Asphalt production, paving and compaction techniques

HIGH RESOLUTION MULTI-LANE ROAD SURFACE MAPPING USING 3D LASER PROFILERS FOR 3D PAVING AND MILLING PROJECTS

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Abstract

Road Transportation and Public Works Departments (DOTs) typically perform annual pavement condition inspections to record cracking, rutting, smoothness, etc., which serve as an important input into Pavement Management Systems (PMS) software. Road surface defects are analysed by PMS software in order to model the deterioration of pavements and to make budget and performance-based recommendations regarding which roads to maintain, what maintenance treatments to apply, and when to apply them. Increasingly pavement condition data are captured using high-speed 3D lasers which acquire the 3D shape of the road surface. These technologies automatically analyse 3D scans in order to detect and quantify pavement defects. There is an untapped opportunity to enhance and repurpose this data in order for it to also be used for the design of reconstruction projects. In the past, designers have relied upon traditional survey to capture elevation data for volumetric estimates as well as Preliminary and Final Designs; however, traditional surveys require lengthy road closures, are costly, limited in resolution, and present dangerous working conditions for survey staff. Alternatively, 3D pavement condition survey scans can be enhanced through the addition high-accuracy Latitude, Longitudinal and Elevation data (via “blended” GNSS + INS systems). When further processed, these 3D scans can provide elevations with comparable accuracy and repeatability to traditional methods, but for a significantly larger number of measurement points (as dense as a 1mm x 1mm grid), without the need for a road closure, in a fraction of the time. Thus, repurposing these data presents a significant opportunity for DOTs to reduce their survey costs, minimize traffic interruptions, decrease turnaround times, improve staff safety, reduce milling, paving and compaction quantities, and deliver superior road surfaces. This paper explores the necessary hardware and software as well as the steps required to generate high-accuracy elevations from 3D pavement scans. Importantly the accuracy and repeatability of this new method is thoroughly evaluated through direct comparison to a large network of surveyed control points.

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1. INTRODUCTION

Road Transportation and Public Works Departments (DOTs) typically perform annual pavement condition inspections which serve as an important input into Pavement Management Systems (PMS) software. Road surface defects (cracking, rutting, smoothness, etc.) are analysed by PMS software in order to model the deterioration of pavements and to make budget and performance-based recommendations regarding which roads to maintain and how and when to maintain them. Increasingly these data are captured using high-speed 3D lasers (such as Pavemetrics' LCMS-2) which acquire the 3D shape of the road surface in order to evaluate its condition [1] [2] [3] [4] [5] [6].

Once it is determined that the road condition has degraded to the point that it needs to be rehabilitated and resurfaced, an elevation survey is required. In fact, road surface elevation data plays a critical part throughout the entire process of rehabilitating a road.

Elevation data are used during the cost estimation phase in early project programming when the Preliminary Design estimate is prepared. During the Preliminary Design stage, Civil Engineers often make use of planning tools like AASHTO's Trn.sport Software in order to perform Volumetric Estimations and to generate a "Length-Width-Depth" (LWD) cost for prospective projects. LWD estimates include the volumes of material that must be removed, put in place and compacted.

Later in the life of the project, during the Final Design stage, elevation data are used by engineers as an input into 3D CAD road design software in order to create Preliminary and Final Project Designs.

During the Construction phase, elevation data are used as an input to laser tracking total stations in order to control 3D pavers and millers. At the conclusion of construction, elevation data plays a role in evaluating whether the new road surface conforms to the geometric design and whether it meets smoothness requirements.

Traditionally the capture of road elevation data relied entirely upon the use of survey crews. While accuracy can be quite high, the process of capturing elevations can require a lot of manpower, is time consuming, requires lane closures and results in a relatively small number of points per kilometre of road with which to perform all of the tasks from early project planning through to construction.

This paper explores an alternate approach which leverages existing 3D laser technology utilized by DOTs to measure the condition of already in-service pavements. Typically, these laser systems capture "relatively-referenced" 3D profiles of the roadway in order to evaluate pavement condition based-on surface distortion. However, there is often no connection between these "relative" 3D profiles and real-world locations. This new approach involves the addition of high-accuracy blended GNSS+INS positioning systems, as well as specialized software, to map the absolute position of 3D profiles in real-world coordinates.

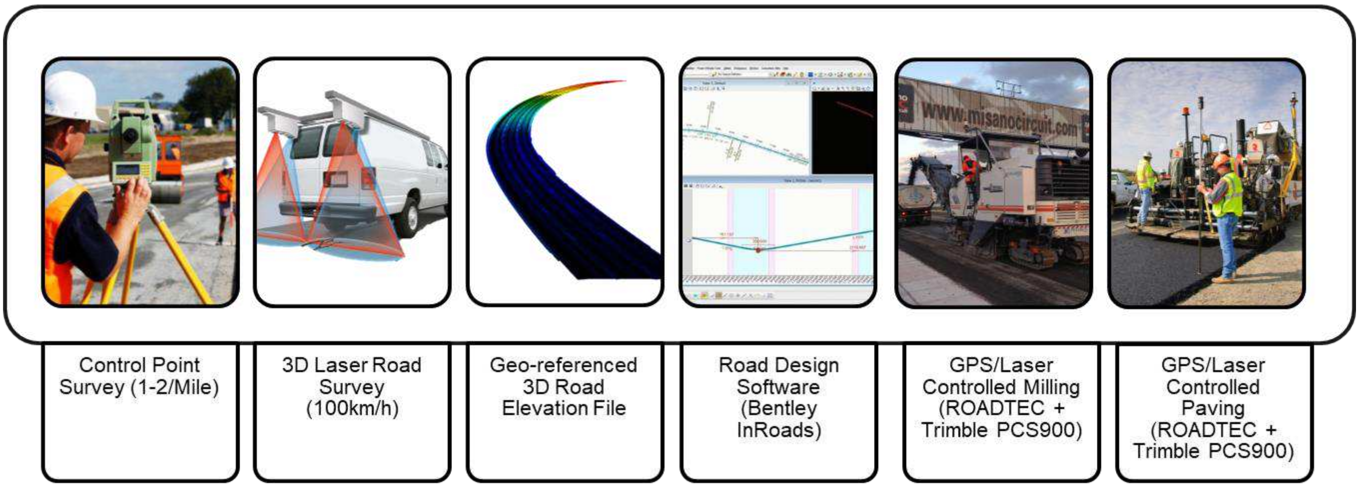

Figure 1: 3D Pavement Scanning Process

The result is effectively a fully surveyed pavement surface, at similar accuracy to traditional survey, captured at speeds up to 100km/h, without the need for lane closures or to make a separate data collection run aside from the existing annual pavement condition survey.

