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Innovative geospatial applications: integration of geospatial data for retaining wall management

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Image source: Google Maps, 2019

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Executive summary

This report details investigations carried out on a retaining wall adjacent to a major road in New Brunswick, Canada. The investigations were carried out to determine the usefulness of terrestrial laser scanning in studying the potential movement of a retaining wall. The opportunity was taken to use data from an unmanned aerial vehicle (UAV) to investigate the potential usefulness of the lower accuracy UAV data where high accuracy data from the terrestrial laser scanner is available, but has incomplete coverage.

This research project was developed to address an issue with a retaining wall constructed to protect a major road in New Brunswick, Canada. It is expected that both geomatics engineers and civil engineers would find the research work informative as – broadly speaking – it is the geomatics engineer's responsibility to monitor the retaining wall, and the civil engineer's to develop solutions if movement is detected by the geomatics engineer. The research was carried out making use of a high accuracy laser scanner and a lower accuracy UAV. The wall is approximately 20m high and 300m long and was constructed in 1999. The wall is constructed of rocks constrained against soil by a restrained wire mesh. The scanner and UAV collected data over the entire length of the retaining wall over a period of two days in August 2015.

The main purpose of the project was to investigate variations in the shape of the retaining wall using the laser scanner, to investigate the precision and accuracy of the laser scanner and determine if data from a UAV could be merged with the laser scanning data to fill in gaps in the laser scanning data caused by vegetation growth in front of the retaining wall. The study area was chosen because the provincial government of New Brunswick did not have, and therefore needed to develop, a strategy to check the stability of retaining walls constructed nearly 20 years ago. In the event of a partial collapse of the wall, the provincial government could be charged with negligence for not checking on the stability of any retaining walls constructed adjacent to major roads.

The research team took the opportunity to carry out an assessment of the laser scanner's accuracy by making use of points coordinated using the Global Positioning System (GPS). The assessment showed that terrestrial laser scanning with a Trimble TX5 instrument has an accuracy of approximately 2 mm, +/- 16 mm when compared to the GPS results.

Other results show that the UAV data can be integrated into the laser scanning data. The research found that the data from the UAV that is filling the laser scanning data gap is at a lower resolution to the laser scanning data due to the lower quality UAV data. This became clear when the data from the laser scanner and UAV were merged together. The study shows it is possible to produce one set of merged data but with varying resolution. The accuracy of any derived product is therefore dependent on its location in the dataset. It may be necessary to attach the source of the data to the data itself, so users are aware of the data's resolution.

1.0 Introduction

In early 2015, the Province of New Brunswick, Canada ('the Province') made a decision to investigate the stability of a large retaining wall protecting a major road. Circumstantial evidence suggested the wall was unstable, although there was no firm proof of this. In order to ensure there would be no collapse of the wall, the Province contacted the University of New Brunswick (UNB) to investigate. A team was established to develop a strategy to confirm the stability of the wall and to evaluate if any movement was occurring. This report details the strategy and results of the work undertaken by the research team.

1.1 The retaining wall

The wall was constructed in 1999 along Route 17 a few kilometres south-east of Campbellton, New Brunswick, Canada. It is approximately 20m high and 300m long (see Figures 1 and 2).

The wall is constructed from stone facing covered by restrained wire mesh (see Figure 3). These are not gabions (wire cages filled with rock) which are more stable. No surveys of the wall were conducted at the time of construction, although construction diagrams were available. The wall is built on a rock base that was blasted to enable the road to be constructed. At the rock base/wall interface there should be a 1.5m bench (see Figure 4).

The above statements are important as they indicate there is no record of the condition of the wall immediately after construction in 1999. There is no record of the how well the stone facing was placed and covered by the wire mesh. There may have been places with too few stones; there may have been places where the wire mesh was sagging under the weight of the stones and where rocks were actually hanging from the wire mesh. In some places there are rocks at the base of the wall which may have fallen from the wire mesh since construction, or may have fallen there during construction (see Figure 5). In addition, there are places where the bench is 1.5m and others where there is no bench. Again, as there was no as-built survey carried out, it is impossible to tell if the variations in the size of the bench were created during the original construction or are the result of changes to the structure over the decades since construction. Finally, there are cracks in the rock face – regretfully there is no information regarding how long the cracks have been there. There is evidence to indicate that some repairs to the wall have taken place since its construction in 1999; there are areas where significant amounts of concrete have been applied to the rock base. However, it is not possible to determine when this was carried out.

Figure 1 **The retaining wall**

Image source: Dare, 2015

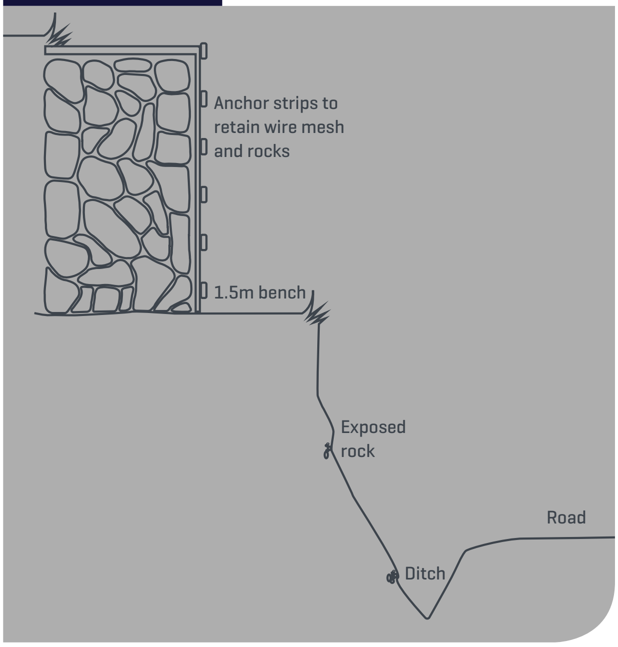
Figure 2 **The retaining wall and rock face**

Image source: Dare, 2015

Figure 3 **Stone facing and wire mesh**

Image source: Dare, 2015

Figure 4 **Wall/rock structure**



1.2 Impact of road closure

Besides devising a strategy to determine the wall's stability, it was also important for the Province to keep the road (Route 17) open as it provides a vital link between communities in northern New Brunswick (especially Campbellton) and those more central and to the south. If this main road had to be closed (due to a collapse of the retaining wall) it would create significant issues for businesses and individuals located near Campbellton, as they would be required to take a long detour on more minor roads to get to other communities in New Brunswick (see Figure 6). It is for these reasons that the Province wanted an investigation carried out.

