Lancaster Environment Centre | Lancaster University

MSc Data Science

A Review of LiDAR Applications in Road Transportation

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1 Introduction

Light Detection and Ranging (LiDAR) is an optical remote sensing technology that utilises Near-Infrared (NIR) light rays to collect information about the surrounding environment. LiDAR data is created by firing rapid laser pulses at the ground and storing the energy reflected as a dense 3D cloud of points, these points can be converted into highly detailed terrain models, and by examining the reflections from the ground and vegetation canopy the terrain and surface models can be derived (see Table 1). Vertical Aerial Photography is an air-based mapping technique, utilising aircraft with a bottom-mounted high-resolution camera which captures reflected light in the red, green and blue (some datasets also capture some of the NIR spectrum). The images that are recorded are stored in various resolutions, which are used for different applications where higher or lower resolution are desirable, such as mapping elevation for the whole UK, 10cm resolution is inappropriate due to the size of the dataset required. Where as if the analysis was to focus on the vegetation canopy around motorways in Cumbria, 2m resolution is inappropriate due to lack of spatial accuracy. Figure 1 demonstrates the output of a LiDAR point cloud where each dot represents a single laser fire. The data is overlayed on a basemap, however the underlying features such as the housing estate and river can clearly be identified.

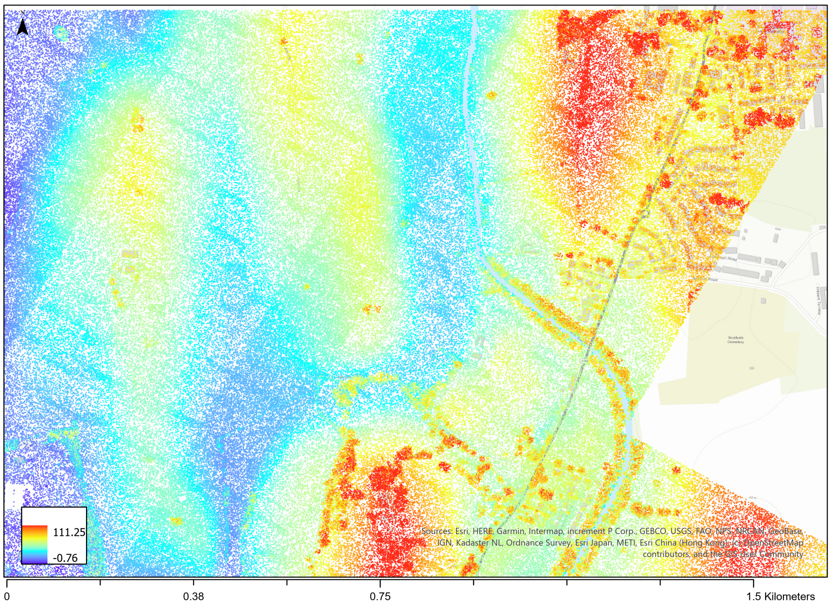

Figure 1: Map of LiDAR point cloud west of Lancaster University, where the red represents higher elevation and blue represents lower. There is also a section that does not have data

LiDAR has three main methods of collection, Aerial Scanning (AS), Mobile Scanning (MS) and Fixed Scanning (FS), generally transportation applications focus on MS due to the high level of detail available, and the focus of the study

Table 1: LiDAR Output Types, origin methodology and short description

LiDAR Product	Acronym	LiDAR Pulse	Description
Point Cloud		all	Discrete LiDAR output, used in the creation of DSM
Digital Surface Model	DSM	last / only	All ground and surface objects
Digital Terrain Model	DTM	last / only	Only ground, surface objects are filtered out
First Return DSM	FZ DSM	first / only	All ground and surface objects, better for measuring tall objects
Intensity DSM	Int DSM	all	Reflectivity of the surface.

can be changed based upon where it is mounted on a vehicle. In 2013, the National Highway Cooperate Research Program (NCHRP) highlighted several potential applications for LiDAR in transportation, these are shown in Figure 2.

