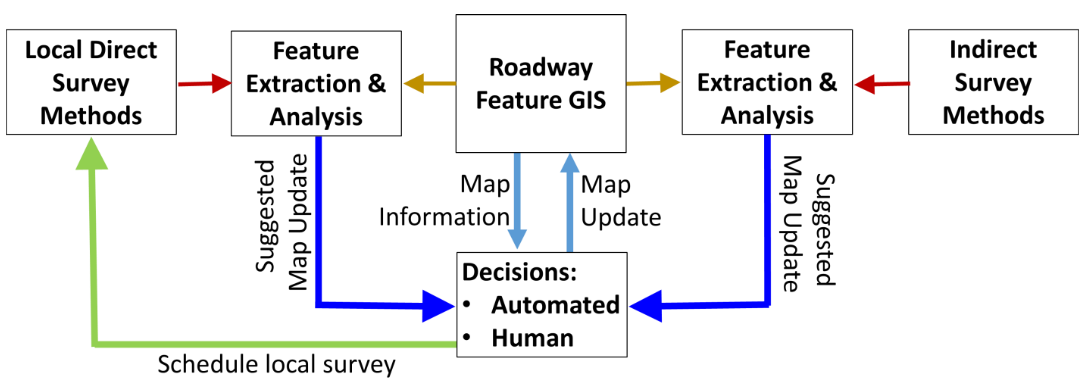


Figure 4.1: Complementary nature of Direct and Indirect map production methods.

Other tasks in this research project describe in detail how the LIDAR-based survey method collects data, followed by a filtering a feature extraction process. It has been shown how a mapping data set can be created (e.g., SAE J2735 map standard) going left to right in Fig. 4.1. In addition, crowd-sourced trajectory data from connected vehicles can be filtered followed by feature extraction, creating similar map features, as illustrated going right to left in Fig. 4.1. Because these methods are independent, they can be used for data and map validation, as well as for triggering a need for updating if the two results do not agree.

5. FEATURE EXTRACTION METHOD

5.1 Introduction

The output of the Mobile Terrestrial Laser Scanning (MTLS) mapping platform is a georectified 3D point cloud of the scanned area which is a set of four dimensional points representing reflection intensity and centimeter level accuracy Earth-referenced position. Additionally, as a byproduct of the georectification process the trajectory of the MTLS platform during the data collection process is available.

The point cloud contains information useful for mapping road features. However, it also contains large amounts of redundant or non-relevant sensor data. The objective of the feature extraction task is to extract relevant road feature information from the available MTLS data in a format, such as the SAE J2735 map message, that is useful for connected vehicle applications. The J2735 map message is designed for convenience of storage and communication between infrastructure and users. Such formats include metadata information such as number of lanes and whether lanes are intersection ingress or egress, which can be extracted from the MTLS platform trajectory data.

Chapter 5 presents the method and results used to extract J2735 map representations from MTLS data for eleven intersections along the Palo Alto testbed in California. For this study, the features of interest near intersections include: lane divider markings, road edges, center of intersection, and stop bars.

Section 5.2 describes this testbed, the data, and data acquisition. Sections 5.3-5.5 describe the data processing for feature extraction. Chapter 6 will describe the feature extraction results.

5.2 Data

The point cloud data used in this study was collected by the AHMCT research center at UC Davis. The data were obtained by scanning the California Connected Vehicle testbed on California State Route 82 (El Camino Real) in Palo Alto. The test bed spans 11 consecutive intersections.

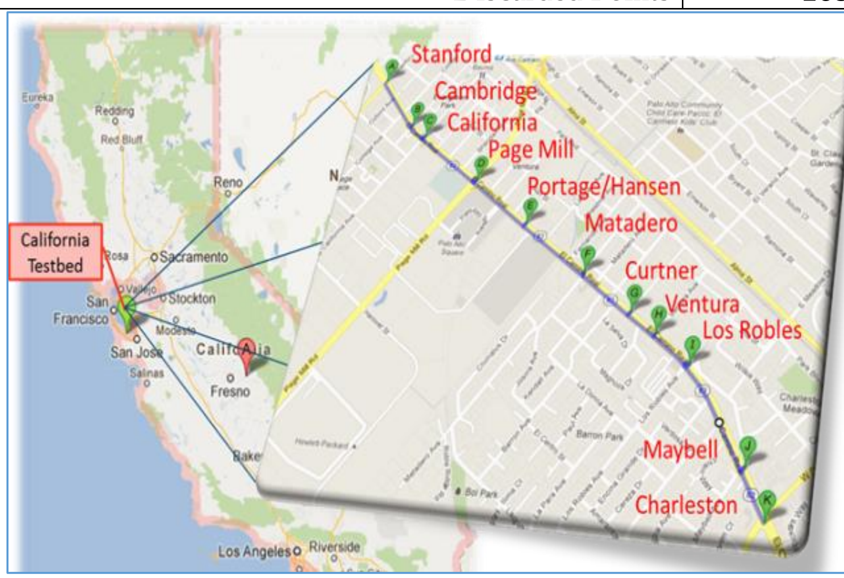
The MTLS includes a Trimble MX8 with two Riegl VQ450 LIDAR scanners, and an Applanix POS 520 platform positioning system. The left LIDAR has vehicle relative azimuth, roll and pitch angles of 143, -19 and 23.5 degrees respectively. The LIDAR has vehicle relative azimuth, roll and pitch angles of -143, 19 and 23.5 degrees respectively [2]. The platform mounted on the vehicle is shown in Fig. 5.1.

Figure 5.1: AHMCT MTLS vehicle.

The platform received corrections from a single GNSS base station that used a Trimble R8 receiver located near the testbed. The GNSS base station location was determined using NGS OPUS: Online Positioning User Service and the two hours GNSS base station log data.

Table 5.1: Attributes of the testbed intersections

Cross street name	Center coordinates		Number of points in million
	Latitude	Longitude	
Stanford Ave	37.4277640	122.1492539	77.57
Cambridge Ave	37.4255950	122.1467851	75.36
California Ave	37.4250803	122.1458624	66.03
Page Mill Rd	37.4230638	122.1420467	95.04
Portage Ave/Hansen Way	37.4210617	122.1382334	154.58
Matadero Ave	37.4191602	122.1345428	68.68
Curtner Ave	37.4176288	122.1315912	70.04
Ventura Ave	37.4168366	122.1300875	50.64
Los Robles Ave	37.4157300	122.1281376	70.48
Maybell Ave	37.4120037	122.1246158	59.78
Charleston Ave	37.4104459	122.1233336	83.45
		Total Size	**871.65**
		Total Data Size	**2559.70**
		Discarded Points	**1688.05**



The testbed contains 11 signalized intersections at the locations listed and as shown in Table 5.1. The MTLS platform was driven along the ingress and egress sections of the main thoroughfare (El Camino Real). At each intersection, The MTLS platform was driven along each cross street at least once. While completing this, the MTLS was driven along each El Camino Real section at least four times, two northbound and two southbound. The multiple passes along each section provide a dense points cloud on the surface of the street, which facilitates reliable feature extraction. A second reason for the multiple passes along a road section is that the effect of dynamic obstructions (e.g., other vehicles) is unlikely to be the same in the multiple passes, so their effect is a slightly lower density of returns, instead of the absence of data that would be caused by a single run. The resulting dataset provides both an MTLS georectified point cloud and the trajectory of the platform. The platform trajectory is shown in Fig 5.2a (left). The entire point cloud acquired along this trajectory contains approximately 2,560 million points.

For each intersection, the J2735 map message requires definition of the intersection center point. This is a designated reference point that should be near the center and later provided in the J2735 map message. All intersections features described in the J2735 for that intersection will be specified as offsets relative to the defined center.

Table 5.1 lists the names of the intersection cross streets, the latitude and longitude defined as the center of the intersection, and the number of points within a radius R=60 meters of the intersection center. On average each intersection contains around 80 million points on average. Of the 2,560 million points in the full point cloud, approximately 872 million are within the radius R of at least one of the intersection centers. The remaining 1688 million points are discarded.

5.3 Intersection Feature Extraction Procedure

The full geo-rectified point cloud P contains a large number of points obtained while driving the vehicle along the roadway during the MTLS data acquisition process. To facilitate data processing, each intersection is processed independently.

The roadway features of interest for this project include lane markings such as lane edges and stop bars. These features are painted onto the road surface using high-reflectivity paint. The point cloud P_i for the i-th intersection is designed to contain LIDAR reflection intensity data from which the desired roadway lane markings and their position information can be extracted. Many other unwanted items with high reflectivity also exist within the roadway environment (e.g., signs and portions of vehicles or buildings). Because the desired lane markings are painted onto the road surface, many unwanted high reflectivity items can be removed by focusing the feature extraction process on the road surface; therefore, an important data processing step is to extract the subset of P_i that contains the road surface. The road surface is modeled as a flat and continuous two-dimensional surface along each ingress or egress portion of an intersection.

The high-level steps in the UCR MTLS roadway feature extraction process can be summarized as follows.

A. Preprocessing to extract the portions of the point cloud (P) and trajectory (T) relevant to each intersection. The portion of the point cloud and trajectory relevant to the i-th intersection will be denoted by P_i and T_i, respectively.
B. Extraction of road surface point cloud for each intersection. The portion of the point cloud P_i that corresponds to the road surface of the j-th section of the i-th intersection will be denoted by S_i^j. Additional extracted information from this step includes roadway inner (median) and outer (curb) edge data that may be extracted during the road surface extraction process. This is useful as these edges are often not marked with high-reflectance paint and therefore not detectable from the LIDAR intensity data in later steps.
C. Conversion of the intersection road surface point cloud to an image. This step enables use of image processing tools that are well established and easily available.

D. Image-based roadway feature extraction.
E. Definition of the J2735 feature map for each intersection, including metadata concerning whether the j-th intersection is an ingress or egress, which is extracted from the trajectory subset T_i^j.

The subsections below provide detailed explanations for input data, output data, and process involved in each high-level step.

Preprocessing to extract Intersection Point Clouds

The accuracy of the geo-rectification process and simplicity of the MTLS data acquisition process are both enhanced by driving the vehicle through the entire sequence of intersections without turning off the sensor suite. Also, by leaving the sensor suite turned on while driving between intersections, the data may be useful for multiple purposes besides projects such as this that are mainly focused on intersections.

The data acquisition process, after geo-rectification provides the point cloud denoted by P and trajectory denoted by T. The point cloud P is too large to process conveniently and contains data not relevant to the intersections that are of interest. See Fig. 5.2a which shows the trajectory acquired for the Palo Alto corridor. The eleven intersections with centers as defined in Table 5.1 are marked with circles of radius R. The intersections are ordered with i=1 at the upper left and i=11 at the lower right. The fifth intersection is decomposed into two distinct parts with two centers due to its unique shape. Fig. 5.2b shows a magnified portion of the trajectories in the vicinity of the sixth intersection.

To develop a computationally reasonable approach, the first step is to subdivide P and T into subsets relevant to each intersection. The center point of the i-th intersection will be denoted as C_i. These centers are user specified. For the Palto Alto dataset, the values listed in Table 5.1, are defined within the metadata of the dataset [2]. The user also specifies an intersection radius parameter R. Given these two parameters, we define for i = 1,…11:

$$P_i = \{\mathrm{x} \in \mathrm{P} \mid \|\mathrm{x} - \mathrm{C}_i\| < \mathrm{R}\} \text{ and } T_i = \{\mathrm{x} \in \mathrm{T} \mid \|\mathrm{x} - \mathrm{C}_i\| < \mathrm{R}\}. \tag{1}$$

The sets P_i and T_i will be processed to extract a J2735 feature map for the i-th intersection. That process will be repeated eleven times to extract the eleven intersection maps necessary for the Palo Alto corridor.

Once P_i and T_i are defined for all intersection then, the original data sets P and T can be decomposed as

$$P = \cup_{i=1}^{11} P_i + Q \text{ and } T = \cup_{i=1}^{11} T_i + U \tag{2}$$

where Q and U contain point cloud and trajectory data not relevant to the intersections, which will be ignored in subsequent processing. For the Palo Alto dataset, the quantity of points in each P_i and in Q is stated in Table 5.1.

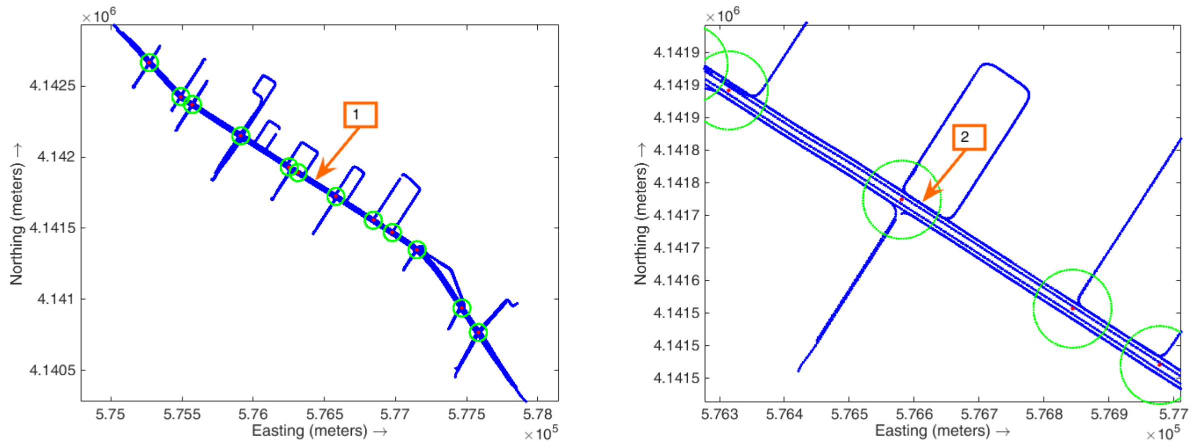


Figure 5.2: (a) The platform trajectory data for all 11 intersections. The orange box labeled 1 indicates the main thoroughfare. Each green circle encloses one intersection. (b) Magnified view of the trajectory through one intersection, clearly showing multiple traversals of the platform along the main thoroughfair.

To further automate the process in the future, the intersection centers C_i can be extracted automatically from the trajectory T or from a network description.

Road Surface Extraction

The inputs for this processing step are the sets P_i and T_i defined in eqn. (1) of Section III.A. The goal of this step is to output a reduced point cloud that only contains those points on the roadway surface, thereby removing high reflectivity points from extraneous objects (e.g., buildings, vehicles, signs). Each extracted intersection is processed separately, so the process described in this section is repeated for i = 1, …, 11.

The roadway is modeled as a smooth 2-dimensional surface. This assumption is only locally valid within each well-defined ingress or egress section of the intersection; therefore, an important step is to process the intersection trajectory T_i to extract useful meta-data such as the number of intersection components and the direction of traffic flow (i.e., ingress or egress). This metadata will then be used to divide each P_i into regions where the 2-dimensional assumption is valid.