1.3 Provincial response

The Provincial department with responsibility for roads is the New Brunswick Department of Transportation and Infrastructure (NBDTI). The NBDTI were aware of the enormous impact that a rock fall over the road would have, and had contacted the company that built the original wall to discuss their concerns. The company suggested building another wall between the road and the existing wall, so that any rock fall would not end up on the carriageway. This solution was rejected by NBDTI, principally due to the cost of building another wall, and the fact that NBDTI were not sure whether or not the existing wall was deteriorating over time. If the condition of the wall had not deteriorated, the money spent on a new wall would not have been necessary. NBDTI therefore decided to make an assessment of the stability of the current wall.

Figure 5 **Areas where there has been a possible loss of rocks**

Image source: Dare, 2015

Figure 6 **Location of Campbellton**

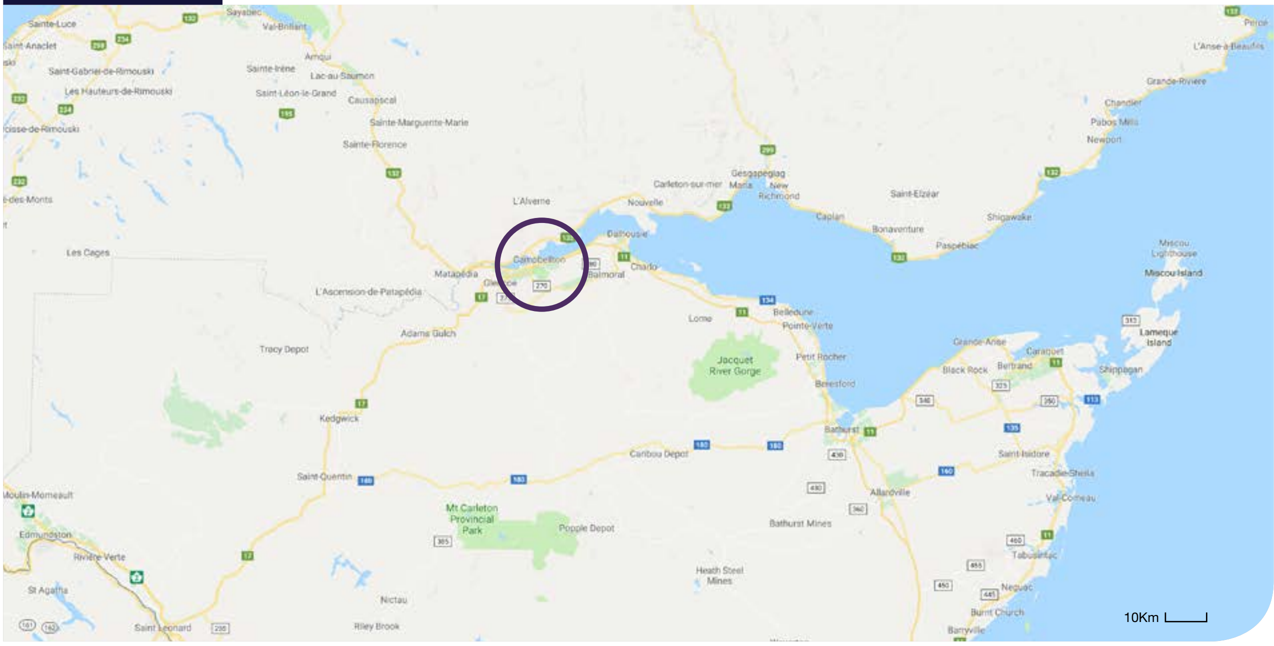


Image source: Google Maps, 2018

1.4 Aims and objectives

This was the first time the Province used laser scanning to help detect and assess potential deformation in a retaining wall. As well as conducting a technical assessment to determine if laser scanning could meet the Province's expectations in terms of (1) accuracy, (2) coverage of the wall and (3) time to complete the fieldwork, it was also important for the Province to determine whether it would be more cost effective to contract out future work of this kind to firms utilising similar equipment, or to hire or purchase its own equipment in order to investigate similar problems in the future.

Although members of the UNB research team have had experience in using terrestrial laser scanning (TLS) equipment on archaeological sites and living museums, this was the first time they were able to use the equipment in this kind of engineering environment.

The UNB team were also able to access data gathered from a UAV survey of the wall conducted by another UNB research group at the time of the laser scanning. As a result, the UNB team were also able to incorporate this into the research methodology.

The aims and objectives of the project were therefore:

1. To assess the accuracy achievable by the laser scanner
2. To determine the ability of the scanner to capture data over the entire wall
3. To assess the usefulness of lower resolution UAV data when high resolution scanning data was already available.

2.0 Literature review

Terrestrial laser scanning has been used in a multitude of applications since its development in the early 2000s. Kankare et al. (2013) used TLS in a forest environment to obtain information on the size of a tree canopy. Rosca et al. (2018) compared the use of UAVs to TLS in the study of the top of tree canopies in tropical forests. Casagli et al. (2017) used TLS to help map landslides immediately after a slip. By rapidly identifying the coverage of the landslip, TLS supported the identification of areas where help is urgently needed. Gumilar et al. (2017) described an approach to landslide monitoring using TLS together with robotic total stations in Rancabali, Indonesia.

