Mobile Laser Scanning in Infrastructure Design and Survey

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ABSTRACT

Tampereen ammattikorkeakoulu
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AARON DAUD SEDIQI:
Mobile Laser Scanning in Infrastructure Design and Survey

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This thesis was written for Roadscanners Ltd. to document and summarize mobile laser scanning services they offer among other non-destructive research methods. This work can be exploited as a marketing document for the customers, which will assist them in choosing the right type of services for their needs. The work was a result of a long research and all material from different sources were examined objectively. Sources available were mainly scientific publications, articles and project reports.

The thesis used a chronological order presenting a brief history of development of laser scanning followed by its uses in modern surveys. The thesis focused on mobile laser scanning as survey tool for infrastructure condition management. Laser scanning produces point clouds as raw data from which all the surface features can be extracted and presented in a photorealistic viewer-friendly manner. Case examples where mobile laser scanning was successfully applied to real life projects were presented and illustrated.

Mobile laser scanning is a tool for both design and survey of structural and functional condition of infrastructure. This survey method is applicable throughout the life span of a project from ground survey and mapping before building structures to quality assurance and as-built surveys. This method could also be exploited in building information modeling (BIM). Laser scanning and digital three dimensional modeling in general has gained popularity and is on its way to becoming a standard tool. This is a result of high accuracy, speed and diversity of data obtained by laser scanning.

Mobile laser scanning, 3d modeling, mobile mapping, infra-structure survey, point cloud

TIIVISTELMÄ

Tampereen ammattikorkeakoulu
Rakennustekniikan koulutusohjelma
Infrarakentamisen suuntautumisvaihtoehto

AARON DAUD SEDIQI:
Mobiili Laserkeilauksen Käyttö Infrarakentamisessa

Opinnäytetyö 60 sivua, liitteitä 2 sivua
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Tämä opinnäytetyö on tehty Roadscanners Oy:lle. Roadscanners Oy:n palveluvalikoimaan kuuluu muiden ainetta rikkomattomien tutkimusmenetelmien ohella mobiili laserkeilaus. Tarkoituksena oli tuottaa kirjallinen dokumentti, jota asiakkaat voivat käyttää tarvitsemansa palvelun valitsemiseen. Työ on usean vuoden jatkuneen tutkimustyön tulos. Lähteinä on käytetty pääasiassa tieteellisiä julkaisuita, artikkeleita ja tutkimusraportteja.

Työ etenee kronologisessa järjestyksessä edeten laserkeilauksen historiasta sen nykyisiin sovelluksiin. Opinnäytetyö keskittyy mobiiliin laserkeilaukseen, jota käytetään tutkimustyökaluna infrarakenteiden kuntotutkimuksissa. Laserkeilauksella luodaan pistepilvi, jonka raakadatasta voidaan jalostaa käyttäjäystävällisessä muodossa olevia esityksiä rakenteiden kunnosta. Työssä esitellään myös esimerkkejä todellisista projekteista, joissa mobiilia laserkeilausta on hyödynnetty onnistuneesti.

Mobiili laserkeilaus on työkalu infrarakenteiden rakenteelliseen ja toiminnalliseen suunnitteluun sekä tutkimiseen. Tutkimusmenetelmää voidaan käyttää koko projektin elinkaaren ajan alkaen maanpinnan muotojen määrityksestä ennen rakennustöitä edeten rakennustyön laadunvarmistukseen ja myöhemmin rakenteen kunnon tutkimiseen. Menetelmää voidaan käyttää myös tietomallintamisen työkaluna. Laserkeilaus ja kolmiulotteinen mallintaminen yleensäkin on yleistynyt ja on saavuttamassa vakiotyökalun aseman. Tämä johtuu laserkeilauksen suuresta tarkkuudesta, nopeudesta ja monipuolisista mahdollisuuksista infratutkimuksissa.

Mobiili laserskeilaus, 3d mallinnus, infratutkimus, pistepilvi

CONTENTS

ABBREVIATIONS AND TERMS

BIM	Building information Modeling
CW	Continues Wave
DMI	Displacement measuring interferometer
EDM	Electronic Distance Measurement
FOV	Field of View
GNSS	Global navigation satellite system
GPR	Ground penetrating radar
GPS	Global Positioning System
IMU	Inertial Measurement Unit
LASER	Light Amplification by Stimulated Emission of Radiation
LCMS	Laser Crack Measurement System
LIDAR	Light Detection and Ranging or Laser Imaging Detection and Ranging
MTLS	Mobile terrestrial laser scanning
NDT	Non-destructive testing
RDLS	Road doctor laser scanner
ROI	Return on investment
STLS	Stationary terrestrial laser scanning
TLS	Terrestrial laser scanning
TOF	Time of flight

1 INTRODUCTION

The word laser is an acronym that stands for “light amplification by stimulated emission of radiation”. There are three major factors that distinguish laser light from ordinary light. These unique characteristics are as follow.

Laser light is monochromatic, which means all the light it produces is almost exactly the same colour. Laser light has far greater degree of directionality (small divergence) than ordinary light which is a key factor in the ability of laser light being focused in to a beam and on a very small spot, increasing its intensity. Phase consistency which means all light (photons) from a laser beam are aligned with each other. (Hitz, Ewing & Hech 2000, 57- 64)

Generally, lasers are classified based on the material they use as source for radiation. Based on this type of classification, the most common lasers used are solid-state lasers, gas lasers, semiconductor lasers, die lasers, excimer lasers, etc. (Petrie & Toth, 2008.)

For scanning, ranging and profiling over long distance, solid-state and semiconductor lasers are the usual choice, owing to their high intensity combined with high degree of collimation (Petrie & Toth, 2008).

1.1 Lasers in measurements, a brief history

Although lasers have been used for geodetic surveys since the beginning of 1960s, within the past decade topographic laser profiling and scanning systems have undergone phenomenal rapid development and have become the most important geospatial data acquisition technology of the millennium. The systems include both land- based and airborne platforms that possess the ability to collect very large quantities of explicit 3D data at an unprecedented speed and accuracy. In addition, the recent advances in the field of information technology, introduction of faster and more reliable computers and software programmes has made the processing of measured and acquired data relatively simple and fast. The introduction of geo-referencing technology in the mid-1990s has been a key factor in proliferation of laser profiling and scanning systems use for topographic mapping commercially viable (Petrie & Toth, 2008).

The recent advances in laser scanning technology, precision of data acquired and availability of technology at an affordable price has marked a new era in the use of lasers in civil engineering and surveys.

In contemporary world of engineering with ever rising demand for sustainable development, environmental limitation and demands, decreasing sources of raw material and increasing construction and renovation costs, non-destructive testing methods are the key to a cheaper faster and more reliable solution. Thus, laser scanning, a non-destructive testing (NDT) method is considered by many as one of the most cost efficient, reliable, and time saving tools in design and survey for engineering applications.

"Laser scanning saves up on both labour and material costs. In addition it improves quality, work safety and productivity." (Sormunen 2012, 32).

1.2 Objectives

The objective of this work is to document and describe the mobile laser scanning services offered by Roadscanners.

The thesis is a detail oriented piece on the services regarding mobile laser scanning Roadscanners has offered so far and will be offering in future, which will help in turn upon choosing the right methodology and equipment for specific projects.

Different laser scanning methods, their purposes and results will be described in detail. Some projects that have been successfully executed by Roadscanners and the partner companies will be presented that will help describe the process of mobile laser scanning and its advantages in terms of speed, accuracy and cost efficiency over more traditional methods of survey.

Since laser scanning is a rather new technology, in spite of the broad spectrum of advantages it offers over traditional methods, it is not yet main stream. But experts' view on the matter is that laser scanning will soon be a standard tool in civil engineering applications for both survey and design.

The work will simultaneously be used as an information leaflet for the customers who may need a thorough description of these services and methods. It will also assist the customers in deciding what services they need.

1.3 Roadscanners

Roadscanners is a consulting company that specialises in developing tools and services for infrastructure condition management and monitoring. Research and development has been one of the focal points for Roadscanners. It was established in 1997 in Rovaniemi and has gone international within the past decade and offers its services worldwide.

Roadscanners' main products are consulting for civil engineering and geosciences, software development for civil engineering and instruments.

The focus of the company's activities has been the structural and functional condition monitoring and analysis and problem diagnosis of roads, streets, bridges, airports and railways. Roadscanners is internationally recognised for its expertise in ground penetrating radars. In addition, it offers other NDT surveys such as mobile laser scanning and thermal camera diagnostics. (Roadscanners 2013.)

1.4 Application

Laser scanning is one of the fastest developing methodologies in engineering surveys. The use of laser scanning is wide spread, from archaeology to architecture to civil and military application. (Petrie & Toth 2008, 1–2.)

In civil engineering, the use of laser scanning ranges from planning to implementation and quality control.

Some of the most common applications are mapping, shoreline surveys, bridge deck and dam surveys, road widening projects, forest surveys, flood risk area mappings, 3D modeling of city infrastructure, monuments and tunnel modeling.

1.5 Limits

As mentioned in the previous section, laser scanners are used in a wide variety of measurement and survey applications fixed on different types of platforms for the respective desired projects. However, this thesis will focus on mobile laser scanning as a design and survey tool.

The following sections will be dedicated to the use of vehicle based laser scanning methods in different planning, survey and quality control projects.
Laser scanning platforms as airborne, space born and stationary will be introduced and illustrated but will not be focused on in this work.

The later part of thesis will focus on mobile laser scanning services offered by Roadscanners. The equipment and software used by Roadscanners for such projects and the services it offers through its cooperation partner Geovap.

1.6 Research methods and structure

In order for the thesis to be broad and the information to be up to date as well as precise and correct, the research will be very objective. For information sources, we will try to use a variety of mediums such as books, journals, magazines, scientific articles, interviews with experts, product user manuals, product reviews, manufacturer’s websites and information published on companies’ web pages that offer these services.

