DESIGN AND TESTING OF A TERRAIN MAPPING SYSTEM FOR MEDIAN SLOPE MEASUREMENT

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ABSTRACT

This paper presents the details of a terrain mapping system that has been used to measure median profiles. Details are presented of the system construction, design, and algorithms to process the data. The capability of the system is gauged by performing tests to compensate for vehicle orientation, tests for repeatability, and tests comparing the system with manual measurement. Results demonstrate the feasibility of using the system for median slope measurement. The advantages of using such a system as compared to traditional manual measurements are also demonstrated in practice as this system has been used to scan over 5000 miles of highways for measuring the slopes of divided rural medians. While the paper focuses on the median slope measurement, the paper can be viewed as providing a general direction for the design and testing of terrain mapping systems.

INTRODUCTION

Median geometry is critical in determining the nature of crashes that occur in a particular median, and selection of geometry requires tradeoffs: "flattened" medians may result in more crossover median crashes, while medians which are steep might cause the vehicle to rollover. The makeup in the vehicle fleet has also been changing aspects of this tradeoff, particularly in regard to rollover. In the past decades, consumers have purchased a significant number of SUVs which have a greater propensity to overturn than some of the smaller cars. The increased travel speeds and traffic volumes also call to attention the need to make possible changes to the AASHTO policy on geometric design of highways and streets, a policy which has remained largely unchanged over the last many years *(1)*. Median geometry also plays a pivotal role in the selection and evaluation of in-median corrective factors such as median barriers. In particular, the relative positioning of a median barrier inside a median directly affects the nature and number of crashes that happen on that median.

While there are a number of research projects that seek to find analytical or descriptive models relating median design to crash incidents, a key shortcoming is the lack of knowledge of median geometries on existing roadways. For example, a descriptive method would be to check for statistical correlation between the median geometry on an existing segment and the roll over and cross over crashes that have occurred therein. However, details of the median geometry within that particular segment are crucial, but often missing. Or one might use an analytical approach where in one simulates the behavior of different vehicles on an idealized slope using vehicle dynamics software packages. However, the selection of representative "idealized" slopes must be motivated by existing median geometries.

Careful study of median geometric design clearly requires collection of significant amounts of median data, a process which in turn requires an easy and reliable method to obtain the median geometry. This paper describes the design of an automated Light Detecting and Ranging (LIDAR) based terrain mapping system which has been used to collect the median profile data for the study. This automated system satisfies a number of design constraints including:

- use of only off-the-shelf items to stay within budget and time constraints,
- keeping the entire system portable so that it could be shipped to any location for rapid mapping,
- allowing the design to be fitted to any existing large sized rental SUV without causing any permanent changes or making any custom modifications to the vehicle,
- developing a simple and intuitive GUI to control the equipment when on the road ,
- designing software that can process the huge amount of data collected by the system and extract the parameters of median geometry (the adjacent slope and the opposing slope),
- testing the reliability of the system through repeated deployments in a wide range of roadway conditions,
- testing the repeatability of the system to evaluate expected variability of the data, and
- calibrating and conducting error analysis to understand the most common sources of error and accuracy versus existing methods of median measurement.

This paper presents a system developed to meet these needs, and in particular details the error and repeatability analysis aspects of the system design and evaluation process.

LITERATURE SURVEY

The most common modern practice to survey wide swaths of geometry is the use of LIDAR, and LIDAR-based terrain mapping technology has been demonstrated across a variety of applications. While aerial LIDAR technology has been present for some time and has been extremely useful in survey applications *(2)*, there are some limitations with regard to the level of detail that could be obtained by this means. For example, a recent study by Souleyrette revealed that it was infeasible to extract shoulder slope data from aerial LIDAR because of the narrowness of the shoulder *(3)*. Road vehicle-based LIDAR mapping technology is another option which typically involves collecting terrain information from

LIDARs and GPS-IMU units mounted on a vehicle. This approach has the advantage of providing the required amount of detail to accurately measure parameters like the road cross-slope, median geometry etc., but has the disadvantage of complexity in calibration and removing vehicle motion, issues discussed herein. Terrain cross-slope measurement with LIDARs was initially patented by *(4)*, cross-slope measurement by using the GPS-IMU system mounted on a vehicle was presented by Mraz *(5)*. Some of the other applications for which LIDAR based mapping has been used are in road profilometry, for measuring pavement and ride quality *(6-11)*. Active research is also being conducted in terrain mapping with the aid of LIDARs for its applications in robotics *(12-14)*.

Another method of terrain mapping is to utilize additional sensors like cameras on the vehicles. This provides interesting opportunities to fuse the information obtained from multiple sensors *(15, 16)*, and vision sensors can also be used to extract interesting features such as road conditions *(17)*, lane markers etc. An example combining vision and LIDAR sensors to obtain road and off-road features for road safety has been presented by the ARRB group *(18, 19)*.

While one may see parallels in some of the above work and the work presented in this paper, it is important to note that this is the first time a detailed study has been performed to study the feasibility of utilizing a terrain based LIDAR scanning system for the purpose of measuring off-road features such as median slopes.

DATA ACQUISITION SYSTEM

The sensors present in a typical terrain mapping vehicle are a LIDAR, a Global Positioning System (GPS) and an Inertial Measurement Unit (IMU). While the LIDAR scans the environment and provides the terrain information relative to the vehicle, the global position of the vehicle is measured at relatively long intervals by the GPS. The orientation and fine motion of the vehicle is measured by the IMU. One can observe that a particular challenge to operate mobile mapping systems is to obtain very accurate position and orientation information at very high bandwidth by fusion of GPS and IMU data, a process which requires high accuracy and high-bandwidth IMU's. Only within the past decade have such units been available at reasonable cost, outside of defense applications.