The road surface extraction process includes the following steps:

1. Definition of a set of polygons R_i^j each expected to contain the portion of one of the intersecting streets from the interior of the intersection to the boundary of P_i;
2. Process the portion of P_i within R_i^j to extract the road and median edges.
3. Extract point cloud subsets S_i^j for each road segment that only contain points on the road surface.

Each of these is discussed in the following subsections.

Definition of Intersection Regions

The point cloud P_i contains many points, only a small percentage of which are on the road surface. At the start of the processing the only information about the location of the road is the trajectory

T_i and the center location C_i. The initial step uses T_i to define polygons R_i^j to decompose the point cloud P_i into overlapping regions that divide each cross street at the intersection and extend along that cross street to the boundary of P_i. For a T-intersection this would produce three polygons: j=1,…,3. For an X-shaped intersection, there would be four regions: j=1,…,4.

Fig. 5.3a shows the extracted trajectory data T_i for the sixth intersection. The trajectory data is first rotated to align the main thoroughfare with the horizontal axis, as illustrated in Fig. 5.3b. Next, a sliding rectangular window, indicated by the yellow box in Fig. 5.3c, is moved vertically from the bottom to top of T_i (i.e., from Y_{min} to Y_{max} in Fig. 5.3c). The horizontal width of the trajectory within that vertical window is recorded as a function of the vertical position, as depicted in Fig. 5.3d. As the sliding window passes through the main thoroughfare, the trajectory width greatly increases. The values of *y* at which this widening begins and ends are recorded as Y_{mid1} and Y_{mid2}. When the sliding window is in the position of Y_{mid1} (and Y_{mid2}), the mean of the horizontal position of the trajectory data within that sliding window is defined to be X_{pos1} (and X_{pos2}).

The first polygon for the main thoroughfare is defined to contain the corners defined by (X_{min}, Y_{mid1}), (X_{min}, Y_{mid2}), (X_{pos1}, Y_{mid1}) and (X_{pos2}, Y_{mid2}). The second polygon for the main thoroughfare is defined to contain the corners defined by (X_{max}, Y_{mid1}), (X_{max}, Y_{mid2}), (X_{pos1}, Y_{mid1}) and (X_{pos2}, Y_{mid2}). The first polygon for the cross street extends vertically between Y_{min} and Y_{mid1} with the x-values of the corners defined by the horizontal width of the trajectory at those y-values. The second polygon for the cross street extends vertically between Y_{mid2} and Y_{max} with the x-values of the corners defined by the horizontal width of the trajectory at those y-values. Each of these corners is expanded horizontally and vertically by a buffer value B=30 meters, because the road surface will be wider that the width defined based on the trajectory T_i. Fig. 5.3e shows the bounding polygons defined for intersection six.

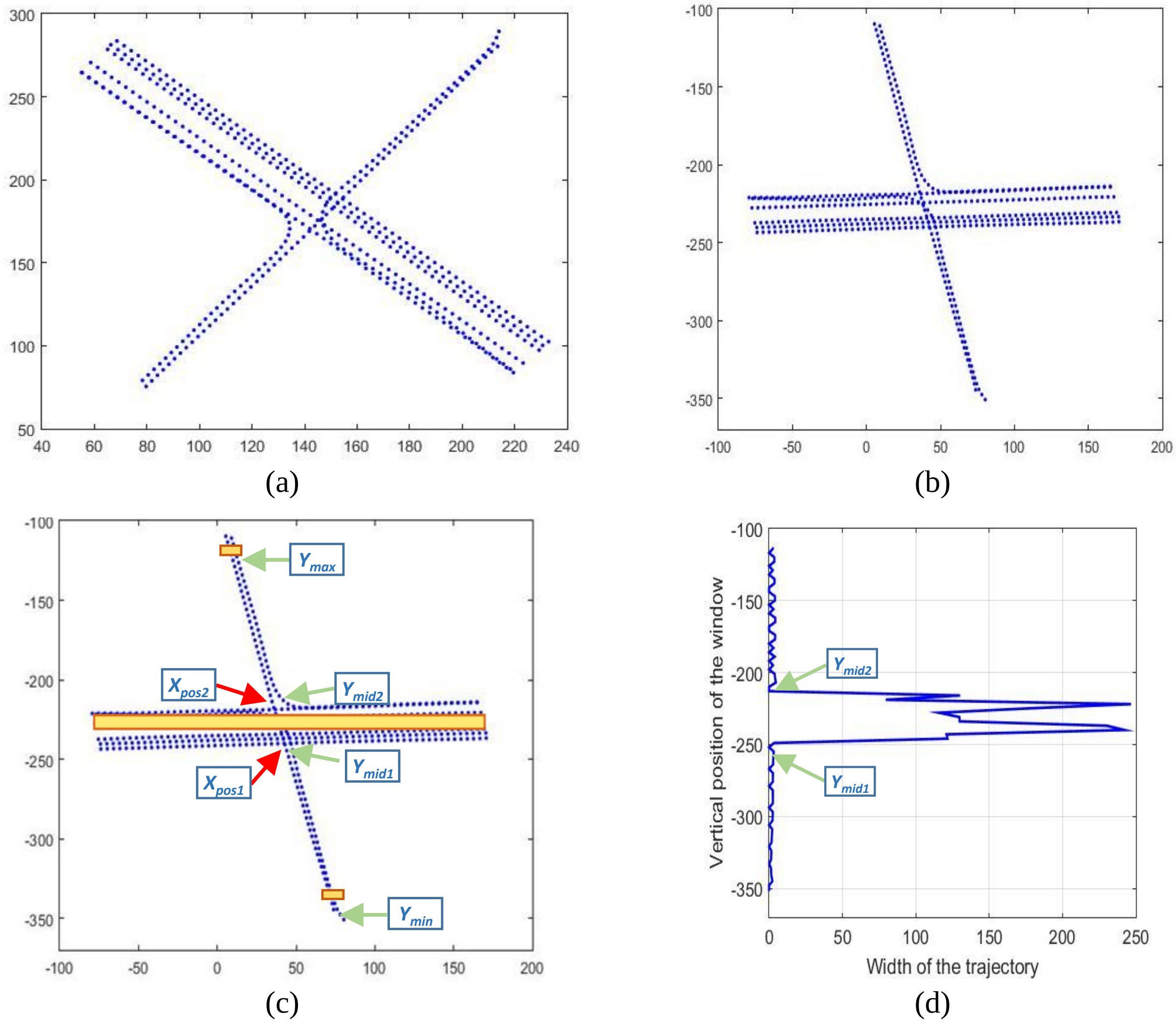
Finally, these polygons are rotated back to the world frame and used to define

$$P_i^j = \left\{(x \in P_i) \bigcap \left(x \in R_i^j\right)\right\}$$

where $x \in R_i^j$ is interpreted as the horizontal components of *x* being in the interior of the polygon. This segmented intersection can be represented as

$$P_i = \bigcup_{j=1}^{J} P_i^j + G$$

where *G* contains the elements of the point cloud that are not in any of the J polygons. The points in *G* will be ignored after this point. The value of J can be 3 or 4 depending on whether the intersection is “T” or “X” shaped.



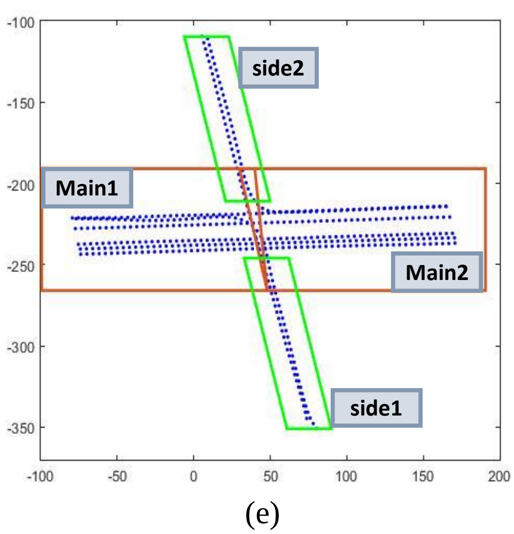


Figure 5.3: (a) Trajectory data T_i for i = 6. (b) Rotated trajectory data. (c) Process for road segmentation. (d) Trajectory width as a function of vertical position. (e) Final output of the road segmentation process.

Extraction of Road Edges per Section

Given the point cloud subsets P_i^j each containing a segment of an intersecting street, the next step is to extract the road and median edges for each segment. If any segment does not contain medians, only road edges are extracted.

For each segment, a one meter wide rectangular window of point cloud data is extracted and processed. See Fig. 5.4a. When this rectangle processing is complete, the rectangle slides along the road segment one meter and the process repeats. Within this narrow window, the road surface is assumed to be two-dimensional. This assumption is used to detect the road and median edges within the window. Once these edges are determined, discarding point cloud elements outside the road edges will automatically remove reflections from roadside entities such as buildings and trees.

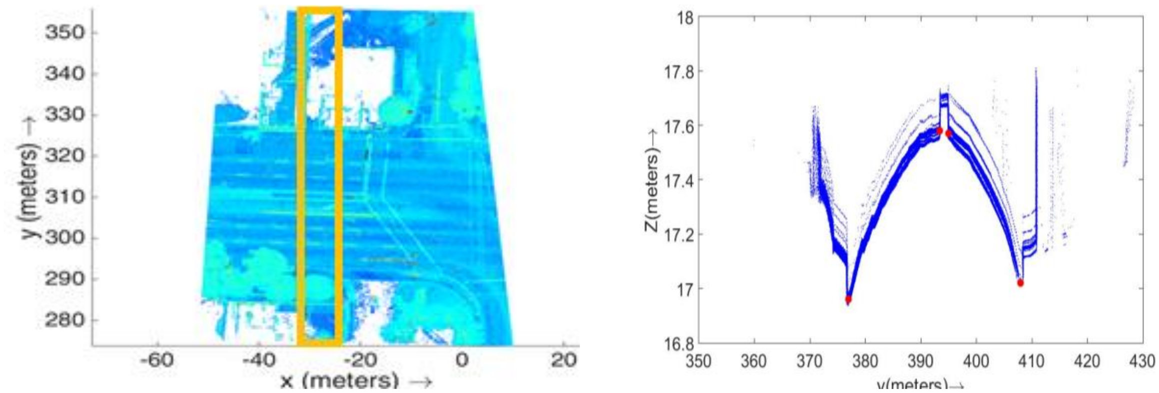
Fig. 5.4b shows a sample of the point cloud elements within P_i^j and the sliding rectangle, with elevation denoted by *z* plotted versus cross-sectional position denoted by y. The processing records the mode of the *z*-value as a function of y. On the road surface, the mode is continuous. At the road and median edges this function changes abruptly. These abrupt changes are detected by monitoring both the derivative and inflection points of the curve. The detected points are indicated by red dots in Fig. 5.4b.

After the road and median edges are extracted for each rectangle, each road and median edge is processed to remove outliers and insert estimates for missing data items. After that a piecewise fitting approach is used to fit lines to the road and meridian edge points. Results for one portion of intersection 6 are shown as red dots in Fig. 5.5. A curve is then defined for each road and median edge.

After the road edge extraction, points outside the road edges are discarded and the reduced point cloud

$$\bar{P}_i^j = \{x_m \in P_i^j | x_m \text{ is within the outer edges of the segment}\}$$

and the road and median curves are passed to the surface extraction process.



(a) (b)

Figure 5.4: (a) Intersection 6 road segment P_i^j. The yellow box depicts the rectangular window that is slid along the roadway (x- axis). (b) Elevation versus cross-sectional position for points within the sliding rectangle. Detected road and meridian edge points are marked with red dots.

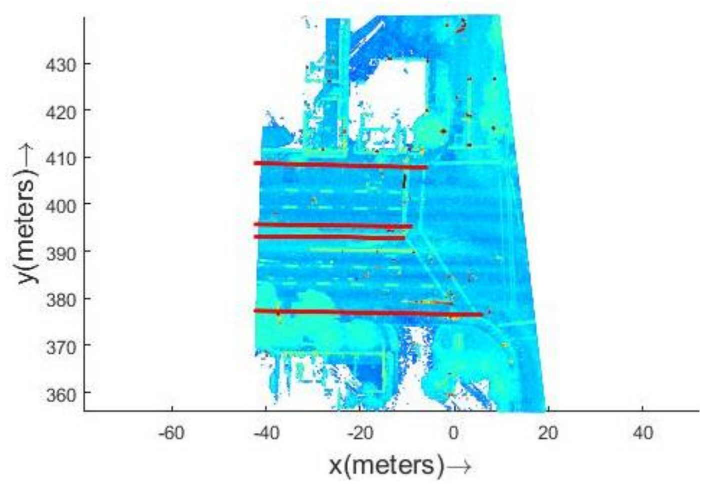


Figure 5.5: The estimated inner and outer edge points of a road segment after discarding the outliers and piecewise line fitting.

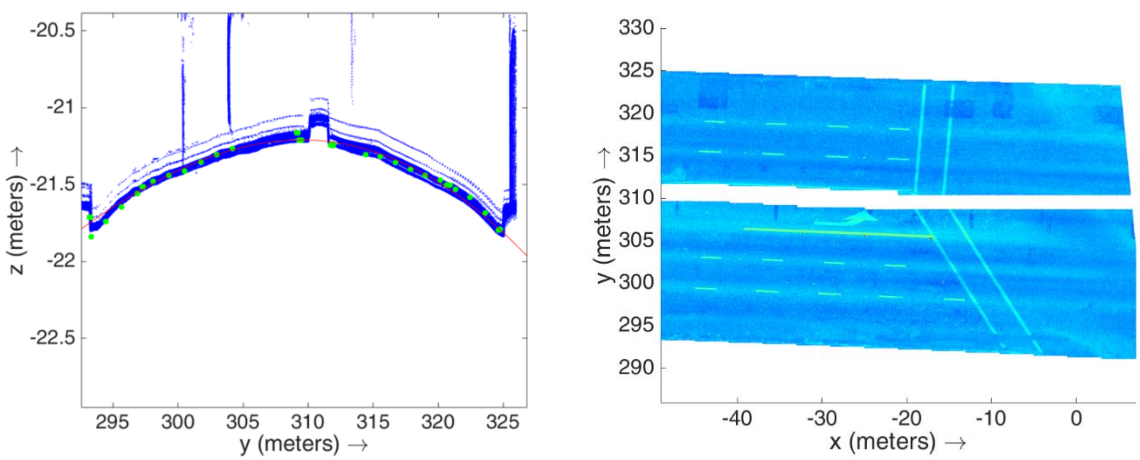
Extraction of the Road Surface per Section

The reduced point cloud $\bar{P}_i^j$ found in the previous step has removed points beyond the road edges, but will yet contain reflections from vehicles, pedestrians, signs or other objects that are within the roadway edges. The objective of this processing step is to extract a further reduced point cloud

$$S_i^j = \{x \in \bar{P}_i^j \mid x \text{ is point on the road surface}\}.$$

The set S_i^j is built up by considering small rectangular cross-sections of $\bar{P}_i^j$ in a manner similar to that illustrated in Fig. 5.4a. A sample elevation versus cross-sectional position distribution of points is shown in Fig. 5.6a. The road surface is within the wide horizontal band of points along the bottom. The vertical strips of points represent reflections from entities on top of the roadway (e.g., vehicles).