The structure of the thesis is chronological in a sense that it flows naturally in order of familiarity. The beginning offers background information and introduction to laser scanning later transiting to mobile laser scanning, its uses in different tasks and its advantages. The last part of thesis will present example case studies of projects conducted by Roadscanners and its cooperation partner Geovap in the past.

2 LASER SCANNING

Laser scanner is an advanced measurement tool that supplements the world of coordinate measurement with a highly detail oriented and precise measurement method. It increases safety and efficiency by enabling measurements from a distance without having to actually touch or get unnecessarily close to the target. The yield of measurement is a 3D point cloud. The scanner itself is the origin or the zero point in distance which emits a laser beam that hits the non-cooperative target and bounces back. Once the rebound signal is detected by the receiver, it calculates the time of flight (TOF) and divides it by a factor of two which gives the distance in meters from the target. TOF measurement is based on the speed of electromagnetic radiation which is a constant. Since we know the angles (both vertical and horizontal) and the range of the emitted beam, we can calculate coordinates of every measured point in the point cloud. In addition to the range and coordinates, the system also records the intensity value of every point based on the strength of the rebound signal. This phenomenon is called light detection and ranging (LIDAR). (Joala 2008, 1.)

Laser scanners are composed of three parts: Laser canon that generates the laser beam, a scanner that circulates the laser beam and a detector that measures the reflected signal and thus measures the distance to the target. (Matintupa & Saarenketo 2011, 8.)

2.1 Classification of Laser Scanning based on the Type of Platform

As early as 1960, lasers were used for range measurements by surveyors. In 1970s, lasers replaced the earlier methods of electronic distance measurement (EDM). Later, laser rangers were incorporated with theodolites to make total station that were capable of precise angular measurements using opto-electronic encoders.

With the development of small and powerful (eye-safe) lasers, reflector-less measurements became possible, which resulted in development of ground-based profiling devices based on laser rangers. Scanning mechanism has been added to these laser rangers and profilers to make the present day terrestrial laser scanners.

The TLS can be used either from Stationary positions mounted on tripods or placed on a vehicle plat for to make mobile laser scanners (Petrie & Toth 2008, 3–4).

Airborne and space borne laser scanning first started with laser altimeters that measured continuous profiles of the terrain from aircraft. This could only obtain elevation data along a single line or path crossing the terrain during a single flight. Therefore, for topographic mapping uses a large number of flight lines have to be conducted to get full area coverage.

Later upon development of scanning mechanism, use of airborne laser scanning became widespread. Present day, airborne laser scanners are supplied airborne platform positions and altitude data coordinates by integrated global positioning system/inertial measurement unit (GPS/IMU) geo-referencing systems to an accuracy of 4-7 cm and 20-60 arc-seconds.(Petrie & Toth 2008, 3–4)

Space born laser profiling is conducted by laser rangers from Earth-orbiting satellite. Since the distance is much greater, very powerful lasers have to be used. The TOF of laser pulse is much greater so the rate of measurements is reduced unless a multi-pulse technique is used. In addition, the plat forms speed is 29000 1km/h which is around 100 times the speed of the survey aircraft. These demanding circumstances limit the laser ranging instruments to acquisition of topographic date using profiling instead of scanning techniques. (Petrie & Toth 2008, 3–4.)

Airborne laser scanning is performed from either high or low altitude based on the purpose of the survey.

2.1.1 High-Altitude Airborne LIDAR

This technique uses sensors mounted on a fixed wing airplane that flies at altitudes between 400 to 2500 meters. GNSS (Global Navigation Satellites System) and IMU systems are used with the sensors to record the location and coordinates of the plane. Due to high-altitude this method is less accurate than other survey methods. Horizontal positioning accuracy can be up to ± 1m, but high-altitude airborne LIDAR is much faster and more accurate method for large-scale topography than older methods such as photogrammetry. High-altitude airborne LIDAR is replacing other mechanisms in state or country mapping surveys.

This could be used for mapping contours, building locations, vegetation, utilities, railways, roads, stormwater infrastructures and more (Autodesk 2012, 4)

2.1.2 Low-Altitude Airborne LIDAR

Helicopters are used in this type of LIDAR measurements, and the flight altitude is between 50 to 800 meters. GNSS receivers are used for positioning purposes and this method offers higher point density and there for relatively higher accuracy making it ideal for large topographic projects. Surveying of transportation corridors would be a good example of this type of project. The data acquired through this method of survey is accurate enough to be used, for example, for repaving plans and design of new features like drainage, curbing structures and expanding of road shoulders. Data required by half a day of survey could potentially supply data for years of maintenance and expansion of many miles of roadway. Another revolutionary potential of this technology is utility route survey. This technology, for example, could be used to survey extensions of exposed pipeline accurately enough to compare and monitor condition of the pipeline as well as movements and displacement over time, as well as facilitate design and improvement. (Laser scanning infrastructure assets 2012, 4.) Figure 1 shows the two different types of airborne LIDAR measurements.

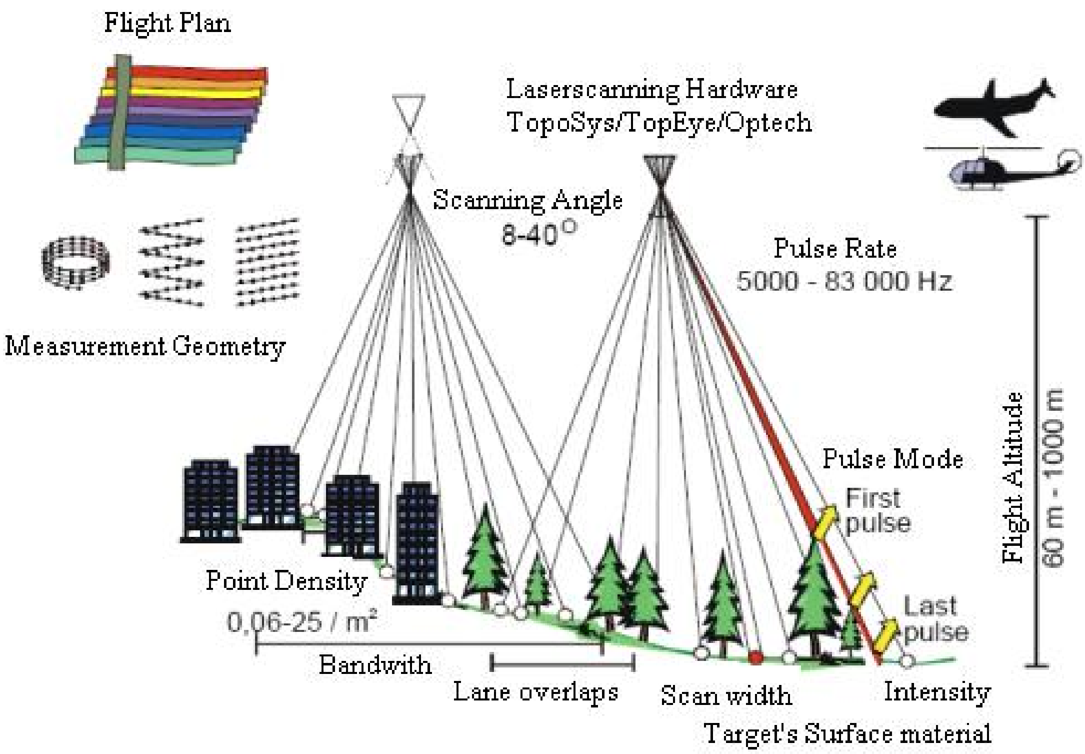

FIGURE 1. Illustration of High and Low-altitude airborne LIDAR (Cronvall, Kråknäs &Turkka 2012, 13).

2.1.3 Stationary Terrestrial LIDAR Scanning

Stationary terrestrial LIDAR scanning (STLS) is one of the most commonly used methods of laser scanning where a laser scanner is mounted on a tripod or any other stationary platform. STLS is common in conventional topography, interior and exterior as-built surveys and monitoring. Combined with digital photography this method can produce photorealistic virtual models better than any other mechanism. This method is effectively used in high-resolution surveys of infrastructure assets such as archaeological surveys, architectural and historical preservation surveys, deformation and monitoring, forensic and as-built surveys, bridge clearances and dams to create highly accurate virtual models which could be used for 3D model based designs. This method offers very high accuracy. This type of design is key to enabling designers to use automated tools for structural analysis, clash and interference detection. (Laser scanning infrastructure assets 2012, 4.)

2.1.4 Mobile terrestrial LIDAR Scanning

Mobile terrestrial LIDAR scanning (MTLS) refers to the use of high-tech laser scanners mounted on a vehicle platform equipped with one or more GNSS receivers and IMUs, real-time processing and other equipments for data capture and analysis, creating a system capable of topographic surveying of drivable corridors collecting information on the move at high speeds. (Laser scanning infrastructure assets 2012, 4.)

Since this survey method is the focus point of the thesis, here a simple introduction will suffice. Later on, whole chapters will be dedicated to clarifying the types of surveys that can be conducted using MTLS.

2.2 The measurement principles of laser scanners

There are two main measurement principles up on which all laser scanners are based. All the laser scanners commercially available today are based on one of these two principles, though some may use both methods simultaneously.

2.2.1 Time-of-flight or TOF

Time-of-flight based measurement also known as “pulse based”, from now on, abbreviated as TOF is the most common type of scanner used in civil engineering measurement projects owing to their effective longer maximum range (typically 125–1000 m). This type of scanner has a data collection rate of 50,000 or more points per second. (CALTRANS 2011.)

TOF laser scanner combines a pulsed laser emitting the beam, a mirror deflecting the beam towards the scanned area and an optical receiver subsystem which detects the rebound signal from the un-cooperative object. Since the speed of light is a known constant, the travel time of the laser pulse is then converted to precise range measurement. Figure 2 illustrates the basic principle of TOF range measurement.

