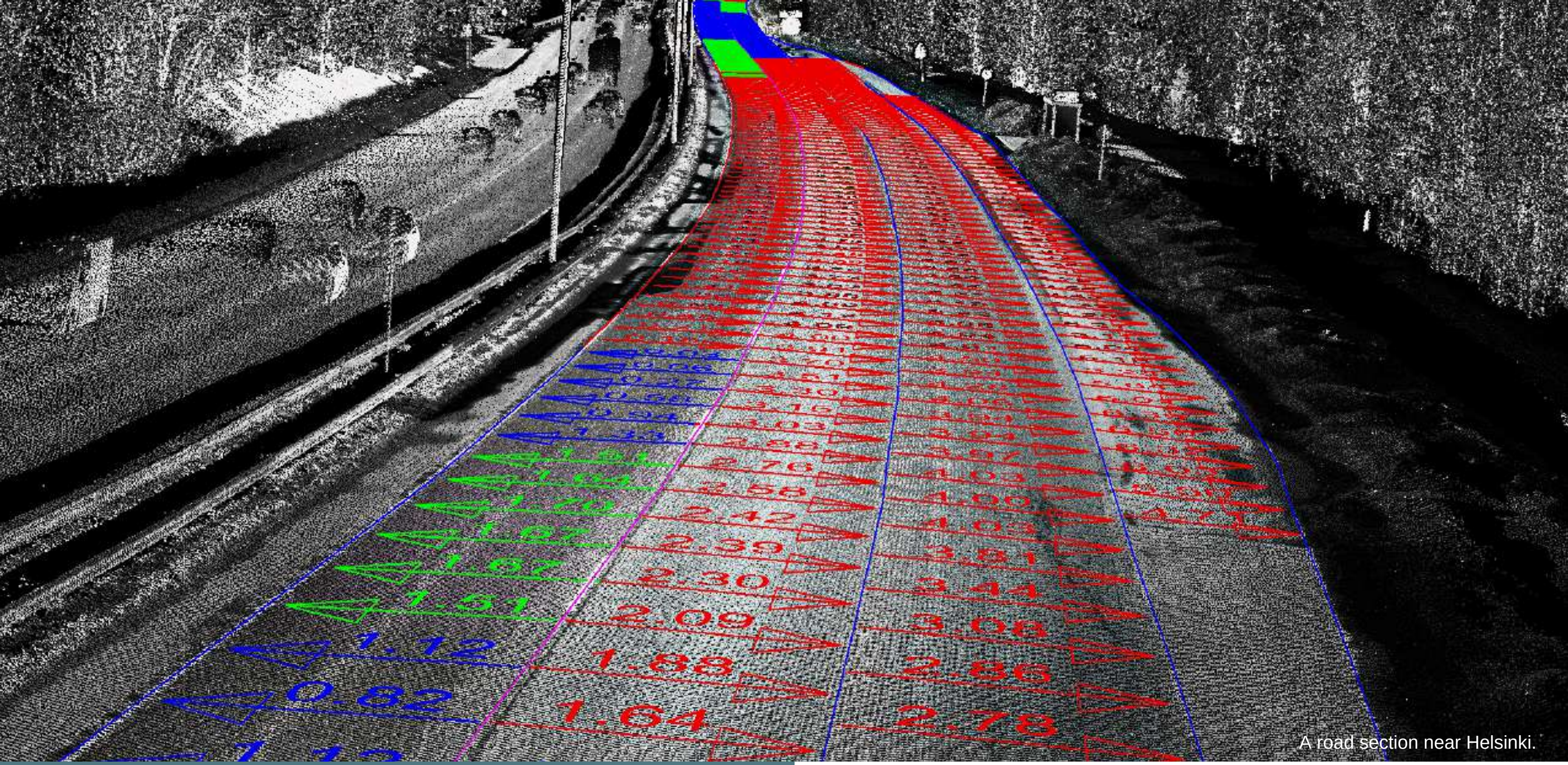

A road section near Helsinki.

High-Precision Mobile Mapping for Accurate Road Surface Condition Parameters

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Is it possible to produce road surface condition parameters using LiDAR data? The simple answer is yes, but first, there must be an understanding of what LiDAR is. LiDAR technologies consist of active sensors that use electromagnetic waves in optical and infrared frequencies. There are several different types of imaging technologies within the wide concept of LiDAR. In this article, we focus on *RIEGL*'s Ultimate LiDAR™ technology, which was used to produce road surface condition parameters passing the official VTI (The Swedish National Road and Transport Research Institute) tests conducted in Sweden. Not all of the current commercial mobile LiDAR systems produce data that is accurate enough for the task that is described in this article. It has been shown that *RIEGL* VMX mobile laser scanning technology can be used in network-level road surface condition surveys at high speeds.