2. SYSTEM CONFIGURATION

The LCMS-2 3D mapping solution operates under the principle of Laser Triangulation and utilizes two 3D laser profilers to acquire 4,000-point 3D transverse profiles of a road lane up to 4m wide. These sensors can operate at profile rates as high as 28,000Hz, allowing the acquisition of a transverse profile at 1mm intervals at speeds up to 100km/h. Data capture rate of the LCMS-2 is more than 100,000,000 points per second which is approximately 100 times that of comparable LiDAR sensors which typically produce only a maximum of 1,000,000 points per second.

Figure 2: Photo of the 3D laser profilers and GPS Antenna on the survey vehicle

For a standard pavement condition application, the 3D point clouds from the LCMS-2 are divided into 4m x 10m scans that are geo-referenced to an accuracy of approximately 60-100cm. These point clouds are processed by automated algorithms in order to extract road surface distresses such as cracks, ruts, pot holes, aggregate loss and surface texture. Reported pavement defects therefore have real-world positional accuracy of approximately 1m.

To utilize these 3D point clouds for a road survey application (in addition to their primary application) the accuracy must be significantly increased and the geo-referencing must extend to individual points in the cloud as opposed to 4m x 10m scans. Additionally, the scans must be corrected for roadway geometry, vehicle and suspension motion, driver wander and vibrations.

2.1. Additional Hardware and Software Required for Surveying

A high-accuracy blended Inertial Navigation System (INS) consisting of a GNSS, a Wheel Encoder (a “DMI” for measuring linear distance), and Inertial Measurement Units (IMUs), must be added along with software to map calculated GPS coordinates to individual points.

The INS combines GNSS positional data and dead-reckoning data (via the IMUs) in order to provide the most accurate position possible as an input to the 3D sensors. GNSS and IMU technology are complementary in that dead-reckoning can be used by the INS to continue to provide a position when GPS signal is lost with the understanding that the accuracy of the solution will degrade over time (a phenomenon known as “drift”). However, when GPS signal is regained, the INS can automatically correct the positional solution based on the now known position.

Figure 3: Photo of Wheel Encoder and INS Including GNSS Receiver, Antenna and IMU

3. SYSTEM CALIBRATION

System calibration is required to map the different physical locations and coordinate systems of the 3D laser surveying system’s components (GNSS, IMU, Laser Sensors and DMI) on the survey vehicle into a single final reference system (GPS). The purpose of the calibration is to establish the digital model of the position of 3D sensors on the vehicle versus the position of the other elements (GNSS, IMU, DMI).

The calibration process consists of four steps:

- Physical measures of the distance between each system component (the “lever arms”),
- Scanning of a calibration object,
- “Stop-and-go” data collection runs,
- Calibration loops.

3.1. Physical measures of the different level arms between each system sensors

During this step, the physical distances between system components are measured and recorded.

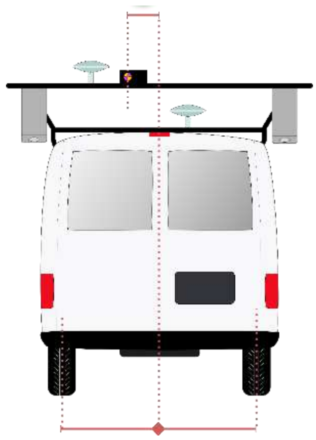

Figure 4: Measuring “Lever Arms”

3.2. Sensor-to-Sensor Calibration

During this step a precisely-dimensioned object is placed on the road surface and the inspection vehicle is driven over the top of it such that the laser scanners capture a scan of it. This step is used to solve the ambiguity between the left and right sensors. The overlap zone between the sensors over the reference object will be used as a reference surface and adjustments will be made in the processing software to account for differences in each sensor’s orientation and mounting position. The end result of this step will be to produce a single combined point cloud from the two sensors which perfectly reproduces the shape of the calibration object.

Figure 5: Scan of the Calibration Object

3.3. "Stop-and-Go" Calibration

The “Stop and Go” calibration measures acceleration in three axes (X, Y and Z) while the vehicle is both stationary (the “stop” part of the calibration) as well as while it is accelerating (the “go” part of the calibration). This information is used to determine the orientation of the sensors relative to gravitational force.

3.4. Dynamic Calibration

This final step in the calibration is used to compensate for the natural degradation of positional accuracy due to IMU drift over time. This step requires three special calibration runs to be performed while driving across the calibration object. Data captured is used to fine-tune the biases of the gyroscope and accelerometres that are contained in the IMU in order to ensure a perfect match of the scans from the two sensors when combined.

