

FUSION OF HIGH-RESOLUTION LASER PROFILE AND LIDAR MEASUREMENTS FOR ENHANCED CONDITION ASSESSMENT

D. Wright, N. Dhillon & A. Wright

Technology Development Group, Transport Research Laboratory, Wokingham, Berkshire,
RG40 3GA, United Kingdom

dwright@trl.co.uk, ndhillon@trl.co.uk, mwright@trl.co.uk

C. CHRISTIE

Highways Agency, UK

colin.christie@highways.gsi.gov.uk

ABSTRACT

Accurate data on pavement condition is essential for the maintenance and assessment of road assets. This is commonly obtained using downward-facing laser survey devices operated traffic-speed to provide detailed measurements of the pavement surface. Interest in the use of LIDAR technology to complement such surveys has increased with better accuracy and cost-effectiveness of commercially-available systems. The potential applications of LIDAR systems have been demonstrated by several groups. These mainly focus on its ability to measure assets other than the pavement, as LIDAR is generally not considered to have sufficient accuracy to measure the pavement shape itself. This work undertakes an initial investigation of how LIDAR could be used in pavement assessment by using LIDAR to combine high resolution measurements collected over multiple survey lanes into a single set of data. This commences with the generation of 3D point clouds from all the measurement systems, followed by alignment and combination. The final hybrid 3D data set describes the pavement surface at a level of detail typical of traffic-speed condition surveys. Potential applications in the field of pavement surveying include the improved identification of locations likely to affect vehicle handling, and the detection of areas at risk from ponding.

1. INTRODUCTION

Accurate data on pavement condition is essential for the maintenance and assessment of road assets. It is established practice in the UK to conduct routine traffic-speed surveys of pavements using downward-facing lasers (either single point or scanning lasers) to measure the road surface shape (transverse and longitudinal profile), from which condition parameters such as rutting and ride quality can be derived. Interest in the use of 360° LIDAR technology to complement existing pavement assessment techniques has increased recently as a result of the increase in accuracy and cost-effectiveness of commercially-available LIDAR, GPS and Inertial Measurement Units (IMU). Although LIDAR systems provide a sparser and less accurate data set than traditional downward-facing lasers, the data is provided over a much longer range, and hence has the potential to provide additional information about roadside assets. The potential applications of LIDAR systems operating at traffic speed on the road network have therefore been investigated by several groups [1, 2 & 3], and applications have been identified such as highway design, measurement of bridge clearances, assessment of structures, inspection of earthworks and determination of barrier height.

However, whereas these applications have focussed on the assessment of assets adjacent to the pavement, there may be potential for the use of LIDAR technology to improve the traffic-speed measurement of the condition of the pavement surface. Initially

this seems unlikely as LIDAR equipment is currently unable to meet the levels of resolution and accuracy that are delivered by current traffic-speed pavement condition survey systems. This work investigates whether LIDAR could be used in combination with laser profile measurements to overcome this limitation and hence improve the assessment of pavement condition.

2. SURVEY EQUIPMENT

We have installed a LIDAR system onto the (Highways Agency Road Research Information System) HARRIS2 survey vehicle, which is a traffic-speed survey vehicle developed by TRL for the Highways Agency (Figure 1). HARRIS2 is currently used as a reference device for the network-level surveys of pavement condition carried out on the English Strategic Road Network (SRN), and also as a platform for developing and testing new approaches to pavement assessment.

For the “traditional” measurement of pavement condition (shape) HARRIS2 is fitted with a Phoenix Scientific Pavement-Profile System (PPS) high resolution transverse profile laser capable of collecting over 1000 transverse points across an approximately 4.2m survey width. The system uses a spinning polygon to scan a laser point across 4.2m of the road surface, measuring up to 1000 transverse profiles per second, and hence delivering high resolution transverse profiles at a longitudinal spacing of 22mm and a transverse spacing of 4mm when travelling at 80km/h [4]. HARRIS2 is also equipped with an Applanix POSLV GPS and IMU.