Motivation of This Work and How It All Started

Nordic Geo Center Ltd in Finland has developed a method to use the *RIEGL* VMX mobile mapping systems in accurate road measurements to replace the total station measurements since 2013. The background for this work is the previous experience of the key personnel in developing software and hardware for road surveys starting in the 1980s. Road surveys have been based on profiles and cross-sections for several centuries in the past due to measurement technologies, but the new data types open up new possibilities for the use of the data. Using LiDAR, the traditional method of measuring longitudinal and latitudinal sections is not needed anymore.

RIEGL Laser Measurement Systems released its first two scanner “crossfire” mobile laser scanning (MLS) system *RIEGL* VMX-250 in 2009. This instrument was presented in Finland already in 2010 and the demonstration convinced Hannu Heinonen, the founder of Nordic Geo Center Ltd, that MLS seemed to be ready for accurate surveying results from the perspective of land surveying.

Development from 2013 - 2023

The development started in 2013 with the *RIEGL* VMX-450 MLS system that was placed on a BMW X5 SUV vehicle. The typical vans of that time used as survey vehicles were deemed too clumsy for on- and off-road surveys and the BMW engine and gearbox technology was assumed to produce less interference for the system’s inertial measurement unit (IMU). It is also easier to produce the required driving dynamics for the proper use of the IMU, even though today many mobile laser scanner users want to acquire the data at constant speeds.

During the years, several *RIEGL* VMX systems have been used in the development. First the VMX-450, then VMX-1HA and VMX-2HA. The latest *RIEGL* VMX-2HA is operated by Nordic Geo Center Ltd since the summer of 2023.

Components of the VMX-2HA high-performance mobile mapping system, see figure 1:

- **two *RIEGL* VUX-1HA profile scanners** based on time-of-flight technology, each with a 1.8 MHz pulse repetition rate and 250 scan lines per second. These laser scanners have multi-target capability which for example enables the penetration of vegetation. The *RIEGL* waveform attributes provide much more information than just a range reading, such as calibrated amplitudes, a range-independent reflectance as well and a pulse shape deviation related to each measured point
- **a high-grade Inertial Navigation System (INS)** based on multi-band GNSS and a fiber-optic-gyro IMU which provides drift stability in challenging GNSS conditions
- **an optional camera system** which can be equipped with up to 240 MP resolution comprising up to 7 x 24 MP directional cameras and an up to 72 MP spherical camera
- **a central trigger & and time stamping unit** that ensures synchronization of all system components (INS, scanners, cameras, external devices) as well as the data transfer with up to 11 Gigabit bandwidths to the control unit. The control unit is a compact trolley-sized portable case that can easily be put in the trunk or the backseat of the car. It precisely controls the management of power, data acquisition, and operation of the laser scanners, INS/GNSS system, and optional cameras
- **the VMX-2HA roof mount** which enables a convenient mounting on commercially available Thule roof bars