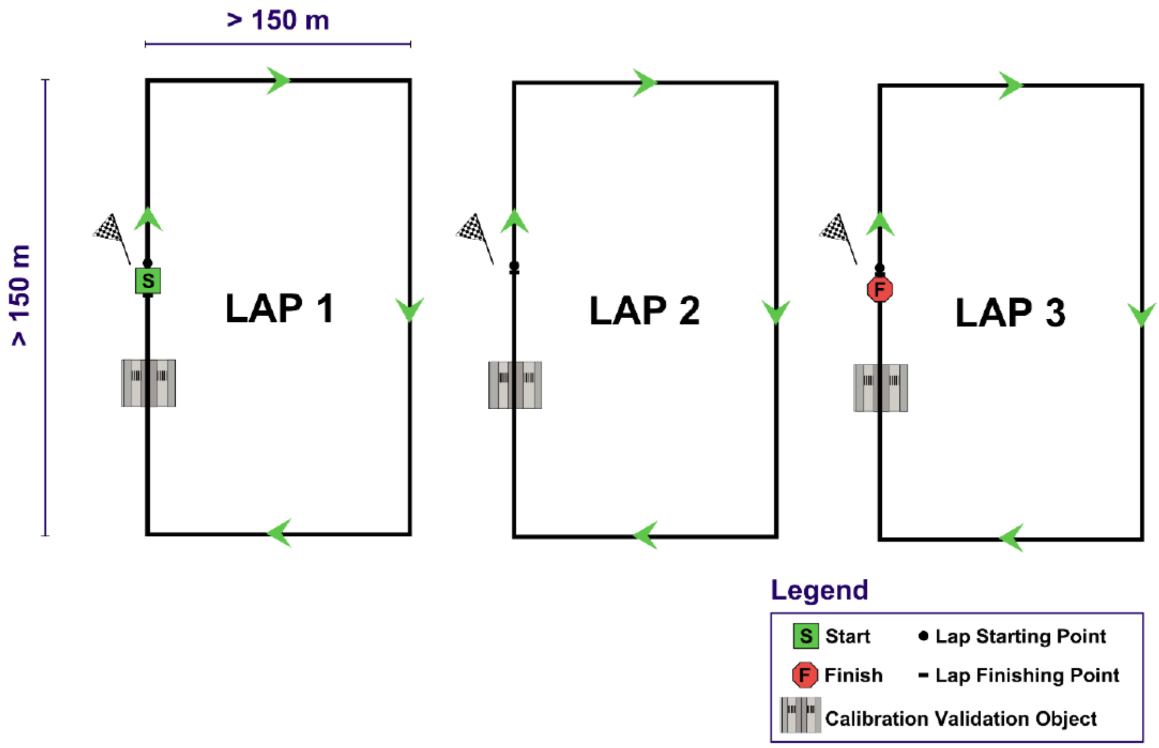

Figure 6: Calibration “loop” runs

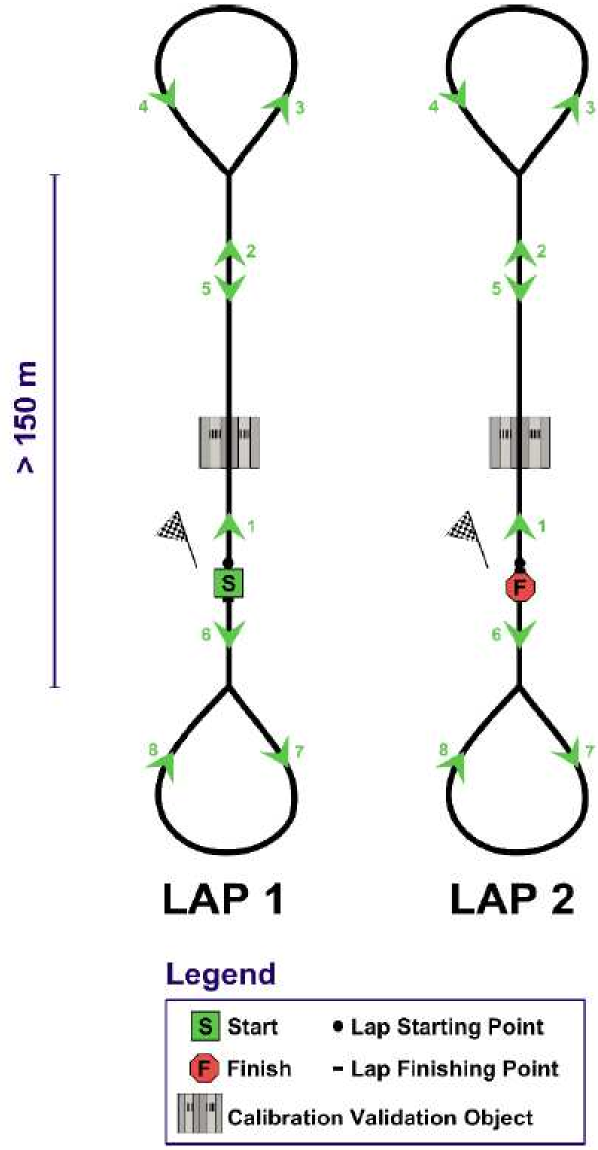

Figure 7: Calibration "Back Thru loop" runs

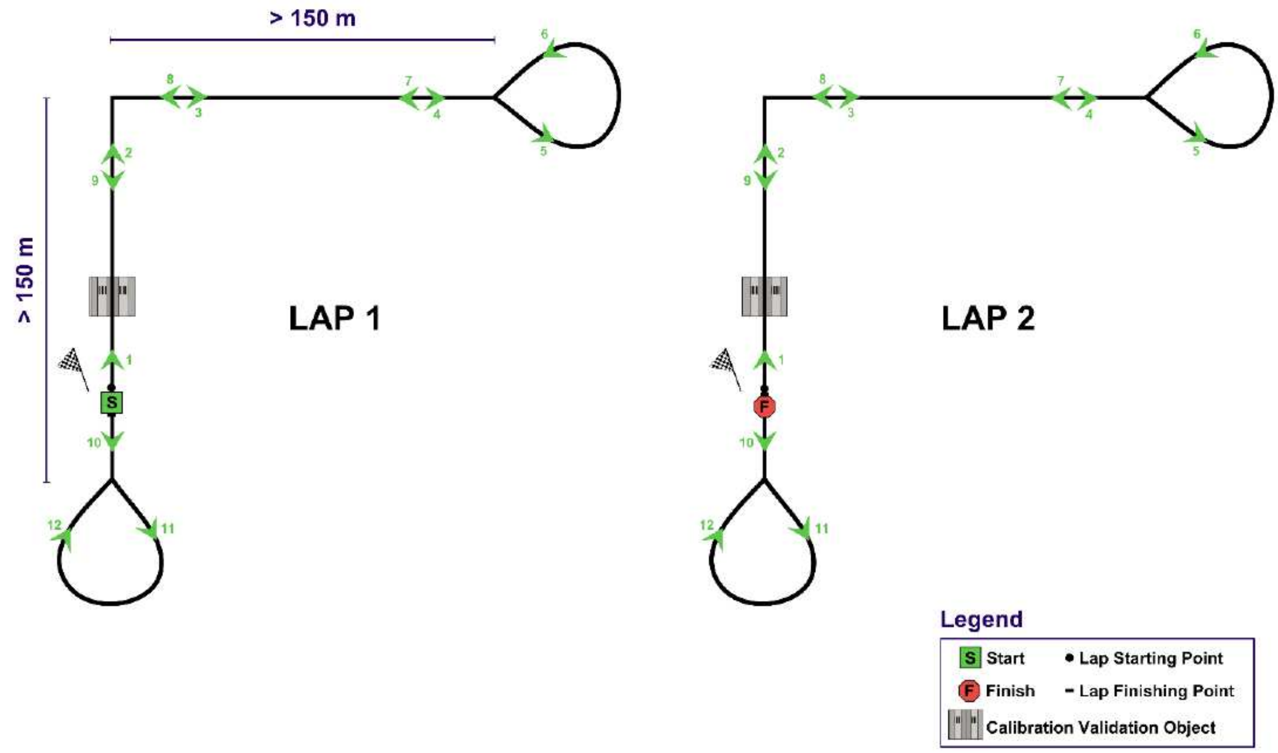

Figure 8: Calibration "Right angle loop" runs

4. DATA CAPTURE AND PROCESSING

4.1. Mapping Vehicle GPS Coordinates to Laser Scan Points

Once 3D scans have been captured in the field and GPS data have been post-processed (if desired), specialized software is used to translate the GPS positional coordinates of the vehicle to the individual coordinates in the 3D point cloud. There are three steps in this process:

1. Post-processing GPS (and optional step),
2. Developing the vehicle navigation solution,
3. Applying "tie points" to "stitch" (merge) left and right sensor 3D scans,
4. Aligning the stitched 3D surface with ground control.