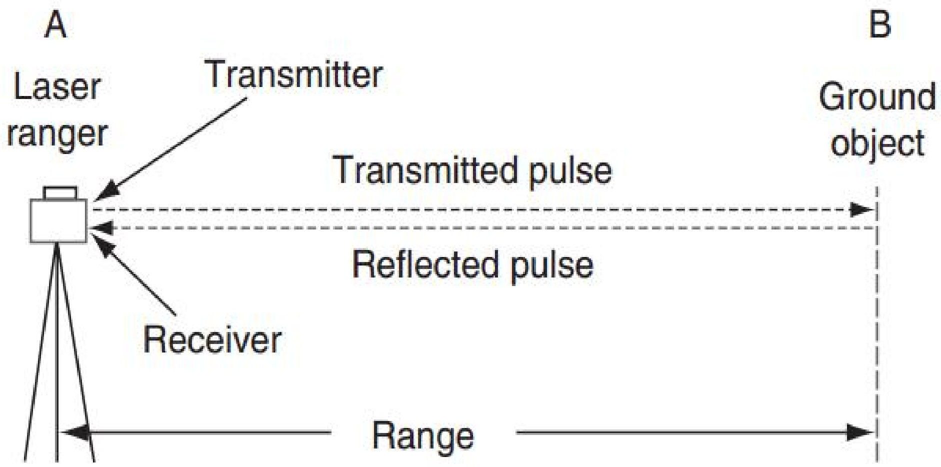

FIGURE 2. Basic operation of timed pulse or TOF method (Petrie & Toth, 2008)

2.2.2 Phase based measurement

In phase based measurement method scanner modulates the emitted laser beam into multiple phases and compares the phase shifts of the rebound signal energy. The scanner uses phase-shift algorithms to determine the distance based on the unique properties of each individual phase. The maximum effective range of phase based laser scanners is shorter than that of TOF based scanners usually ranging between 25–75 m but their data collection rate is much higher. (CALTRANS 2011, 2.) The following figures 3 and 4 compare the two measurement principles

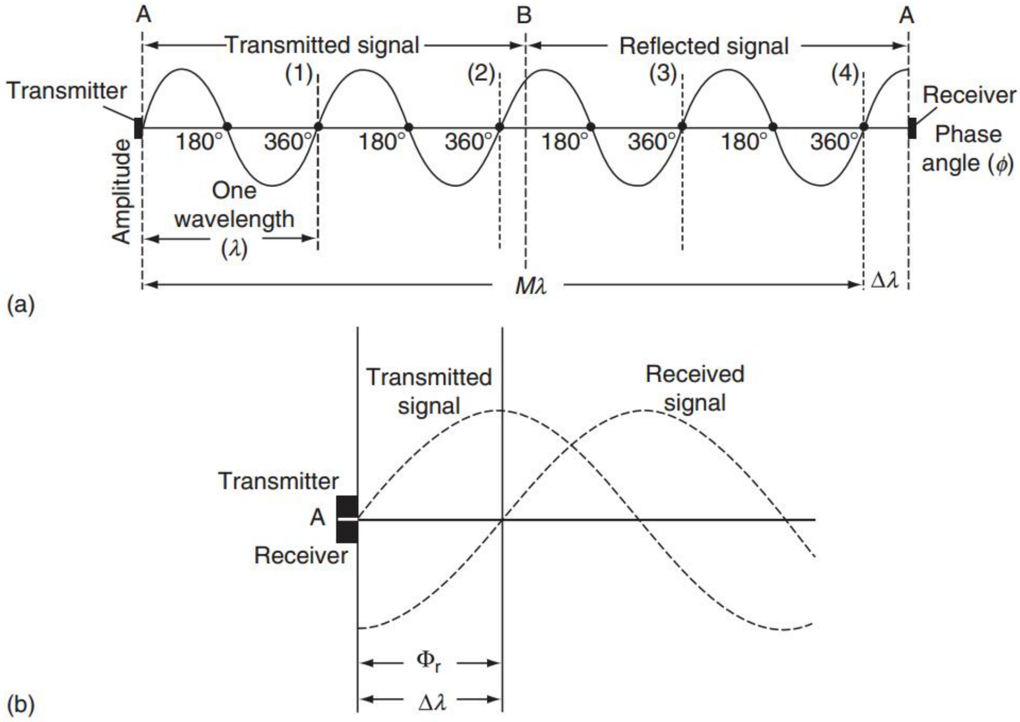

FIGURE 3. Phase shift comparison between transmitted and reflected signals (Petrie & Toth, 2008)

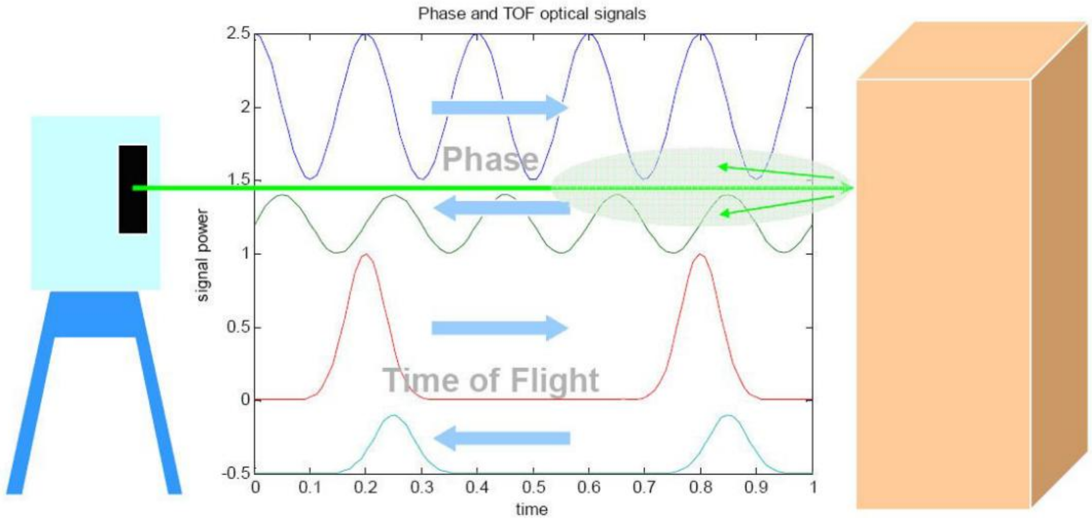

FIGURE 4. Comparison of Phase and TOF (CALTRANS 2011)

2.3 Data acquisition rate

The data acquisition rate of TOF scanners used to hover around 50000 points per second however the latest scanners offer a much higher rate of up to a million points per second for 120 m range.

The data capture rate of phase based scanners is usually higher than million points per second. However, these figures keep changing as the technology advances (Survtech Solutions 2011).

2.4 Classification of laser scanners

Laser scanners are generally classified in to three major groups based on the type of measurement they are used for. Each class has its range and precision demand. The three groups are summarized below.

2.4.1 Remote sensing laser scanners

This class of laser scanners are used in airborne and space borne applications mounted on airplanes or earth- orbiting satellites. These are often very powerful gas or semiconductor lasers. (Joala 2008, 1) The range or measurement distance varies from 0.1 km to 100 km and the accuracy of measurement points are as much as 10-20 cm which makes the acquired data usable for mapping purposes. (Airborne laser survey 2006.)

2.4.2 Terrestrial laser scanners

This type of laser scanner is usually used in measurements for distances ranging from 1 m-300 m. The measurement accuracies of up to 2 centimetres in general are reached although the accuracy of a single point could be close to 1 mm depending on environmental factors, hardware, and range.

2.4.3 Industrial laser scanners

Industrial laser scanners are used for measurements with much smaller objects where accuracy requirements are under millimetre. The usual range in this type of measurements is less than 30 metres.

2.5 Terrestrial laser scanners FOV

Based on their field of view (FOV) measurement principle, terrestrial laser scanners are divided in to four categories. Figure 5 illustrates three types of FOV.

a) Domical
b) Panoramic
c) Conic
d) Optical triangulation.

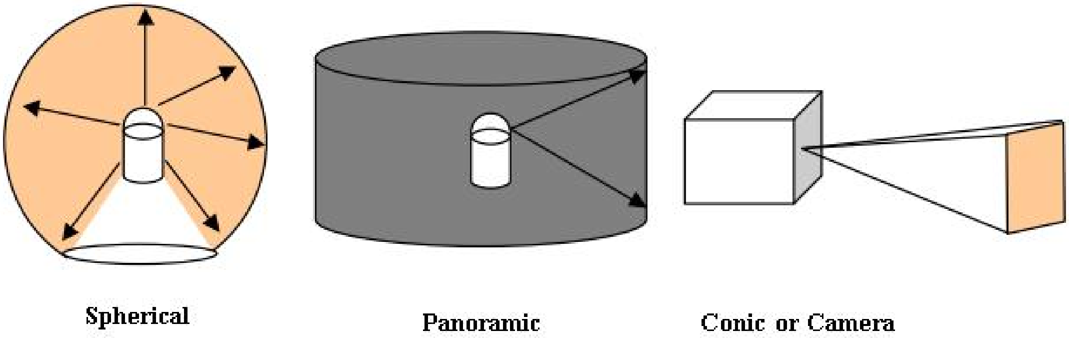

FIGURE 5. Terrestrial Laser Scanner Field of View (Joala 2006)

The majority of today's scanners use spherical FOV because the area coverage is much higher than the other methods and it leaves only a small blind spot right beneath the scanner (technical limitation). The problem with this type of scanner is that the distance between measured points increases as function of distance. Increased distance means wider area to cover that leads to weak coverage over longer distance. Detailed coverage over of 20 m distance is already problematic. However, some scanners possess the ability to focus therefore the density of point cloud does not suffer and detailed measurement is still possible but this elongates measurement time. (Joala 2008, 2)

The limitation with scanners that use panoramic FOV is the inability to cover wider vertical distance which leads to them not being ideal in tunnel measurements.

Optical triangulation is the rarest method. This offers more precise and accurate point measurement. But the restriction to this method is the limited distances that could be measured and it leaves more blind spots than other measurement techniques.