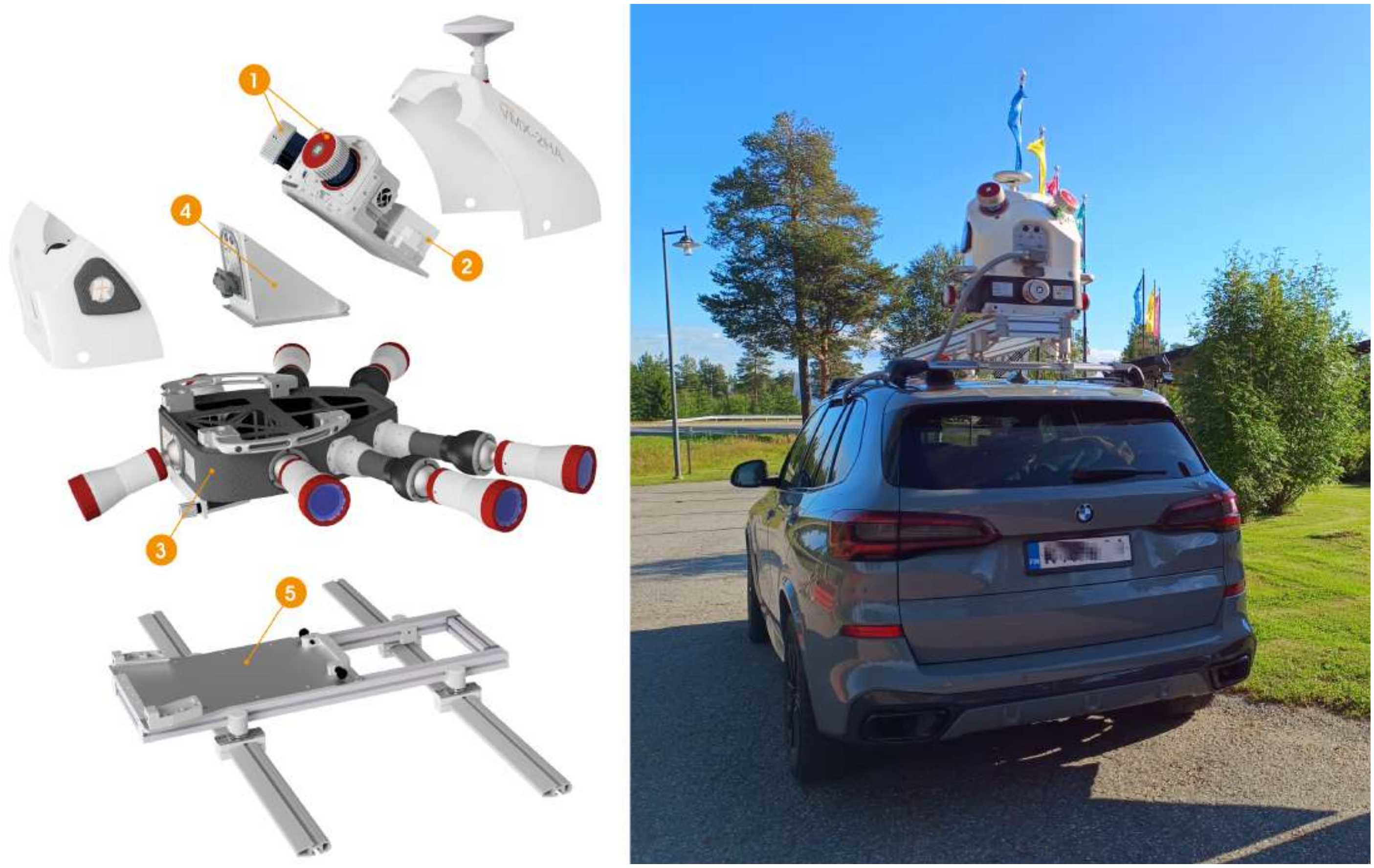

Figure 1: On the left an exploded view of the *RIEGL* VMX system and on the right the system attached to the surveying vehicle.

The BMW X5 has remained the surveying vehicle as the results have been good and every new vehicle type needs to be tested for suitability. Hannu Heinonen at Nordic Geo Center Ltd considers the vehicle as the equivalent to the tripod used in total stations and thus part of the measurement system. When aiming for the highest accuracies, all parts of the measurement system including the people using it, the ambient environment, weather, etc. start to add up to the total uncertainty.

Contrary to many guidelines, they use as few as possible survey tie points in the processing. The data is not good enough if tie points are needed every 50 - 500 meters just to connect the parallel records or match as it is generally called. Control points to check the accuracy of the data are another matter and there can be as many as the procurer wants to provide. In engineering-level surveys with *RIEGL* VMX, height control points are needed every few (3…6 km) kilometers and there is also a need for control points in GNSS-limited locations such as within forests or urban canyons.

According to the philosophy of Tauno Suominen and Hannu Heinonen from Nordic Geo Center Ltd, the human-intense acquisition of tie points/control points is expensive, so the value of MLS must be provided by diminishing the need for additional human resources. A second note on the control points is that they must be part of a reliable geodetic network measured with GNSS base stations and total stations. The heights should be leveled if possible. It is of no use to worsen a geometrically accurate point cloud by controlling it with RTK-GNSS survey points.

From Engineering Road Survey Projects to Road Surface Condition Surveys

The question at Nordic Geo Center Ltd has always been what else can be done with this quality of data and one direction led to road surface condition parameters. Would their data be good enough? The initial hypothesis based on their knowledge was positive, so they started to look into how to calculate the results from their data which is very different than the traditional data created by parallel highly accurate point lasers that provide sub-millimeter accuracy in distance measurement. As the results mean nothing without control to current standards, they took part in a couple of development projects by the Finnish Transport Agency (nowadays Finnish Transport Infrastructure Agency). The first results encouraged them to develop further until in 2019, when they were asked to participate in the VTI tests in Sweden. The VTI tests are arranged for the winners of the public tenders to check that their measurement systems provide data according to the standards.