For each such rectangular slice, the platform trajectory points are first projected down onto the road using the known platform calibration parameters. These points are represented by green dots superimposed on the distribution in Fig 5.6a. Additional points are estimated between these projected points using the mode of the elevation distribute as a function of cross-sectional position y. Finally, a 6-degree polynomial is fit to this set of green dots. Point cloud elements within 20 cm of this curve-fit are extracted as the road surface points (S_i^j). An example surface is shown as a top-down view in Fig. 5.6b.



(a) (b)

Figure 5.6: (a) Blue dots are the elements of the point cloud $\bar{P}_i^j$. The green dots a points extracted either by projections of the sensor platform trajectory or the point cloud elevation distribution. (b) The extracted road surface S_i^j.

Map 3D points to 2D image

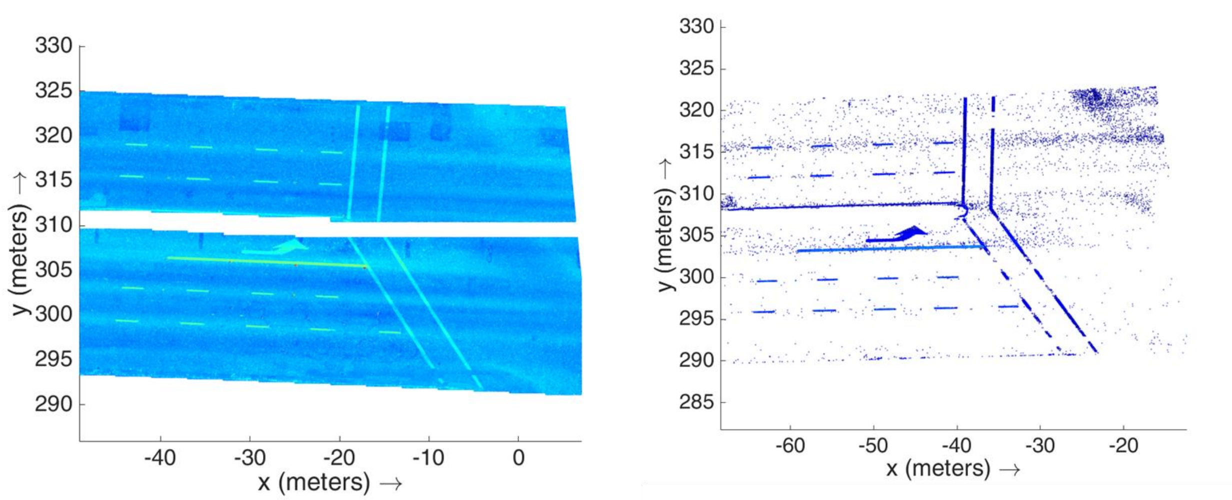
The purpose of this step is to convert each road surface point cloud S_i^j into either one or two raster images, one for each ingress or egress roadway section separated by a median. Many image processing tools are available to extract features from such images. This conversion is completed in the following steps.

First, for roadway segments where Step B detects a median, the median curve is used to divide S_i^j into two separate branches S_i^{jk} for k=1, 2. If a road segment does not have a median, then the segment is treated as one branch with k=1.

Second, for each road surface segment branch S_i^{jk}, points with low reflectivity are removed from S_i^{jk} to generate a new point cloud subset

$$\bar{S}_i^{jk} = \{x \in S_i^{jk} \mid I(\mathrm{x}) > \tau\}$$

where τ is a user defined intensity threshold. A segment before (i.e., S_i^{jk}) and after (i.e., $\bar{S}_i^{jk}$) intensity thresholding is shown in Figs. 5.7a and 5.7b.



(a) (b)

Figure 5.7: (a) Two branches S_i^{jk} for k=1, 2 of an extracted road surface segment. (b) Two branches $\bar{S}_i^{jk}$ for k=1, 2 of an extracted road surface segment after intensity thresholding.

A 2D raster image $\bar{R}_i^{jk}$ is generated from each point cloud $\bar{S}_i^{jk}$. The pixel size of the raster image in meters is a trade-off between computational complexity and feature position estimation accuracy. For the feature extraction approach described herein, each raster pixel is $3\,cm \times 3\,cm$. Therefore, each raster pixel maps to a 3 cm square cell in the XY region. The value of the pixel for each cell depends on the elements of $\bar{S}_i^{jk}$ that map to the cell. When no elements of $\bar{S}_i^{jk}$ map to a cell, the pixel value is zero. Otherwise, the pixel value is the average value of the intensities of the elements of $\bar{S}_i^{jk}$ that map to the cell. The raster image corresponding to Fig. 5.7 is shown in Fig. 5.8.

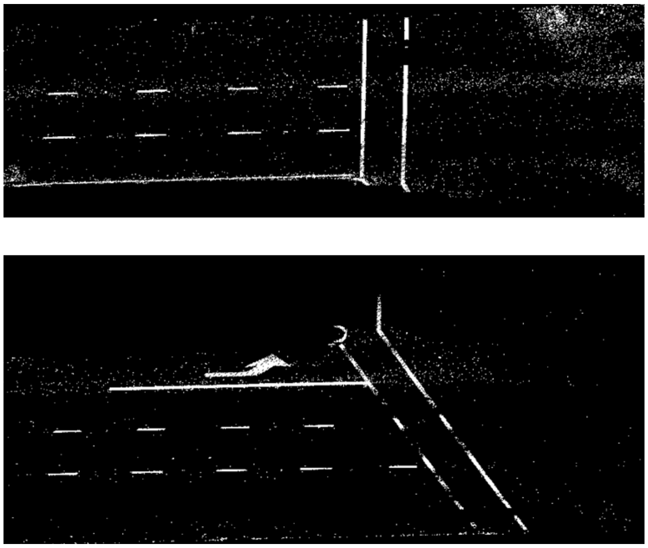


Figure 5.8: The two raster images generated from the intensity thresholded point cloud $\bar{S}_i^{jk}$

The world coordinates of the corner points of the raster image are saved as metadata so each pixel can be converted back to UTM coordinates later for feature mapping. This is referred to herein as a calibrated raster image.

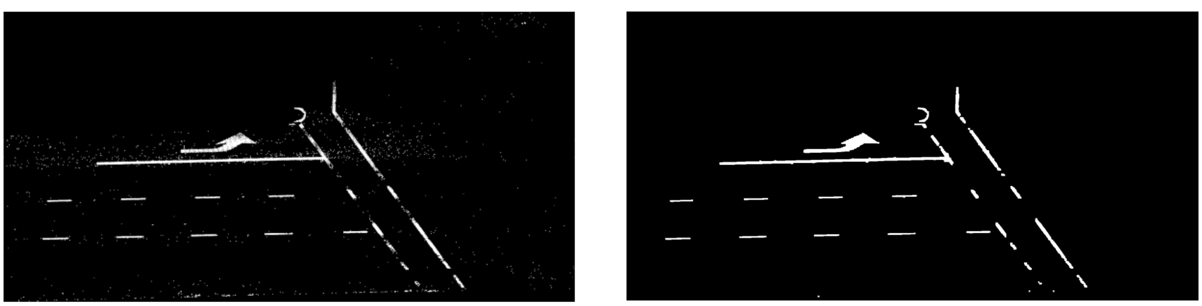
5.4 Roadway Feature Extraction

This section describes the methods used to extract the J2735 map message data from each calibrated raster image $\bar{R}_i^{jk}$. J2735 map message includes lane centerline nodes, lane widths and stop bar locations.

The process includes the following steps: image processing to improve the detectability of the desired features; detection of stop bars; detection of lane dividers; definition of lane centerlines and lane widths.

Image enhancement

Noise and unwanted artifacts can degrade performance of the feature recognition algorithms. Lane edge and stop bar markings are each composed of rectangular elements with standard dimensions [36]. In this step, these known characteristics are used to design templates for image processing methods (erosion and dilation) that will preserve and clarify matching features while deemphasizing elements of the image that do not match the known characteristics. Fig. 5.9 shows an image example before and after the image enhancement process.



(a) (b)

Figure 5.9: Image enhancement process. a) Original image. b) Processed image. Artifacts smaller than a certain size are removed from the image, high intensity regions are closed, linear features are emphasized.

Stop Bar Detection

Stop bars are identified using the Hough transform to detect lines, keeping on those lines with sufficient length and orientation (approximately) orthogonal to the trajectory direction. Because more than one line may fit these criteria when a pedestrian crosswalk exists, the detected line farthest from the intersection is processed. Its line is estimated and passed to the next steps for further processing. An example result of stop bar detection is shown in Fig. 5.10. The stop bar line is shown in red. Other detected lines of sufficient length that are oriented (approximately) orthogonal to the lane direction are shown in green.

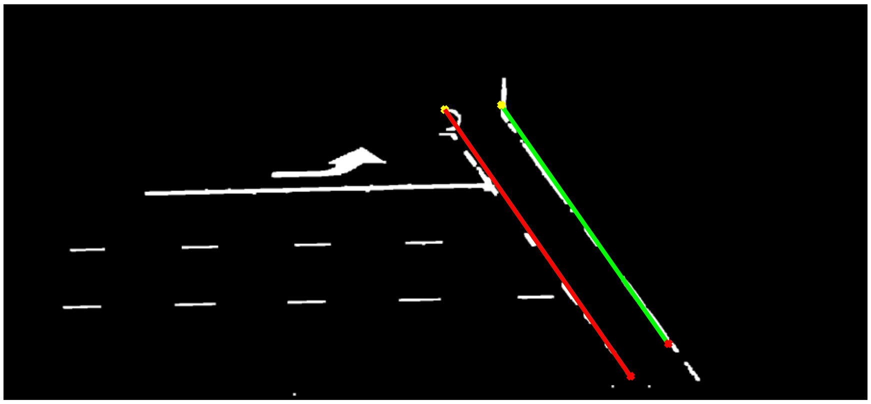


Figure 5.10: Example of detected stop bar candidates.

Lane Divider Detection

The goal of this step is to divide each branch into lanes. The inputs to this process are the calibrated raster image $\bar{R}_i^{jk}$ and the curves defining the road and median edges.

The Hough transform of $\bar{R}_i^{jk}$ from the previous step also returns lines parallel to the direction of traffic flow, which are candidates for lane dividers. Good candidates will have sufficient length, sufficient separation from other lane dividers, and match one of the templates defined in the subsequent sentences. Left turn lanes are frequently set-off by a solid line to their right. On multi-lane roads, lanes are separated by dashed lines where dashes are 2-3 m long and 4-6 m apart (approximately) [36].

The software uses a decision tree to process the lines returned by the Hough transform and road and median edge curves. Depending on the branch width as determined from the median, lane dividers, and road edge curves, the algorithm labels the branch as a single lane or multi-lane. The algorithm first checks for solid lines, as used to demarcate turning lanes. The criteria for accepting solid lines as lane dividers include distance of the line from the branch edges, distance of this line from already accepted lane edges, line direction and length. After finding solid lines that demarcate lane edges, the remaining road width is computed, as the basis for a decision concerning the maximum number of remaining lanes. Given this estimate of the maximum number of remaining lanes, the algorithm begins searching through the remaining dashed line checking direction, dash length and spacing, and separation between previously accepted lane edges and median and road edges. The process concludes either when the remaining maximum number of remaining lanes is less than one or when there are no remaining suitable lines to serve as lane dividers. In some cases, for cross-streets, the branch is too narrow to support multiple lanes and has not lane markings. In this case, the lane edges are defined to be the road and or median edges. In some cases, such as cross-streets, the branch has two lanes with no or undetectable markings, yet has width sufficient for two lanes. In this case, the algorithm defines the curve half way between the branch edges as the lane separator and processes each lane as a single lane.

Once the lane edges are determined, the lane centerline is computed by dropping nodes midway between the two lane edges. Nodes are separated by a distance D = 6 m (200 pixels apart). The first node of the centerline is defined to be at the midpoint of the line segment between the intersections of the lane edges and the stop bar. Lane width is calculated as the inner product of the line connecting the two points defined by the two lane edges intersecting with the stop bar and the unit vector that is perpendicular to the lane edge.

Fig. 5.11 illustrates the output of the feature extraction algorithm. The input image $\bar{R}_i^{jk}$ is the background. The input road edges are shown as green dotted lines. The extracted stop bar by a solid yellow line and extracted nodes by blue circles.

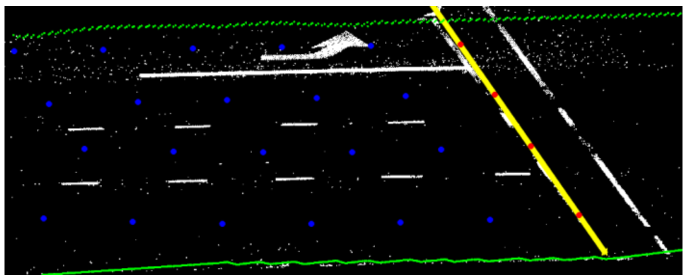


Figure 5.11: Output of the feature extraction algorithm.

Challenges

When the road markings are severely faded, the road has no markings, or the input image is very noisy, the algorithm cannot succeed in its automated processing. In such cases, it generates a warning and marks the segment for human oversight or intervention. Another issue arises when only one stop bar is detected, in which case the algorithm proceeds with the detected stop bar and generates a warning for further human inspection.

Further examples of when such warnings occur are presented in Section IV.

5.5 J2735 Intersection Feature Map Estimation

After the lane centerline nodes and lane widths are estimated, the image coordinates of these nodes are converted back to UTM coordinates using the metadata saved during raster generation. The intensity thresholded road surface segments are first rotated back to their original orientation and then joined together to get an intensity thresholded point cloud $\bar{S}_i$ for the whole intersection. These nodes are then superimposed R_i for analytic comparison.

Top-down view of an intensity thresholded point cloud $\bar{S}_i$ with the extracted J2735 nodes superimposed is shown in Fig. 5.12. According to the specification of the J2735, the first node of each lane starts from the position of the stop bar which is represented with a red node. The rest of the nodes in the lane are marked green if it's a ingress lane and yellow if it's a egress lane. Sometimes, in the side road segments, the mapping vehicle did not go through all the lanes; therefore, due to the absence of a meridian, the algorithm was unable to conclude the direction of travel for those lane. Those lanes are marked with black nodes. In addition, the nodes coordinates are converted from UTM to lat-long to superimpose on Google Earth to make a second comparison. The Google Earth image is shown in Fig. 5.13.