4.2. Post-Processing GPS Data

While the onboard INS is capable of providing a highly-accurate stream of GPS data in real-time, the positional solution can be further improved through the use of a GPS Base Station within thirty-fifty (30-50) kilometres of the data collection site.

While in the past this task would have required the setup of a dedicated base-station for a project, many countries have large networks of already established base stations which the user can obtain data from for free, or for a reasonable fee. For example, in the United States, the National Geodetic Society (the NGS) Continuously Operating Reference Stations (CORS) network provides free base station data across the country.

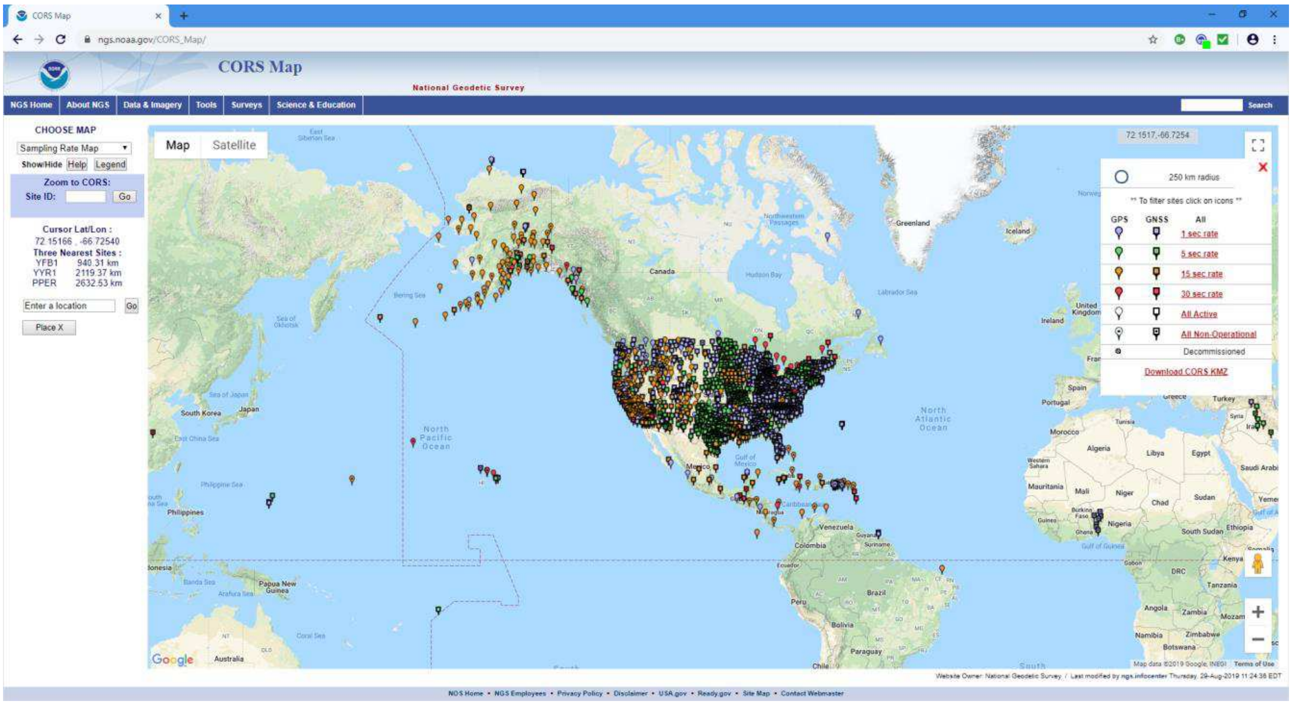

Figure 9: USA CORS Network

Post-processing of the real-time GPS positional solution using base station data can significantly improve the overall accuracy of the final positional solution which is key for road survey applications. This post-processing is normally performed using software included with the INS hardware.

If there is no post-processed data available, it is always possible to produce a 3D surface using the real-time GPS data recorded in the files during the data acquisition; however, accuracy and repeatability will be affected.

4.3. Turning 3D Pavement Scans into Ground Survey Data with LDTM Software

During this step 3D scans from the field (in FIS format) are imported into the LDTM software along with the real-time or post-processed GPS track of the inspection vehicle.