2.6 Principle of tachometric laser scanning

Laser range finders combined with tachometric devices to digitalize area of interest. The common frequency of such rangers are 1000 Hz or higher. Each point acquired by this method contains information of oblique distance s' and two orthogonal angles w1 and w2 as shown on the figure 6 below.

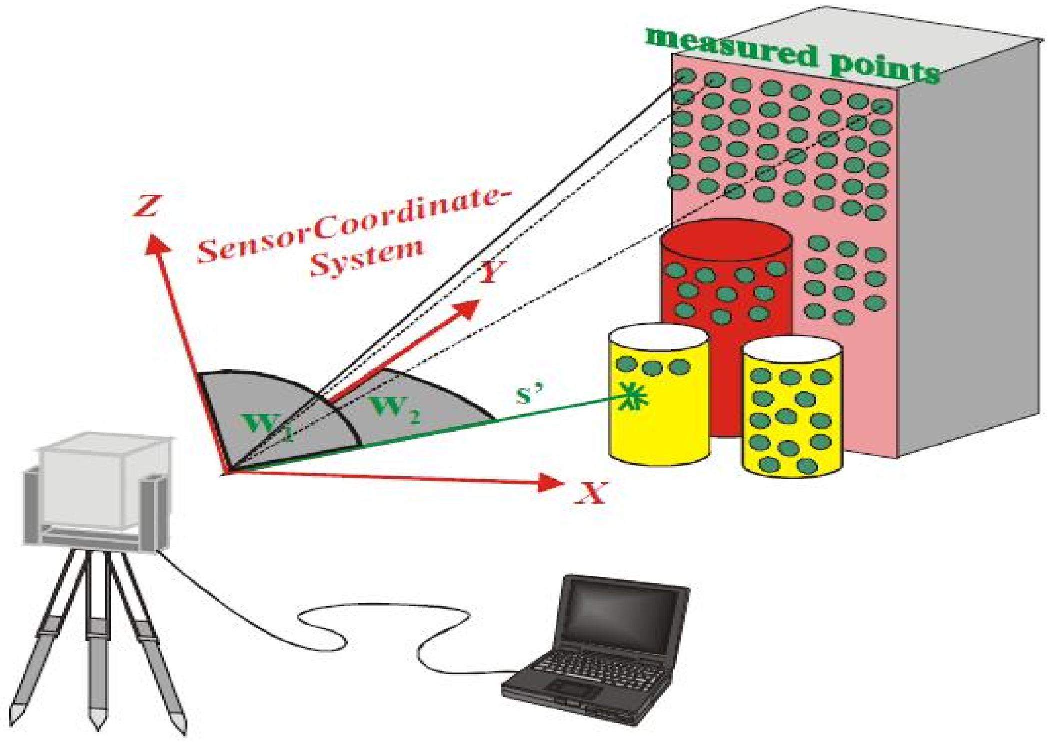

FIGURE 6. Principles of tachometric laser scanning (Staiger 2003, 2)

In addition to X, Y, Z coordinates and angles, the system also registers intensity value of the returning signal for each point in a 3D local coordinate system (SCS). The intensity information is usually referred to as the fourth dimension and it contains very useful information for visualization process especially in dense and complex point clouds (Staiger 2003, 2).

Point clouds can be coded by both intensity and range. While the range value is pure numerical value of the linear distance between the scanner and the object, the intensity value captures information regarding the type of surface such as color, material, texture and so on. This is sometimes really helpful in creation 3D models in that it offers a greater deal of detail. (Staiger 2003, 3.)

In the example below (figure 7) two models have been created using the point cloud acquired. In the first from the left the point cloud is coded by intensity and range where as the model on the right has been coded by only range.

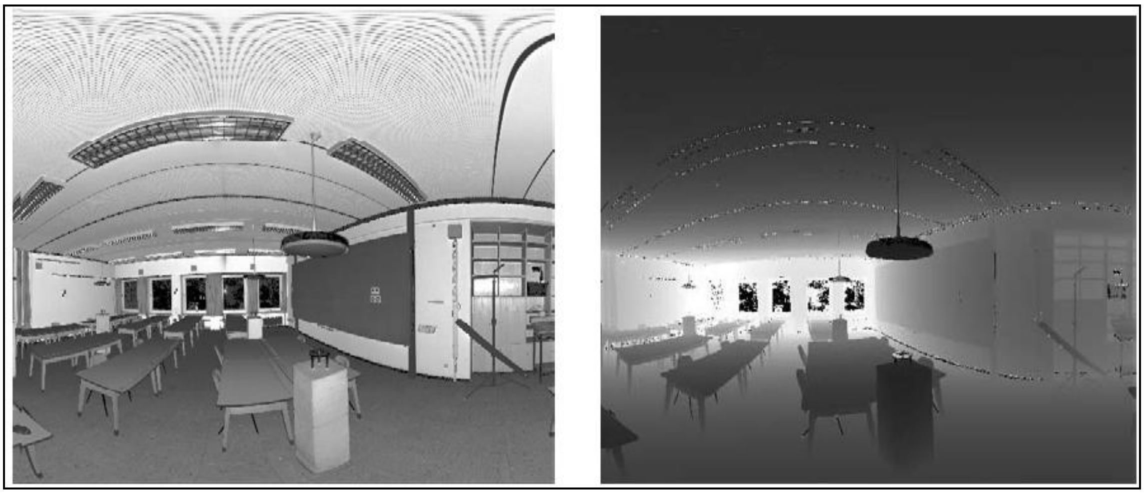

FIGURE 7. Comparison of models coded by intensity and range (Staiger 2003, 3)

3 MOBILE LASER SCANNING IN GENERAL

Mobile laser scanning also called mobile terrestrial laser scanning is an emerging technology that combines the use of a laser scanner, and global navigation satellite system, and an inertial measurement unit on a mobile platform to produce accurate and precise geospatial data (Mandenhall 2011, 2).

3D laser scanning offers up-to-date, highly accurate, visually compelling and easy-to-navigate view of a project. Users get a very real understanding of a scanned area complete with x, y, z coordinates and photorealistic images for preconstruction risk management assessment, design, construction sequencing, onsite progress monitoring. Scanning can save hours or even days from field measurements and data collection compared to traditional methods. The measurement process itself is safer for both measurement personnel and the public because of the fast remote sensing capabilities of present scanners. (Hohner 2009.)

3D laser scanners used in mobile platforms collect x, y and z coordinates and a number of reflection and emission characteristics of an entire environment using a single device to generate a high-resolution point cloud (Roadex 2001-2011.) Thanks to the development of georeferencing technology and improvement to scanner FOV, today's mobile scanner units collect full field-of-view scan and do not require location inputs, as the points collected are spatially referenced to the instrument, and not real-world coordinates. As a non-contact, line-of-sight device, laser scanners can capture three-dimensional measurements with accuracies of up to 2 mm. Another benefit of implementing laser scanning in surveying is the increased level of detail it provides. Laser scanning allows users to take a full field-of-view of an area, capturing the very dense point cloud made up of millions or even billions of points which can then be used for mapping land contours and providing a very accurate approximation of what the land looks like.

Mobile laser scanning, (also laser scanning in general) is a non-intrusive method of survey, which can be conducted from a safe distance without the need of close contact to the object being surveyed. This helps avoid the dangerous environments of survey which is a major risk factor in any field survey task. Example of such hazardous and unsafe work environments are power and chemical plant surveys, high way surveys, etc.

This technology saves time, manpower and makes the acquisition of more comprehensive, detailed data and allows for virtual return trips to the site and reduces the need for additional measurements.

Laser scanning provides high level of detail and high degree of data accuracy that is not possible through conventional methods. Moreover, the acquired data is not prone to human error. The 3D data collected by laser scanners is versatile, and could be used for further study of the area and provide trustworthy raw material for a variety of tasks and studies of the surveyed area.

Mobile laser scanning units are divided in to two main classes based on the accuracy of the system quality and precision. Each class has its limitations and capabilities. (Varin, 2013)

3.1 Application and classification of measurement equipment

Mobile laser scanning has been the key factor in the greatest advancements of the NDT techniques of road surveys in recent years. The ever increased use of this technique in a variety of survey tasks in road condition management makes it safe to say that it is an inevitable future survey tool (Matintupa & Saarenketo 2011, 8.)

Mobile laser scanning is used efficiently in a wide variety of infrastructure survey tasks such as

- Engineering topographic surveys
- As-built surveys
- Structure and bridge clearance surveys
- Quality control and assurance
- Deformation and frost heave monitoring
- Road and track geometry survey
- Corridor study and planning surveys
- Assets inventory and management
- Urban mapping and modeling
- Coastal zone erosion analysis
- Environmental surveys

- Sight distance analysis
- Road widening planning and application
- Drainage analysis etc.

3.1.1 2D laser scanner

This is a more basic laser scanning system consisting of a scanner mounted on a vehicle appropriate for the terrain, an accurate GPS receiver, portable PC equipped with compatible data capture software. Distance measurement equipment mounted and calibrated with the vehicle wheel and other sensors and equipment such as video cameras required. The equipment is project specific and largely depends on the requirements of the projects. This type of system offers limited precision and reduced distance measurements capability and accuracy (Matintupa & Saarenketo 2011, 8). Figure 8 shows the 2D laser scanner mounted on the survey vehicle of Roadscanners.

FIGURE 8. Survey van equipped with LMS 151 laser scanner (Matintupa & Saarenketo 2011, 8.)

The mobile laser scanner unit assembled by Roadscanners consists of the following components:

- The survey van
- The laser scanner (SICK LMS151-10100) See appendix1 for details
- The fixed platform that is at the height of 3 meters form the road surface
- Survey-wheel used to measure the distance
- High definition video camera (the number of video cameras depends on type the of project and or the number of views needed)
- Other optional devices such as GPR units, accelerometers and thermal cameras
- A laptop (Panasonic Tough-book equipped with Road Doctor Camlink^{TM} software for GPS, video, accelerometer and laser scanner data capture)

The laser scanner used by Roadscanners is an all-terrain all weather outdoor scanner. The scanner itself has class 1 laser which means it is eye safe and can be operated in populated areas without any obstacles. Some of the important specs of SICK LMS151-10100 are listed below. For further information see appendix 1.