TLS has also been used to analyse the strength of different structures. Yang et al. (2018a) used TLS to study the behaviour of structures under load, while Yang et al. (2018b) studied the deformation of concrete slabs from loads applied at its endpoints. Chen et al. (2017) studied TLS to determine the minimum detectable change a TLS instrument could detect. Law et al. (2018) tested the ability of TLS to detect new cracks in concrete structures to enable monitoring of these structures to take place without having to access the structure itself.

There have been many published examples of TLS being used to record the condition of historical monuments and some societies have produced their own guidance notes on using TLS. For example, Historic England (HE, 2018) published the guidance note ‘Advice and guidance on the use of laser scanning in archaeology and architecture’ while Wessex Archaeology (WA, 2018) have also made use of TLS. Castellazzi et al. (2017) discuss the use of TLS when conducting structural analyses of historical buildings and in recording the current condition of historical buildings. Dare and Papaioannou (2017) provide the justification and design of a TLS survey of an ancient basilica in Greece. Dare and Papaioannou (2017) includes details of the methodology adopted to enable the survey and data processing to be completed, despite significant issues with the hardware and software.

In van Veen et al. (2017) there is a discussion regarding the development of a method to detect rock fall from slopes above a Canadian National railway using TLS. This required scanning over a long range (approximately 500m) with a resulting resolution of close to 10cm. The developed method has enabled the researchers to detect thousands of rock falls over a two-year period, as well as the volume of the rock fall. Oskouie et al. (2016) investigated the laser scanning of retaining walls constructed using Mechanically Stabilised Earth (MSE) walls. They focused on studying the joints between adjacent MSE blocks and managed to identify the joints with a 94% accuracy. The developed method was tested using 540 different simulated scenarios for which they managed to achieve an accuracy of 1mm. Martínez-Sánchez et al. (2016) used TLS (a Riegl LMS-Z390i) to estimate the amount of concrete sprayed onto an almost vertical surface in Vigo (Spain) to improve its stability. Accurate assessment of the thickness and volume of the sprayed concrete is important to ensure contractors get paid the correct amount, and to ensure enough concrete is sprayed to guarantee stability of the structure. They used rock bolts as their fixed targets as these were visible in the scans before and after concrete spraying. A total of 91% of the bolts could be detected after scanning, and the volume of sprayed concrete was estimated to be 3,597 litres. Wolfe (2018) is initiating a study of the use of low cost cameras (including mobile phone cameras) in place of laser scanners. Whilst this method is likely to be of lower accuracy comparted to laser scanning, it is expected that it would enable surveys of retaining walls to be carried out more frequently, faster, and at lower cost, than at present.

This report uses TLS to estimate the movement of rocks lying over sloping land that are held in place by a wire mesh. Parts of the structure are hidden by vegetation. It was therefore necessary to supplement the TLS data with data from a UAV.

3.0 Proposed assessment solution

UNB proposed a solution based upon TLS utilising multiple scans of the wall. A Trimble TX5 laser scanner (also known as the Faro Focus 3D scanner; see Figure 7) was used and the scans were registered utilising spheres visible in adjacent scans. An accuracy assessment of the scan was also carried out; NBDTI marked a number of points along the edge of the road coordinated by Real-Time Kinematic GPS (RTK GPS). These points were also scanned, allowing the wall scans to be attached to the provincial coordinate system.

To provide additional redundancy in the collected data, and to help ensure enough data was collected at each scanner setup, two scans were carried out at each setup:

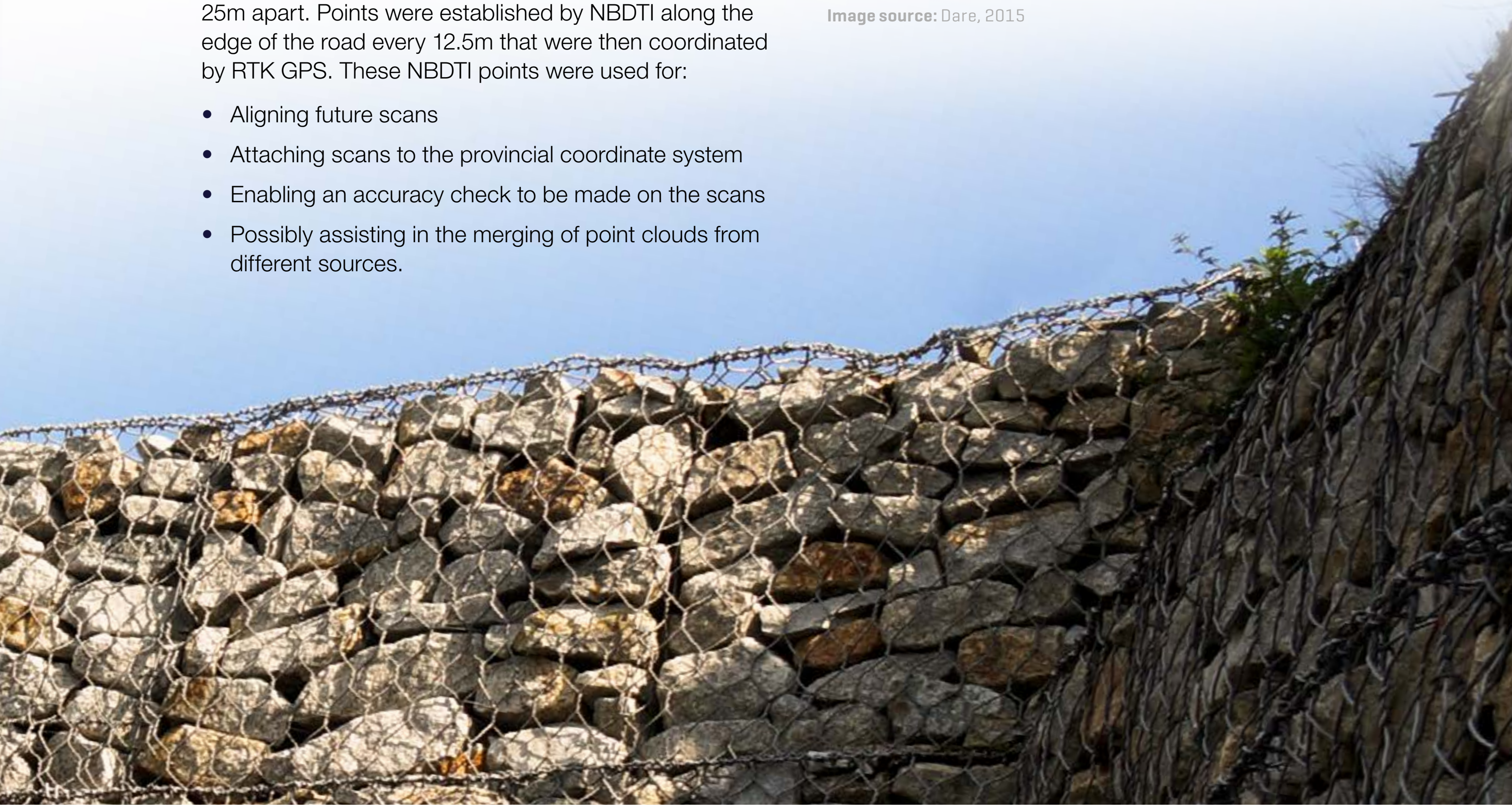
- **Quick scan** – 10 minutes, half resolution, medium quality
- **Full scan** – 40 minutes, full resolution, medium quality.