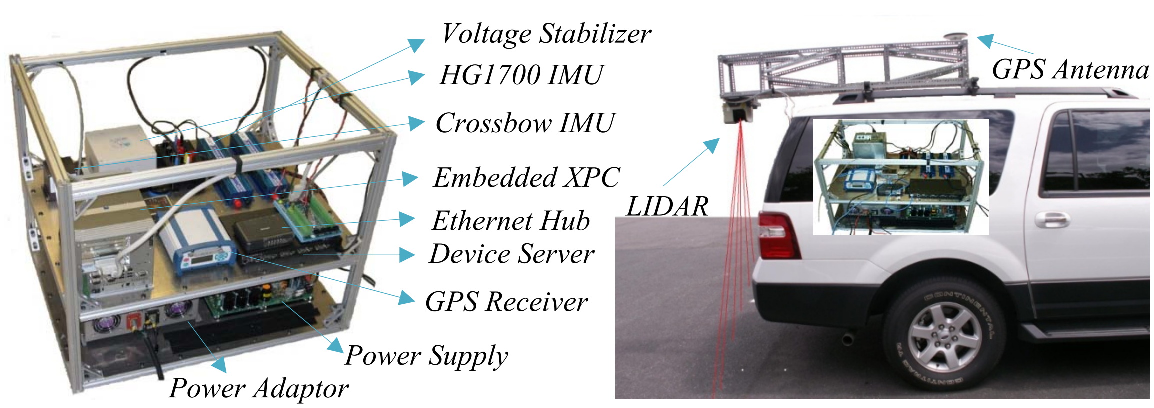

FIGURE 1: Data acquisition system

To measure information from these three sensors simultaneously, an integrated data acquisition system is needed. Such a system was developed by the Intelligent Vehicles and Systems Group at Penn State University (Figure 1), and the resulting unit is a portable instrument frame that has been designed to acquire data from multiple sensors simultaneously. The main aspects of the system including power electronics, sensor systems, data routing architecture and, the data acquisition software, are described below:

Power Electronics
A key problem with mobile data acquisition, particularly with a moderate power laser scanner, is the issue of power quality. To solve this, a complete stand-alone power system was developed alongside the data-collection system. A two-level design of the instrument frame was adopted to separate the power electronics systems from the sensor and the computer systems; the power circuitry is located on the bottom level. While details of this power circuitry are not appropriate for this paper, this system basically combines the power input from the on-board battery packs and the vehicle's alternator to provide well-regulated output independent of the highly variable vehicle power system.

GPS – IMU Unit
To obtain integrated GPS-IMU data at the rate of 100Hz, the NovAtel's Synchronized Position Attitude Navigation (SPAN) system was used, based on an OEM4 DL4-PLUS GPS receiver and the HONEYWELL HG1700 military tactical IMU. This is a defense-grade system whose position errors in the latitude and longitude data, with full satellite visibility, are about 2 meters (one sigma) and the errors in the orientation angles are 0.017, 0.02 and 0.042 degrees (one sigma) for the roll, pitch and the yaw angles respectively *(20)*. While the GPS location errors are large, the high-accuracy IMU filters the errors such that the data exhibits a very slowly drifting bias, not a measurement-to-measurement random change typical of most GPS systems. The orientation accuracies are critical in determining the repeatability and the accuracy of the terrain data mapped by using this system.

The IMU unit has been placed inside the vehicle for safety purposes, but this placement assumes that in-vehicle IMU measurements are equivalent to measurements made with the IMU rigidly mounted to the sensor. To confirm this assumption, an experiment was conducted with the IMU mounted in both locations while the vehicle is driven as close as possible to the same path. The results (figure 2) indicate a very small average difference of 0.22 degrees and a RMS difference of 0.13 degrees. This agreement is mainly because the frame holding the LIDAR is very rigid and because it is impossible to traverse exactly the same path twice. During operation, the only observable motion of the sensor relative to the vehicle is a small oscillation in the vertical direction; this would only affect the pitch angle of the LIDAR but not the roll. As seen in Figure 2, sensor placement does not significantly affect the vehicle pose estimate, and hence the slope calculations based on this pose.