In the 2022 VTI tests, Nordic Geo Center Ltd successfully produced all the parameters required for the systems used on Finnish roads. This time there were four about 1 km test sections in Sweden and one around 300 km test section in Finland.

Figure 2: *RIEGL* VMX measurement principle: The image illustrates the “crossfire” scan lines of the two scanners (colored in red and green). The foreground shows the VMX point cloud colored with the reflectance attribute, the background shows the optional RGB colored point cloud.

"At first, we did not produce all the required parameters, but we did pass the five about 1 km short sections which were needed to be repeated five times each at different speed. We also passed one of the more than 120 km loops which needed to be repeated twice. Due to rain, we could not acquire all the length of the second loop. As the VTI reference is well documented and measured, the results showed that we are on a right path."

Hannu Heinonen

At first, no one could believe that *RIEGL* VUX scanners could produce anything similar compared to these sub-millimeter lasers used for many decades. These lasers are also located very close to the road surface in front of the vehicle whereas the *RIEGL* VMX lasers do not meet the road surface perpendicularly but in a sloped angle. The profiles they produce are not perpendicular to the direction of the road either.

To check the results, it is also relevant to measure the reference measurements carefully and the references should be more accurate than the tested measurement systems. In Sweden, the reference values for transverse profiles were measured with the VTI-XPS which consists of seven LMI Gocator 2375, a GPS receiver and inertial navigation unit (OXTS Survey +). The values are measured for the width of 3.6 m and filtered for the width of 3.2 m. The profile is collected at every 0.1 m with one value every 1 mm in transverse direction. The transverse profile is used to calculate values for the rut depth, ridge and crossfall variables.

The longitudinal profiles were measured using a total station every 10 meters and the Primal, which will collect the values every 4 mm between the total station points while moving. The IRI values are calculated using these profiles. For curvature and hilliness, a XYZ position is measured every 4 and 10 m along the road. The radius is calculated for every three points along the section and the longitudinal slope is calculated every 2 m and 4 m points.

The position will be calculated with a combination of GPS and total station measurements. Only the first 100 m of the test sections are used for reference to minimize the length differences between different systems.

What Can We Produce With *RIEGL* VMX Systems?

Road surface condition parameters

A key product based on VMX mobile mapping data is road surface condition parameters. At the 2022 VTI tests, Nordic Geo Center Ltd successfully produced the following road surface profile parameters: IRI right, IRI left, Rut depth max, Rut depth right, Rut depth left, Height of Ridge, Position XYZ (SWEREF99 TM), Position Z (RH 2000) Crossfall, Hilliness and Transverse profile.

Table 1 shows the requirements and the acceptance interval for the Finnish vehicles in the 2022 test. (Source: VTI[1]). The longitudinal profile is based on the standard SFS EN 13036-5, the date and time of the measurement needs to be saved in the data according to ISO 8601 standard, the transverse profile needs to be filtered as instructed in the draft prEN 13036-8 for a standard or in a similar fashion and the IRI is calculated using the SFS EN 13036-5 standard. All of the above-mentioned standards are based on their international counterparts.