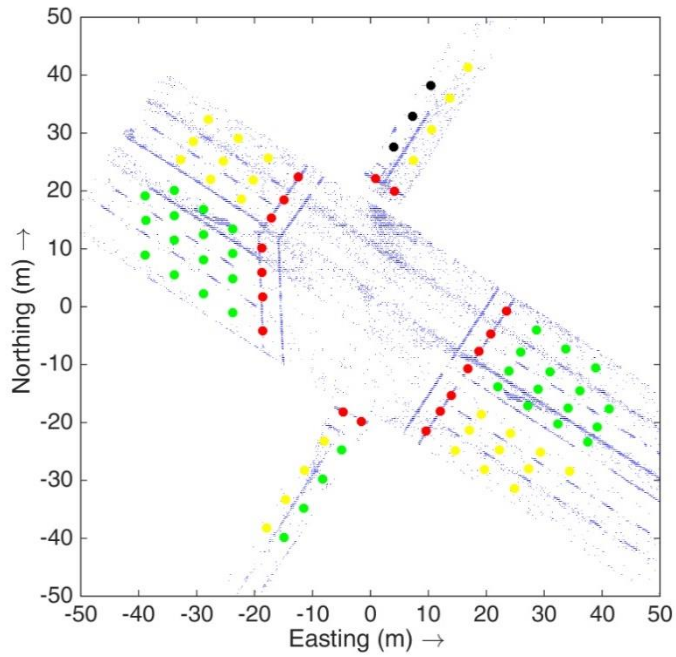


Figure 5.12: Extracted nodes superimposed on the point cloud.

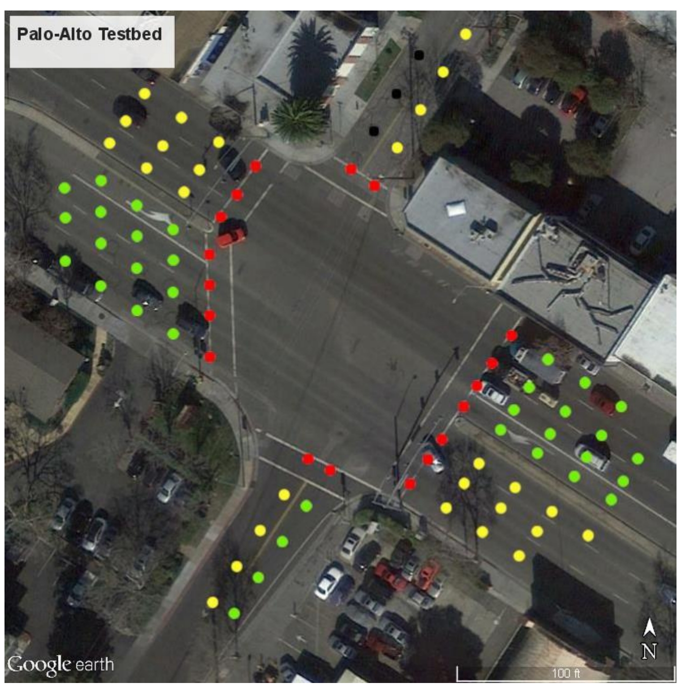


Figure 5.13: Extracted nodes overlaid on google earth.

5.6 Summary of Automation Status

Fig. 5.14 summarizes the automation status of the various processing steps described above. Given the short (one-year) period of the project, the algorithms that UCR developed focused on "standard intersections". These are described by two straight streets intersection at near right angles and possibly one meridian separating the ingress and egress lanes of each road.

Step	Function	UCR Automation level	Comments
1	Preprocessing	Given a list of intersection locations, the process is semi-automated.	Most articles in the literature do not describe their approach to this step. Segment detection may fail for non-standard intersections.
2	Road Edge Detection	Automated for road sections with one curb and one median, no islands.	
3	Road surface extraction	Automated	
4	Mapping of 3D point cloud to 2D image	Semi-automated	Intensity threshold parameter are tuned for different road segments.
5	Image Enhancement and Feature Extraction	Semi-automated.	A new graph construction and cutting method using Otsu's method shows much more automated performance, combining steps 4 and 5.
6	Map message (e.g., J2735) metadata extraction	Automated for segments with straight lanes. Semi-automated for non-standard intersections with curved lanes.	Performance is affected by faded or missing roadway markings.
7	Three dimensional J2735 output with metadata	Automated	

Figure 5.14: Summary of Automation status of the various steps in the process of generating J2735 intersection maps from MTLS data.

Fig. 5.14 highlights various directions for future work. The automation level of Step 1 might be enhanced by using existing (low accuracy) roadway network descriptions both to identify to rough intersection locations and metadata such as the number of ingress and egress lanes per road at each intersection. The automation level of Step 2 could be generalized to accommodate more general intersection entities such as pedestrian islands (see example in Fig. 6.4). Step 4 is the fragile step of the current approach. The comment for Step 5 points to an approach that would automated and robustify the choice of the intensity threshold and eliminate Step 4 (conversion to an image).

6. EXPERIMENTAL RESULTS

This section presents the results of applying the method of Chapter 5 to all eleven intersections along the Palo Alto testbed. Each intersection map is output in the SAE J2735 format.

The J2735 map message includes:

- coordinates for the intersection center
- the number of lanes
- a data structure for each lane including
  - a lane identifier
  - a sequence of nodes defining the lane centerline
  - the lane width
  - a point indicating the start of the centerline at the stop bar
  - lane attributes such as whether the lane is for ingress or egress.

This project has focused on standard intersections, where essentially orthogonal and straight streets intersect. The MTLS based approach assumes that the lane markings are clearly painted.

The automated mapping results are illustrated by drawing the J2735 map centerline nodes overlaid on both the point cloud and a Google Earth image of the intersection. The point cloud data acquisition process includes surveyed control points such that the point cloud has a known accuracy at the centimeter level [2]. The J2735 overlaid on the point cloud allows evaluation of the absolute accuracy of the J2735 intersection map. The J2735 overlaid on the Google Earth image gives a visually interpretable result. The Google Earth imagery is only accurate to 2-5 meters [33, 34, 35]. Therefore, in some instances the entire J2735 overlay is offset relative to the Google Earth image while aligning well with the point cloud. Such images clearly show the lesser accuracy of the Google Earth imagery relative to the point cloud. The visual overlay of the J2735 onto the Google Earth imagery is useful for detecting relative errors between portions of the J2735, for example a stop bar at the wrong location.

Most of the intersections process completely with correct outputs. In cases where the road markings are severely faded, the road has no markings, or the input image is very noisy the algorithm generates a warning and marks the segment for human processing. Another issue arises when only one stop bar is detected, in which case the algorithm proceeds with the detected stop bar and generates a warning for further human inspection. In case no stop bar is detected and the algorithm generates a warning. For these cases, in our results, a stop bar is added manually so the algorithm can perform the rest of the tasks. The discussion will point out any known processing issues or errors.

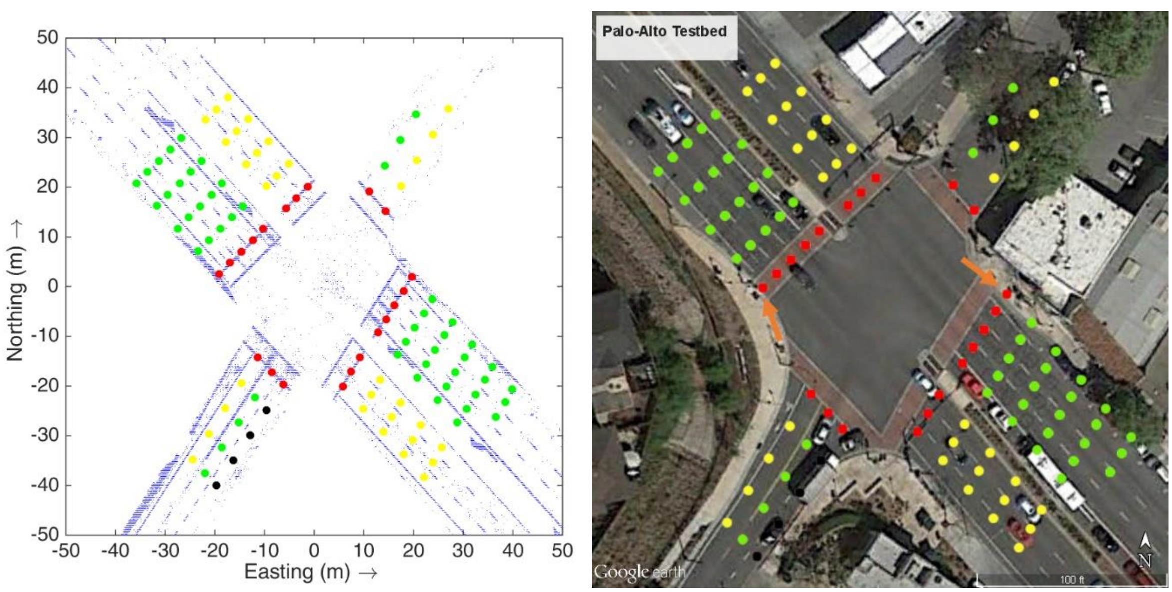
6.1 Intersection 01:

Intersection 01 is a standard cross shaped intersection where the stop bars form a regular rectangular shape.

Fig 6.1a shows the extracted J2735 overlaid on the point cloud. Each lane centerline starts from a red dot that should be on the stop bar. For an ingress lane, a sequence of green dots should fall on the lane centerline. For an egress lane, a sequence of yellow dots should mark the lane centerline. Fig. 6.1b shows the same J2735 overlaid on the Google Earth image.

Visually inspecting the two images details several items:

- All lanes were extracted. No lanes were missed.
- From the point cloud overlay, all lane centerlines and stop bar locations are correct.
- The Google Earth image shows that the image and J2735 are shifted relative to each other, clearly showing the relative inaccuracy of the Google Earth image relative to the more precise point cloud [33, 34, 35].
- Fig. 6.1b contains two orange arrows. These markers indicate two non-standard lanes that have been detected and mapped as traffic lanes. The point cloud image shows that these two lanes satisfy the current definitions of lanes, so they are included in the J2735 output. In future work, either their narrowness, narrowing as they approach the intersection, or position near the road edge can be used as triggers either to eliminate them from the J2735 output or to request human oversight.



(a) (b)

Figure 6.1: (a) Extracted J2735 nodes superimposed on the intensity thresholded point cloud $\bar{S_i}$ for i = 1. (b) Extracted J2735 nodes overlaid on Google earth image.

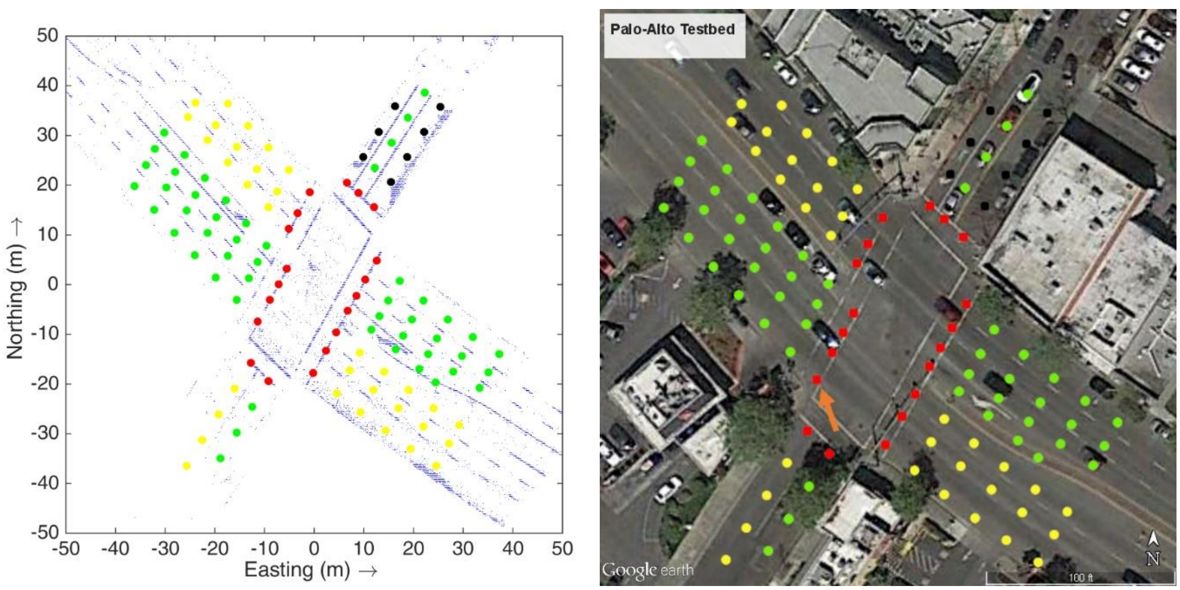
6.2 Intersection 02:

This is an almost regular shaped intersection. The main thoroughfare is slightly curved and the intersecting streets not quite orthogonal, yet the approach worked well.

Fig. 6.2a shows the extracted J2735 overlaid on the point cloud. Each lane centerline starts from a red dot that should be on the stop bar. For an ingress lane, a sequence of green dots should fall on the lane centerline. For an egress lane, a sequence of yellow dots should mark the lane centerline. Fig. 6.2b shows the same J2735 overlaid on the Google Earth image

Visually inspecting the two images details several items:

- All lanes were extracted. No lanes were missed.
- From the point cloud overlay, all lane centerline locations are correct.
- The Google Earth image shows that the image and J2735 are shifted relative to each other, such that the J2735 centerlines sit on the paint stripes. This clearly showing the relative inaccuracy of the Google Earth image relative to the point cloud [33,34,35].
- Fig. 6.2b has two orange arrows. These markers point to two J2735 stop bar locations which have been detected and mapped at the wrong line of the pedestrian cross walk. For the arrow at the lower left, the error is due to worn lane markings. In future work, this issue could be detected by the fact that stop bar location discontinuously changes from the ingress and egress portions of that road segment.



(a) (b)

Figure 6.2: (a) Extracted J2735 nodes superimposed on the intensity thresholded point cloud $\bar{S}_i$ for i = 2. (b) Extracted J2735 nodes overlaid on Google earth image.