- Operates at λ=905 nm (invisible infrared light).
- FOV= 270°
- Rotation frequency= 25/50 Hz
- Scanning range of up to 50 m with >75% object remission

3.1.2 Highly Effective high accuracy mobile laser scanners

This type of equipment is offered by several different manufacturers and vendors. It is the latest invention in mobile laser scanning technology. It consists of a highly accurate LIDAR sensors combined with state of the art GPS, IMU and DMI systems, portable PCs equipped with data capture software. This system is capable of acquiring highly accurate high density point cloud of the environment while traveling at high speeds. Such systems are built on a movable platform that can be mounted on a vehicle. The commercial name of such systems is Mobile Mapper. (Lorio & Rossi 2009, 1.) The following figures 9 and 10 show Quantum 3D mapper of Geovap.

FIGURE 9. Quantum 3D Mapper in transport and parking position (Geovap 2013)

FIGURE 10. Quantum 3D Mapper in operation mode with platform at the height of 3 m (Geovap 2013)

The Mobile Mapper comprises of integrated modules fixed on a platform and positioned on a vehicle.

- POS position and orientation module: Applanix POS LV-420 guarantees high precision even at high data acquisition speeds. The module comprises of three systems: A satellite navigation system (GPS), and inertial system (IMU) and precision odometer (DMI)
    - The IMU is made up on three accelerometer and three gyroscopes to measure the acceleration and angular velocity to calculate the trajectory and geometry of the vehicle (position, speed, acceleration, orientation and rotation) at any instant. The IMU has a frequency of positional data acquisition of 200 Hz so that at 80 km/h it supplies data at an 11 cm interval.
- The constant integration of the two systems the IMU+GPS compensates for any weak or lost signal and constantly maintains high accuracy levels under all operation conditions.
- The odometer restitutes 1800 impulses per second and offers a precision of more than 0.2‰. The central unit (PCS) uses the Kalman algorithm to optimize the available data in terms of expected position via IMU as well as calculates best accuracy of position established by the dynamic model of the system. When the satellite coverage is at its best, the system can reach planimetric precision (that of X, Y) of 0.05 meters and 0.15 meters for the Z-axis.

The system is capable of dynamic geocoded scanning of territory at speeds of up to 100 km/h and reconstructing the infrastructure and its surrounding territory in real-time. The supplied information includes a dense point cloud, sections, altitude, curves, and dimension of objects etc. A Mobile Mapper scans an area of 200 meters from the point of origin. This covers 100 meters of terrain on both sides of the measured corridor. The density of point cloud is inversely proportional to the platform speed there for the faster the vehicle travels the lower the resulting point cloud’s density gets. Since the point cloud density is a function of vehicle speed for the speed of 10 km/h the point density is about 4500 points per square meter of the surface whereas at 40 km/h the point density is around 1000 points per square meter.

The laser scanner module comprises of two latest generation state of the art LIDAR laser sensors. The system specification for each sensor is summarized in table 1.

TABLE 1. LIDAR laser sensors' specifications (Lorio & Rossi 2009, 2)

Rotation speed	9000 revs/minute
Measurement precision	±7 mm (1 sigma)
Spatial resolution	up to 1 cm at 50 km/h
Range	>100 meters (with 20% reflectivity)
Scanning angle	360 degrees
Number of shots	200000 per second
Measurements for each point	up to 4 simultaneously
Operation temperature	-20 C° to + 40 C°
Sight security	IEC/CDRH Class 1, Innocuous

For video capture any number of 1 to 5 high resolution video cameras may be used based on the project requirements. The orientation of the cameras are usually so that two camera are pointed parallel to direction of travel (vehicle trajectory), two camera at an angle of +45° and -45° to direction of travel and one camera +90° to direction of travel. But these settings are only guide lines and may be modified to meet the needs of the project. (Lorio & Rossi 2009, 3.)

4 POINT CLOUD

A point cloud is the result of laser scanning of an object. This could be described as the raw data that is acquired during a survey. This seemingly simple set of points contains virtually all the information needed to reconstruct a virtual model of the surveyed sight or object as shown in figure 11.

FIGURE 11. Example of a model constructed from point cloud acquired by Mobile Mapper (IGI 2013)

A point cloud is defined as a set of points linked to a coordinate system. In a three dimensional coordinate system, theses points are defined by X, Y and Z coordinates and often represent the external surface of the surveyed object. In addition to the X, Y and Z coordinates, most present day scanners also assign and record the intensity value for each point (Wikipedia, 2013).

Point clouds are acquired automatically using 3D scanners. They are usually made up of a large number of points, numbering in millions or even billions depending on the size of the object, in our case length of a road way, and the precision suitable for the project. These point clouds are stored as data files and used for a variety of purposes such as creation of 3D models of the objects, visualization and animation. Point cloud is raw material and while it may be rendered or inspected directly, it is usually converted to polygon mesh or triangle mesh models by surface reconstruction in order to be usable in 3D application. (Wikipedia, 2013)

4.1 The intensity and dispersion of points in point cloud

Dispersion of points is an important factor which is affected by angle of incidence. It is important to monitor the residuals when constructing models. The strength of the returned signal is inversely proportional to its distance from the scanner. In addition, the condition and material of surface of the object affects the returning signal. Curves in the survey area may also affect the strength of the return signal. (Joala 2006, 3.)

Some scanners record the intensity of the return signal. This information can be used while constructing emission maps. The intensity of the return signal can be visually presented by assigning a color for every intensity value or one could use different shades of grey. This information could also be used to distinguish different surface materials and textures. It is possible to assign color to every measured point through the scanners own digital camera or use images from an external digital camera to assign the true color for every measured point. (Joala 2006, 3.)

4.2 Density of the measured point cloud

The reason for obtaining a point cloud is to construct a 3D model, obtain information on cross-sections and obtain other important aspects such as the geometry of structures, shapes and condition of the terrain (P.Varin 2013). The density of a point cloud determines the precision of the model. A measure of density is given by either the distance between point clouds or number of point clouds per unit of surface area. So a denser point cloud results in a better model. (Joala 2006, 3.)

The density of a point cloud decreases as a function of distance. Scanners that use phase based measurement can have a density of 8 mm grid up to 50 m distance, while the scanners using TOF can reach up to 2 mm grid for the same distance. (Joala 2006, 3.)

4.3 Combining point clouds

When surveying a large area such as a long stretch of highway, tunnel or field it is possible to divide an area into manageable sections to measure and combine point clouds together. Combining point clouds may also be needed in cases where more than one survey vehicle is used to cover the ground faster or minimize blind spots such as noise barriers or other similar structures that could create blind spots. Dividing the survey area into smaller sections could also be a safer method in case of mishaps to avoid having to do the measurement over again.

There are several different methods of combining point clouds. The first method is the usage of common targets or pre-calculated points. For point clouds to be combined there needs to be at least three common points in order to join the point clouds in the same coordinate system. This method offers a precision of up to 1 mm. (Cronvall, Kråknäs, & Turkka 2012, 19.)

Point clouds can also be incorporated into one by using already modeled common objects or areas. This method is less accurate. The accuracy loss can be 1 to 5% depending on the accuracy of the already modeled object or area. (Cronvall, Kråknäs & Turkka 2012, 19.)

The second method is through common ground. This means the overlaps between measured areas can be used to join the point clouds. There needs to be enough overlapping area between the two measured point clouds for this to succeed. This method can reach an accuracy of up to 5 cm. (Cronvall, Kråknäs & Turkka 2012, 19; Joala 2006, 3.)

In projects where high accuracy is needed a combination of these three methods may be used to achieve better accuracy (Cronvall, Kråknäs &Turkka 2012, 19).

4.4 Quality control, error sources and risk analysis

Advantages of mobile laser scanning are, for example, the sheer speed and accuracy of the method and the fact that it reduces field survey risk through non-intrusive remote sensing capabilities so it can be used even when working in difficult risky environments

(Suominen 2006.). When the acquired point cloud is precise and of high density, it results in a high resolution model of the road and its environment. The precision of a point cloud depends on the precision of each point in the cloud, the density of the points in the point cloud and the method and precision of merging the point clouds (Joala 2006, 3). The rule of thumb is that the more dense the point cloud, the more accurate the model it yields. If the accuracy of individual points is poor, they cannot result into accurate point cloud, thus the model is of poor precision and most often not usable. (Cronvall, Kråknäs & Turkka 2012, 19.)

Factors that weaken visibility such as fog, dust, rain and snow affect the accuracy of measured a point cloud. These conditions cause reflection, refraction and divergence of the laser beam when traveling from the laser canon to the object or on the way back before being received by the sensor. The laser beam is reflected before it reaches the target or it is diverged and scattered so it never returns and thus not recorded which will result in erroneous information about the true elevation, height and position of a surface. (Matintupa 2010, 6-10.) Figure 12 shows an example of a road cross-section where the presence of dust has caused the laser beam to reflect before reaching the road surface resulting in incorrect color-coded surface map and high peaks in the cross-section. The season and weather condition of the area that is being surveyed is an important factor when planning a survey. In order to get accurate results the survey should be planned to avoid heavy rainfall, dust, snow covered terrain and standing water on the surface. In addition, the time window should be chosen so that vegetation is at minimum when measuring the ditches, for instance. (Matintupa & Saarenketo 2011, 12.)