Parameter	Category	Acceptance interval	Limit
IRI Right	Reference ≤ 2.00 mm/m	Ref-0.35 mm/m ≤ TV ≤ Ref + 0.35 mm/m	72%
IRI Right	Reference ≤ 2.00 mm/m	Ref-(0.35 + (Ref-2.00) x 10%) mm/m ≤ TV ≤ Ref + (0.35+(Ref-2.00)*10%) mm/m	68%
Rut depth max	Reference ≤ 7.5 mm	Ref-1.0 mm ≤ TV ≤ Ref. + 1.0 mm	77%
Rut depth max	Reference ≤ 7.5 mm	Ref-(1.0 + (Ref-7.5) x 5%) mm ≤ TV ≤ Ref + (1.0+(Ref-7.5) x 5%	77%
Rut depth left	Reference ≤ 7.5 mm	Ref-1.0 mm ≤ TV ≤ Ref + 1.0 mm	77%
Rut depth left	Reference ≤ 7.5 mm	Ref-(1.0+(Ref-7.5) x 5%) mm ≤ TV ≤ Ref + (1.0+(Ref-7.5) x 5% mm	77%
Rut depth right	Reference ≤ 7.5 mm	Ref-1.0 mm ≤ TV ≤ Ref + 1.0 mm	72%
Rut depth right	Reference ≤ 7.5 mm	Ref-(1.0+(Ref-7.5) x 5%) mm ≤ TV ≤ Ref+(1.0 + (Ref-7.5) x 5%) mm	72%
Height of ridge	Reference ≤ 7.5 mm	Ref-1.0 mm ≤ TV ≤ Ref + 1.00 mm	77%
Height of ridge	Reference ≤ 7.5 mm	Ref-(1.0+(Ref-7.5) x 5%) mm ≤ TV ≤ Ref+(1.0+(Ref-7.5) x 5% mm	77%
Position X,Y SWEREF99		|TV-Ref| ≤ 0.75 m	95%
Position Z RH 2000		|TV-Ref| ≤ 4 m	95%
Crossfall regression	|Reference| < 3.00%	|TV-Ref| ≤ 0.50%	85%
Crossfall regression	|Reference| ≥ 3.00%	|TV-Ref| ≤ 0.50% + (|Ref|-3.0) x 5%) %	85%
Curvature	|Reference| < 10.0 1/m	|TV-Ref| ≤ 5.0 1/m	85%
Curvature	|Reference| ≥ 10.0 1/m	|TV-Ref| ≤ 5,0+(|Ref|-10,0) x 10%) 1/m	85%
Hilliness	|Reference| < 3.00%	|TV-Ref| ≤ 0.75 %	85%
Hilliness	|Reference| ≥ 3.00%	|TV-Ref| ≤ 0.75 + (|Ref|-3.0) x 5%) %	85%
Transverse profile		Point by point |TV-Ref| ≤ 0.5 mm	80%

Table 1: Acceptance limits for validity at the test sections.

Abbreviations and explanations:

- *TV (abbreviation for Tested Vehicle); this is the value that the participants provide from their systems.*
- *Ref is VTI reference value.*
- *The percentage limit means that e.g., 72% or more of the values you have provided should be with the acceptance interval. Your IRI does not pass if only 71% of the IRI values are within this limit.*
- *Position Z means the height given in the Swedish geodetic height system RH2000.*
- *Position XY is also given the Swedish system which in turn is based on the European reference ETRF frame.*

These parameters needed to be calculated from the data acquired five times at two different speeds, 40 km/h and 70 km/h in four 1 km test sections and two times in a longer, around 300 km section. The data for the latter long section was acquired in two consecutive runs during the same day, so the results also show if the time and temperature-dependent errors in the scanning system are kept well under control. The data for the longer section was acquired at normal traffic speeds varying between 40 – 80 km/h and checked for repeatability and reproducibility. Speed dependency means that the maximum absolute value of the difference between the average value of all measurements at different speeds is calculated and should remain within the specified limits.

The processing of the *RIEGL* VMX-2HA data to produce road surface condition parameters is a semiautomatic process that starts with the calculation of the trajectory geometry. Once the trajectory quality meets the requirements of the project, the rest of the point cloud processing is a largely automatic process in *RIEGL*'s RiPROCESS software. If necessary, the different runs can be matched together, but this is not always required. It should be noted that due to the nature of network-level road condition surveys, sometimes thousands of kilometers are surveyed and results need to be provided in a very short time period, the use of signal/control points is not possible in terms of time. Many LiDAR systems seem to need signal points to achieve the required level of accuracy or even just to combine different data sets. In this test, the positional accuracy requirement is ± 0,5 m for both X and Y and ± 2m for Z value. Note, that the position needs to be within limits also in forested areas where trees are on both sides of the road. More than 50% of the roads in Finland are in forested areas and many of them are narrow as well which means that the positioning of any used surveying system needs to be good.

Compared to the traditional, profilometer-based road survey methods, LiDAR is easier to acquire, because the vehicle does not need to be kept in a specific location on the lane. As an active sensor - LASER - is used, mobile laser scanning is also inherently independent of the ambient light and hence, to improve productivity, data acquisition can be done day and night. Ambient light is only required if images are to be taken simultaneously.

The traditional road surface measurement technology seems to achieve repeatability by driving the acquisition runs in a specific part of the road in relation to the painted lines. The technology has also problems with the length of the roads, which is why the test teams calibrate their vehicles on designated road sections during the tests in Sweden. During the contract period, the acquisition vehicles are also regularly cross-checked for data consistency. Therefore, it is also worth noting that the *RIEGL* VMX systems are factory calibrated and do not need to be calibrated at any point during the field acquisition. The solidly build structure is very stable and designed for work in industrial production. In particular, the geometry and position data are several orders of magnitude better than with typically used traditional mobile road survey methods.