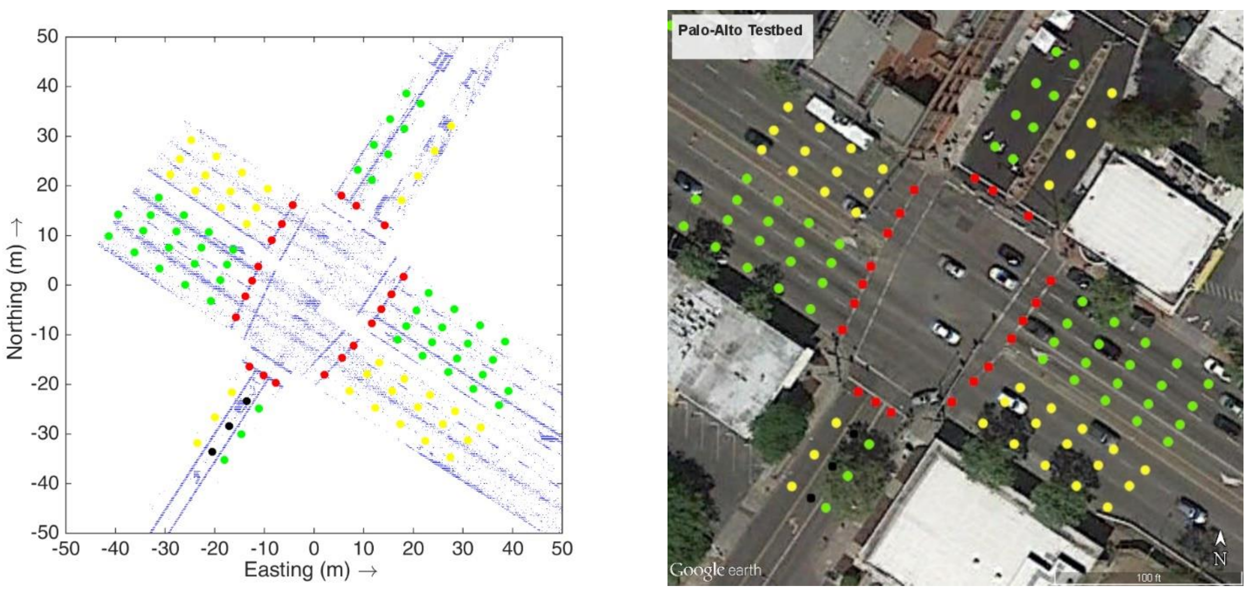
6.3 Intersection 03:

Intersection 03 is a regular rectangular shaped intersection.

Fig. 6.3a shows the extracted J2735 overlaid on the point cloud. Each lane centerline starts from a red dot that should be on the stop bar. For an ingress lane, a sequence of green dots should fall on the lane centerline. For an egress lane, a sequence of yellow dots should mark the lane centerline. Fig. 6.3b shows the same J2735 overlaid on the Google Earth image.

Visually inspecting the two images details several items:

- All lanes were extracted. No lanes were missed.
- From the point cloud overlay, all lane centerline locations are correct.
- The Google Earth image and J2735 are well aligned.
- Note in the Google Earth image that the upper half of the cross street appears to be newly paved without any lane striping. The point cloud image indicates high intensity lines, so we suspect that the point cloud was acquired prior to the street being repaved. The mapping process worked well. This bullet clarifies why no lane striping is visible on this road segment.



(a) (b)

Figure 6.3: (a) Extracted J2735 nodes superimposed on the intensity thresholded point cloud $\bar{S}_i$ for i = 3. (b) Extracted J2735 nodes overlaid on Google earth image.

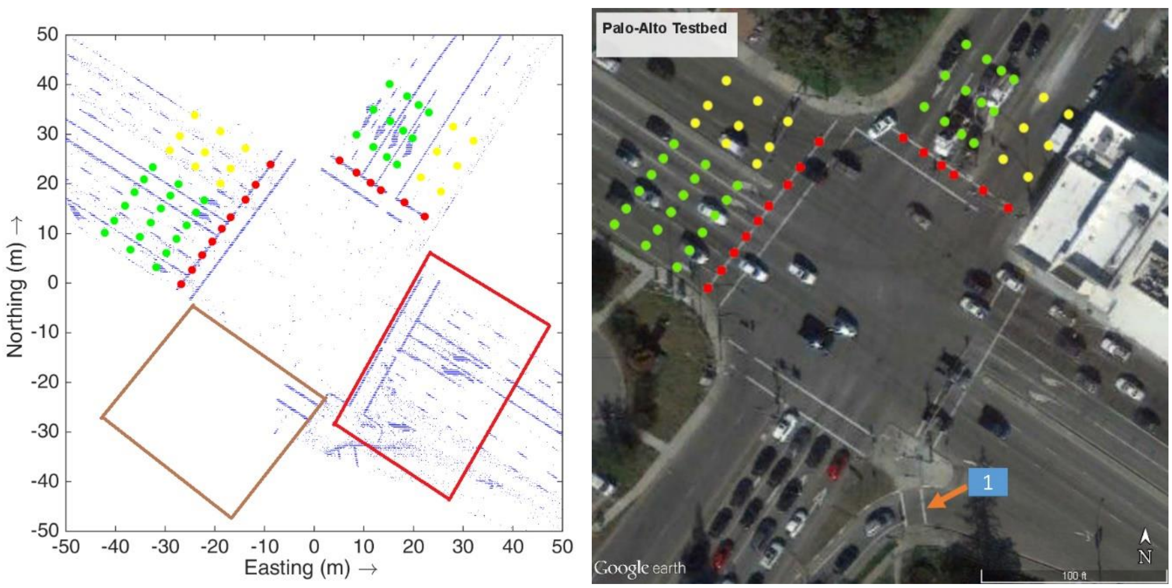
6.4 Intersection 04:

Intersection 04 is an irregularly shaped intersection that has one side road with a dedicated right-turn lane with an extra stop bar (see box 1 in Fig. 6.4b), wide side roads with medians, and faded paintings.

Fig. 6.4a shows the extracted J2735 overlaid on the point cloud. Each lane centerline starts from a red dot that should be on the stop bar. For an ingress lane, a sequence of green dots should fall on the lane centerline. For an egress lane, a sequence of yellow dots should mark the lane centerline. Fig. 6.4b shows the same J2735 overlaid on the Google Earth image.

Visually inspecting the two images details the following items:

- The region indicated by the brown and red boxes could not be processed due to the non-standard road geometry and faded lane striping.
- For other road segments the detection of centerline nodes of every lane in all the ingress and egress branches and the position of the stop bars are estimated correctly.



(a) (b)

Figure 6.4: (a) Extracted J2735 nodes superimposed on the intensity thresholded point cloud $\bar{S}_i$ for i = 4. (b) Extracted J2735 nodes overlaid on Google earth image.

6.5 Intersection 05:

Intersection 05 has two T-shaped intersections in close proximity. See Figs. 6.5 and 6.6. Due to this special structure we decomposed the intersection into intersections 5a and 5b, which are each much closer to being standard. Each is processed separately.

Intersection 5(a): It is a T-shaped intersection with three road segments. Fig. 6.5a shows the extracted J2735 overlaid on the point cloud. Each lane centerline starts from a red dot that should be on the stop bar. For an ingress lane, a sequence of green dots should fall on the lane centerline. For an egress lane, a sequence of yellow dots should mark the lane centerline. Fig. 6.5b shows the same J2735 overlaid on the Google Earth image.

Visually inspecting the two images details several items:

- There are no stop bar markings on the pavement at the egress section marked as item 1 in Fig. 6.5b. Given this situation, this system generated a warning to the human operator for inspection. To proceed, the human manually extends the stop bar line from the parallel ingress section.
- With the manually inserted stop bar, all roadway feature nodes (i.e., centerline and stop bar nodes in every ingress and egress section) have been detected and mapped correctly. The stop bar nodes extracted from the manually inserted stop bar are marked with orange.
- Note that the stop bar of the left segment of the main thoroughfare (i.e., item 2) is not a straight line; nonetheless, all the stop bar positions have been correctly detected.

In future work, the insertion of stop bars could be automated, for the cases where the pavement is unmarked. It is still recommended that the human be alerted, for verification, since this extrapolation of information may not be applicable in non-standard situations. The item 2 in Fig. 6.5b is an example of a non-standard situation where extending the stop bar between roadway sections would be inappropriate.

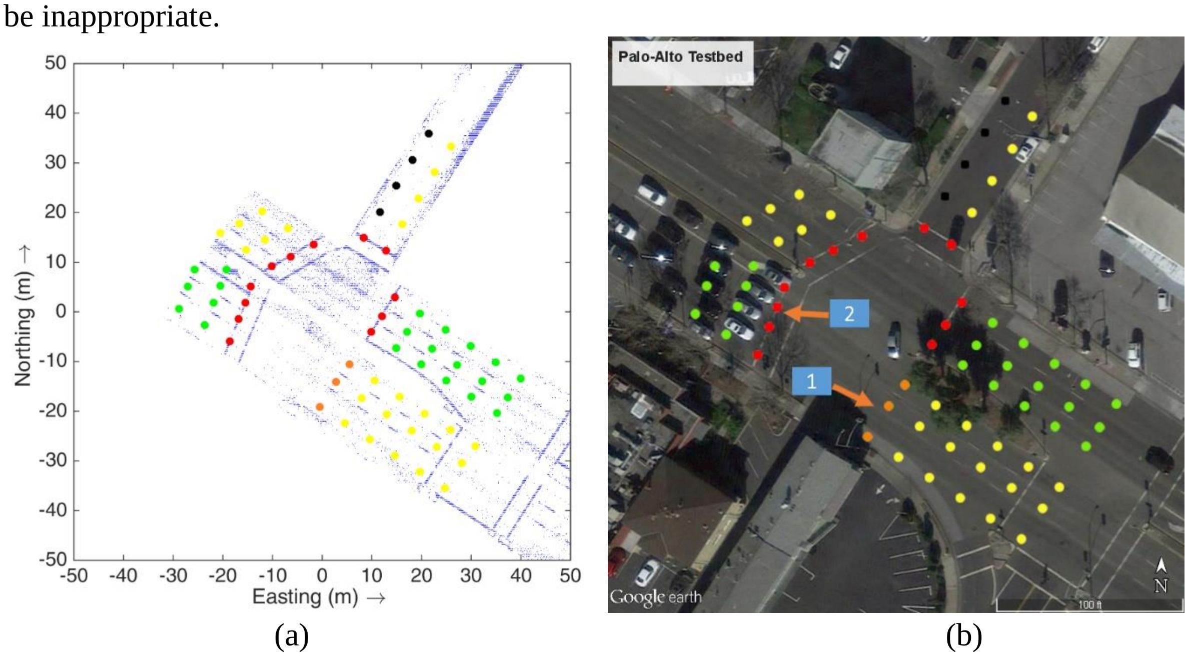


Figure 6.5: (a) Extracted J2735 nodes superimposed on the intensity thresholded point cloud $\bar{S}_i$ for i = 5a. (b) Extracted J2735 nodes overlaid on Google earth image.

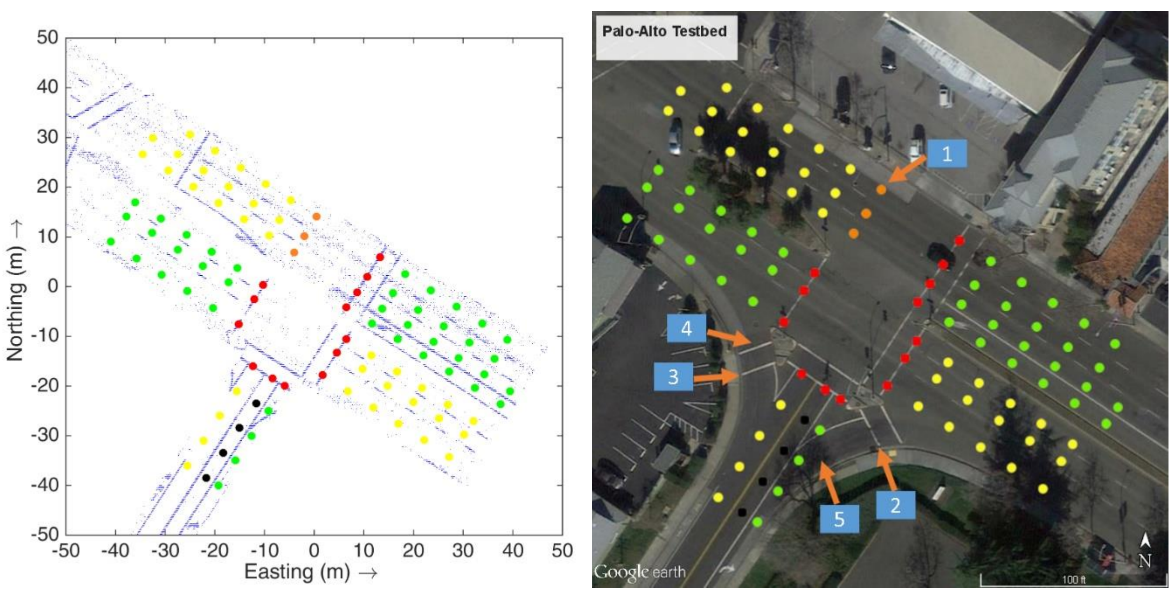
Intersection 5(b): It is a non-standard T-shaped intersection with three road segments. The side road has two dedicated lanes for ingress and egress with extra stop bars (marked in Fig. 6.6b as items 2 and 3). Along with that structural ambiguity there is an egress segment of the main thoroughfare without a painted stop bar (see item 1 in Fig. 6.6b).

Fig. 6.6a shows the extracted J2735 overlaid on the point cloud. Each lane centerline starts from a red dot that should be on the stop bar. For an ingress lane, a sequence of green dots should fall on the lane centerline. For an egress lane, a sequence of yellow dots should mark the lane centerline. Fig. 6.6b shows the same J2735 overlaid on the Google Earth image.

Visually inspecting the two images details several items:

- At the egress to the main thoroughfare indicated as item 1, there is no painted stop bar on the road surface. In this case, the program alerts the user, who manually extends the line from the parallel ingress lane so that the stop bar definition can be completed.
- Items 2-5 all relate to the non-standard structure of the intersection. The current software is not written to accommodate the curved lane marked by items 4-5 nor the extra stop bars indicated by items 2-3.
- Other than the exceptions note above, the stop bars and centerline nodes of all lanes of both ingress and egress have been identified correctly.

In future work, the insertion of stop bars could be automated, for the cases where the pavement is unmarked. It is still recommended that the human be alerted, for verification, since this extrapolation of information may not be applicable in non-standard situations. It is also expected that the curved right-hand turn lanes can be incorporated into the automated process.



(a) (b)

Figure 6.6: (a) Extracted J2735 nodes superimposed on the intensity thresholded point cloud $\bar{S}_i$ for i = 5b. (b) Extracted J2735 nodes overlaid on Google earth image.