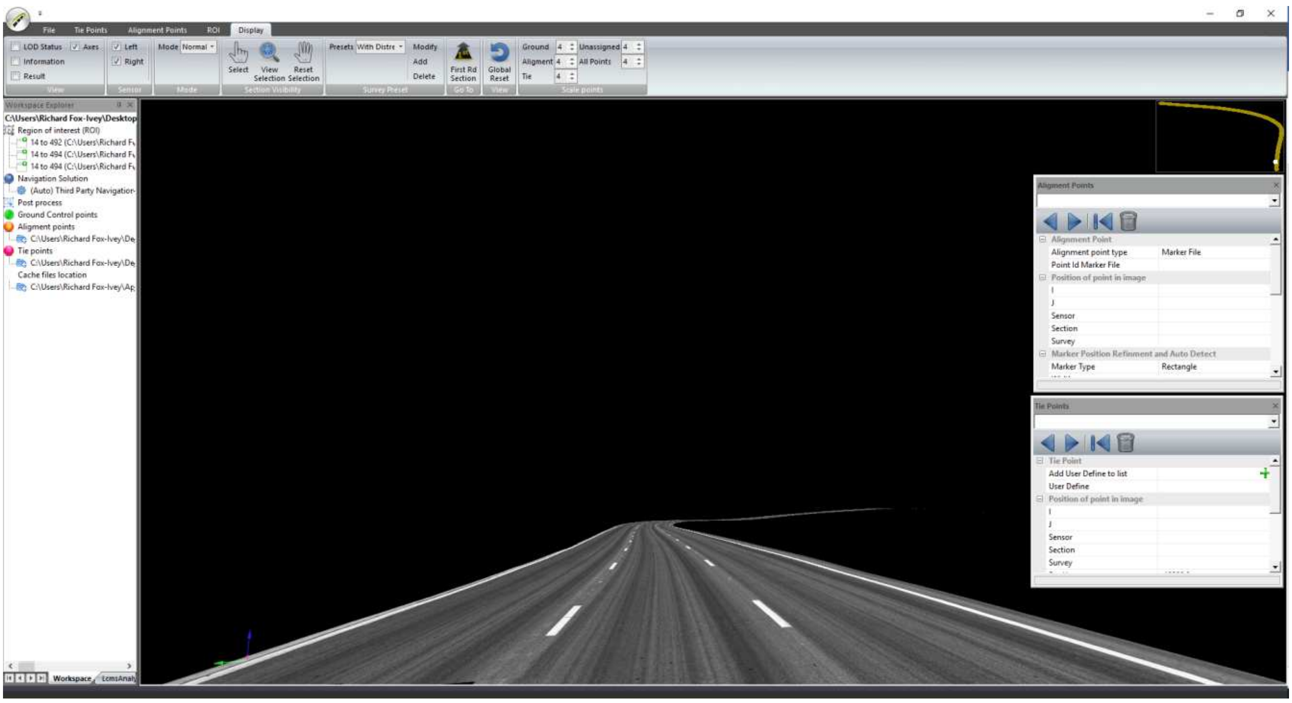

Figure 10: LDTM Software

The LDTM software application supports the import of 3D pavement scans, post-processed GPS data, and ground control coordinates. Available outputs include LAS files containing the ground survey elevations as well as BMPs containing a high-resolution view of the pavement surface.

Before exporting survey data, the software allows the user to scale the resolution of the data in order to reduce point densities as desired; very detailed maps can be generated at resolutions of 100 x 100mm for example. Points are decimated to fixed resolutions (x,y) and the vertical (z) position is filtered to avoid reporting the elevation of loose aggregate or the pavement surface or of a pavement defect such as a crack.

3D surface models outputted by LDTM can be used by engineers to design better roads [7] [8] [9] compared to traditional survey and lidar. Traditional surveys typically only provide three (3) elevation points every twenty (20) metres longitudinally with which to design surfaces. Likewise, lidar-based solutions are often limited in terms of accuracy; compared to traditional survey and the LDTM solution, lidar-based elevations are often only accurate to a few centimetres.

The increased resolution of the LDTM solution allows the user to better optimize the quantity of material that needs to be carried into and out of the construction site. The use of LDTM models and automated laser-controlled milling machines that adjust the height of cutting heads, can be used to correct the road's longitudinal profile (compared to fixed-depth milling). 3D controlled Pavers can also benefit from this enhanced technology by creating variable thickness asphalt layers designed for smoothness and longer life due to reduced axial dynamic loads imparted by heavy vehicles.

4.4. Developing the Navigation Solution

This step is performed using the LDTM software and transfers the GPS coordinates of the vehicle, compensated for attitude and vehicle motion through the earlier calibration process, to individual 3D points in the laser scan. At this time the accuracy of individual elevation points in the reported surface will be at the same level as the accuracy of the reported vehicle position.

With the application of a high-accuracy INS and the use of post-processed GPS data, this solution will be in the range of a couple of centimetres accuracy (however it will be significantly enhanced in later steps).

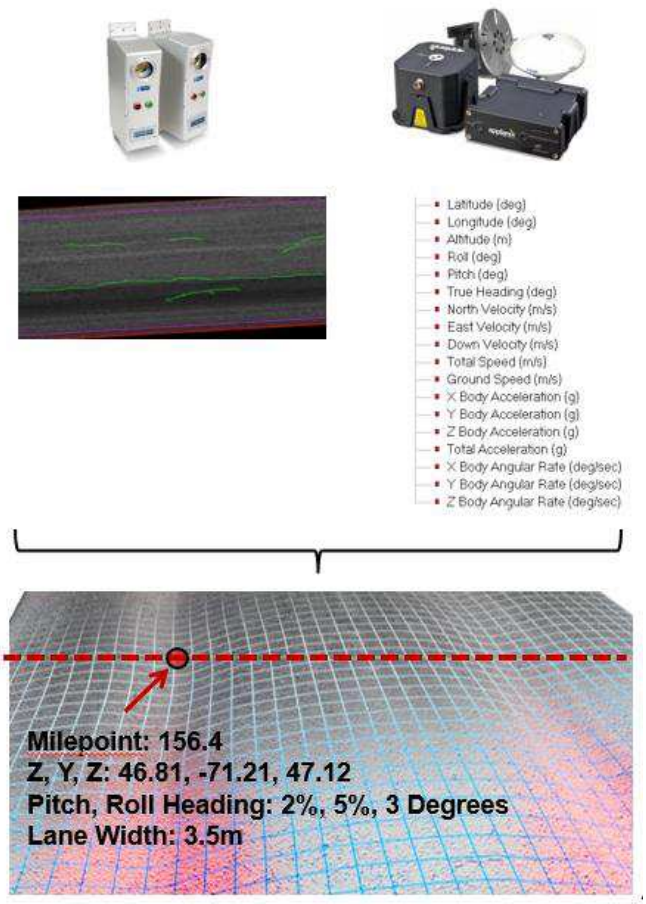

Figure 11: Location system components

4.5. Combining Multiple Adjacent 3D Scans into a Single Surface

When surveying wide surfaces, such as runways or multilane highways, it will be necessary to make multiple 4m wide over-lapping data collection scans. Following field work, these scans must be merged together in order to create a single final 3D surface to replace a traditional survey.