To assess the use of LIDAR, HARRIS2 was fitted with a Velodyne HDL-64E S2 LIDAR unit (Figure 2). The Velodyne HDL-64E S2 system uses a rapidly rotating (up to 900rpm) measurement head containing 64 individually-aligned laser emitters capable of scanning a 24° vertical arc at ranges of between 1m and 100m in a 360° envelope. The system is rated to provide distance returns with an accuracy of no better than $\pm 20\text{mm}$. The Velodyne system is suited to traffic speed LIDAR survey work because the rapidly-rotating head allows it to generate a 360° “3D image” of a road environment, as a spiral of data as the LIDAR head spins, when moving at motorway traffic speeds.



Figure 1 - The HARRIS2 vehicle with PPS laser and Velodyne HDL-64E-S2 LIDAR



Figure 2 - The Velodyne HDL-64E S2 LIDAR system

3. PROCESSING LIDAR DATA TO OBTAIN 3D DATA FROM TRAFFIC-SPEED SURVEYS

3.1. Raw data

Velodyne LIDAR data is captured in a bespoke binary format and processed into a point cloud from which measurements and calculations can be made. A typical point cloud from the Velodyne system contains positional and colour information as shown in **Figure 3**.

```

1319.30, -2875.32, 208.40, 107, 107, 107
1337.29, -2912.78, 243.56, 117, 117, 117
1310.47, -2692.31, 255.17, 119, 119, 119
1272.00, -3733.04, 272.49, 109, 109, 109

```

Figure 3 - Typical Point Cloud excerpt data for 4 points. Each line represents 1 point (the X, Y, Z co-ordinates of the point and the Red, Green & Blue levels)

The point cloud is obtained using a series of banks of lasers that are positioned at known orientations within the rotating LIDAR head. Figure 4 shows the geometry of a single LIDAR laser observing a point at distance D m from the rotating head. The laser is mounted at an azimuthal angle A° and a rotational angle R° , and at a known distance from the base of the unit. The head spins anti-clockwise (looking from the top down) and at any given moment has spun an additional θ° from its initial position.

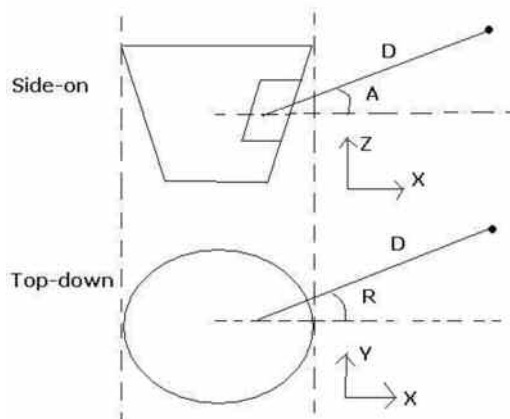


Figure 4 - Side-on and Top-down views of the Velodyne LIDAR measuring a point at distance D , rotational angle R and azimuthal angle A .

To use the LIDAR data the measurements must be translated into a reference frame that can be compared with other survey measurements such as those provided by the PPS, a reference frame that we refer to as the *Survey Space*. To obtain this information we

construct the position of an observed point in the *LIDAR space*, translate into the *HARRIS2 space*, and then into the *Survey space*.

3.2. LIDAR Space

We first obtain the location of an observed point in a cylindrical co-ordinates (r, θ, z) in the reference frame of the LIDAR system:

$$r = D + \Delta D \quad [1]$$

$$\theta = \text{Rotational Head Position} \quad [2]$$

$$z = r \sin(A) + \text{VerticalOffset} \quad [3]$$

Such that ΔD is a laser-specific corrections to the measured distance of the measuring laser and *VerticalOffset* is the physical distance above the base that a laser is mounted. These values are known for each laser and supplied by Velodyne in an XML file.