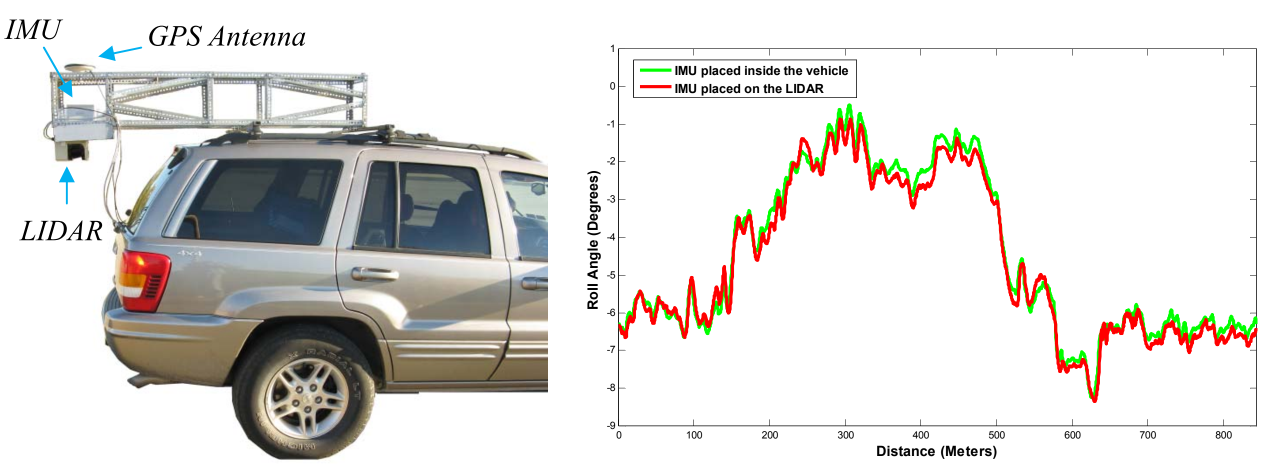

FIGURE 2: The figure shows the roll measured under two different conditions in which the IMU is placed inside the vehicle (Figure 1) and on the LIDAR (as seen in the above picture).

LIDAR Unit
The LIDAR sensor used on the system is the SICK LMS 291. With a range of up to 30 meters and accuracy of +/- 35mm, it is able to view most traversable medians, e.g. medians without obstructions to

vehicle motion such as barriers, trees, etc. It has a scan rate of 37.5 Hz, and each scan includes 361 LIDAR data points subtending an angle of 180 degrees at 0.5 degree increments. The data rate of the LIDAR corresponds to having a combined laser-GPS-IMU data packet, and hence one complete lateral scan, once every 0.8 meters of road when travelling at highway speeds (30 meters/sec).

Data Routing Architecture

The schematic in figure 3 illustrates the data routing architecture of the instrumentation setup. The setup consists of an Ethernet hub which routes data between the sensors and the data acquisition laptops. A network of sensors approach was used because it facilitates distributed processing of the data and complex command and control structures through different laptops.

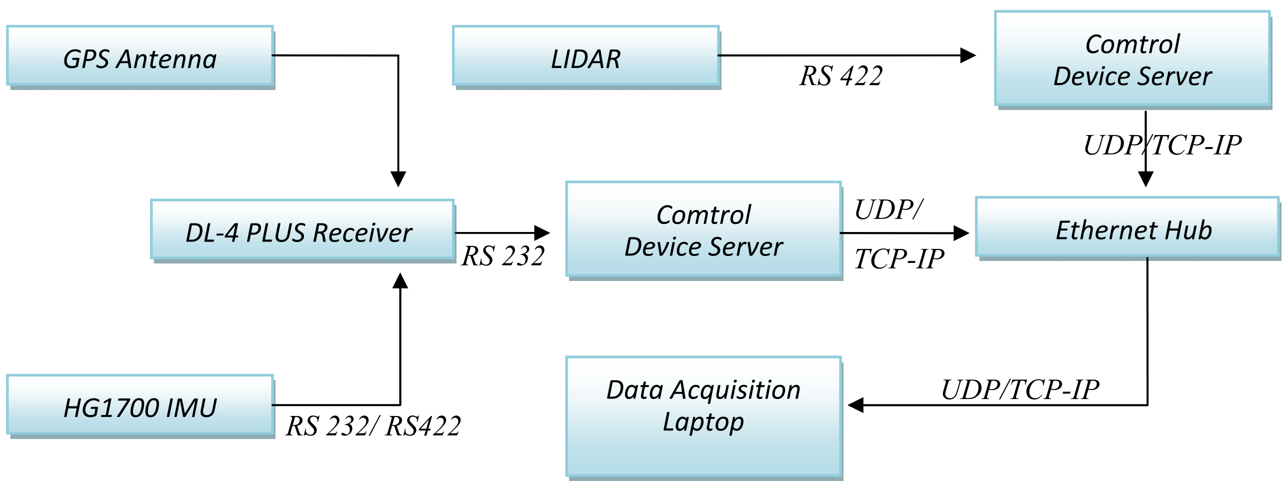

FIGURE 3: Data Routing Architecture

Software

To facilitate debugging, the data acquisition interface was coded in Simulink within a Windows environment. The LIDAR acquisition code was written in the PLAYER environment *(21)*. The field data is then post-processed to obtain the adjacent and the opposing median slopes using a code written in MATLAB.

DATA PROCESSING ALGORITHM

Each scan contains within it information that provides estimates of the adjacent and the opposing slope, but extraction of this information is not trivial. The task of the data processing algorithm can be broken down into four main parts:

Step 1) Correct the laser scan for vehicle orientation.

The LIDAR is positioned on the vehicle to look down perpendicularly to the road, orthogonal to the direction of travel, and any deviation from the perpendicularity of the laser with respect to the road must be corrected. Static offsets are initially identified through an offline calibration routine. Dynamic offsets are caused mainly by vehicle roll angle changes while on the road, pitch and yaw effects are both found to be minor. To correct for the roll, a single laser data point (r, θ) where r is the distance of the laser hit at an angle θ. The equations to transform the laser data into a Cartesian coordinate system while compensating for just the vehicle roll angle (α) and the initial calibration angle (φ) are as follows:

$$x = r\ \cos(\theta - \alpha - \varphi)$$

$$y = r \sin(\theta - \alpha - \varphi)$$

Once the coordinate data is obtained the data is re-sampled so that the final data is at regular intervals of the x coordinate. This re-sampled data is used in all subsequent analysis.

Step 2) Identify the road and road edge

As the LIDAR is setup perpendicular to the road, the LIDAR data points obtained from immediately underneath the laser are assumed to be from the road. These form a very smooth line up to the point of the road edge, and by applying regression, a road line (RL) is identified.