The data collection was also windowed to reduce the size of the datasets. Data was not collected on the side of the road opposite the retaining wall or on the area that was above the height of the retaining wall. Ten spherical targets were deployed per setup, giving an overlap of five for each pair of setups. This is much more than the minimum needed but would minimise the chances of not being able to register the adjacent scans by having more than the minimum required. Eleven scans were needed in total to cover the entire length of the wall, each scan setup was 25m apart. Points were established by NBDTI along the edge of the road every 12.5m that were then coordinated by RTK GPS. These NBDTI points were used for:

- Aligning future scans
- Attaching scans to the provincial coordinate system
- Enabling an accuracy check to be made on the scans
- Possibly assisting in the merging of point clouds from different sources.

Figure 7 **Trimble TX5 laser scanner**

Image source: Dare, 2015



3.1 TLS data processing

The Trimble supplied software 'SCENE' by Faro Technologies Inc. was used for the data processing. After importing all the data into SCENE, the eleven scans were registered manually rather than using the SCENE automatic registration. This gave the research team the ability to determine how well registration can be done manually. As a result, a fully registered point cloud comprising of 500 million points was created (see Figure 8).

The point cloud was then used to analyse the wall and identify any possible weaknesses in the wall. This analysis identified:

- Areas of the wall not reached by the laser of the TLS
- Areas with no bench
- Changing width of the wall
- Departure of wall from a smooth surface.

What is evident from the point cloud is that there are areas of the wall of significant size which were not hit by the laser – these areas are called shadow areas since there was an object blocking the laser from reaching the wall. These are the grey areas in Figure 8. In this scan, there are two sources of shadow areas:

- Vegetation in front of the wall
- Presence of the bench.

Those shadow areas that indicate the existence of the bench are particularly relevant in this work; a lack of shadow area at the interface of the wall and the rock implies there is no bench. Without the bench, the strength of the wall could be severely reduced because of the increased forces exerted on the exposed edge of the rock base. It is not known if the wall was constructed with a bench, which has collapsed since 1999, or if the wall was built on the rock base in 1999 without a bench in some places.

The analysis also identified where there has potentially been a change in the width of the wall. This can be seen in Figure 9 (a view of part of the wall from directly above it). The wall is the thin black line that extends along the entire length of the figure, and as can be seen it does vary in width. This does not necessarily represent areas where the wall has thinned, but could reflect non-verticality of the wall where the wall is at its thickest when viewed from above.