We convert from a cylindrical co-ordinate system to a cartesian system in the reference frame of the LIDAR system:

$$X = (r + \text{Corr}_X) \cos(A) \sin(\theta) - \text{HorizOffset} * \cos(\theta) \quad [4]$$

$$Y = (r + \text{Corr}_X) \cos(A) \cos(\theta) - \text{HorizOffset} * \sin(\theta) \quad [5]$$

$$Z = z \quad [6]$$

Corr_X and Corr_Y are calculated from information about the laser and supplied by Velodyne.

3.3. HARRIS2 Space

Given the location of the observed point in an (X, Y, Z) co-ordinate system centred on the LIDAR, we perform a rotation and translation to place this point in a co-ordinate system centred on the HARRIS2 vehicle – this is the *HARRIS2 Space*. Figure 5 shows the HARRIS2 Space, in which a second set of Cartesian co-ordinates (X', Y', Z') are centred on the vehicle – X points upwards, Y points to the left and Z points behind*.

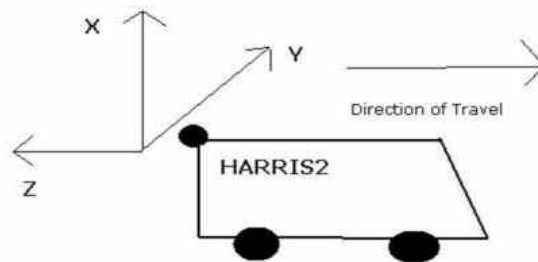


Figure 5 - Side on view of the co-ordinate system of the HARRIS2 space. Note the direction of travel and the location of the LIDAR system indicated at the top and back of the vehicle.

The LIDAR system is mounted at an angle of 22.6° to the horizontal – angle M in Figure 6. We perform a rotation of 22.6° to the horizontal:

$$Z' = Z \cos(M) - X \sin(M) \quad [7]$$

$$X' = X \cos(M) + Z \sin(M) \quad [8]$$

* This is a non-standard selection for axis orientation, however it is convenient to retain this orientation

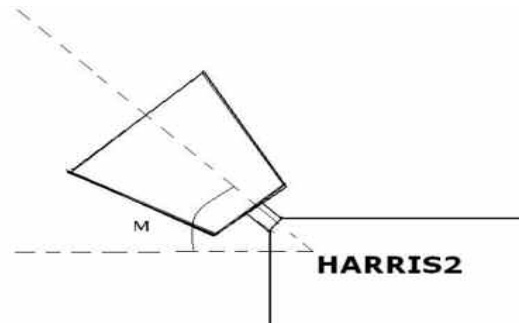


Figure 6 -The Velodyne LIDAR is mounted on Harris 2 at an angle of M degrees to the horizontal.

After rotating, a translation resets the (0, 0, 0) point for the (X', Y', Z') co-ordinate system. Figure 7 shows the translation that is used to move the (0, 0, 0) point between the co-ordinate systems. The (0, 0, 0) in the (X', Y', Z') co-ordinate system is at the reference point for the IMU installed in the HARRIS2 vehicle.

Data in the HARRIS2 space is referenced to a (0, 0, 0) point inside the HARRIS2 vehicle. To generate a picture of the environment space around the vehicle we must make one final transformation into the *Survey Space*.

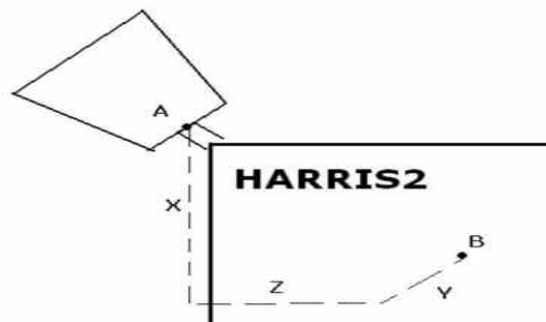


Figure 7 - The (0,0,0) point for the Velodyne LIDAR is located at an offset from the inertial reference point for the Applanix system on Harris 2.