Once the road line is identified, the edge of the road must be inferred and because this determination is based on LIDAR data, it might not be the true road edge. A definition to arrive at the edge of the road from the LIDAR data points, given the equation for the line of the road, has been formulated by incorporating multiple thresholds as a single threshold would be very noise sensitive. The definition uses the metric $perp(\alpha, \beta) = \left|\frac{a\alpha + b\beta + c}{\sqrt{(a^2+b^2)}}\right|$ which is the perpendicular distance of a point (α, β) from a line $ax + by + c = 0$. The definition presented here has been used in computing the edge of the adjacent and the opposing slopes as well. We also define the Point of Significant Departure(PSD): Given a set of n points (x_i, y_i) where $i \in C$ and $C = \{1,2,3 \ldots . n\}$. Suppose there exists a line $ax + by + c = 0$ and there exists $j \in C$, such that j is the smallest value that satisfies

$$perp(x_p, y_p) > thre1 \quad for\ all\ j < p < j + thre2$$

Then the Point of Significant Deviation $(P.S.D)$ is defined as the point (x_m, y_m) where $m \in C$ and m is the smallest value that satisfies

$$perp(x_q, y_q) > thre3 \quad for\ all\ m < q < j$$

where $thre1, thre2$ and $thre3$ are empirically determined thresholds and $thre3$ is set lower than $thre1$. The road edge is defined as the PSD of the road line.

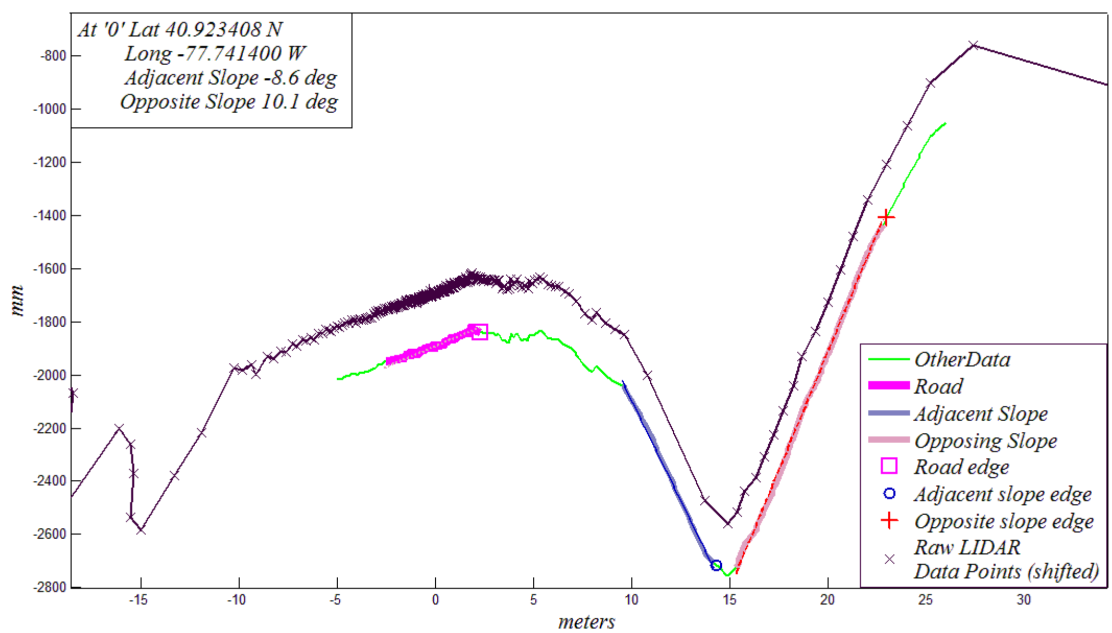

FIGURE 4: The processed scan data for a typical road cross section showing the Road, the adjacent slope and the opposing slope as idenitifed by the algorithm. (The Raw LIDAR scan data has also been shown and has been shifted up for visibility)

Step 3) Given the road edge, identify the adjacent slope from the scan and approximate it to a line and then identify the edge of the adjacent slope.

Given the road edge, a simple search algorithm looks for lines that pass through points beyond the road edge that satisfy a set of criterion. The criterions, presented below, are selected so that the search algorithm restricts its search space to reasonable limits. Each line that satisfies the criterion is characterized by the means of an optimization function which calculates the number of points whose perpendicular distance from the line is less than a threshold (25mm). Once a given number of lines are obtained, the search is terminated and the line having the optimal value, e.g. the most points fit by that line, is selected as the adjacent slope. Once this line is identified, the PSD of the line is selected as the edge of the adjacent slope.

The set of criterion used to select a line are as follows:

1) The PSD for the line is identified and the line is checked to confirm that the length of the data segment fitting this line is within reasonable limits (between 1.5m and 10m).
2) If the slope of the line isn't within a reasonable limit (between 4 degrees and 18 degrees), the line is eliminated.
3) If the perpendicular distance of any point between the road edge and the PSD for the line is beyond a certain threshold (250mm) away from the line, the line is considered to have an obstruction and is eliminated.

Step 4) Given the edge of the adjacent slope, identify the opposing slope from the scan and approximate it to a line and then identify the edge of the opposing slope.

Step 4 is identical to Step 3 and it finds the opposing slope. The PSD for the line representing the opposing slope is identified as the edge of the opposing slope. As an example of these steps, Figure 4 illustrates a raw LIDAR data scan and the data points and lines obtained after processing the scan.