Figure 8 **Registered point cloud, with close-up of one area**

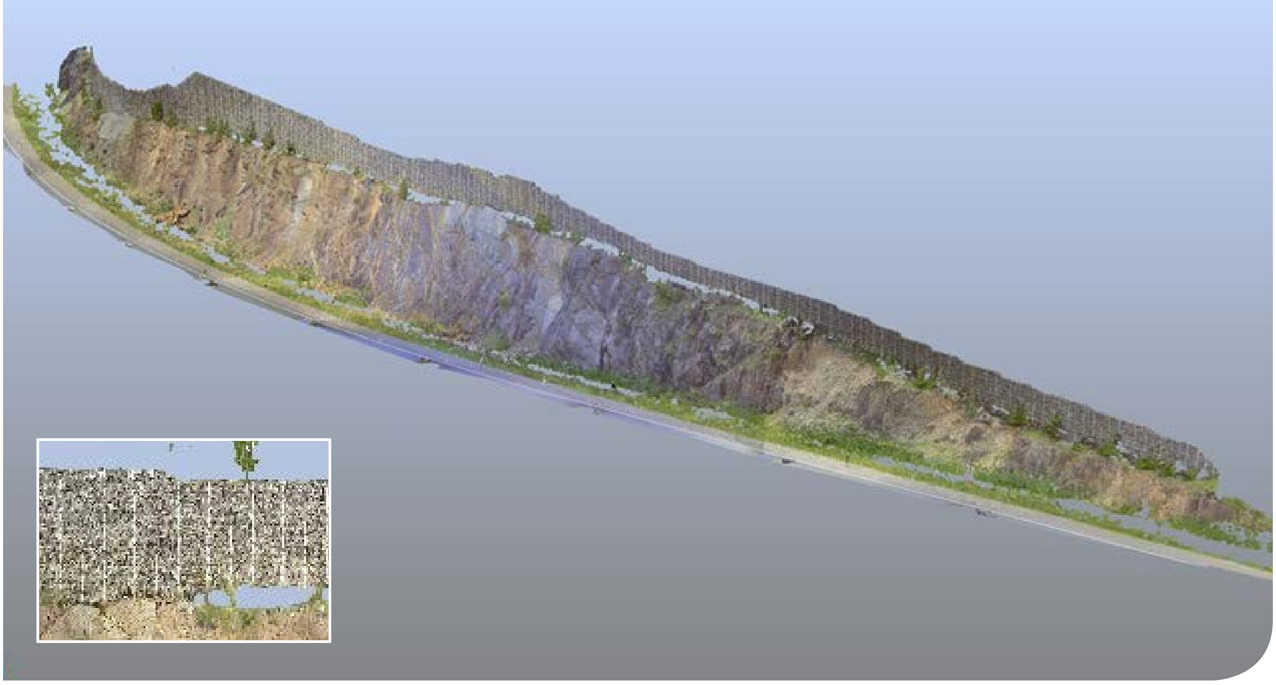


Image source: Image created using FARO SCENE, version 6.0, 2016

Figure 9 Changing width of the wall

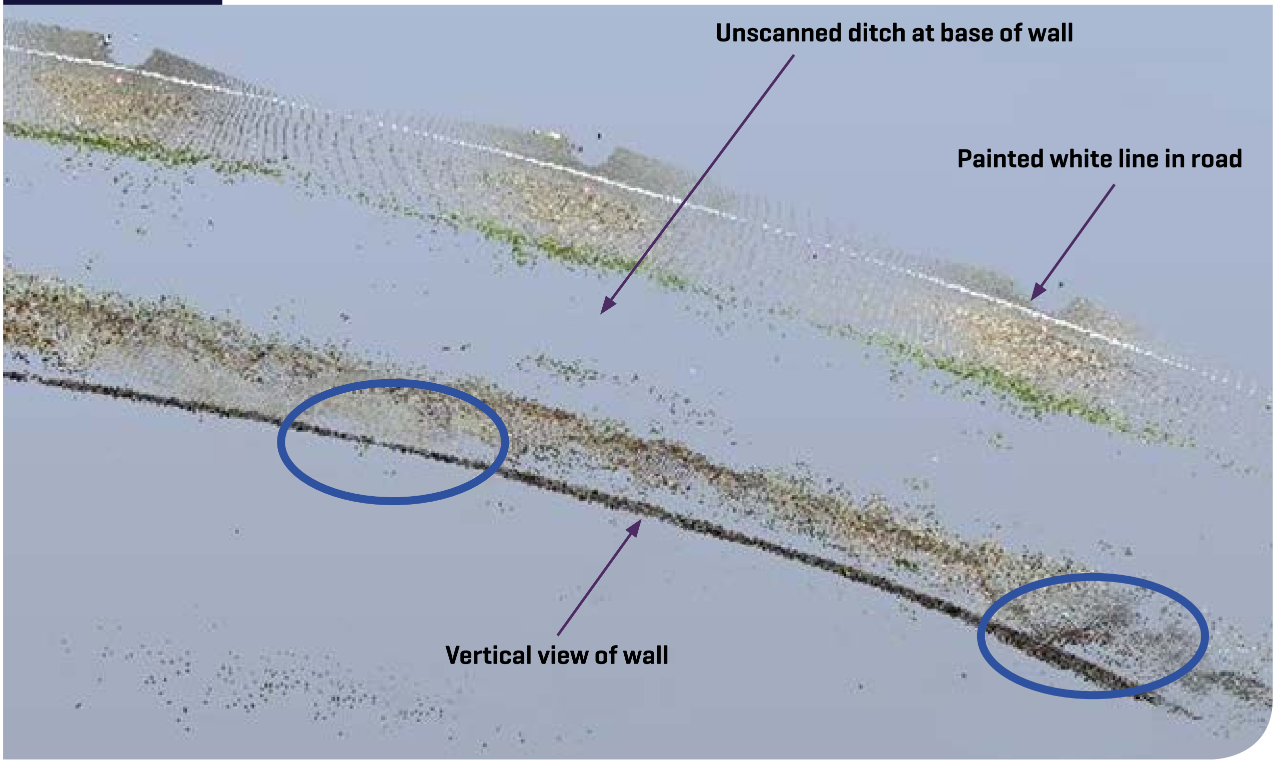


Image source: Image created using FARO SCENE, version 6.0, 2016

The software package 'CloudCompare' was used to estimate a 'best-fitting' surface to the data. The surface used was a "Quadric" of the form:

$$(a + b.x + c.y + d.x^2 + e.y^2 + f.x.y = 0)$$

In this equation, the unknown parameters to be solved for are a, b, c, d, e, and f, while x and y are coordinates of the points. The discrepancy of the wall (from the point cloud) was then determined from this 'best-fitting' surface to identify parts of the wall that deviate from this 'ideal' wall (see Figure 10). Departure of the wall from this surface does not indicate any movement (as the wall could have been built that way), but it may show areas that should be further investigated in future scans. Figure 10 shows the discrepancy of the wall from the quadratic function. Grey coloured areas show where the actual wall is extending outward towards the road (away from the land, more over the rock base) from the 'best-fitting' surface up to 10-12cm, while green coloured areas indicate areas where the wall is inward away from the road (further into the land) up to 20cm.

3.2 Accuracy assessment

An accuracy assessment of the point cloud was conducted by making use of the permanent ground markers (PGMs) installed by NBDTI. These points were coordinated using RTK GPS by NBDTI and they are visible in the point cloud as they were scanned during TLS data collection. The spatial 3D distances between adjacent points established by NBDTI were computed from both the RTK GPS results and the TLS point cloud, and the results were compared. Analysis of the results determined that the mean difference between the RTK GPS derived distance and the TLS derived distance was 0.002m, with a standard deviation of 0.016m (see Figure 11 and Table 1).

Since RTK GPS is considered to have an accuracy of approximately 2cm horizontally, the results show that TLS results are compatible with the RTK GPS results. Given the accepted precision of RTK GPS, it is likely that the TLS data has better accuracy than the RTK GPS results and is more likely sub-centimetre.