3.4. Survey Space

Given the location of a point in the *HARRIS2 space* (X', Y', Z') we can use the known position and dynamics of the vehicle during a survey to convert to the *Survey Space* (X'', Y'', Z''). For this work we have defined the survey space with reference to the British OSGB36 grid.

Position and dynamics information about the HARRIS2 vehicle is provided by the IMU and GPS system installed in the vehicle, which we have integrated in the vehicle so that the measurements are closely synchronised with the LIDAR measurements. The major components of the position and dynamic data are the Pitch, Roll, Yaw and OSGR grid coordinate. These dynamic movements are accounted for in our transformation using Tait-Byron relations [5].

3.4.1. Roll

When cornering or driving on a cambered road a vehicle experiences roll. Roll is defined as an angle from the vertical at which a vehicle is leaning – see Figure 8.

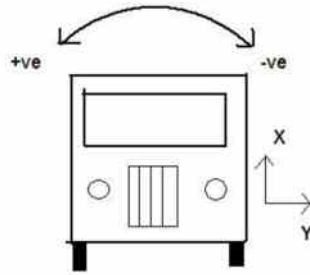


Figure 8 - Vehicle Roll Dynamics

Roll is accounted for by adjusting the co-ordinate system as follows:

$$X' = X' \cos(\text{Roll}) - Y' \sin(\text{Roll}) \quad [10]$$

$$Y' = Y' \cos(\text{Roll}) + X' \sin(\text{Roll}) \quad [11]$$

3.4.2. Pitch

A vehicle experiences Pitch when traversing slopes, or when braking / accelerating. Pitch is defined as a deviation in the vehicle's orientation from the horizontal – see Figure 9.

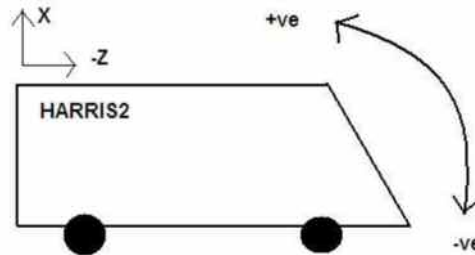


Figure 9: Vehicle Pitch Dynamics

Pitch is accounted for by adjusting the co-ordinate system as follows:

$$X' = X' \cos(\text{Pitch}) - Z' \sin(\text{Pitch}) \quad [12]$$

$$Z' = Z' \cos(\text{Pitch}) + X' \sin(\text{Pitch}) \quad [13]$$

3.4.3. Yaw & Position

The vehicle yaw equates to its bearing, i.e. its instantaneous direction of travel. The yaw is defined as an angle relative to north – see Figure 10

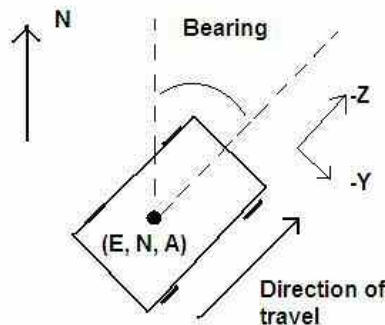


Figure 10 - Yaw and vehicle location dynamics. The OSGR position of the vehicle (E, N, A) is also known.

Vehicle heading (Yaw) is accounted for by rotating the Y and Z co-ordinates:

$$Y' = -Y' \cos(\text{Yaw}) - Z' \sin(\text{Yaw}) \quad [14]$$

$$Z' = -Z' \cos(\text{Yaw}) + Y' \sin(\text{Yaw}) \quad [15]$$

Once this is done, the final part of the transformation is to simply add the position data from the GPS to deliver a globally-referenced position for the point we originally measured in Figure 4. The co-ordinate system used is the OSGB36, for which an Easting (E), Northing (N) and Altitude (A) value is reported from the HARRIS2 IMU. The final result is:

$$\text{Easting} = Y'' = Y' + E \quad [16]$$

$$\text{Northing} = Z'' = Z' + N \quad [17]$$

$$\text{Altitude} = X'' = X' + A \quad [18]$$

3.5. 3D point clouds

The process described here allows a set of data obtained from the LIDAR (the Velodyne system used for this application having been designed for static use) to be visualised as a 3D map of the environment around a moving survey route. The original LIDAR data collected in the LIDAR space contains information that cannot be related to the environment in which it was collected, which significantly reduces its usefulness. The process of converting it into the survey space provides crucial spatial information – see figure Figure 11.