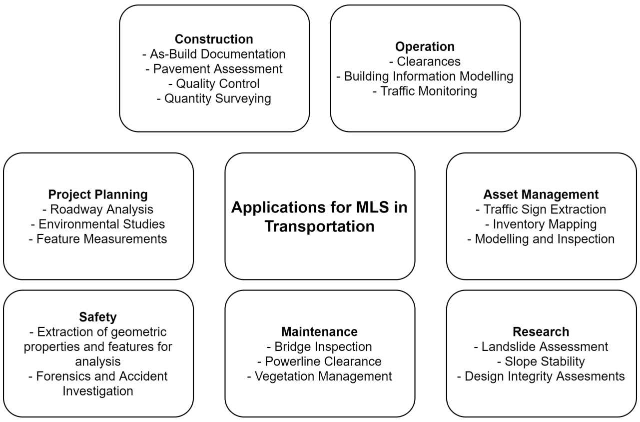

Figure 2: Potential applications of mobile laser scanning outlined by NCHRP [adopted from Gargoum and Basyouny 2019; Olsen and Roe 2013]

Since the NCHRP report in 2013, interest in LiDAR has grown extensively. This could be attributed to the use of LiDAR in autonomous vehicles, or to the reduction in cost of LiDAR units. Despite the growing interest, the research is somewhat disorganised and some areas have received more interest than others. Following the grouping of Gargoum and Basyouny 2019, Figure 3 shows a summary of the transportation feature that are considered in this review. Furthermore, it highlights current gaps in literature, and it must be noted the previous attempts that review LiDAR applications in transportation Gargoum and Basyouny 2019; Gargoum, Karsten et al. 2018; Guan et al. 2016; Williams et al. 2013. Hopefully this review can build on previous to give a critical review of techniques where those have missed.

2 Surface Extraction

The current research into road surface extraction (RSE) is rather limited, the initial paper outlining a method of surface extraction Lam et al. 2010 relied on Random SAmple Consensus (RANSAC) classification on multiple planes leveraging Kalman filtering, the method was tested on several areas and the authors described the results as "satisfactory". However a simpler version of this problem is differentiating ground and non-ground points from LiDAR

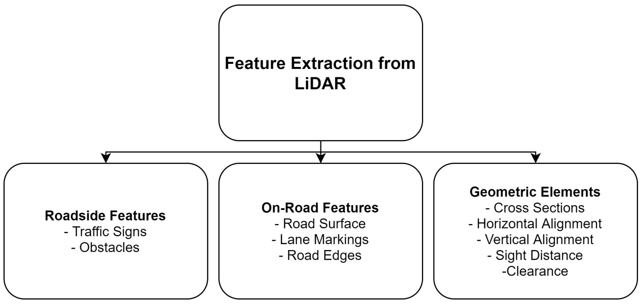

Figure 3: Roadway feature extraction from LiDAR [adopted from Gargoum and Basyouny 2019]

point clouds. These attempts are usually a preliminary step to extract other information such as traffic poles, or sign locations. And as such, the accuracy of these methods usually is not explicitly stated in the reports. Yadav, Singh and Lohani 2017 Proposed a segmentation algorithm, splitting ground and non-ground, then further splitting the ground points into road and non-road. This was performed in three stages, (1) data filtering (2) road surface extraction (3) road boundary refinement. This method uses pre-classification to optimise ground filters whilst minimising computation time, and by removing non-road surfaces based upon intensity and recovery the boundary can be refined faster. This was tested on three areas in India with an average completeness of 93.8%, correctness of 98.3% and quality of 92.3%. Zhou and Deng 2014 leveraged LiDAR scan-lines to differentiate ground and non-ground points, which was extended in Yadav, Lohani et al. 2016 where overlapping cylinders were used instead - points that are at the base of the cylinder were grouped and extracted as ground points, then refined using a height based approach. Raster based approached are common too, Cabo et al. 2014; Wu et al. 2013, Yu et al. 2015 used a 2D XY grid and determining whether each pixel was ground or non-ground via a threshold.

3 Edge Detection

Detecting curbs, lane markings and edges from LiDAR has seen far more research than RSE. An autonomous method that can accurately classify lanes and road edges is of great interest to autonomous vehicles, and stands as one of the main challenges. W. Zhang 2010 developed a realtime approach involving elevation-based filters and pattern recognition to identify "road segments", the paper stated the approach was "successful in detecting most road points, road-curb points and road-edge points correctly" and it has a false positive rate of 0.83%. Y. Zhang et al. 2018 extended these attempts using a plane method to distinguish road and non-road regions, with further segmenting from a sliding beam method. The algorithm was tested on an autonomous vehicle with average precision and recall rates of 84.49% and 82.87% respectively. Serna and Marcotegui 2013 presented a novel point cloud based approach, of mapping to range images using the λ-flat zones algorithm. By utilising bezier curve calculations to reconnect missing information the proposed method was tested in the Netherlands and France with completeness rates 60% and correctness 94%. McElhinney et al. 2010 extended the concept of using bezier logic, by using 2D cubic splines which modelled intensity, pulse width, slope and proximity to the vehicle to classify road edges (their results were not presented). Thuy and León 2010 presented the initial lane detection algorithms, involving the probability density function of the intensity of all data points. The concept was that, as the LiDAR was mounted on the vehicle, most points would be road-points. And from that you could deduce pavement-points. A dynamic threshold, based on the peak std, was also used to enhance contrast and filter out road-points via binarisation to detect lane markings. A Canny filter was also applied to improve sharpness of the lane markings.