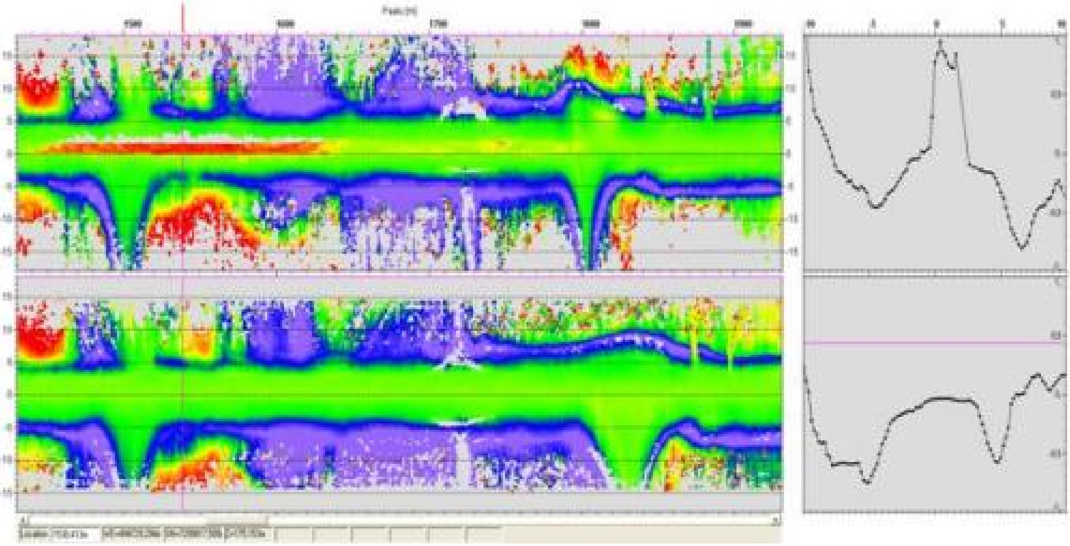

FIGURE 12. Effects of dust on laser scanning process (Matintupa & Saarenketo 2011)

4.5 Phases of a mobile laser scanning project

There is no definitive right or wrong flow diagram when it comes to project planning and execution but there are recommended methods. A rule of thumb is that each surveying project has 3 major steps: data acquisition, data treatment and visualization. (Staiger 2003, 3.)

4.5.1 Data acquisition

Data accusation can be further divided into steps such as scanning of the area which results in point cloud each point of which is defined by 3D-coordinates (x, y, z) and intensity (i). Registration, which is fusion of point clouds into one coordinate system, is done using reference points or pass points or natural structures in the point clouds. The use of reference points results in better accuracy. For stationary terrestrial laser scanning the use of tacheometer in addition to control points eliminates the need for overlapping scans, the scan is geometrically controlled and it allows transformation into a geodetic coordinate system. For mobile laser scanning reference points are more commonly used. (Staiger 2003, 3.)

4.5.2 Data treatment

The point cloud may contain perturbations which can be the result of reflexes from objects other than the target. In road environment other vehicles, people, animals and other such objects or obstacles could cause these early reflections. Another type of perturbation is total reflection that results in black hole or virtual objects. (Staiger 2003, 3.) In order to get a realistic 3D model, such points need to be omitted from point cloud before visualization

4.5.3 Visualization

Visualization is the process of constructing models using point clouds. A 3D projection of point clouds is used as a first visual check. This may use color or grayscale-coded intensity representation. Derived geometrical data may also be incorporated to point cloud. The registered point clouds can furthermore be used with digital images to produce "True" orthophotos. The treated data is similarly used to make 3D-models and "Virtual flights" through the modeled scenes. Figure 13 illustrates and summarizes the data collection and processing of laser scanning.

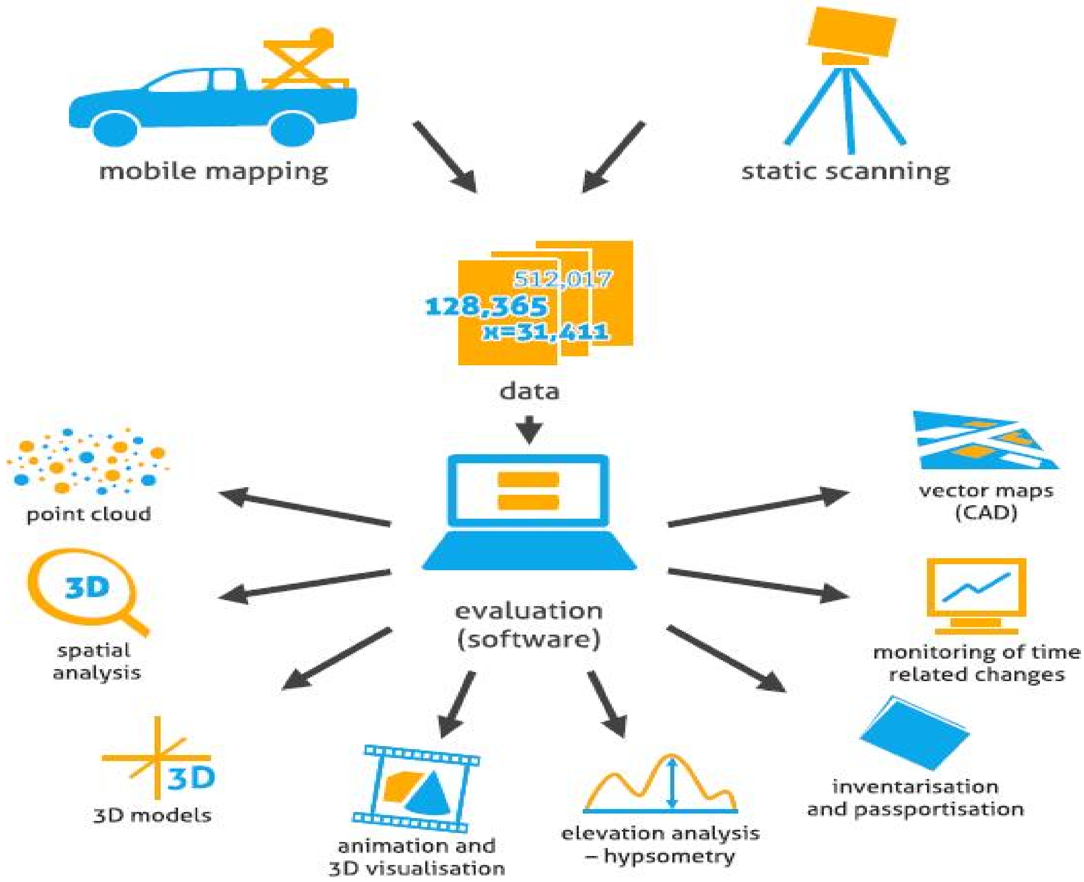

FIGURE 13. Laser scanning data collection and processing (Geovap 2013)

5 ROAD CONDITION MANAGEMENT AND PLANNING USING MOBILE LASER SCANNING

According to Timo Saarenketo (2013) the future of sophisticated road condition management lies in the integration of subsurface GPR data with accurate surface data (point clouds) (GEOVAP 2013,13).

Mobile laser scanning is considered the prevailing method that will be the standard technique of future surveys in road condition management. MTLS can be used to determine road gradient measurements, traffic portal and bridge clearances, the transversal and longitudinal profiles and dimensions of carriageways, elevation analysis to determine terrain elevation, drainage conditions along the roads, examine vertical deflections of real road surface so it could be compared to the plans and detect other types of deformation such as rutting. It is an excellent tool for monitoring of time related changes. MTLS can be used to detect deformation, erosion, landslide, development of greenery, temperature related elevations and depressions such as frost heave and thaw cycles. It can be used to create driver's view visualisation. Combined with digital photos the data acquired by MTLS can be used to create photorealistic 3D model of the road and its surroundings. Data obtained through MTLS is versatile and it can be used for several different purposes in road condition management. Examples of such uses would be updating of road condition maps and risk analysis. (GEOVAP 2013, 9)

5.1 Quality assurance survey using mobile laser scanning

MTLS is a fast and relatively cheap method of as-built survey. The sheer speed of data collection combined with the high degree of accuracy makes it a perfect fit for quality assurance survey.

A one hour survey would be sufficient to cover a stretch of high way as long as 100 km. The point cloud obtained can be used to make 3D model of the road which contains virtual information such as surface elevation, cross section, longitudinal and transversal grade, pavement width, shoulders' width, ditch slope and depth, land cut and fill, drainage mechanisms so they could be compared to the plans.

Figure 14 shows a typical carriageway cross section obtained by extraction of data from point cloud. Important information such as cross slope or camber and pavement condition (holes, cracks, ruts) can be studied.

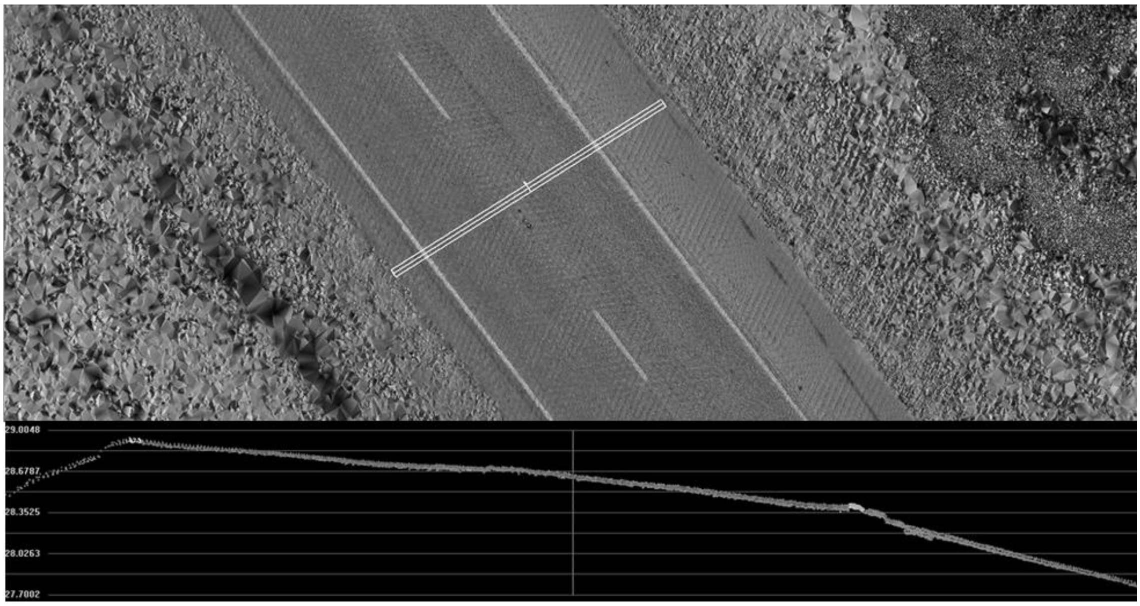

FIGURE 14 Road cross section extracted from point cloud (Amadori 2014)

5.2 Pavement surface condition analysis using mobile laser scanning

Laser profilometer technique has been used for a long time to measure pavement roughness and rutting as well as cross-fall (Saarenketo 2011). Today’s MTL scanners can scan road surface and its environment to form point clouds. 3D models are built from these point clouds which can be used to measure most road surface parameters quickly and efficiently. (Varin 2013.)