Figure 10 **Departures from best-fitting surface**

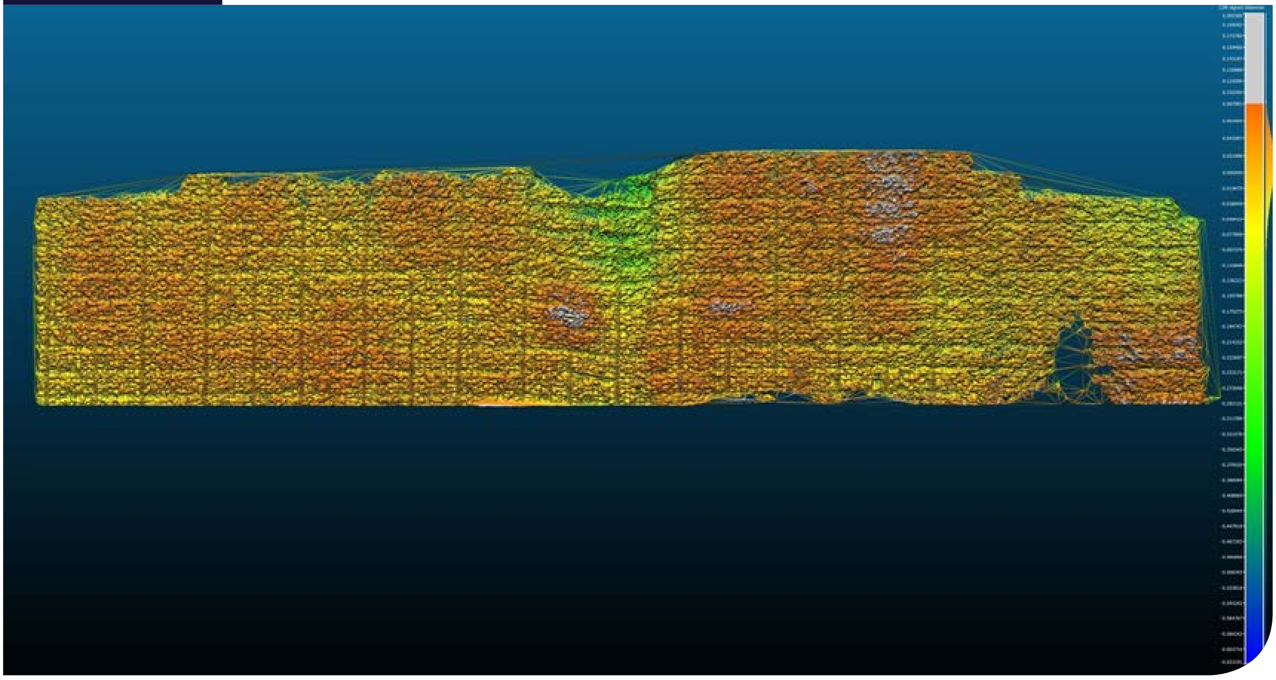


Image source: Image developed using CloudCompare, Version 2.7, 2016

Figure 11 **Points created by NBDTI**

Image source: Google Earth, 2018

3.3 Summary

The project produced a number of suggestions that could assist in future analysis of the stability of artificial structures. This work has shown that TLS data can have a greater accuracy than RTK GPS – this is not surprising, but the data analysis confirms what would be expected. By determining a best-fit surface through the point cloud, areas of the wall that have significant deviation from this surface have been identified. These areas warrant closer study for any potential movement in the future. Through the study of shadow areas, the research has been able to identify areas of the wall that are resting on the rock base without any bench – again, these areas should be studied in the future.

3.4 Next steps

As a result of the plant and sapling growth at the base of the wall, and the bench, it was impossible to collect laser scanning data spanning the entire wall – there are 'shadow' areas (or 'holes' in the data) as mentioned previously. These shadow areas are extremely common in laser scanning work, but are highly problematic as it is impossible to determine any movement in the shadow areas since the laser did not touch the wall in those locations. This research therefore developed a method to fill-in the shadow areas by creating a 'patch' from the UAV data to fill-in the hole in the laser scanning data. This resulted in 3D data covering the entire wall, created by a combination of both the laser scanning data and the UAV data.

Table 1 Differences between RTK GPS distances and TLS distances

Difference in CPs	A: GNSS RTK (DTI) (units: meters)	B: Scanner (UNB GGE) (units: meters)	Differences (units: meters)	Comment
CP1-CP2	12.5199	12.5227	-0.0028	
CP2-CP3	12.5133	12.5300	-0.0167	
CP3-CP4	12.5595	12.5250	+0.0345	abs(x)=Largest
CP4-CP5	12.5218	12.5335	-0.0118	
CP5-CP6	12.5643	12.5457	+0.0186	
CP6-CP7	12.5325	12.5349	-0.0024	abs(x)=Smallest
CP7-CP8	12.5133	12.5298	-0.0186	
CP8-CP9	12.5181	12.5324	-0.0142	
CP9-CP10	12.5524	12.5285	+0.0239	
CP10-CP11	12.4823	12.4913	-0.0090	
CP11-CP12	12.4930	12.4962	-0.0032	
CP12-CP13	12.5235	12.4994	-0.0241	
CP13-CP14	12.4883	12.4925	-0.0042	
CP14-CP15	12.4760	12.4891	-0.0131	
CP15-CP16	12.5143	12.5074	+0.0069	
CP16-CP17	12.5010	12.4903	+0.0107	
CP17-CP18	12.4947	12.4978	-0.0031	
CP18-CP19	12.4862	N/A	N/A	CP19 Issue
CP19-CP20	12.4961	N/A	N/A	CP19 Issue
CP20-CP21	12.5071	12.4953	+0.0117	
CP21-CP22	12.4813	12.5033	-0.0220	
CP22-CP23	12.5232	12.5006	-0.0226	
CP1-CP23 (first - last)	269.9834	269.9714	-0.0120	

4.0 The UAV

Figure 12 **DJI Phantom 3 UAV**

Image source: Dare, 2015

The NBDTI used a DJI Phantom 3 Professional UAV (see Figure 12). This has a built in 4K camera which is mounted on a three axis (pitch, roll, raw) gimbal stabiliser so that it is able to record with a constant heading. It also takes 12.76 megapixel images. The UAV has a vertical accuracy of ±0.5m and a horizontal accuracy of ±1.5m (DJI, 2018). The UAV is controlled through an app on a mobile phone, and the battery provides 15-20 minutes of flying time with a one-hour recharge time. The UAV is able to take both still pictures and movies. For the purposes of this research, photo overlaps were used to enable the images to be stitched together. To process the UAV data, Pix 4D was used.