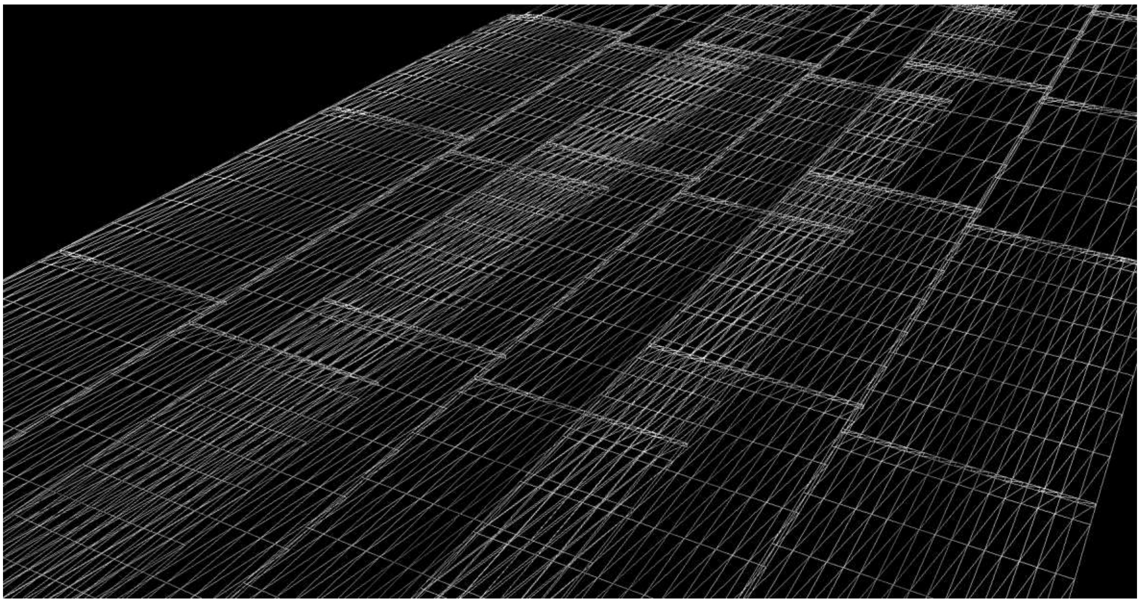

Figure 12: Overlapping 3D Scans (prior to Stitching)

The process of merging multiple scan passes is referred to as “stitching” and it is an automated process wherein a computer algorithm searches for common features between adjacent over-lapping scans. Common features can include anything that is visible on the surface of the pavement (e.g., a pavement marking or an embedded reflector) or something with a unique 3D profile such as a pavement distress (e.g., a crack, or a construction joint).

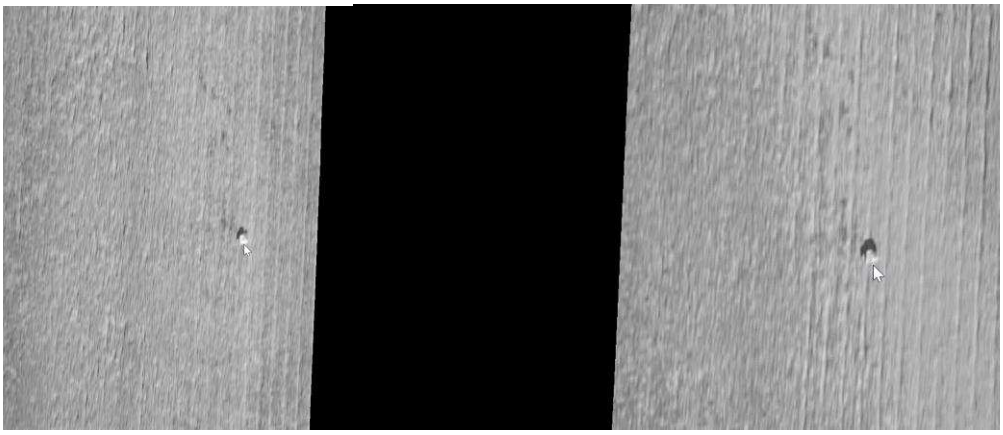

Figure 13: Tie point example

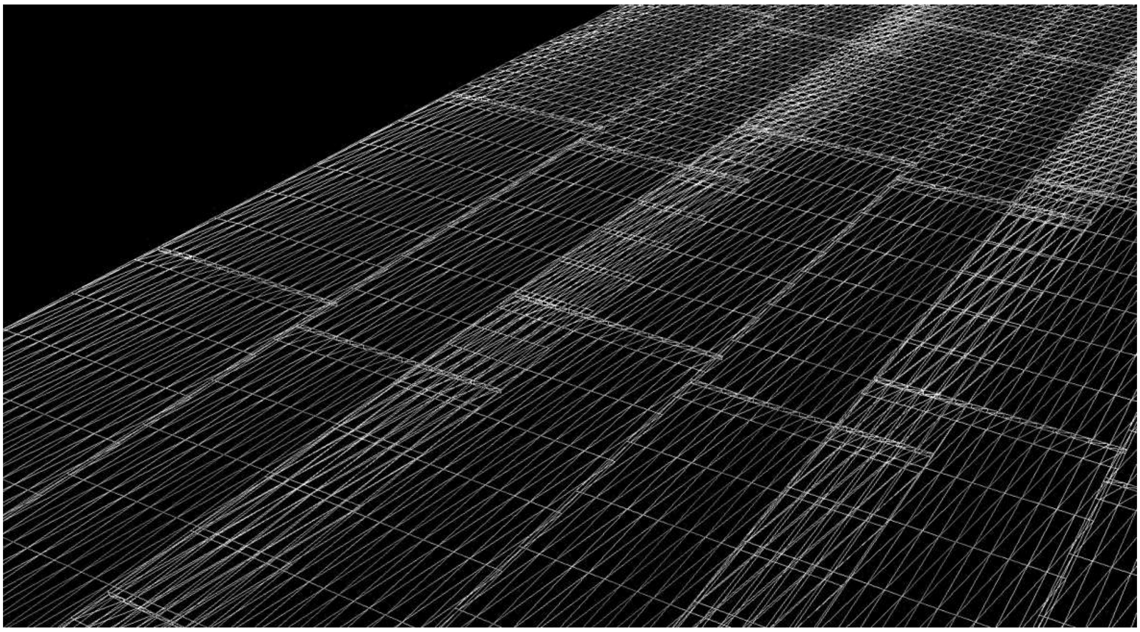

Figure 14: Overlapping Scans (Post Stitching)

4.6. Aligning the 3D Surface to Ground Survey

This is an optional step that can be used to further refine the accuracy of the Navigation Solution by "tying" it to local surveyed control points. This step is recommended for Final Project Surveys which will be used during the construction phase, but could be omitted if the data are being used as a preliminary survey or for a project estimate.

As opposed to a traditional road resurfacing survey that would involve hundreds or thousands of surveyed points per kilometre across the width of the pavement, this process only requires one control point at the very edge of the pavement surface per kilometre.

During this step, circular reference targets are painted at the start of each kilometre on the pavement shoulder, and the Latitude, Longitude and Elevation of the centre of the targets are recorded using a Robotic GPS Total Station. This approach avoids the need for a full lane closure and allows survey staff to work from the safety of the road shoulder.