Engineering surveys

However, the *RIEGL* VMX system's main task is to create geometrically accurate data when properly used. The excellent data quality is the base for all types of engineering surveys such as road design, controlling and monitoring as-build infrastructures such as bridges, tunnels, and drainage. There are software tools that allow to calculation of the road geometry that represents the current state of the road. This kind of best-fit road geometry as well as the other parameters also allow one to check the state of the road in an accident investigation. In particular, older, heavily trafficked roads might be already structurally damaged in such a way that a repair or lower speed is necessary.

Harald Teufelsbauer, MLS Business Division Manager at *RIEGL* Laser Measurement Systems, puts the spotlight on the versatility of the VMX Laser Scanning System and the increase in efficiency and productivity for the users. "On the one hand our mobile mapping systems provide the precision to deliver road profile parameters, as e.g., proven by VTI acceptance tests. On the other hand – with the same equipment, during the same mission, and without spending

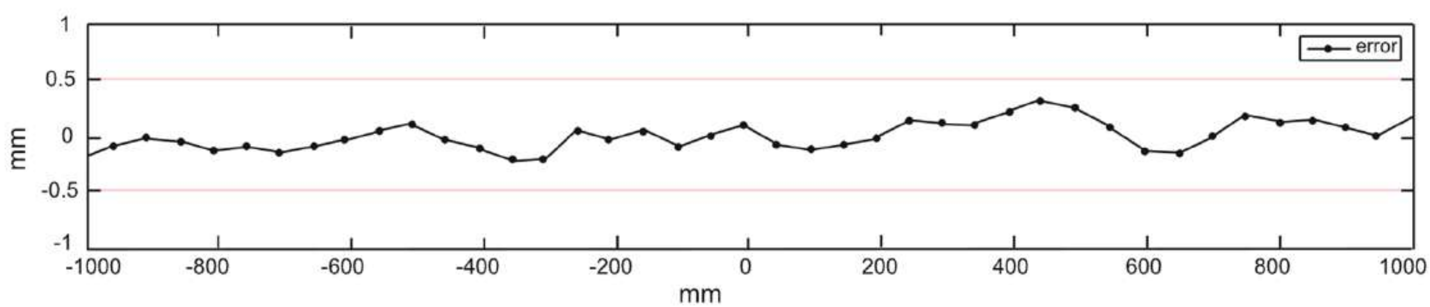

Figure 3: An example of the transversal profile difference between the VTI reference value and the value created with the *RIEGL* VMX. The difference is marked as an error and the vertical scalebar shows the difference in millimeters.

any additional time in the field – the user will get so much more information out of the system, whereas traditional methods need the acquisition with different systems in multiple mission in order to achieve the goals. The benefit of *RIEGL* Mobile Mapping is the accurate mapping of the complete 360 degrees clearance profile along the travelled path. That allows to capture in a single run not only the lane travelled, but also the surrounding environment along the travelled path. Since the visibility of some objects of interest might be obstructed by any obstacles such as traffic, multiple