The latest in 3D technology in pavement surface condition monitoring is the Laser Crack Measurement System (LCMS). This new technology is measured at the network level to examine the system’s performance to automatically detect and classify cracks. A length of 9000 km was examined and then compared to manual results. It proved to be 95% accurate in general classification. (Laurent, Francois, Lefebvre & Savard.)

The LCMS system uses two high performance laser profilers to measure complete transverse road profiles with 1 mm resolution at high speeds. Special algorithms are used to process this 2D and 3D data to automatically extract crack data including crack type (transverse, longitudinal and alligator) and their severity. It also detects rut depths and types, macro-texture (digital sand patch) and ravelling (loss of aggregate). Below is an illustration of LCMS system and laser profiling of cracks.

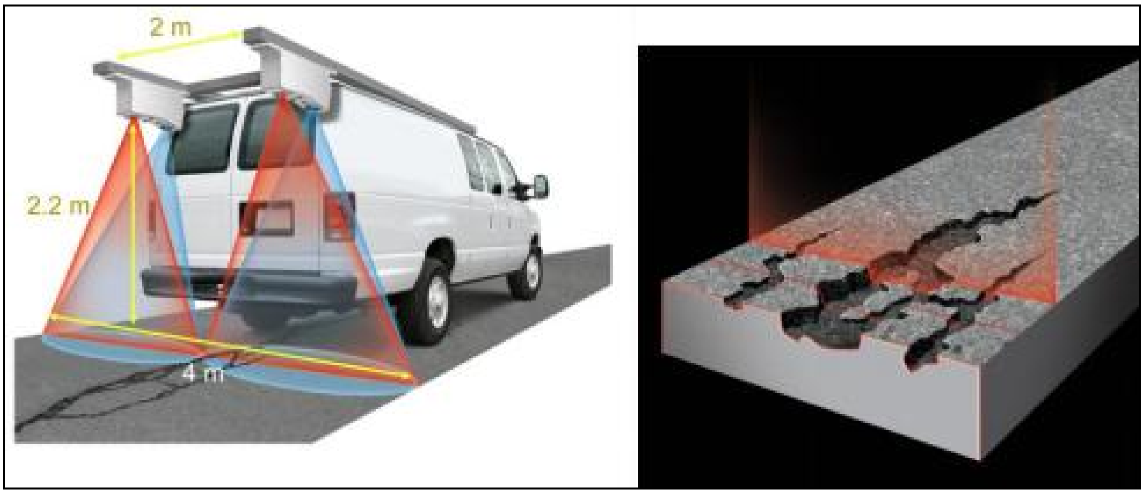

FIGURE 15. LCMS system (left) and profiling of cracks (right) (Laurent, Francois, Lefebvre, & Savard)

TABLE 2. Summary of LCMS specification (Laurent, Francois, Lefebvre & Savard)

Number of laser profilers	2
Sampling rate (max.)	11200 rpfiles/s
Vehicle speed	100 km/h (max)
Profile spacing	Adjustable
3D points per profile	4096 points
Transverse FOV	4 m
Depth range of operation	250 mm
Z-axis (depth) accuracy	0.5 mm
X-axis (transverse) resolution	1 mm

The LCMS system is capable of acquiring both range data and intensity data. These different types of data can be exploited to characterize different road features. The intensity data is used to detect lane markings and sealed cracks while range data is used to detect ruts (low intensity only), macrotexture, cracks (longitudinal, multiple, alligator, transverse), expansion joints, potholes, and raveling. Both intensity and range data can be used to detect other features such as manholes, curbs, train rails etc.

5.2.1 Intensity data

The intensity profiles obtained by LCMS are used to prepare continuous images of road surface. This information is used to identify road limits. This algorithm detects lane marking to determine position and width of the lane to compensate for driver wander. The position data is then used to avoid surveying flaws and defects outside the lane. Highly reflective painted road marks are easier to detect in 2D. By using suitable pattern recognition algorithms different markings can be identified. Figure 16 shows results of different kinds of images (intensity, range and 3D merged) made from LCMS data. First image on the left shows range data image in which elevation has been converted to gray scale. The darker the point, the lower is the surface. The darker areas along the wheel paths correspond to the presence of ruts. The middle image is the same area but coded by intensity. The image on right uses intensity and 3D merged.

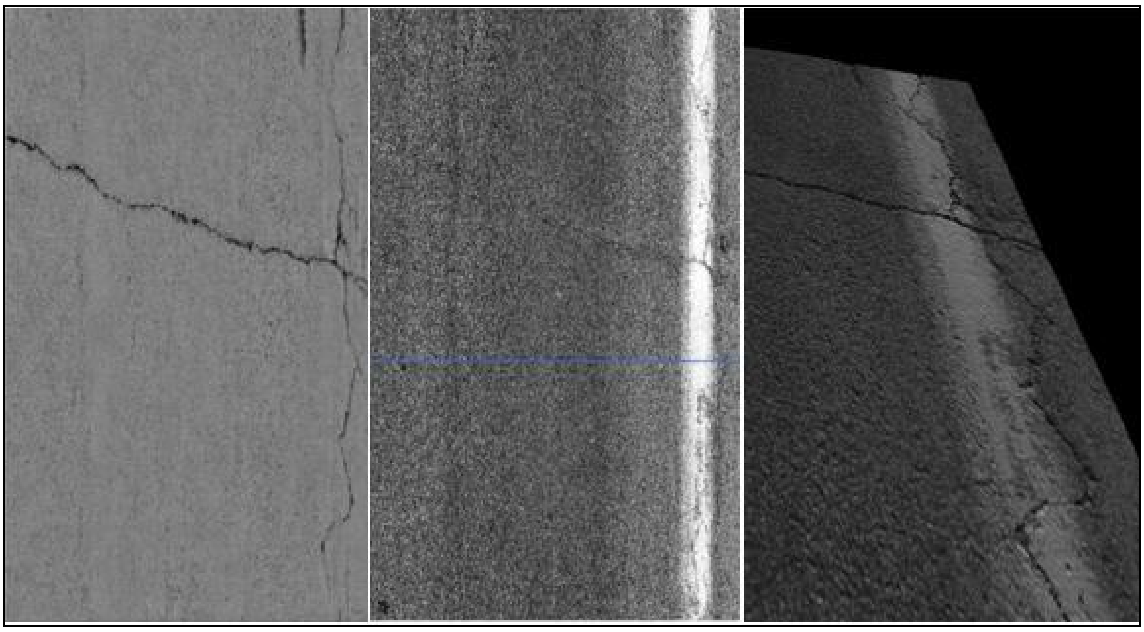

FIGURE 16. From left to right range, intensity and 3D merged (Laurent, Francois, Lefebvre & Savard)

5.2.2 Range data

The 3D data from LCMS measures distance from road surface to sensors for every sample point on the road. Height variations can be observed in longitudinal directions of the road due to unevenness in longitudinal direction causing movements in suspension of the vehicle holding sensors. Large-scale height variations correspond to low-spatial frequency of content of range information in the longitudinal direction. Most features that need to be detected are in the high-spatial frequency portion of the range data. Figure 17 shows a 2 meter transverse profile, where the general depression shows rut, the sharp drop in the center, circled red, corresponds to crack and the height variations. The area circled with green show macro-texture of the road surface.

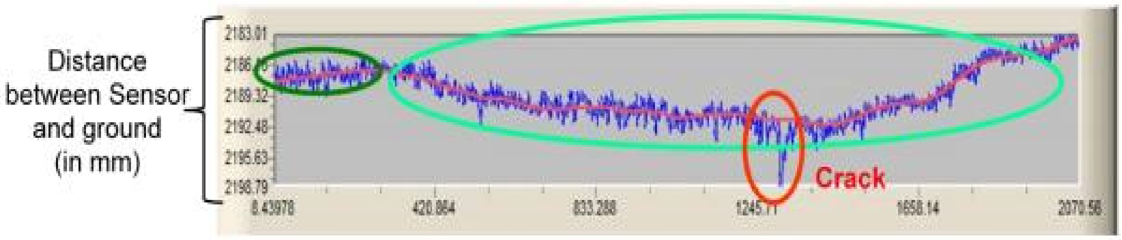

FIGURE 17. Transversal profile with rut, crack and macro-texture (Laurent, Francois, Lefebvre & Savard)

5.3 Mobile laser scanning in road widening

Roadscanners has used 2D mobile laser scanning during Roadex road widening research project to obtain continues cross-section profiles and height information of roads. This information has been profitable in obtaining such information as angle of side slopes to study the effects of side slopes in road widening. The scans can also provide data on other useful parameters such as width and ditch depth. The cross section profiles are then used to compare before and after situations. The information provided by laser scanner data combined with other NDT survey date can supply excellent grounds for analysing reasons for structural failure of the existing road.

Figure 17 below is an example of Finnish Roadex test site on highway 9 illustrating height and cross-section information of laser scanner survey before and after road widening.