TESTS AND ANALYSIS

To illustrate the ability of the IMU data to dynamically compensate for vehicle roll in the laser scan data, the data collection vehicle was rocked violently in roll while it was parked on a horizontal surface and simultaneously scanning. This is a worst case scenario because the roll amplitude is significantly higher than what would be expected by the vehicle under ordinary road conditions. The rocking motion moves the laser and consequently the horizontal surface underneath it as seen from the perspective of the laser. While the roll of the vehicle can be obtained from the IMU onboard, the change in the roll of the vehicle can also be computed by observing the change in the slope of the ground as observed by the LIDAR, since the same surface is being repeatedly measured.

Figure 5 illustrates the data collected by the sensors in this test, and the small diagram to the bottom-right corner of the figure illustrates the back-view of the motion of the vehicle as this test is performed. The close match between the blue line, indicating the change in roll as measured by the IMU, and the green line, which is the change in the slope of the horizontal surface as seen through the LIDAR, indicates the effectiveness of using the IMU for roll compensation. There is a small phase difference (e.g. delay) between the IMU data and the laser slope measurement due to data buffers and other time delays in the electronic equipment associated with the 37 Hz scan rate. This constant phase delay is easily corrected in post-processing, and with this correction, the difference between the slopes is indicated by the black line in figure 5, and the difference amounts to a standard deviation of the error of about 0.03 degrees.

The effect of the compensation on the laser scan data acquired when rocking the vehicle is clearly illustrated in Figure 6. In this figure, the raw laser data of the horizontal surface underneath the vehicle is plotted in red, the laser data with roll compensation is plotted in blue, and the laser data with roll compensation and phase correction is plotted in green. Higher accuracy might be obtained if each point within a scan were delay-corrected individually rather than the entire scan as implemented here; however, this level of accuracy was found unnecessary for the mapping task. After scan-level compensation, the maximum error in this test was about 0.2 degrees.The vertical band of the error data (green) visible at 0 meters in Figure 6 is due to a combination of the small vertical motion of the frame holding the LIDAR when the vehicle was rocked and the error in the LIDAR measurements (+/- 3.5mm).

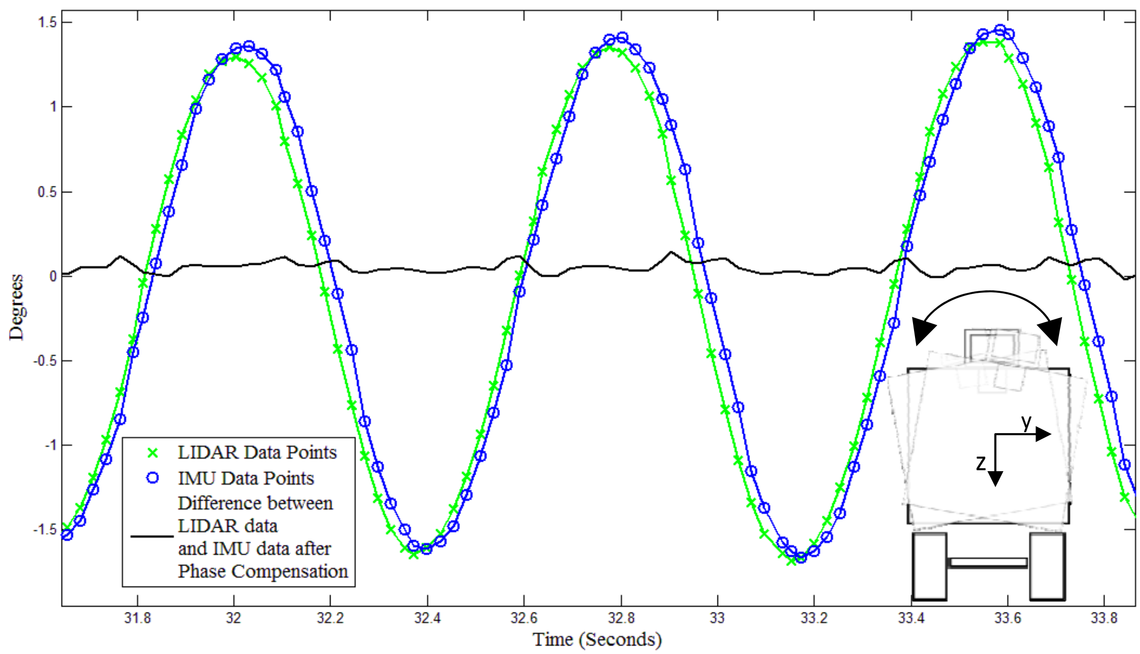

FIGURE 5: The figure illustrates the ability of the IMU data to compensate for the roll experienced by the vehicle.