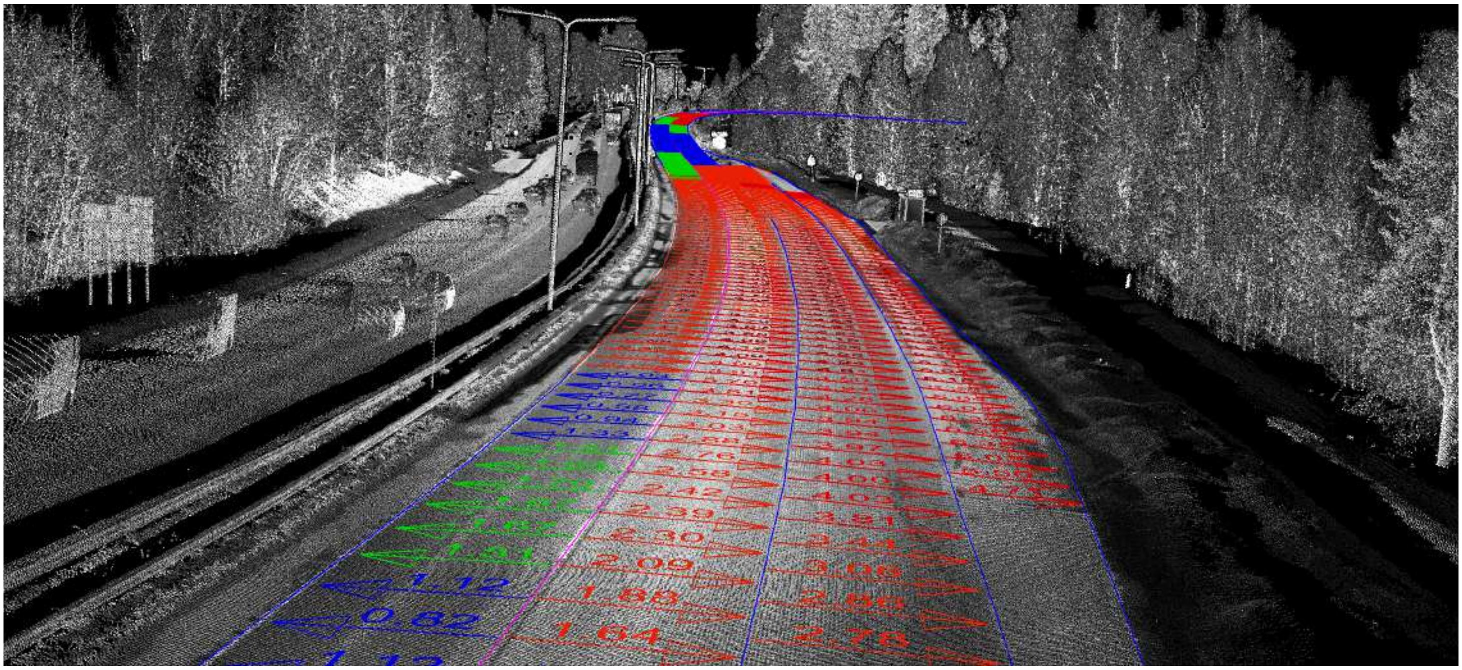

Figure 4: A road section near Helsinki, where the structure of the road has clearly failed. The arrows show the direction of the crossfall in each lane and for visualization purposes all the values sloping from left to right are painted red illustrating the wrong sloping direction in a curve.