6.6 Intersection 06:

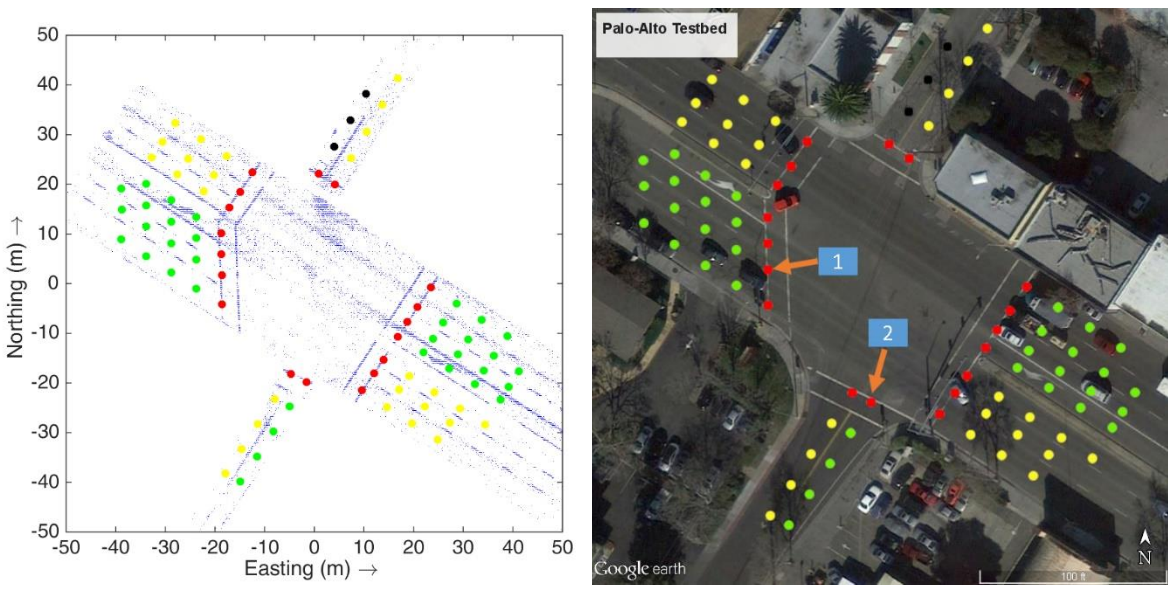
This is a non-standard cross-shaped intersection. Note that the cross street sections are off-set laterally relative to each other and the stop bar indicated as item 1 is not orthogonal to the lane centerline and not a straight-line across the entire road.

Fig. 6.7a shows the extracted J2735 overlaid on the point cloud. Each lane centerline starts from a red dot that should be on the stop bar. For an ingress lane, a sequence of green dots should fall on the lane centerline. For an egress lane, a sequence of yellow dots should mark the lane centerline. Fig. 6.7b shows the same J2735 overlaid on the Google Earth image.

Visually inspecting the two images details several items:

- Despite its nonstandard aspects all the lanes of every egress and ingress section have been correctly extracted.
- The lane striping is barely visible on the google image.
- All the centerline nodes of every lane have been identified correctly.
- All the stop bars are positioned correctly except for one side road segment part (indicated in Fig. 6.7b as item 2).

The misplaced stop bar is expected to be fixable in future efforts.



(a) (b)

Figure 6.7: (a) Extracted J2735 nodes superimposed on the intensity thresholded point cloud $\bar{S}_i$ for i = 6. (b) Extracted J2735 nodes overlaid on Google earth image.

6.7 Intersection 07:

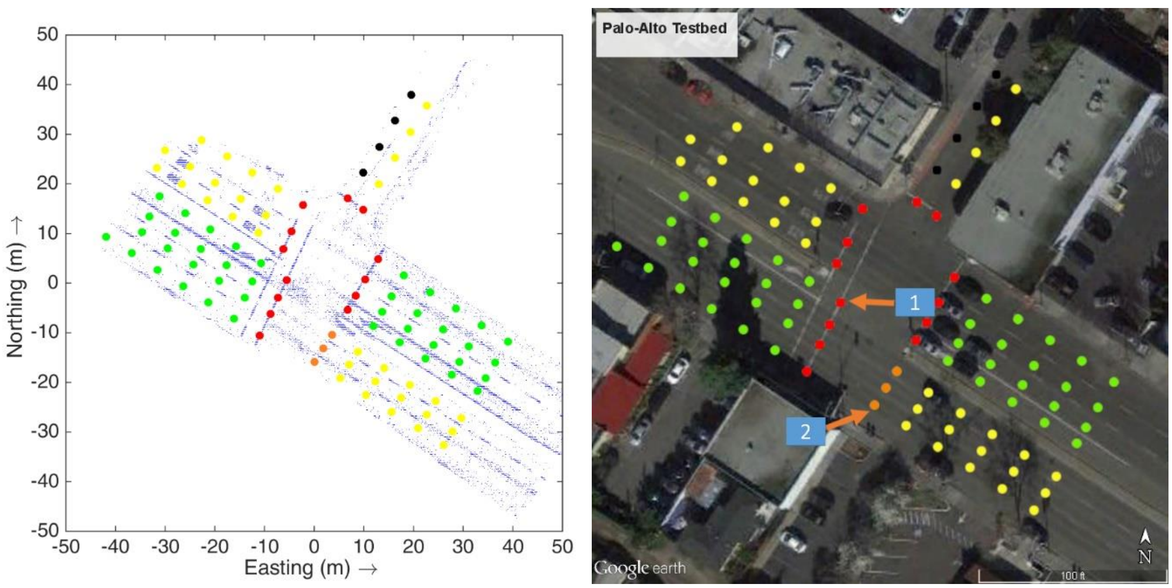
This is a standard T-shaped intersection with three road segments.

Fig. 6.8a shows the extracted J2735 overlaid on the point cloud. Each lane centerline starts from a red dot that should be on the stop bar. For an ingress lane, a sequence of green dots should fall on the lane centerline. For an egress lane, a sequence of yellow dots should mark the lane centerline. Fig. 6.8b shows the same J2735 overlaid on the Google Earth image.

Visually inspecting the two images details several items:

- All lanes were extracted. No lanes were missed.
- All centerlines are correct.
- Box 1 shows misplacement of stop bar at an ingress branch of the main road.
- Box 2 indicates a main thoroughfare egress where there is no painted stop bar. In this case, the program alerts the user, who manually extends the line from the parallel ingress lane so that the stop bar definition can be completed.

The issues pointed to by boxes 1 and 2 could both be addressed in future work.



(a) (b)

Figure 6.8: (a) Extracted J2735 nodes superimposed on the intensity thresholded point cloud $\bar{S}_i$ for i = 7. (b) Extracted J2735 nodes overlaid on Google earth image.

6.8 Intersection 08:

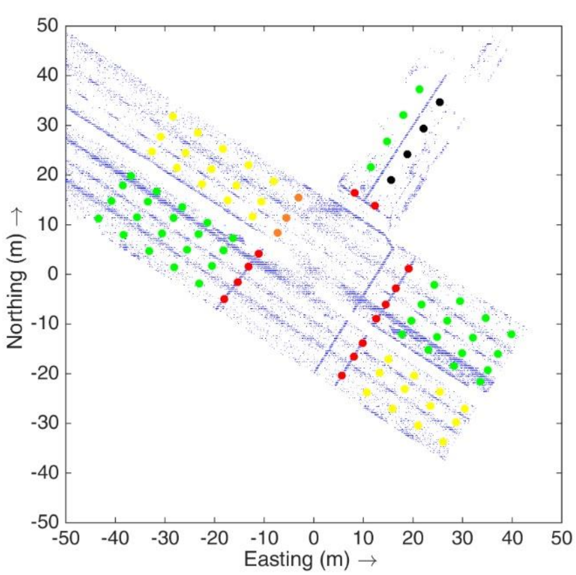
This is a standard T-shaped intersection.

Fig. 6.9a shows the extracted J2735 overlaid on the point cloud. Each lane centerline starts from a red dot that should be on the stop bar. For an ingress lane, a sequence of green dots should fall on the lane centerline. For an egress lane, a sequence of yellow dots should mark the lane centerline. Fig. 6.9b shows the same J2735 overlaid on the Google Earth image.

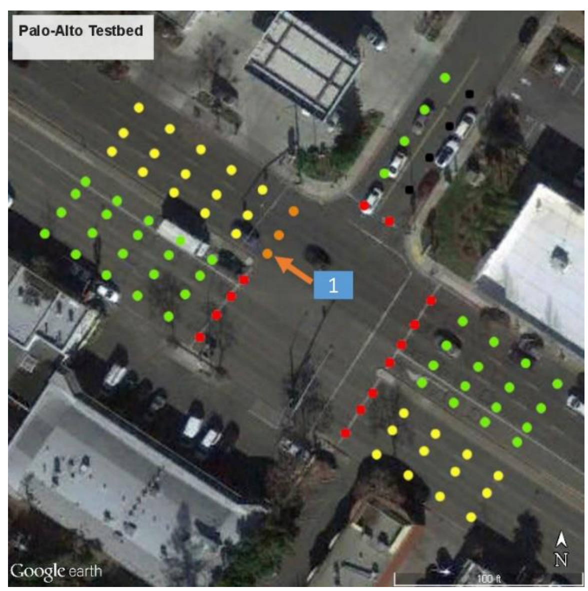
Visually inspecting the two images details several items:

- The number of lanes, lane centerlines, and lane widths in every ingress and egress branch are extracted correctly. No lanes were missed.
- Box 1 points to a main thoroughfare egress section for which there is no stop bar painted on the road surface. This is clear in the point cloud image. The Google Earth image appears to show a stop bar; however, more careful observation shows that this is an overhead traffic signal and its shadow on the road surface. The absence of the painted stop bar on the road surface causes the automatic processing to end with an alert to the user. The user then manually extends the line of the stop bar from the parallel ingress road section to allow definition of the J2735 stop bar for each egress lane.
- With human interaction for the stop bar at the single egress section, correct extraction and placement of all stop bars and lane centerline nodes has been achieved.

In future work, the insertion of stop bars could be automated, for the cases where the pavement is unmarked. It is still recommended that the human be alerted, for verification, since this extrapolation of information may not be applicable in non-standard situations.



(a)



(b)

Figure 6.9: (a) Extracted J2735 nodes superimposed on the intensity thresholded point cloud $\bar{S}_i$ for i = 8. (b) Extracted J2735 nodes overlaid on Google earth image.

6.9 Intersection 09:

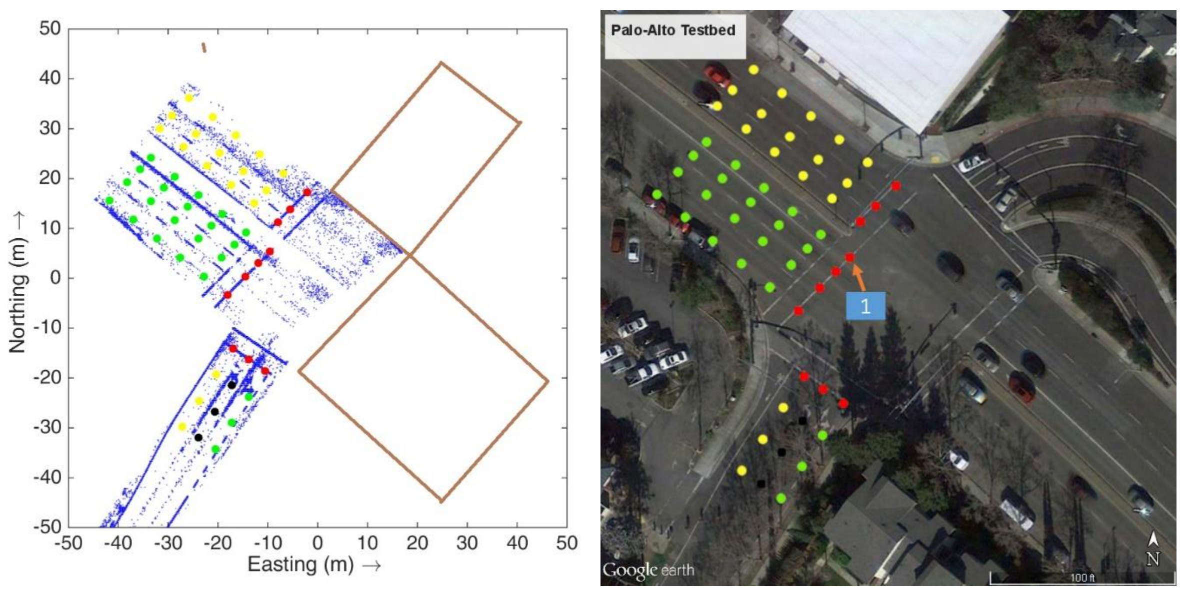
Intersection 09 is an irregularly shaped intersection with one curved and two merging road segments.

Fig. 6.10a shows the extracted J2735 overlaid on the point cloud. Each lane centerline starts from a red dot that should be on the stop bar. For an ingress lane, a sequence of green dots should fall on the lane centerline. For an egress lane, a sequence of yellow dots should mark the lane centerline. Fig. 6.10b shows the same J2735 overlaid on the Google Earth image.

Visually inspecting the two images details several items:

- The two brown boxes mark two road segments that cannot be processed due to irregular geometric structure and light paint markings. The irregular structure prevents segmentation, therefore, the remainder of the feature extraction process cannot complete for those segments of the intersection.
- The experiment operated successfully on all the regular shaped road segments with all centerlines mapped identified correctly.
- The orange arrow marked box 1 indicates the misplacement of the stop bar of the ingress branch of the main road segment.

Improvement of the segmentation process for non-standard intersections is a topic for future work.



(a) (b)

Figure 6.10: (a) Extracted J2735 nodes superimposed on the intensity thresholded point cloud $\bar{S}_i$ for i =9. (b) Extracted J2735 nodes overlaid on Google earth image.

6.10 Intersection 10:

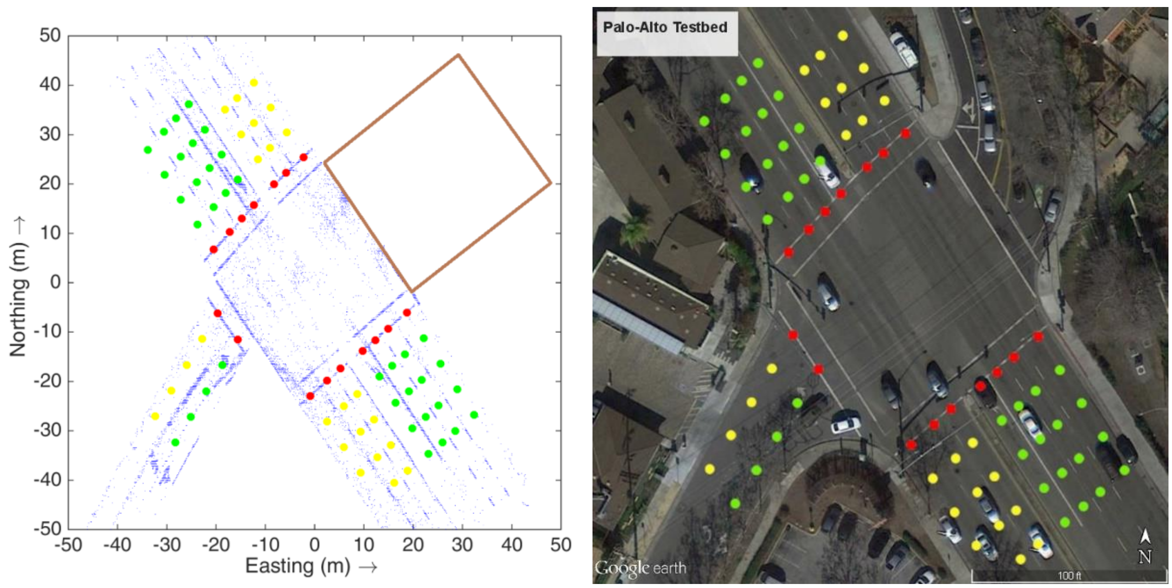
Intersection 10 is a cross intersection with an irregularly shaped side road segment. The non-standard side road is identified with a brown box of Fig. 6.11a.