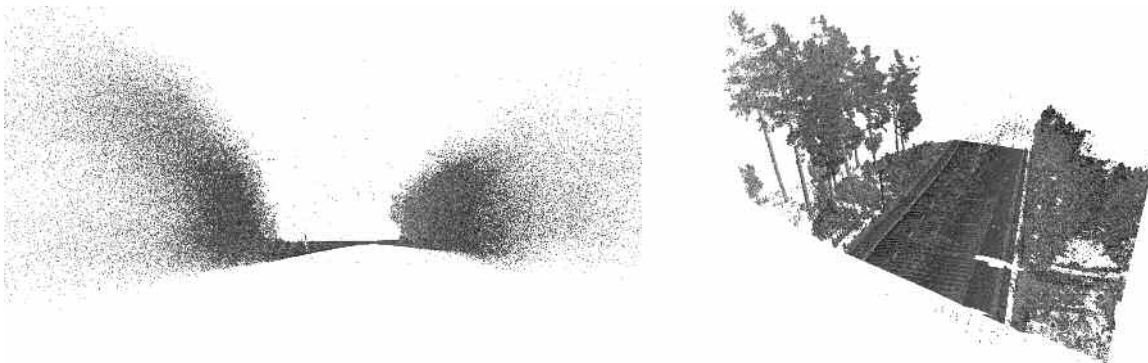


Figure 11 – LIDAR space (left) and Survey space (right) of the same point clouds

In figure Figure 11 the LIDAR space point cloud consists of a mist of points centred on a very small region. This is because the cloud is effectively compressed into the reference frame of the static LIDAR system. The Survey space point cloud contains geometry, and as such a picture of the surveyed environment (pavement and trees) emerges.

4. USING LIDAR DATA TO ENHANCE PAVEMENT SURVEYS

Though LIDAR technology is capable of surveying the environment in a 360° envelope around a survey vehicle moving at traffic speeds, the measurement accuracy of is not as high as that achieved in pavement surface measurements systems, such as the high resolution transverse profile system PPS installed on HARRIS2. Typical measurement accuracies for LIDAR is of the order of a few cm. In comparison, better than a tenth of a mm is achieved by the PPS. As such LIDAR is usually considered unsuitable to replace downward-facing laser systems for the measurement of pavement shape for the assessment of condition (e.g. rutting and ride quality). However, a limitation of current

surveys is their inability to measure the pavement shape outside of the survey width of the measurement system (e.g. 4.2m for the PPS). Therefore it is very difficult to measure (in high resolution) the shape of a multiple lane highway with current systems such as the PPS. We propose that LIDAR has the potential to assist in obtaining high resolution data across multiple lanes by providing information on the surrounding environment which can be used fuse together the high resolution shape information collected in survey runs of adjacent traffic lanes. We have carried out initial work to investigate how this might be achieved.

4.1. Linking LIDAR and PPS data across survey lanes

Our proposal is that LIDAR data could be used in the collation of pavement shape data across multiple lanes by providing a framework at a low resolution over multiple lanes over which the high resolution data can be overlaid. The first stage of this process is to express all the measurements in the same reference frame. This can be achieved by converting both the LIDAR data and the PPS data into 3D co-ordinates in the Survey Space using the methods developed above. In theory it now appears trivial to obtain the multiple lane data by simply combining the 3D co-ordinates from each survey into a single data set. However, this is not the case because errors and drift in the GPS and IMU measurements cause the data from each dataset to be offset in all three directions (x, y and z) from each other, resulting in the introductions of steps between pavement lanes where the data from the surveys join. The LIDAR data across multiple lanes is not subject to such drift because a single LIDAR run can be used to obtain LIDAR 3D co-ordinate data from several lanes. The high resolution 3D co-ordinates provided by the PPS from several separate surveys can then be overlaid on this single LIDAR point cloud.