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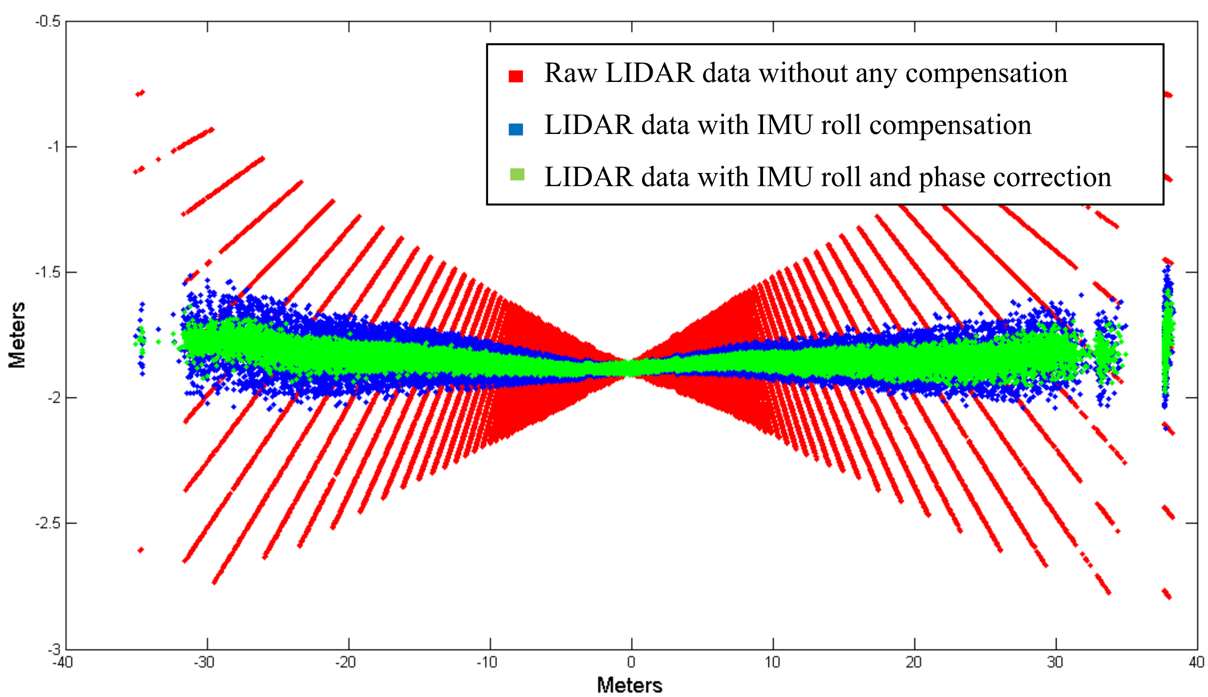

FIGURE 6: The figure shows the horizontal surface underneath the laser, under different levels of correction for the vehicle roll.

In order to test the ability of the system to measure slopes in a controlled environment, two boards (40in x 32 in) were placed as shown in Figure 7a to represent a controlled, constant-slope surface to serve as a reference for comparison of manual and LIDAR measurements. The slopes of the boards were measured manually by using a digtal inclinometer (PRO SMART LEVEL) which has a resolution of 0.1 degrees, and length of 4 feet. This manual measurement process is a low-order survey method commonly used for the measurement of median slope. While higher-order survey methods would facilitate point-to-point correspondence checking, point correspondence is not trivial to obtain from LIDAR data. Fortunately, such validation is not necessary if the LIDAR data is only used for automated median slope measurement.

To test the median scanning system, the LIDAR data was collected while driving past the boards at a spacing of 2-3 meters between the vehicle and the boards. The LIDAR slope data was then compared to manual measurements, as shown in Figure 7a. Figure 7a also compares manual and LIDAR slope measurements for an actual median, a test performed by scanning a stretch of road with the system and manually measuring the median slope at different mile marker locations with the same digital inclinometer. The controlled surface measurements showed an average error of 0.36 degrees, and an average variation of 0.62 degrees was observed in actual medians. Possible reasons for the larger variation observed in actual medians are due to the LIDAR scans hitting vegetation (grass) on the median, while the same grass is impressed by the inclinometer when the slope is measured manually. The errors have been calculated on V-style medians whose center was an average distance of 10 – 20 meters away from the vehicle, and this larger distance versus that of the controlled surfaces can also explain some of the added inaccuracy.

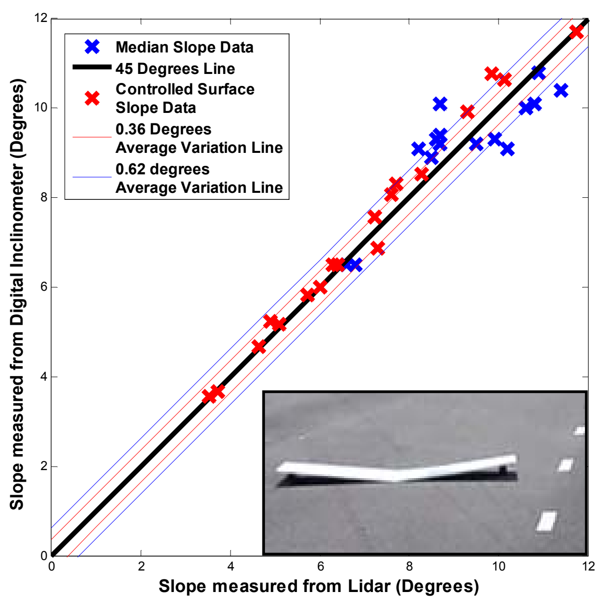

FIGURE 7a: Comparison of LIDAR slope measurements to manual slope measurements. The control surface used for the measurements is shown in the picture to the corner.