4 Roadside Feature Extraction

Roadside Feature Extraction (RFE) has also seen significant research, again due to the implications for autonomous vehicles, but also with more diverse motivations. These can generally be classified into two distinct categories; (1) real-time (2) video recordings. Zhou and Deng 2014 attempted real-time extraction where LiDAR point clouds were converted into raster images then detected the existence of signs using a linear Support Vector Machine (SVM) using CCS and reflectivity as additional features. Which is then recognised/classified using Histogram of Oriented Gradient (HOG) feature and linear SVMs. This was one of the most successful attempts to classify roadside traffic signs in real-time and saw positive results with a detection rate of 95.87%, a recognition rate of 95.07% - however this is not robust enough to be used solely by an autonomous vehicle in real-time. Soilán et al. 2016 used a novel reduction method by removing points further than 20m away, and also points on the ground. Replacing the heuristic filters of previous work, a Gaussian mixture model-based intensity filter improves model stability, and using a density-based clustering algorithm with PCA to filter clusters based on sign properties. This method was used on various sections of road, with decent accuracy attaining detection rates of 86.1% and 92.8% on urban and rural roads respectively. Interestingly, the authors stated that pedestrians and metallic surfaces had an impact on detection rates. This was extended in Riveiro et al. 2016 by using a standard image-based classifier of signs to improve robust detection rates to 88% (this represented widescale testing in 3 countries, and can be considered far more robust than the previous).

5 Geometric Feature Extraction

Detecting roadside features is a far simpler problem with relatively explicit boundaries, however feature extraction moves towards using full RGB cameras instead of LiDAR techniques - they are simpler to work with, and significantly cheaper. LiDAR is perfectly positioned to be used for geometric feature extraction, accuracy is of utmost importance in this field and would look to replace traditional laser based measuring methods. The key sections of geometric feature extraction are the makeup of the road; cross-section slope, incline, vertical and horizontal alignments, clearances and sight distances.

5.1 Cross Section Slope Evaluation

Evaluating the cross-section slope of a road has important implications for ensuring road maintenance, such as sufficient water drainage which reduces the risk of hydroplaning. Tsai et al. 2013 presented a cross slope analysis method defining a perpendicular Region of Interest (ROI), the points were used to estimate slope using linear regression. This method was tested in a controlled environment and was within 0.28% of the digital level readings. Shams et al. 2018 attempted slope extraction by defining the endpoints of the region using survey nails in the field, and drawing a reference line between the points, with ArcGIS clipping some of the buffer. Fitting a mesh grid to points within each buffer and lane markings identified using intensity. The cross-slope was calculated by evaluating the ratio of run to rise between the lane lines. This method reported as being within <0.19% of digital readings - although it must be noted, the manual element of this method meaning it is not necessarily practical in wide scale convenient slope mapping.

5.2 Road Alignment Profiles

Traditionally, using fixed LiDAR to accurately measure road horizontal and vertical alignments require road closures and cause significant disruption. The first seen use of mobile LiDAR extracted vertical alignment by manually tracing road edges in ArcGIS and using linear regression along the centerline to estimate grade and slope. Testing revealed that the results deviated significantly from the true measurements.

5.3 Sight Distance Analysis

Assessing the sight distance is critical to the safe operation of high speed roads. It is an important metric that defines the distance a driver is required to see to be able to complete any manoeuvre safely (such as lane changes and emergency stops). Being able to quantify the sight distance from the geometry of the road is a difficult, manual process that requires complex 3-dimensional assessment as factors such as bends, valleys or bridges can have varying impacts on the distance that can be seen. Researchers are recently moving into using LiDAR to solve this problem but there is not much research yet.