The method by which this is done is to create a 3D point cloud for each PPS data set that is to be aligned. Each point cloud is referenced to the British OSGB36 standard by using data from the HARRIS2 IMU. At the same time a 3D point cloud in the Survey Space is created for the LIDAR survey that accompanied each PPS transverse profile. LIDAR point clouds for separate surveys are plotted and overlaid in a suitable software tool, then manually inspected for drift. By identifying reference points in multiple LIDAR surveys, it is possible to identify the drift between those surveys at that point. This drift fundamentally arises from errors in the GPS and IMU measurements, and can be used to correct and align the PPS surveys corresponding to those LIDAR surveys.

In practice this can be achieved by conducting PPS and LIDAR surveys in all lanes of a multiple lane carriageway and using roadside features visible in the LIDAR to generate a series of drift corrections between each lane surveyed. For all PPS data points in each PPS survey, an appropriate drift correction can be calculated (using a linear interpolation between consecutive corrections if required) and applied to ensure that each PPS survey aligns with a) the surrounding environment and b) all other PPS surveys.

4.2. Experiment and Results

Tests of this approach were carried out on the TRL test track, which contains a length of pavement 500m long and 5 lanes wide, with crash barriers on either side. Each lane was surveyed using HARRIS2, equipped with the PPS, Velodyne HDL-64E S2 and Applanix IMU. To ensure that suitable reference points would exist in each survey dataset, marker posts were laid out along the survey route every 100m for use in the alignment. LIDAR data was collected in Lane 1 of the test section (one survey run) using the Velodyne system and converted into a 3D point cloud in the survey space to – as shown in the left hand side of Figure 12. High resolution transverse profile data was collected in all five

lanes of the test section (using 5 survey runs) with the PPS. The data from these runs was also converted 3D point cloud in the survey space and aligned with LIDAR data to obtain a high resolution profile over multiple survey lanes – as shown in the right hand side of figure Figure 12. Comparison of the left and right hand sides of figure Figure 12 shows the vast improvement in measurement detail that is obtained by the PPS measurements. The combined data covers multiple lanes, but with much reduced noise, and the crossfall of the pavement is clearly visible. However, we have found in this initial investigation that there are problems in the alignment process that can result in the introduction of discontinuities in the measurements across the full carriageway width. The resolution of these problems will be the subject of further research.