Figure 15: Ground Control Target

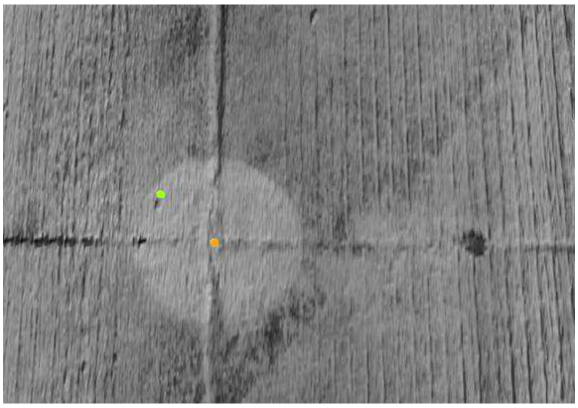

Figure 16: Unaligned Target Centre (green point) and Aligned Target Centre (Orange point)

The Latitude, Longitude and Elevation of the targets can then be entered into the LDTM software and the 3D surface aligned accordingly. This final step creates a 1mm x 1mm elevation survey of the pavement surface with a vertical accuracy matching traditional methods (approximately 3-5mm for elevation). The final surface can be exported using the non-proprietary LAS format to facilitate direct import into 3D CAD road design applications such as AutoCAD®Civil 3D®.

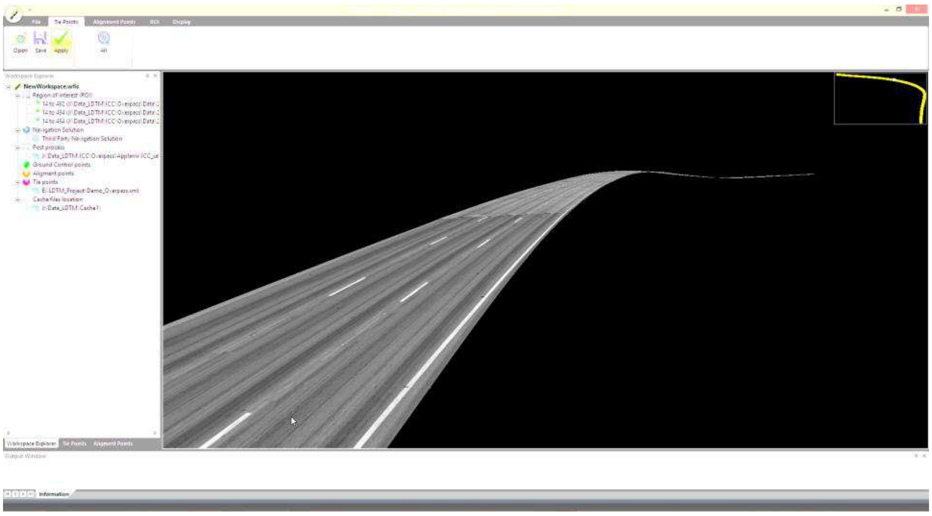

Figure 17: Final 3-5mm Absolute Elevation Accurate Surface (containing three lanes and a bridge deck)

5. ACCURACY VALIDATION

In order to establish the absolute accuracy of the system, a pavement elevation reference site was developed which included more than five-hundred (500) reference points. Reference points were created by painting circular targets at five-hundred separate locations spread throughout the test site and then surveying the centre of each target a total of three (3) times using a Robotic Total Station and a laser level.

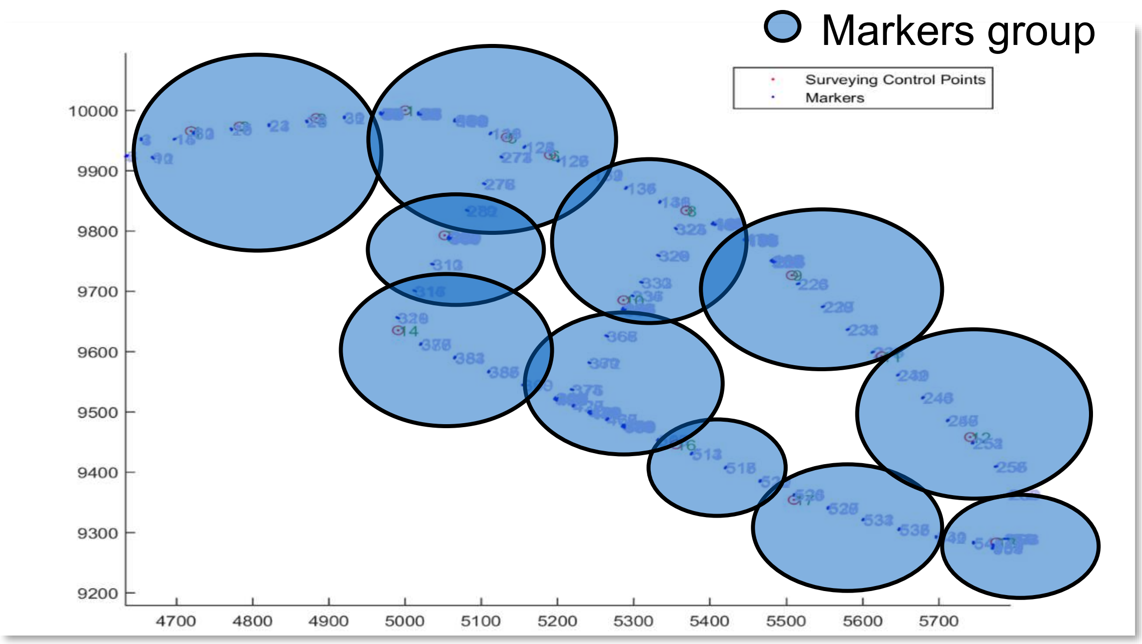

Figure 18: Reference site

Repeat measurements were used to minimize the error of reported elevations in order to create a “ground truth” that was as accurate as possible. Using this method, the absolute elevation accuracy of the reference points was determined to be between two and five (2 and 5) milimetres.

Following the generation of reference points, a survey vehicle equipped with the LCMS-2 sensors (and associated hardware) was driven a total of twelve (12) times through the reference site. Repeat runs were used to ensure a thorough evaluation of the average accuracy of the system compared to ground truth as well as to determine repeatability.

5.1. Aligning the 3D Surface to Ground Survey

As discussed prior, aligning the 3D points to ground survey is an important step in maximizing the accuracy of the final surface. Generally-speaking the more alignment points that are utilized, the greater the accuracy of the final surface. However, as alignment points require the deployment of traditional survey crews and therefore impose the very limitations outlined in the problem statement, the objective was to limit the use of alignment points to as small a number as possible.

Of course, it should be noted that the capture of a few survey points per kilometre for this method still represents an enormous reduction in cost, time and impact to the traveling public when compared to traditional methods.

5.2. Generating Results

Two standards for alignment point spacing were evaluated in order to determine their impact on the accuracy of the final solution. The first approach utilized an alignment point spacing of three-hundred metres (300m; roughly three per kilometre) and the second approach utilized a spacing of eight-hundred and fifty metres (825m; roughly one per kilometre).