5.4 Clearance Assessments

Another important use is the assessment of vertical clearance, generally it is only possible to assess the clearance of bridges on roads. Typically this is collected via routine inspections which can incur significant disruption and cost. These are performed relatively often compared to other methods discussed as it can be used to assess structural problems with the bridge in addition to be being used to issue over height permits for oversized vehicles. The adoption of digital tools for this has been a slow process and there are still many using manual tools such as theodolites and total stations. Liu, Chen and Hasuer 2012 theorised a method using aerial LiDAR scans to automatically match points on top of bridges with points on the lower ground surface. The authors did not state they performed experiments and so the accuracy is unknown.

6 Conclusions

Each chapter presents different LiDAR-based road analysis techniques from previous research. This review demonstrates the potential value of LiDAR for road applications, although these methods are directly translatable to both railway and airports. The focus of research to date looks to classify on-road features, without much attention to the possibility of LiDAR in improving the efficiency of extracting and evaluating geometric design element of roads - currently a laborious task requiring road closures. Road feature classification has seen far more research due to the implications previously discussed regarding the use in autonomous vehicles, a far more lucrative industry than mapping and highway maintenance, as well as the majority of this research from experts in non-geographical backgrounds whom are also not interested in the design elements of roadways. The value that could be attained from automatically extracting road information from both UAV-mounted LiDAR or vehicle-mounted LiDAR extends beyond increase efficiency of inventorying information, but to highlight potential improvements in road design and safety. Jalayer et al. 2015 stated that "if properly utilized and efficiently processed, mobile LiDAR datasets represent a valuable tool when collecting roadside data for the purpose of safety analysis". The geometric feature extraction methods discussed previously have some common limitations, namely, for cross section extraction the reliance of lane marking information to define the edges of the road region. For most roadways line markings see varying levels of degradation, which limits where the algorithms can be succesfully applied (to achieve accuracy and precision that is usable). For clearance assessment, most studies only discuss vertical clearance and most do not discuss bridges in enough detail - though LiDAR is very well equipped to assess both vertical and lateral clearance. Eyesight distance assessment has a significant number of previous studies, again suffering from some limitations. Most previous assesments do not account for overhanging objects - such as motorway gantry's. This makes the motorway DSM biased, and therefore the results of the assessment are biased Castro, Lopez-Cuervo et al. 2016. Another issue is the use of solely aerial LiDAR scans for their methods Castro, Anta et al. 2014; Khattak and Shamayleh 2005. Which, while useful for urban planning, the vertical nature of aerial LiDAR scans and low point density compared to mobile datasets means that not all obstructions are recorded and represented properly in the point cloud. In the introduction, the Digimap LiDAR products were mentioned to compare uses, where the lowest accuracy is 10cm, which is fine for large solid gantrys or bridges but can suffer when identifying smaller poles (like street lights, or cameras), or mesh-style gantrys where they are not easily differentiable objects. This could have a large impact on the overall accuracy of the assessment. The studies described previously also suffered from potential location biases, where they only tested very limited segments of road - selected for good conditions, such as being straight, with little elevation change - which raises doubts on overall testing accuracy. Limited testing is also a problem for lane information extraction, where most studies focus on straight, clearly defined roads on sunny days. Studies in the future must test in a variety of weather conditions with varying levels of road marking degradation, additionally using the methods on longer segments of road where there are variations in the roads alignment such as lane width, shape and slope. Although not covered in this review, another area that has been covered extensively is the use of LiDAR to extract signage from the roadside, again because of its implications in the operation of autonomous vehicles, however it remains an area with huge potential as the cost of LiDAR units decrease. Gargoum and Basyouny 2019 briefly mentions that an improvement could attempt shape-based classification of traffic signs using LiDAR point clouds - which could prove very useful, especially in the UK with varying sign colours and shapes depending on the message the sign conveys. More research could also be performed on the use of the intensity DSM to assess the conditions of the road and signs. Addressing these issues algorithmically is required before any widespread usage of LiDAR can be considered.

In conclusion, this review states that, despite the increasing use of LiDAR in research focusing on transportation as a whole, more work is still required before it can replace other traditional methods. The review states that future research could go in several directions including;

- using LiDAR to extract more roadside features - data storage / processing
- developing better algorithms to overcome current limitations - algorithmic / processing

However the final decision of whether LiDAR should replace existing methods should be based upon processing time, accuracy, precision, robustness, and especially cost however in 5-10 years, none of these may be issues as LiDAR becomes more accessible to the masses.

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