4.1 UAV point cloud

Figure 13 represents the fully registered point cloud of the retaining wall resulting from the laser scanner. The areas coloured blue represent the gaps where the laser beam failed to reach. Therefore, those gaps contain no information. An example is shown in Figures 14 and 15.

Figure 16 represents the fully registered point cloud of the retaining wall resulting from the UAV. The viewing angle is different to the laser scanner, but the quality of the registered point clouds were confirmed to be a few centimetres when a comparison was made with the GPS control points (the laser scanner precision was 16mm).

Figure 17 is an enlargement of a small area of Figure 16. Some blue areas can be still seen, but most of the blue areas where the laser scanner could not record were covered by the UAV. This is the data that can be used for integration into the TLS data.

4.2 UAV integration method

The Trimble TX5 Laser Scanner has an accuracy of a few millimetres, while the UAV has an accuracy of a few centimetres. The research team therefore attempted to avoid having large overlapping areas of the laser scanner data with the lower accuracy UAV data, which is a possibility when the datasets of the same subject area are integrated.

Figure 13 Complete point cloud from laser scanner

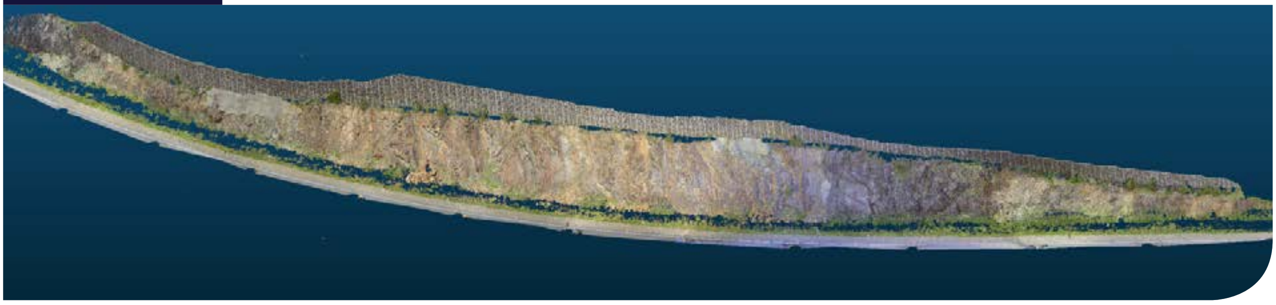


Image source: Image created using FARO SCENE, version 6.0, 2016

Figure 14 Enlarged area of laser scanner point cloud

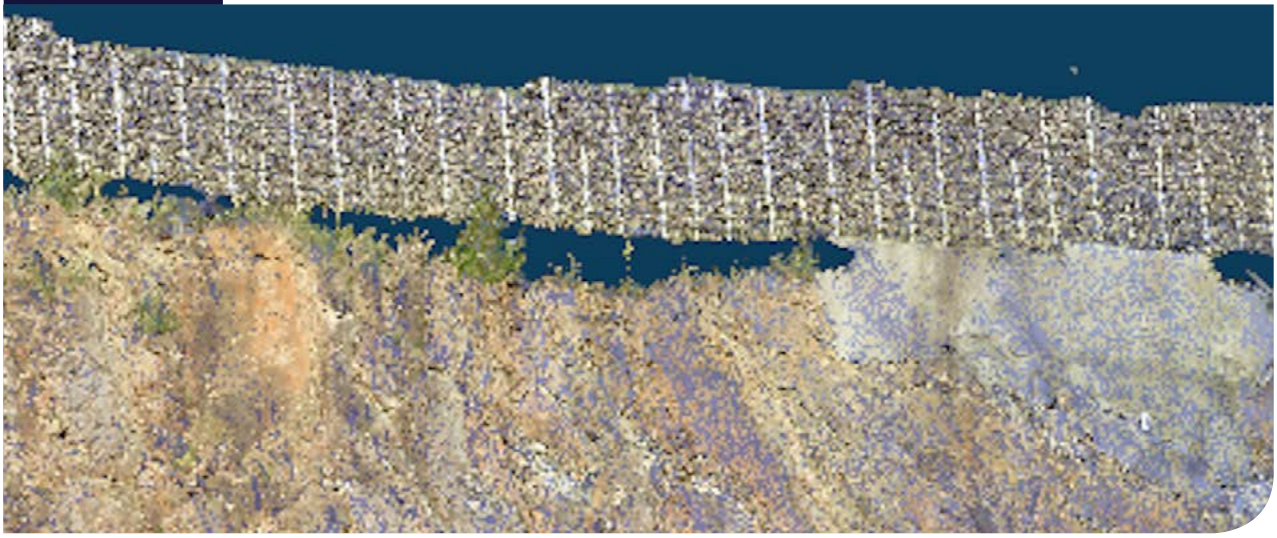


Image source: Image created using FARO SCENE, version 6.0, 2016

Figure 15 Further enlarged area of laser scanner point cloud

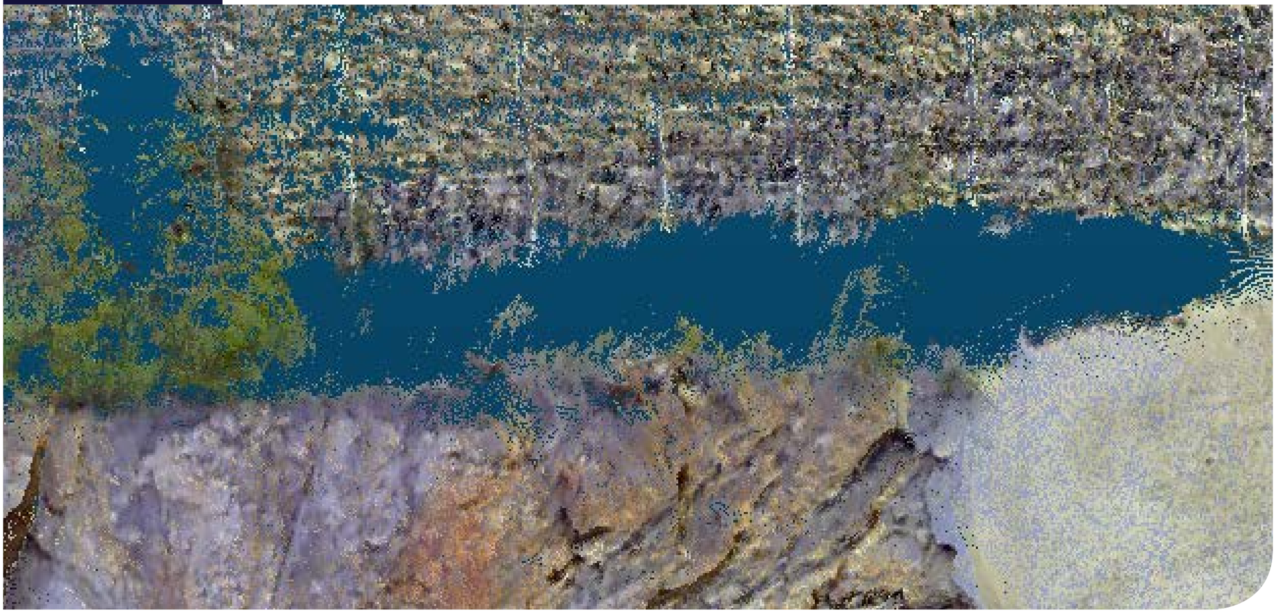


Image source: Image created using FARO SCENE, version 6.0, 2016

Figure 16 UAV point cloud of entire wall

Image source: Image created using FARO SCENE, version 6.0, 2016

Figure 17 Enlarged area of UAV point cloud

Image source: Image created using FARO SCENE, version 6.0, 2016

Figure 18 Location of the four control points

Image source: Image created using FARO SCENE, version 6.0, 2016

The coordinates of the NBDTI control points for the two measurement techniques had a slight mismatch at the centimetre level. To utilise the datasets, a preliminary test for the integration of the two data sets was carried out. Four control points were chosen to enable a comparison to be made between the UAV and laser scanning data.

Figure 18 illustrates the location of the four control points chosen from within the UAV and laser scanning point clouds.

Table 2 shows the difference (labelled 'Error') at the control points (labelled 'R0' to 'R3') between the coordinates determined by the laser scanner and the UAV. For the calculation and integration, the CloudCompare software was used. The maximum difference was just over 7cm while the smallest difference was just over 3cm.

Table 2 Laser scanner and UAV coordinate differences at the control points

	X	Y	Z	Error
R0	53.0699	80.272	104.328	0.0329252
R1	39.237	6.38296	102.348	0.0661337
R2	2.08423	-86.3617	101.684	0.0731399
R3	-41.8985	-147.005	102.969	0.0576924

Software: CloudCompare, Version 2.7, 2016