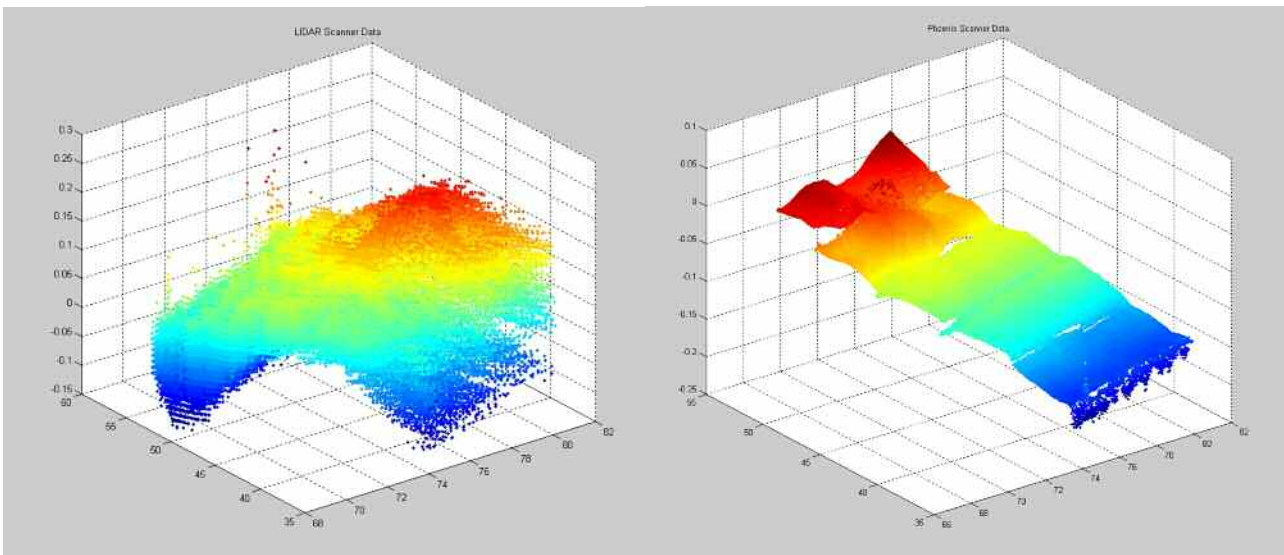


Figure 12 - Traffic Speed LIDAR scan of the TRL test track (LHS) and high resolution PPS data (RHS) of the same part of all 5 surveyed lanes.

Following alignment, we can combine the PPS with the LIDAR data to visualise both in the same survey space. Since both data sets are referenced to the OSGB36 co-ordinate system, it is a trivial task to plot them on the same axes – see Figure 13.

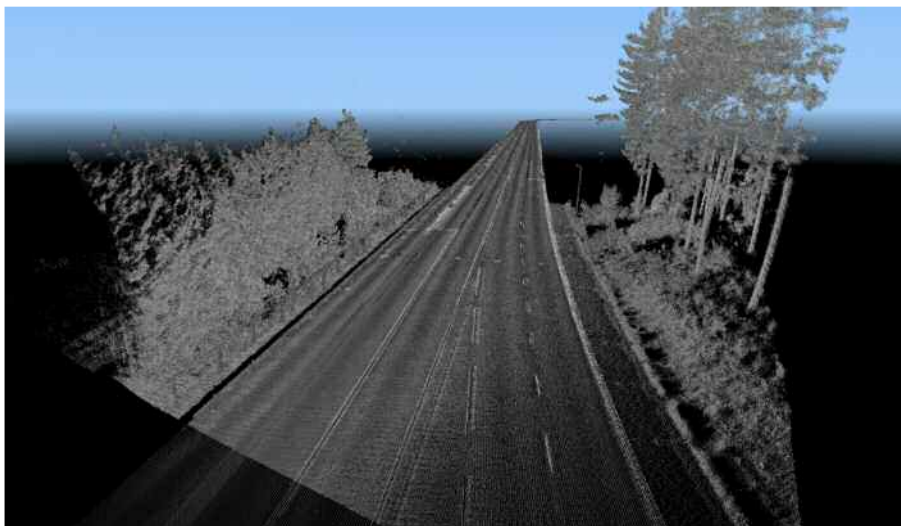


Figure 13 – LIDAR and PPS data overlaid. The LIDAR provides a map of the environment, the PPS provides a detailed scan of the whole carriageway.

To demonstrate the integration of the high-resolution data with the LIDAR data across the multiple lanes figure Figure 14 shows a section of test site in more detail, with the pavement coloured according to height (purple lowest and green highest). This colouration

demonstrates how full carriageway crossfall can be measured using a multi-lane PPS style survey, then visualised in the context of the full roadside environment.