Fig. 6.11a shows the extracted J2735 overlaid on the point cloud. Each lane centerline starts from a red dot that should be on the stop bar. For an ingress lane, a sequence of green dots should fall on the lane centerline. For an egress lane, a sequence of yellow dots should mark the lane centerline. Fig. 6.11b shows the same J2735 overlaid on the Google Earth image.

Visually inspecting the two images details several items:

- All lanes along the main thoroughfare were extracted correctly. No lanes were missed.
- The lanes of the lower portion of the cross street are extracted correctly.
- For the top portion of the cross street, the J2735 map cannot be extracted due to failure at the segmentation step, caused by the non-standard intersection geometry.

Improvement of the segmentation process for non-standard intersections is a topic for future work.



(a) (b)

Figure 6.11: (a) Extracted J2735 nodes superimposed on the intensity thresholded point cloud $\bar{S}_i$ for i = 10. (b) Extracted J2735 nodes overlaid on Google earth image.

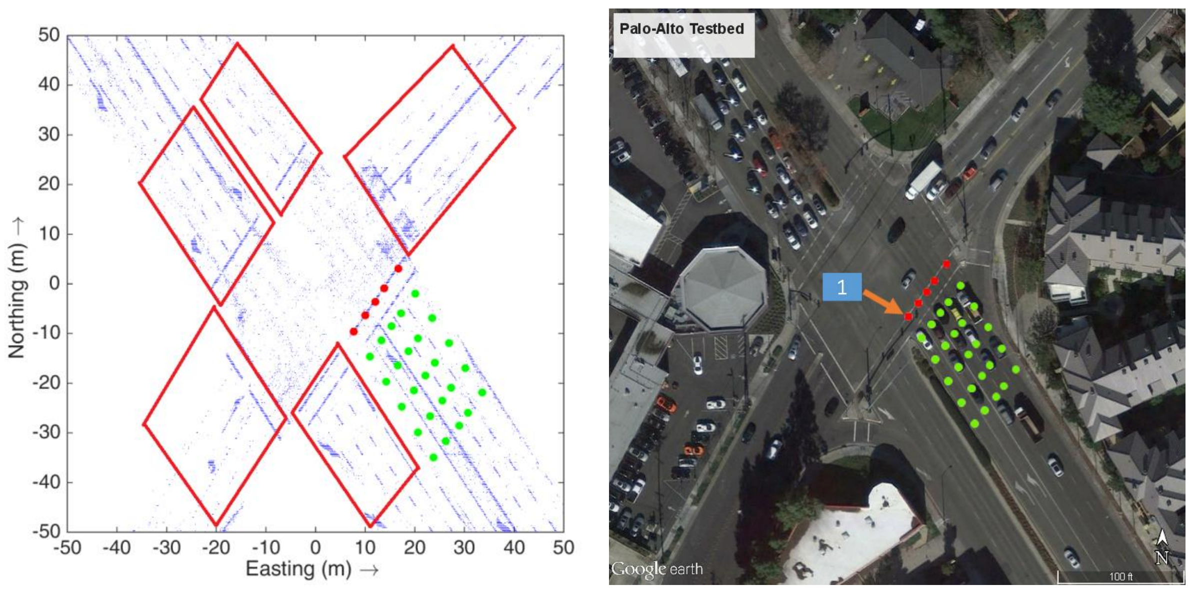
6.11 Intersection 11:

Intersection 11 is an almost standard cross-shaped intersection.

Fig. 6.12a shows the extracted J2735 overlaid on the point cloud. Each lane centerline starts from a red dot that should be on the stop bar. For an ingress lane, a sequence of green dots should fall on the lane centerline. For an egress lane, a sequence of yellow dots should mark the lane centerline. Fig. 6.12b shows the same J2735 overlaid on the Google Earth image.

Visually inspecting the two images details that:

- Both egress and one ingress portions of the thoroughfare and both sections of the cross street could not be processed due to faded lane stripes. This is indicated by the red rectangles in Fig. 6.12a.
- One ingress portion of the main thoroughfare has all lanes extracted correctly, but marked the wrong stop bar as indicated by the orange arrow in Fig. 6.12b.



(a) (b)

Figure 6.12: (a) Extracted J2735 nodes superimposed on the intensity thresholded point cloud $\bar{S}_i$ for i = 11. (b) Extracted J2735 nodes overlaid on Google earth image.

6.12 Performance Summary

Fig. 6.13 on the following page summarizes the performance of the UCR methodology for extracting J2735 intersection descriptions for the eleven intersections along the Palo Alto testbed corridor.

Intersection Number	Intersection Type (Standard cross, Standard T, Non-standard)	Performance Analysis								Remarks
		Road Edge Detection	Ingress Branch			Egress Branch			Lanes without markings	
			Surface Detection	Lane Edge Detection	Stop Bar detection	Surface Detection	Lane Edge Detection	Stop Bar Detection		
1	Standard cross	8 of 8	100%	13 of 11	4 of 4	100%	8 of 8	4 of 4	2	• 2 bike lanes were detected in addition to traffic lanes
2	Non-Standard cross	8 of 8	100%	11 of 11	4 of 4	100%	8 of 8	4 of 4		• 1 stop bar line has been detected and mapped at the wrong line of the pedestrian cross walk
3	Non-Standard cross	8 of 8	100%	11 of 11	4 of 4	100%	8 of 8	4 of 4		• The direction of flow for one lane could not be automatically determined because the mapping vehicle did not drive in that ingress section.
4	Non-Standard cross	7 of 8	100%	9 of 20	2 of 4	100%	5 of 11	2 of 4		• 2 road segments (both ingress and egress) could not be processed due to the non-standard road geometry and faded lane striping.
5(a)	Non-Standard T	6 of 6	100%	8 of 8	3 of 3	100%	7 of 7	2 of 3	2	• The direction of flow for one lane could not be automatically determined because the mapping vehicle did not drive in that ingress section. • One stop bar has been detected manually because stop bar marking was absent
5(b)	Non-Standard T	6 of 6	100%	9 of 9	3 of 3	100%	7 of 7	2 of 3		• The direction of flow for one lane could not be automatically determined. • One stop bar has been detected manually because stop bar marking was absent.
6	Non-Standard T	6 of 6	100%	10 of 10	3 of 3	100%	8 of 8	3 of 3		• 1 misplaced stop bar is expected to be fixable in future efforts.
7	Standard T	7 of 8	100%	9 of 9	3 of 3	100%	7 of 7	2 of 3	2 of 2	• The direction of flow for one lane could not be automatically determined because the mapping vehicle did not drive in that ingress section. • 1 stop bar has been detected manually because stop bar marking was absent. • 1 misplaced stop bar is expected to be fixable in future efforts.
8	Standard T	6 of 6	100%	9 of 9	3 of 3	100	7 of 7	2 of 3		• The programmer specified one stop bar due to the absence of a painted stop bar on the road surface. • The direction of flow for one lane could not be automatically determined because the mapping vehicle did not drive in that ingress section.
9	Non-Standard cross	4 of 8	100%	6 of 13	2 of 4	100%	4 of 8	2 of 4		• 2 road segments (both ingress and egress) could not be processed due to the non-standard road geometry. • 1 ingress lane could not be identified because there was no trajectory information
10	Non-Standard cross	6 of 8	100%	9 of 11	3 of 4	100%	7 of 9	3 of 4		• 2 road segments (both ingress and egress) could not be processed due to the non-standard road geometry.
11	Standard cross	8 of 8	100%	4 of 14	1 of 4	100%	0 of 9	0 of 4		• 2 road segments (both ingress and egress) could not be processed due to the non-standard road geometry.

Figure 6.13: Tabular summary of the J2735 intersection map extraction from MTLS data along the Palo Alto testbed corridor.

7. BEST PRACTICES FOR MTLS BASED AUTOMATED EXTRACTION OF ROADWAY RELEVANT FEATURES

This section summarizes several recommended practices based on the outcomes of the research effort.

7.1 Equipment

- **LIDAR**: As an active imaging sensor for roadway feature mapping, LIDAR should have a field-of-view sufficient to simultaneously capture inner and outer roadway edges when the vehicle is driven in the center lane.
- **High-resolution 360 degree camera**: This sensor will enable photogrammetry to assist visual interpretation.
- **Two-frequency carrier phase GNSS receiver**: This enables high-precision (centimeter accuracy) georectification (estimation of position and attitude) of the LIDAR and camera data.
- **Inertial Measurement Unit (IMU)**: An IMU enables georectification to be implemented at the high LIDAR (15-20 Hz) and camera rates (30 Hz), even though the GNSS makes precise, independent position and attitude dependent measurements only at much lower rates.
- **Differential GPS corrections:** This is necessary to achieve the desired centimeter to decimeter map position accuracy. One means of implementation is by a proximal (< 10 km) base station. Another is by network computation of corrections. In either case, corrections may be communicated by RF means in real-time or combined with GPS in post-processing.
- **Power**: Sufficient support power is required to run all equipment.
- **Data-storage**: Sufficient to save the raw, time-stamped, sensor data over the time required to complete the data collection exercise.

7.2 Data collection procedure

The goal is to ensure a high-density of LIDAR reflections from roadway relevant features, to facilitate reliable automated extraction and mapping of those features.

- **Means to obtain a high-density of reflections:**
  - **The mapping vehicle should traverse each entry and exit point for each intersection a few times.** These traverses should travel along different lanes. It is not necessary to traverse each lane, but one traverse of the inner-most and outer-most lanes is useful, due to the different perspectives that they provide. The tradeoff is that more traverses gives a higher density of LIDAR reflections, different perspectives, and different obstructions; however, each traverse adds cost due to time, fuel, and data storage.
  - **Mapping vehicle should travel at reduced speeds (20-30mph)**, when appropriate. The tradeoff is slower speeds provide gives a higher density of LIDAR reflections; however, adds cost due to time and data storage requirements.

- **Including multiple LIDAR's**, directly improves the density of reflections, per mile driven.
- **Ensure that the LIDAR's are mounted such that they illuminate the regions expected to contain the roadway features of interest.**

- **Means to facilitate automatic extraction of features:**

  - In post-processing, the GNSS and IMU data will be used to estimate the platform trajectory and to geo-rectify the LIDAR and camera data. **Both the geo-rectified data and the platform trajectory should be saved for the feature extraction processing**. The platform trajectory provides useful data, such as the number of intersection entry and exit points and direction of travel along each.
  - For roads without a meridian, to aid the automatic extraction of the divider between ingress and egress lanes, the mapping vehicle should be driven along those lanes nearest to this divider. This is recommended so that the direction-of-travel metadata for each lane can be extracted.

- **Means to avoid occlusion of roadway features:**

  - Fore and aft rolling closure and/or traffic break minimizes artifacts from vehicle intrusions.
  - Performing multiple traverses provides multiple opportunities to receive reflections from each roadway feature. The traverses occurring at different time improves the chances that the occluding object is no longer occluding the same features.

- **Means to confirm accuracy:**

  - Occasional control points (known locations) consisting of highly reflective material allows both instrument calibration and confirmation of the accuracy of mapped features.

7.3 Data post processing

After determining the platform trajectory and collecting the georectified LIDAR point cloud and camera photolog, the key recommendations for data post processing are as follows:

- Retain the raw sensor data as long as possible.
- Retain the point cloud data for the entire roadway region of interest.
- Utilize control points to assist with calibration, validation, and merging of data sets.
- For georectification and feature mapping use a consistent Earth Center Earth Fixed (ECEF) reference frame in addition to other formats (state plane; latitude, longitude, elevation)

In the mapping of intersections, the following have also proved useful:

- Define a reduced point cloud for each intersection, for example all points within a radius *R* for the defined origin of the intersection.
- Within this region, process the sensor platform trajectory to determine the number of approaches and exits to the intersection.

- From the intersection point cloud, extract a subset that represents one approach or exit.
- Filter and remove data from interfering objects (e.g., vehicles, trees, people). This can be accomplished for example by extracting from the point cloud only those points that form a smooth two-dimensional surface, discarding any points too far from that surface.
- Perform feature extraction as necessary for the application of interest.
- Use the sensor platform trajectory to specify directions of travel metadata.
- Store the extracted lane markings, road edges, and other features of interest with precision (perhaps 10 times) greater than the desired accuracy of the map.

8. CONCLUSIONS

Connected Vehicle applications require roadway feature digital maps stored and communicated using uniform methods for representation and reference. These maps must conform to well understood accuracy specifications to ensure the safety of life and infrastructure. Due to the scope of the mapping requirements, when considered at the national and global scales, automated and data driven mapping approaches must be considered.

Numerous methods exist to acquire and record data indicative of geospatial objects and terrain. Based on our analysis, the preferred existing acquisition methods for roadway mapping utilize GPS/IMU integrated LIDAR sensing to generate a three dimensional georectified point cloud data set. At present, the state of the art approaches to feature extraction are human intensive. When data acquisition is conducted with multiple integrated sensors at a high frequency and national (or global) scale, the resulting dataset is sufficiently large that automated and application specific data processing become necessary for economic feasibility. This project report has presented an automated feature extraction approach and demonstrated its use on eleven intersections. The resulting processed dataset presented herein provides a meaningful representation of roadway features of interest for intersections, while excluding irrelevant data.

The roadway feature extraction process included the following primary steps:

- Preprocessing to extract the georectified point cloud and associated trajectory portions of interest for given intersections;
- Identification and extraction of the road surface point cloud, road edge curves, and median edge curves;
- Conversion of the intersection road surface point cloud to an image to enable feature extraction by image processing methods;
- Image-based roadway feature extraction; and
- Translation to a J2735 feature map for intersections of interest.

This methodology for feature extraction and map representation has been presented with a detailed explanation of data processing and integration. This detailed approach allows for future feature extraction of relevant roadway features in connected vehicle environments.

Mapping needs relevant to the *USDOT Connected Vehicle Pilot Deployment Program* are discussed in Appendix C.