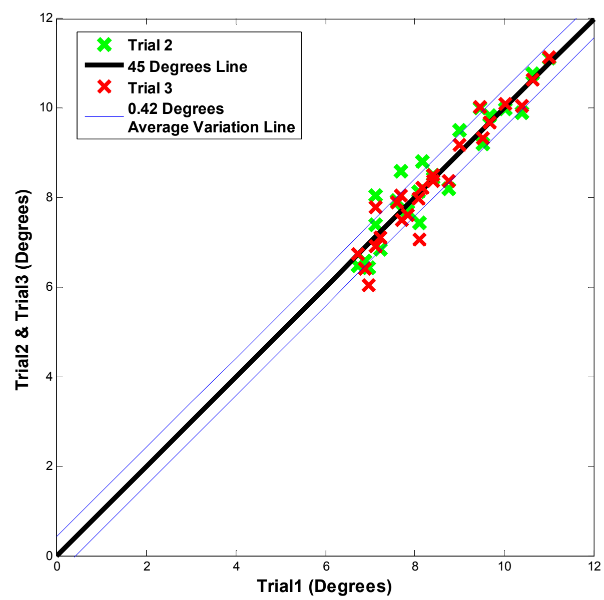

FIGURE 7b: Repeatability test for LIDAR slope measurement at different known GPS locations

Figure 7b shows results where the repeatability of the system was examined. To test the repeatability of slope measurements, the vehicle was driven at highway speeds on the same section of the road for three different times, and the slopes measured by the system in two of the trials are plotted against the first trial. An average variation of 0.42 degrees in the slope data was observed across all trials. A possible cause for the variation in the data could be that the laser scans aren't obtained from exactly the same location in each of the trials, simply due to the motion of the vehicle and uncertainty in position. The system is obviously constrained in its ability locate a particular scan by the accuracy of the GPS system and the resolution of the scans. It is interesting to note the variation of the slope in the opposing slope is 0.29 degrees, while that on the adjacent slope is 0.56 degrees.The reason for the better opposing slope measurement (despite this slope being farther away) is that the opposing slope is angled towards the laser system and thus has greater number of laser hits when compared to the adjacent slope. Figure 8 illustrates these concepts in a clear way as one can observe the shift of the blue scan away from the red and the green scans because of positional inaccuracies of the GPS system. One can also observe that the laser points on the adjacent slope are sparser than the opposing slope.

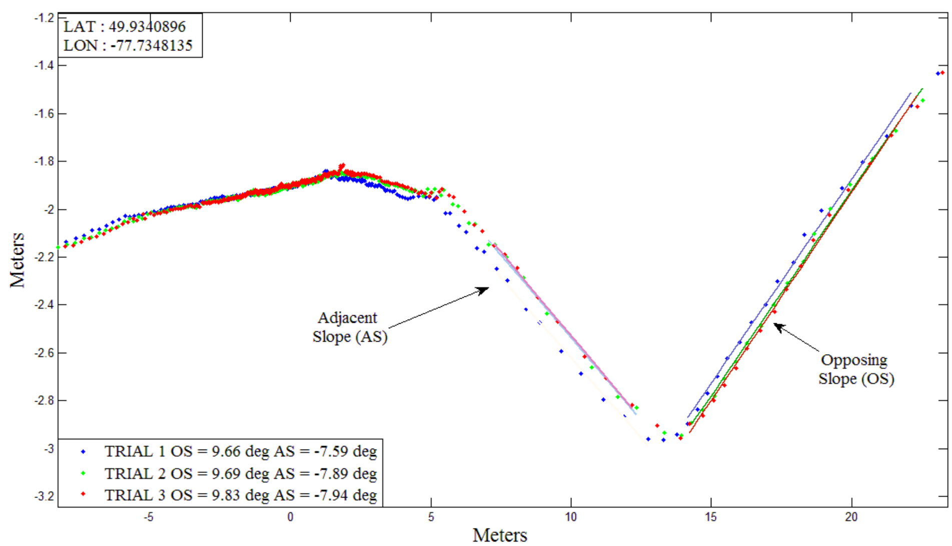

FIGURE 8: LIDAR scans obtained in three different runs at a known GPS location

VARIATION IN MEDIAN SLOPE

An interesting observation that was made during these measurements was that significant variations of the slope could occur within a single median cross section and between several scans separated by a relatively short distance. This was unexpected given that build plans generally specify a constant slope within the median sections that were scanned. Figure 9a illustrates the manual and the LIDAR based slope measurements over small sections of a single median. The manual locations were not surveyed but instead measured using a tape guide from the edge of the road, and hence have lateral position error visible in the graph. Even so, the graph clearly shows that a significant variation in slope is possible depending on where one placed the manual slope meter. Hence, the manual measurement system typically used for measuring the median slope might not be very repeatable. The source of this problem is that a hand measurement usually records slope data at only a few points and with a relatively short span (1 meter) of the entire slope. This large source of potential error is not evident until one compares to the LIDAR based measurement that uses the entire slope to characterize the median.

The LIDAR scans for road sections have also revealed that there could be a significant variation of the median slope even across a small stretch of a road. This is illustrated in Figure 9b. By providing a vastly larger amount of data, one can conclude that the LIDAR system might present a clearer picture of the median than conventional manual measurement. Further, the scanning can be done at highway speeds without any obstruction to the on-going traffic.