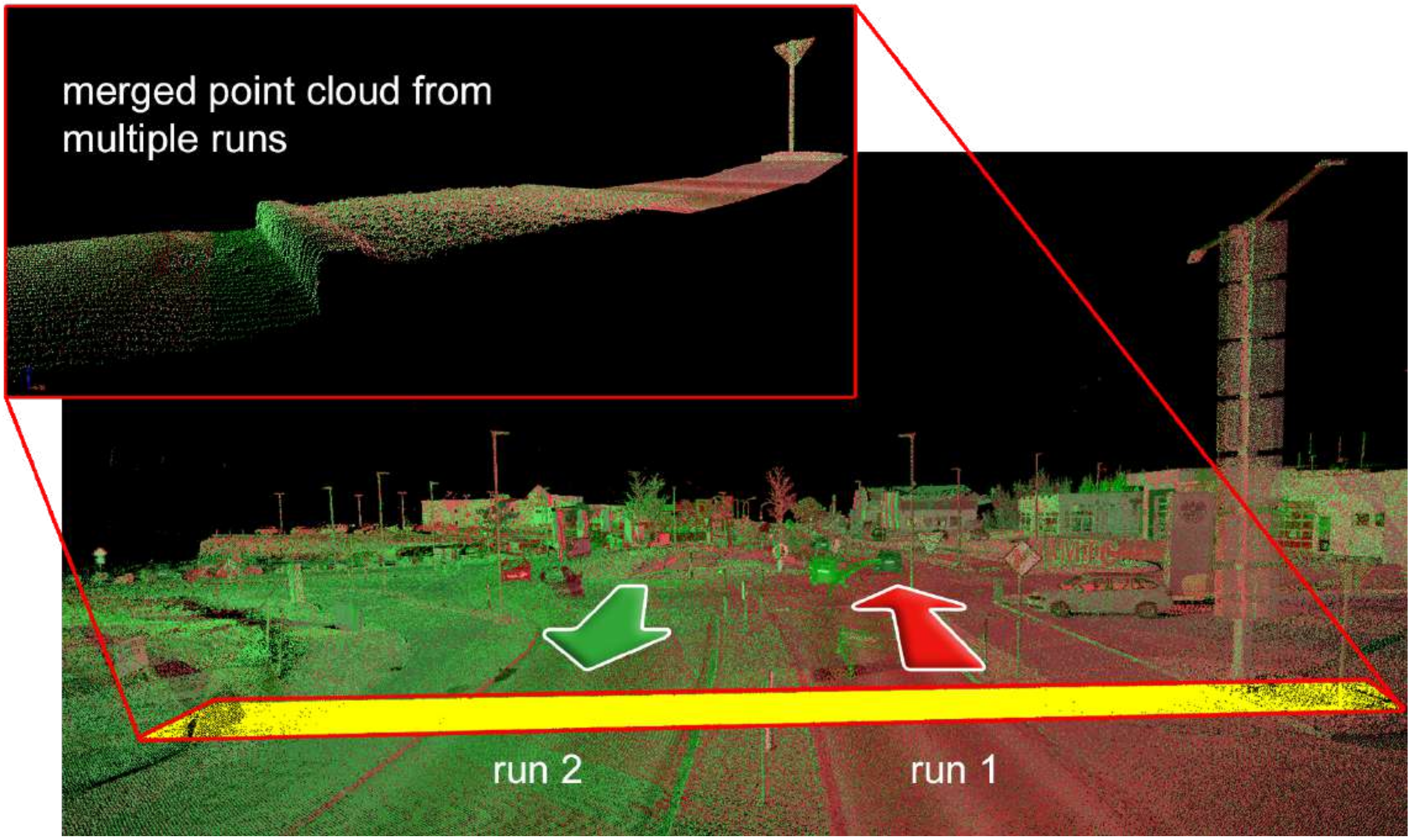

Figure 5: The point cloud shows the results of *RIEGL* rigorous scan data adjustment, resulting in a precisely aligned point cloud acquired by two runs driving in opposite directions (run 1 colored in red; run 2 colored in green).

runs on different lanes or in different directions are common practice in mobile mapping. Due to a highly accurate geo-referencing of each individual scan pass as well as a rigorous scan data adjustment of overlapping scan data captured from multiple runs, the result is a consistent point cloud with a feature rich 3D representation of the complete transportation infrastructure as well as the surrounding topography."

In addition to high accuracy surveys, the same VMX data can be used for example to model and check road furniture, document bridges in high accuracy, monitor deformation of rock cuttings and slopes along the road (see figure 6), conduct a vegetation analysis and passage analysis for oversize vehicles, but is also widely used to produce high-definition maps for autonomous vehicles. The digital elevation model of the surrounding area next to the road, in combination with the precise information of crossfall, rutting, potholes and other road defects allow a very precise modeling of water runoff, drainage or aquaplaning risk in the case of heavy rain.

Future Plans

One of Nordic Geo Center's future goals is it to check which other road surface condition parameters can be extracted from the VMX data. It is clear that the calibrated reflectance values could be used to check the reflectivity of the road signs and paintings. Furthermore, the shape, area, and volume can also be calculated from the data and the ruts with steep edges can be classified as more dangerous than the ruts with gently sloping edges.

It is also of interest to use this type of data for the road resurfacing workflow as minor geometric issues can be fixed during resurfacing. Similar in concept to railways, where the rails and minor rail geometry issues are corrected at the same time when repairing the track. When the geometry problem is too large, the tamping machines can no longer fix it. Currently in Finland the resurfacing vehicles on the road are often guided using a total station. Nordic Geo Center's approach would be to survey the road surface in order to generate a 3D model first and then it will be possible to attain the height position of the machine-controlled vehicles from the model. The accuracy of the GNSS is then sufficient for the XY positioning of the resurfacing vehicle. The process of milling and resurfacing will become much more simple and more accurate than the current total station-based machine control.

The new 3D laser mapping technology provides new kind of raw data which can be used to create new types of products, 3D visualizations, reference data for road design, or, for example, it can be used to create a best fit road geometry. These products could be used directly instead of processing the data into old output formats such as excel spreadsheets. The development of measurement tools and methods is only part of the overall process, where the use of data as part of the overall process also needs to be inspected in a new way.

[1] Source: VTI Test Description – 20022-09-01. Quality requirements and approval procedures Procurement of Road Condition Measurements in Finland, Thomas Lundberg, Diarienummer: 2019/0076-9.1.

Figure 6: *RIEGL* Mobile Mapping point cloud data: High resolution coverage of the road infrastructure as well as the surrounding terrain. The zoomed area shows a rock formation close to the clearance profile of the road.