The analysis of the algorithm performance shows that it works very well for "standard" intersections. However, additional work is required to achieve functionality for non-standard intersections. Also, on the continuum between manual and fully automated, the algorithms described in Chapter 5 are somewhere in the middle, and are considered to be human-assisted. When the algorithm detects an anomalous situation, it stops to alert the human before moving further forward. This is considered good practice as the generated maps have implications for human safety. The authors caution against learning or deep learning approaches as they cannot discriminate those portions of the map that are certain and those that are not.

9. FUTURE WORK

The feature extraction methodology and its evaluation on eleven intersections demonstrate the complexity of representing relevant roadway features in a standard usable format within a connected vehicle environment. The algorithm worked well in spite of these complexities, making a significant advance from manual feature extraction toward automated data processing for roadway relevant feature extraction. Following are a few avenues fruitful for future efforts:

- **Georectification**: The accuracy of roadway feature maps rests upon the georectification process. That step relies on accurate and reliability knowledge of the sensor platform trajectory during data acquisition. Both accuracy and reliability are challenging in dense urban environments where GNSS signals are not reliable. Multisensor approaches fusing GNSS, LIDAR, Camera and IMU data should be investigated.
- **Feature Extraction and Mapping**: Several directions are available for future work:
    - This project focused on lane edges and stop bars. The method worked well in a semi-automated fashion for standard intersections. Advancing toward more fully automated processes enhances the rate and decreases the cost of roadway mapping.
    - Methods should be developed to accommodate more complex, non-standard intersections.
    - As CV applications develop, additional features will become of interest. Additional feature extraction algorithms will be required, across a wide range of roadways and features.
    - This effort has worked with georectified LIDAR point clouds. Also including georectified photologs in the automated processing could yield enhanced reliability and performance.

  Research should be done in conjunction with government agencies, academic groups, and commercial entities for testbed applications and demonstration projects that require roadway relevant maps and allow the opportunity for advancements within the automated mapping field.
- **Crowd-sourced data:** This area is in its infancy and could yield more efficient approaches for detecting the need for map database updating; collection of map metadata such as intersection lane connectivity; and real-time detection of road hazards.
- **Integration of Crowd-sourced and MTLS:** Crowd-sourced and MTLS data have very different characteristics in accuracy, security, reliability, and timeliness. Studies of how to securely and effectively combine this information is critical.
- **CV Application Mapping Requirements:** As CV pilot deployments progress the achieved mapping and vehicle positioning accuracy should be noted and studied relative to the performance and capabilities that could have been achieved with greater accuracy.
- **Development and Demonstration:** The approach presented herein was limited in scope to a small set of intersections (11) and specific features. Broadening this to a larger set of intersections across the country is critical for characterizing existing capabilities and discovering their strengths and weaknesses prior to large scale deployment.

Evolution of geospatial data acquisition will yield increasingly accurate and reliable topology data for the roadway environment. The necessity to identify and automatically extract relevant roadway features will become significantly more valuable. The methodology presented herein focused on roadway attributes associated with intersection relevant road surface features. It should be viewed as a glimpse of what is possible in the future as the technology develops. Present and future sensing and computing resources are not the limiting factors. This field is in its infancy. Feature extraction algorithms, mapping standards, commercial approaches, and potential connected vehicle applications are still in their formative and demonstration phases.

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APPENDIX A: ACRONYM DEFINITIONS

ALS – Aerial Laser Scanner

CV – Connected Vehicles

DOT – Department of Transportation

GNSS – Global Navigation Satellite Systems

IMU – Inertial Measurement Unit

LAS – American Society for Photogrammetry and Remote Sensing laser file format

LIDAR – Light Detection and Ranging

MIRE – Model Inventory of Roadway Elements

MMITSS – Multi-Modal Intelligent Traffic Signal System

MMSTS – Manufacturing Major Subsystem Technical Specification

MTLS – Mobile Terrestrial Laser Scanner

NCHRP – National Cooperative Highway Research Program

PPM – Points per square meter

RINEX – Receiver Independent Exchange Format

STLS – Stationary Terrestrial Laser Scanner

UAV – Autonomous Aerial Vehicle

APPENDIX B: CONTACTS

This report was written in part using notes from many interviews with the people noted below. We greatly appreciate their enthusiasm in discussing the related topics. The report has not yet been distributed for comment. All statements and any errors are the responsibility of the authors.

People Interviewed:

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APPENDIX C: USDOT CONNECTED VEHICLE PILOT DEPLOYMENT PROGRAM: MAPPING NEEDS

As part of the Connected Vehicle Pilot Deployment (CVPD) Program, in late 2015, the USDOT selected three U.S. sites to deploy large scale connected vehicle applications. In this appendix, we briefly describe these different CVPD locations, their applications, and potential mapping needs. This is based on information available as of May 2016. It should be noted that these CVPD sites are currently defining their detailed concept of operations for various CV applications and are not yet available publically.

Interstate-80 (I-80) Wyoming

I-80 is a major commercial and goods movement corridor with 30% to 70% of the road traffic consisting of heavy-duty trucks. The length of I-80 extends greater than 400 miles with large portions consisting of mountain passes at elevation greater than 7000 ft.

Due in part to challenging weather conditions, I-80 has an elevated frequency of collisions and vehicular accidents. The weather conditions considered to increase travel risks include poor visibility due to heavy snow or fog, icy roads, and high winds. Winds exceeding 65 mph impact high profile vehicles especially when empty or lightly loaded. An additional challenge is providing route closure and parking information to the drivers during closure events lasting many hours. Much of I-80 is located in rural areas with towns located 45 to 150 miles apart with little or no parking facilities in between. Fig 13.1 shows the map of this Wyoming CVPD site.

Figure 13.1: Map of Wyoming CVPD site.

The Connected Vehicle applications proposed for I-80 address the inherent safety issues described above. This includes a variety of road weather applications. Roadway weather information can be linked with enabled connected vehicles and will alert drivers to hazardous weather conditions, roadway closures, and contingency planning. Other Connected Vehicle applications will allow equipped vehicles to monitor roadway and vehicle conditions in close proximity.

The following CV applications envisioned for I-80 site need only general location information (i.e., where-on-road) with mapping/positioning accuracy at approximately 10m:

- Providing parking information based on vehicle location and directing drivers to safe parking location during road closures;
- Automatically notifying first responders of a crash and providing information about the location and severity of the crash based on vehicle metrics such as airbag deployment;
- Travel planning and fleet management by providing road condition information.

In addition, there are a few CV applications that may require mapping/positioning accuracy better than 10m (i.e., lane level accuracy). These include:

- Managing the following speed and distance between vehicles and alerting vehicles of slowing traffic ahead in poor visibility conditions such as snow, fog or icy roads.
- Providing custom alert and advisories for travelling speed based on vehicle weight and profile in high winds, work zones, and other risk such as low bridge clearance for the vehicle.

Meridian Avenue, Tampa, Florida

The second USDOT CVPD site is Meriden Avenue passing through downtown Tampa with a population of 250,000. This region includes residential areas, industrial offices, government buildings, and concert halls. The Tampa CV pilot program proposes to address the following issues:

- Significant delays during the morning peak hour resulting in, and often caused by, a correspondingly large number of rear-end crashes and red light violation collisions;
- Wrong way entries into reversible lanes;
- Pedestrian safety near crowded places such as the courthouse and the concert hall; and
- Transit delays that can be improved with a Transit Signal Priority (TSP) system.

These mobility issues can be alleviated with several proposed CV applications. The specific CV solutions are described below with corresponding mapping/positioning accuracy requirements.

To minimize collisions, a speed change warning CV application is proposed for drivers exiting the expressway onto arterials. This application would require lane-level mapping/positioning, an infrastructure map, and associated traffic/signal status. The equipped vehicle would be alerted to significant speed deviations, congestion, and downstream signals.

Reversible lanes provide increased roadway capacity with the requirement for managing the direction of traffic flow. A proposed wrong way entry CV application would mitigate hazards associated with reversible lanes. The application would alert equipped vehicles of the current flow direction and provide alerts for vehicles travelling against the direction of flow. This application would likely require lane-level mapping/positioning accuracy with associated infrastructure map/status.

A CV pedestrian warning application is proposed to improve safety and minimize incidents associated with pedestrian crossings. The application would alert drivers to active pedestrian zones.

This application would require notification in the vicinity of pedestrian crossings and would be possible with coarse mapping and positioning accuracy. However it would be greatly enhanced with lane level accuracy.

Transit Signal Priority is proposed in conjunction with an Intelligent Traffic Signal System to help maintain a consistent bus schedule. The transit vehicles would communicate with infrastructure to help manage signal phase and timing. We believe that lane-level mapping/positioning accuracy is ideal for optimizing system functionality. Fig 13.2 shows Connected Vehicle Pilot Deployment location and associated applications at Downtown Tampa.

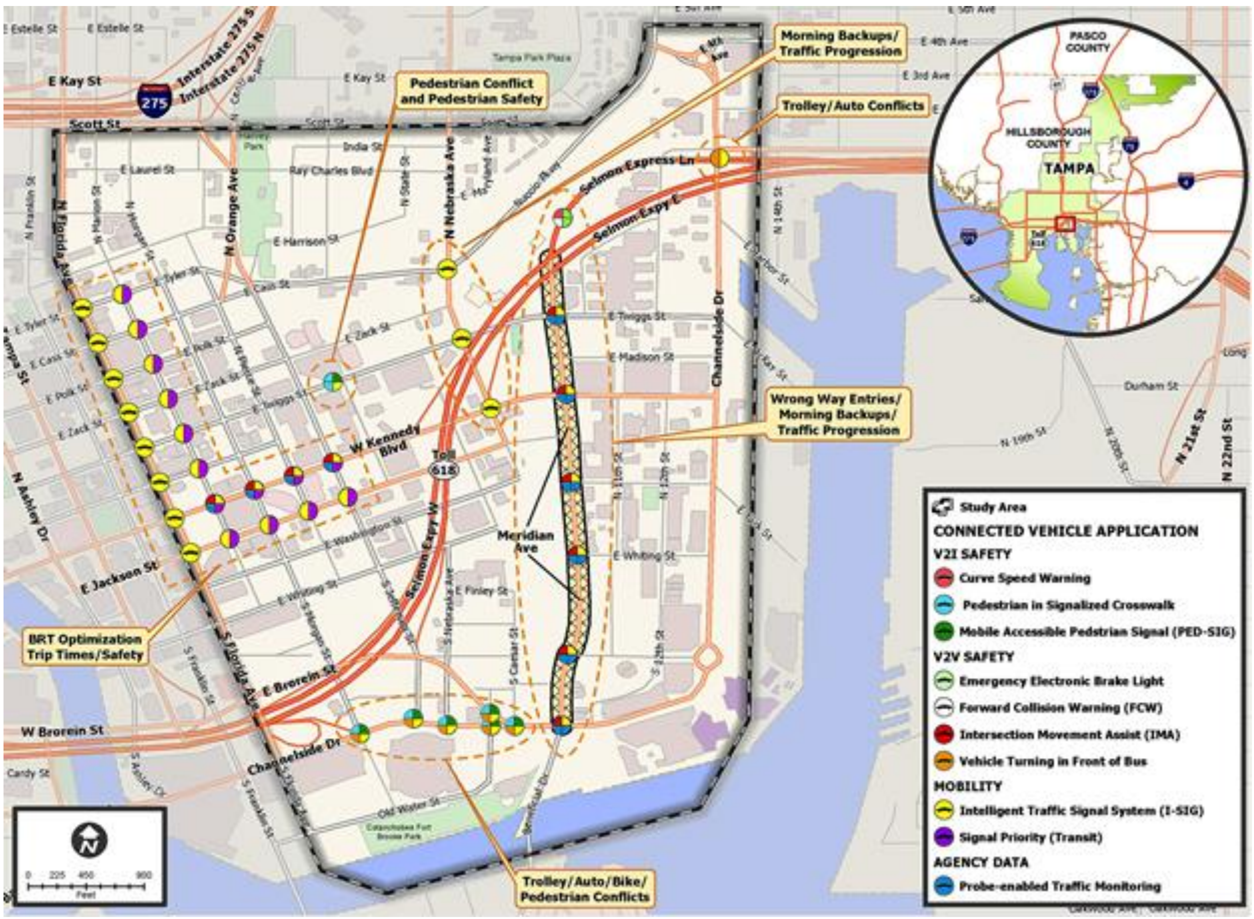

Figure 13.2 Connected Vehicle Pilot Deployment location at Downtown Tampa.

New York City (NYC)

The New York City CVPD project includes three corridors of mixed residential and commercial areas with tightly-spaced intersections typical in a dense urban transportation system. Figure 13.3 shows the three corridors. The three corridors are briefly described below:

Manhattan Grid: This is a mixed residential and commercial area with 204 intersections. The region has high accident rates (e.g., 20 fatalities and 5,007 injuries in 2012-2014).

Manhattan FDR Dr.: This is a limited access highway which excludes trucks and buses. It has short radius curves and over-height restrictions.

Brooklyn Flatbush Ave.: This roadway has an average speed of 15 mph along 35 intersections. It is a high accident rate arterial with 1,128 injuries and 8 fatalities in 2012-2014.

A B c

Figure 13.3 NYC deployment sites. **a)** Manhattan Grid. **b)** Manhattan FDR. **c)** Flatbush Ave.

The primary objective of the NYC CV Pilot deployment site is to improve the safety of travelers and pedestrians in New York City through connected vehicle technologies. The mobility and safety issues that are to be addressed are as follows:

- Discourage spot speeding;
- Reduce accidents at high incident intersections;
- Improve pedestrian safety and reduce bus related crashes on heavily traveled bus routes;
- Improve safety of for disabled pedestrians (V2P);
- Improve truck safety;
- Address bridge low clearance issues;
- Enforce truck route restrictions;
- Improve work zone safety;
- Balance mobility in heavily congested areas; and
- Reduce crashes, injuries and delays.

The targeted improvements in the highly congested region will require a high accuracy maps with coordinated status between vehicles and infrastructure. Lane-level mapping/positioning will be required for almost all of the CV applications due to vehicular density and pedestrian interaction. Generalized driver notification of roadway status can be achieved with low mapping/positional accuracies, however applications targeted at specific vehicles and driver behavior will require increased mapping/positional accuracy with corresponding infrastructure information. Another significant concern is that many of the NYC CV applications will be carried out in areas where GPS signals are blocked or suffer from a high degree of multi-path error. Both mapping and positioning methods will need to deal with these potential problems.

This brief review of CVPD programs provides initial insight into the mapping, vehicular, and positional requirements for the proposed implementations. Each application discussed has the potential to achieve higher levels of performance with improvements to positional accuracies, infrastructure maps, and related data. This review serves as a general guide with the expectation that any single CV application will undergo a thorough analysis for specific roadway conditions and system requirements.