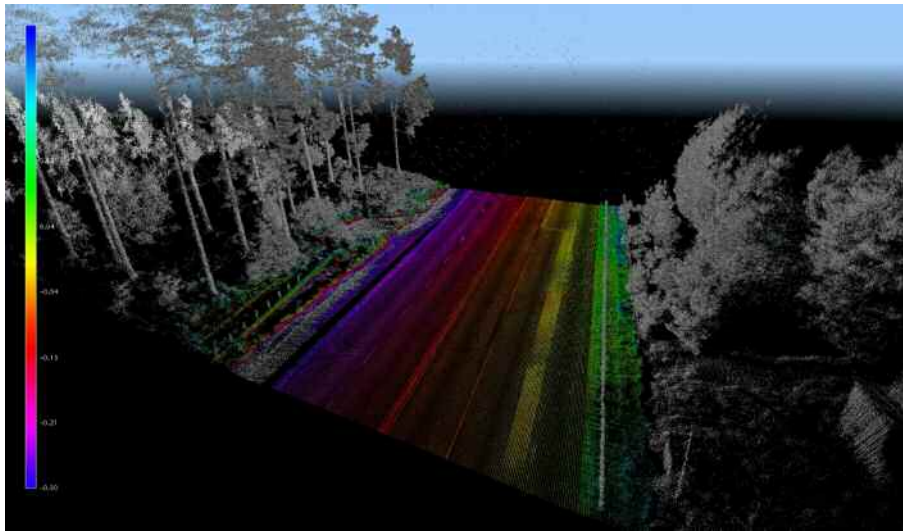


Figure 14 - A portion of the combined data with the pavement coloured to show the crossfall, showing no step changes in height

5. CONCLUSIONS & FUTURE WORK

Although the measurement of pavement condition at traffic-speed is well established using high resolution laser measurement systems, interest in the use of LIDAR technology to complement such pavement assessment techniques has increased as a result of the increase in accuracy and cost-effectiveness of commercially-available LIDAR, GPS and Inertial Measurement Units (IMU). Because of its ability to measure over longer distances LIDAR has significant potential to assist in the measurement of assets adjacent to the pavement. However, it is not considered to have sufficient accuracy to measure the pavement shape itself. We have investigated how LIDAR could be used in such an application by complementing existing technologies and in particular to allow high resolution measurements to be combined over multiple survey lanes. This commences with the generation of 3D point clouds from all the measurement systems, followed by alignment and combination. By thus combining high-resolution data with relatively coarse LIDAR survey data, it has been possible to align several pavement condition surveys of different lanes of the same carriageway length. GPS and IMU data were used to convert raw LIDAR and PPS data into 3D maps, then marker posts in the LIDAR scans were used to manually correct for drift in each PPS scan. The final result is a hybrid 3D data set that describes the pavement surface in a level of detail typical of traffic-speed condition surveys, but also shows and the surrounding infrastructure and environment.

This work has been an initial demonstration, with the processing used to align these data sets requiring manual intervention and physical markers to assist in the alignment. This was done as a simple way to reliably identify the same objects in multiple LIDAR data sets for this application, without the need to develop algorithms to achieve this automatically. However, it is expected that, with improving LIDAR technology and analysis algorithms, automated alignment will become possible in the future.

There are numerous potential applications of this in the field of pavement surveying. The generation of a full-carriageway survey with pavement detail that is normally only possible

in a single lane allows for the calculation of a profile across the entire carriageway. This in turn means that a full 3D picture of a carriageway can be constructed to enable, for example, the improved identification of locations likely to affect vehicle handling, and the of detection of areas at risk from ponding.

ACKNOWLEDGEMENTS

Copyright TRL Limited 2012. The research described in this paper was supported by the UK Highways Agency. The views expressed do not necessarily reflect the views of the Highways Agency.

REFERENCES

1. Jaakkola A, Hyyppa J, Hyyppa H, Kukko A. (2008). "Retrieval Algorithms for Road Surface Modelling Using Laser-Based Mobile Mapping", *Sensors* 2008, 8, (5238 – 5249)
2. Gandolfi S, Barbarella M, Ronci E, Burchi A. (2008). "Close Photogrammetry and Laser Scanning using a Mobile Mapping System for the High Detailed Survey of a High Density Urban Area", *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Services*. Vol. XXXVII. Part B5. Beijing 2008. (909 – 914)
3. McCarthy T, Zheng J, Fotheringham A. S. (2008). "Integration of dynamic LIDAR and image sensor data for route corridor mapping". *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Services*. Vol. XXXVII. Part B5. Beijing 2008. (1125 – 1130)
4. <http://www.phnx-sci.com/PPS/Home.html>
5. [Tait-Bryon Relations](#)