For the 300m scenario, the average error in elevation measurements across twelve (12) inspection runs for the LCMS-2 survey was 2.5mm for elevation (Z) when compared to “ground-truth.”

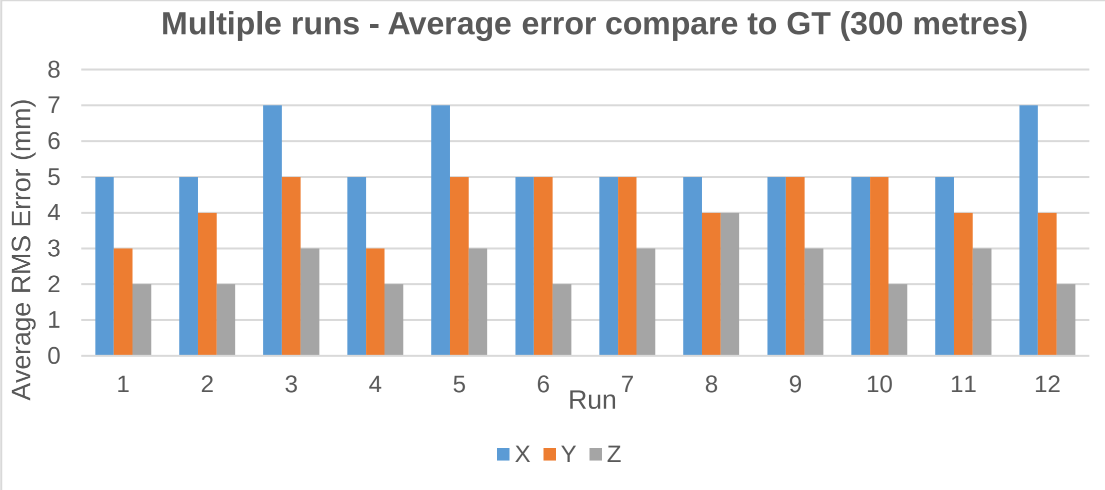

Figure 19: Accuracy LDTM vs GT (300 metres)

Accuracy compare to GT (Avg. in mm):	X: 5.0	Y: 4.0	Z: 2.5
Repeatability compare to first scan (mm)*:	X: 3.0	Y: 5.0	Z: 2.0

As the accepted accuracy of the ground-truth itself was between two and five millimetres (2-5mm), a reported accuracy of 2.5mm for the LCMS-2 survey effectively makes it identical to traditional survey. Repeatability of the LCMS-2 survey was also excellent with a reported error of just 2mm for elevation (Z) when comparing the eleven (11) repeat runs to the initial run.

In the 825m scenario, the number of alignment points used per kilometre of road was reduced from three to just a single point at the edge of pavement. In this scenario the average error in elevation measurements across the twelve (12) inspection runs was 5mm for elevation (Z) when compared to "ground-truth."

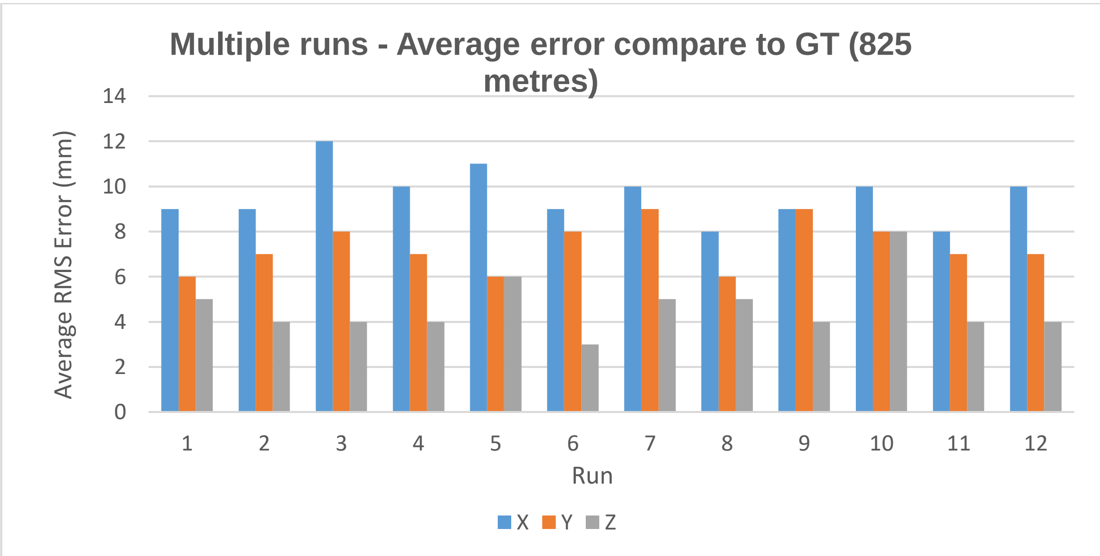

Figure 20: Accuracy LDTM vs GT (825 metres)

Accuracy compare to GT (Avg. in mm):	X: 9.0	Y: 7.0	Z: 5.0
Repeatability compare to first scan (mm)*:	X: 6.0	Y: 6.0	Z: 4.0

While the average error of the 825m alignment scenario was slightly higher, at five millimetres (5mm) instead of two-point-five millimetres (2.5mm), it is still within the range of the accepted accuracy of the ground-truth itself (2-5mm). Repeatability for the 825m scenario was also excellent with a reported error of 4mm for elevation (Z) when comparing the eleven (11) repeat runs to the initial run.

6. CONCLUSION

There is an untapped opportunity to enhance and repurpose 3D scans that are being collected solely for the purpose of pavement condition evaluation, such that they can provide the necessary elevation data for project estimates, preliminary designs and final designs of roads slated for resurfacing and reconstruction.

By integrating high-accuracy Inertial Navigation Systems with 3D scans, and the use of specialized software, it is possible to generate 3D surfaces of roads while performing existing annual pavement condition survey inspections. The resulting absolute accuracy of elevation data is in the range of three-five millimeters (3-5mm) which is effectively the same accuracy as traditional methods.

This method presents numerous advantages over the traditional approach including:

- Time savings at the project planning stage as elevation data for the entire road network can be made available without the need to dispatch a survey crew,
- Significant cost savings through the project planning and construction stages as the number of traditional survey points per mile can be reduced to just a single point,
- Reduced impact to the travel traveling public by nearly eliminating the need for road closures related to survey,
- Increased safety by reducing the exposure of survey staff to traffic.

7. REFERENCES

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