4.3 Result

The final Root Mean Square (RMS) value for the entire integration was approximately 6cm (see Table 3). The laser scanning and the UAV point clouds integrated well and the UAV data has successfully filled the data gaps caused by obstructions to the laser. The diagonal elements in the matrix shown in Table 3 are all very close to 1.000 indicating there is no significant scale difference between the UAV and the laser scanner.

Figure 19 represents the same enlarged area shown in Figure 15 but with the merged UAV data. Data points in the blue area within the rectangle are now visible. Figure 20 shows the entire integrated point clouds based upon both the laser scanning and UAV point clouds.

Table 3 RMS for the data integration

Final RMS: 0.0594466

Transformation matrix

0.994	-0.060	0.092	-13.167
0.062	0.998	-0.013	3.254
-0.091	0.019	0.0996	2.506
0.000	0.000	0.000	1.000

Scale: fixed (1.0)

Software: CloudCompare, Version 2.7, 2016

Figure 19 **Enlarged image of merged point clouds**

Image source: Image created using FARO SCENE, version 6.0, 2016

Figure 20 **Merged point clouds**

Image source: Image created using FARO SCENE, version 6.0, 2016

Image source: Google Maps, 2019

4.4 Further research

This research demonstrates the possibility of using UAV data to fill data gaps in laser scanning data. The methodology introduced is an approximate but fast method as it does not involve any demanding calculations. Further, as the location of the data gaps is identified, only the necessary surrounding areas of the point clouds are needed.

This 'patching' technique would be useful in other laser scanning projects where there are difficult to access shadow areas. An example would be rooftops of buildings where the sides of a building can be scanned, while the rooftop is unlikely to be visible from the ground. The work described here will be useful to the laser scanning community as it helps solve a common problem.

5.0 Conclusions and recommendations

The aim of this project was originally to evaluate the use of terrestrial laser scanning as a tool to determine deformation of a retaining wall. The research team took the opportunity to analyse the accuracy of TLS by comparing these with scanning points coordinated by GPS. This report has shown that a Trimble TX5 laser scanner has a precision of approximately 2mm, +/-16mm when compared to RTK GPS results.

The results show that UAV data can be integrated into the laser scanning data. The data from the UAV that is filling the laser scanning data gap is at a lower resolution to the laser scanning data due to the lower quality UAV data. This became clear when the data from the laser scanner and UAV were merged together. This is an important point as it means it is possible to have one set of merged data but with varying resolution. The accuracy of derived products therefore becomes dependent on its location in the dataset. It may therefore be necessary to attach the source of the data to the data itself, so users are aware of the varying data resolution.

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