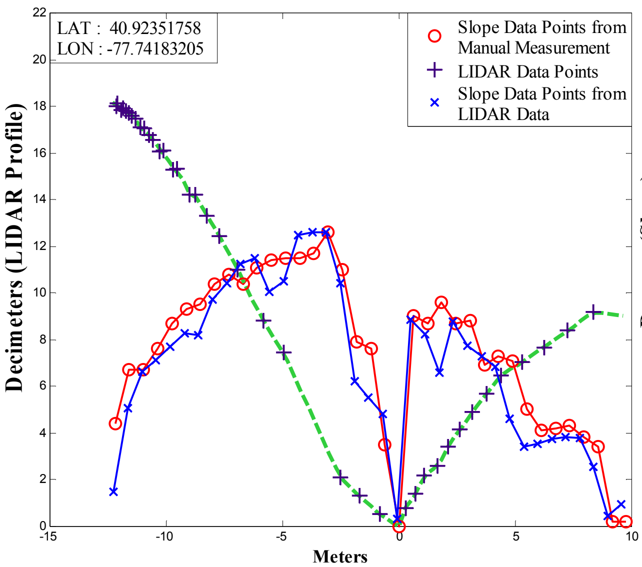

FIGURE 9a: The variation of the slope along the profile of a median cross section measured manually and with LIDAR

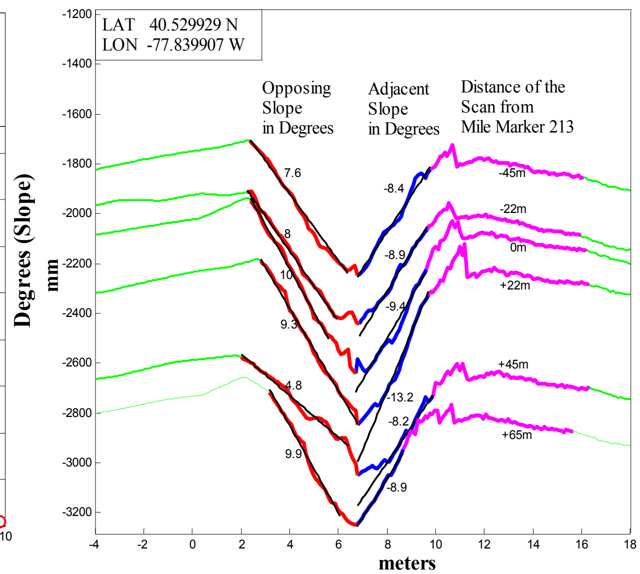

FIGURE 9b: The plot illustrates the variation of the median profile along a distance of +/- 50 meters around mile

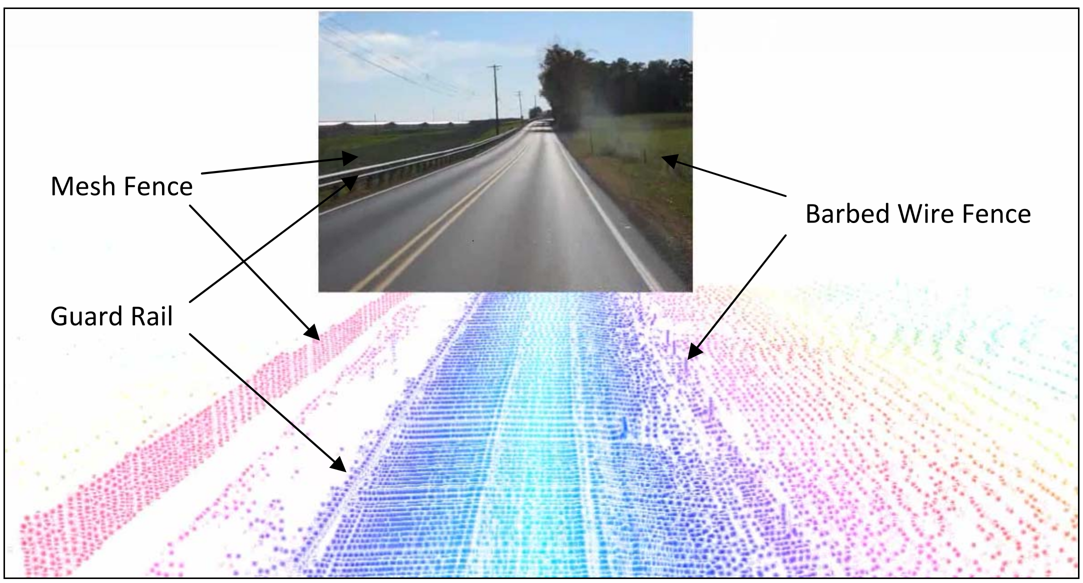

FIGURE 10: 3-D visualization of LIDAR point cloud, taken at Foxhill Road westbound, State College, PA.

CONCLUSIONS AND FUTURE WORK

This paper presents a LIDAR-based scanning technology for measuring the median slope and compares it to manual measurement techniques. The results indicate accuracies on the order of 0.36 degrees in controlled tests with fixed surfaces, and 0.62 degrees for tests on actual medians. Repeatability was found to be approximately 0.42 degrees for actual median scans. The compensation of vehicle motion was found to be quite good, and independent of whether the IMU was mounted on the LIDAR sensor or mounted within the vehicle. Using tests where the vehicle was aggressively rocked back and forth, the error due to compensation for vehicle motion was found to be 0.03 degrees

The system is very cost effective with an approximate expense of $1/mile (2250 data points/mile/minute) to take measurements as compared to manual measurement which has been estimated to cost $96/mile (5 data points/mile/100 minutes), an estimate from past work by researchers at Penn State. This 100 times cost savings agrees with estimates from other researchers *(22)*.

Thus far, this particular system has been used to scan more than 5000 miles of road in order to extract slopes from divided rural median highways. A number of design modifications have been made in the system over the past year and the final version and algorithms presented in this paper are a product of this extensive field testing.

A simple way to avoid the inaccuracies in measuring the adjacent slope as compared to the opposing slope would be to measure the slope of the road from either side. Currently work is being done to fuse such data in 3D. Additionally, this also enables one to visualize the terrain information in a 3 D environment, and Figure 10 shows an example in this regard for a road segment with many interesting near-pavement features.

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