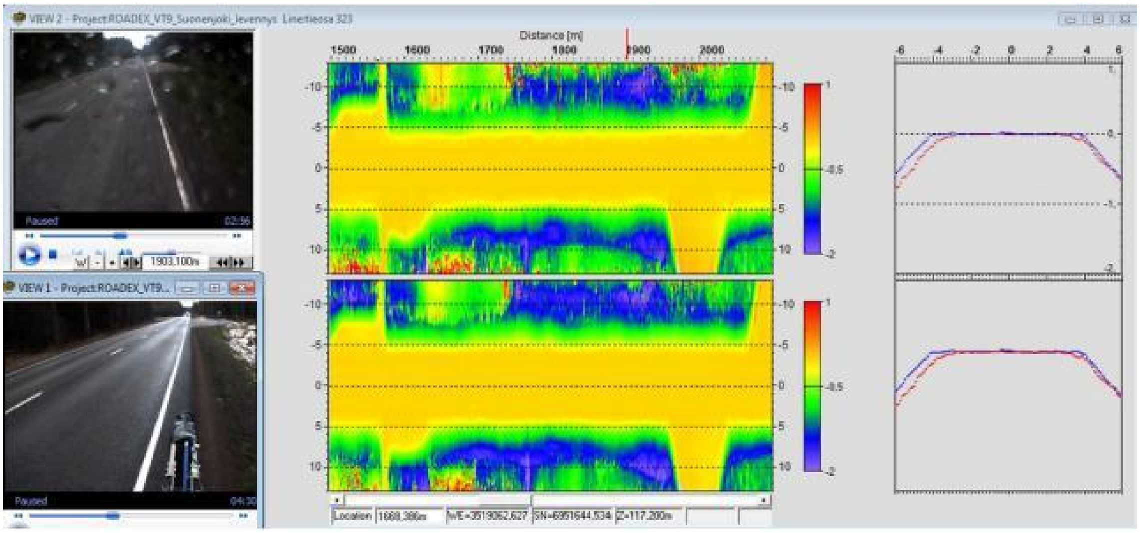

FIGURE 17. Road widening cross-section red dots show road profile before and blue dots after widening (Varin & Saarenketo 2012)

Figure 18 shows another example where 3D point cloud model is color-coded by height to evaluate the affects of frost heave on the recently widened road structure. The frost heave on the widened side of the road is 40-50 mm smaller than the frost heave on the old road. (Varin & Saarenketo 2013, 8)

FIGURE 18. 3D point cloud model color coded for surface height (Varin & Saarenketo 2012)

5.4 Mobile laser scanning in road shape and drainage analysis

Mobile laser scanning has proven to be a very useful tool in measuring road cross-sections, ditch bottoms and slopes. The shape of verges could be checked from emission maps to see if they are higher than pavement and therefore cause water to accumulate on the pavement and prevent its flow (Matintupa & Saarenketo 2013, 8). The results of laser measurements could be combined with other NDT methods such as thermal camera imagery and GPR data to accomplish a thorough analysis of surface and subsurface structure of road (Varin 2013).

In order to obtain best results and minimize noise, MTLS for drainage analysis should be carried out at times when vegetation is not an obstacle. Spring time is ideal for this method of survey. In order to get the true ditch bottom values it is also necessary to avoid measurements when the ditch is filled with water or snow. Dust, fog and rain can also affect the resulting point cloud negatively. The negative effect of fog on accuracy of point cloud is observable from the figure 19 where only a partial cross-section could be extracted from point cloud compared to figure 20 where the extracted cross-section is of acceptable quality. (Matintupa & Saarenketo 2013, 8.)

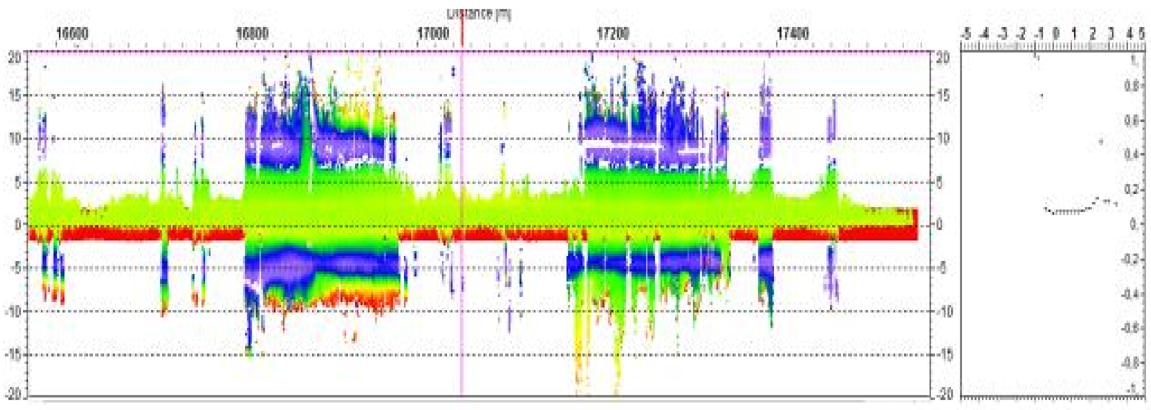

FIGURE 19. Affect of fog on point cloud (Matintupa & Saarenketo 2013)

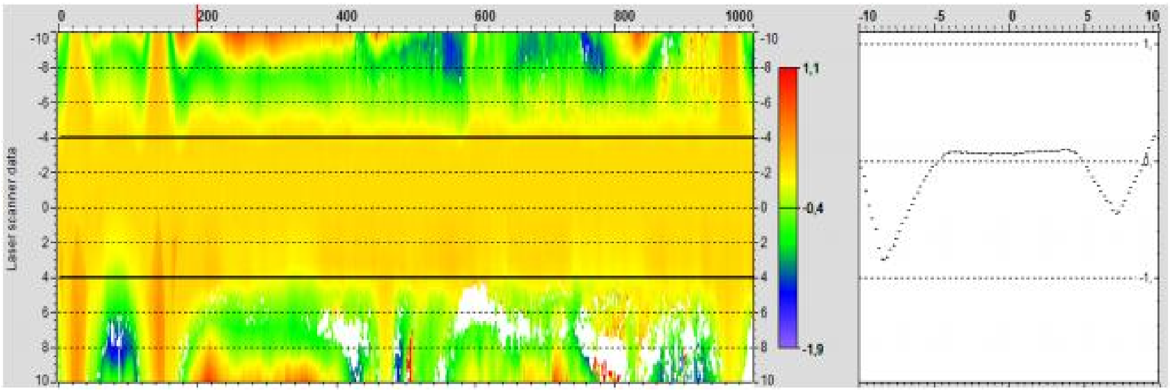

FIGURE 20. Cross-section with no interruption in the point cloud (Matintupa & Saarenketo 2013, 13)

MTLS survey carried out by Roadscanners with SICK LMS151 in spring and summer of 2011 to observe the affect of seasonal change on the shape and geometry of road concluded that while the spring measurements yielded satisfactory results regarding the road cross-section and depth of ditches, the summer measurements conducted at the end of June did not yield good results. This was due to abundance of vegetation in the ditch.

The summer survey also indicated that ditch bottoms where on average about 30-40 cm at higher position than the winter survey. This was because of frost swelling in the road structure. A graphical comparison of the two data sets is shown in figure 21 below.

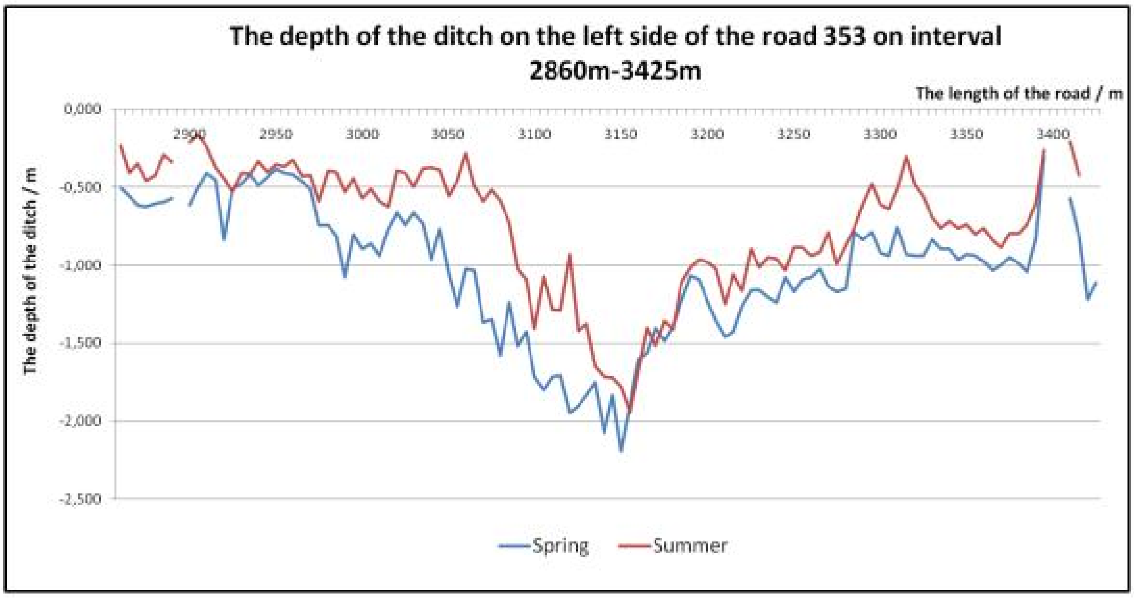

FIGURE 21. Comparison of ditch bottom from two sets of point clouds (Matintupa & Saarenketo 2013, 12)

Laser scanning can be a very useful tool for contractors in ditching work to monitor depths and inclination of ditch. The road cross-sections, ditch depths and slopes information could be extracted from point cloud to be compared to construction plans and drawings. (Matintupa & Saarenketo 2013, 8–24).

In figure 22 the 3D point cloud has been color coded where it is easy to observe that a blocked culvert on the right side of the road at the intersection has caused water to accumulate and caused frost heave to be much higher than other parts of the road (Roadscanners 2012).

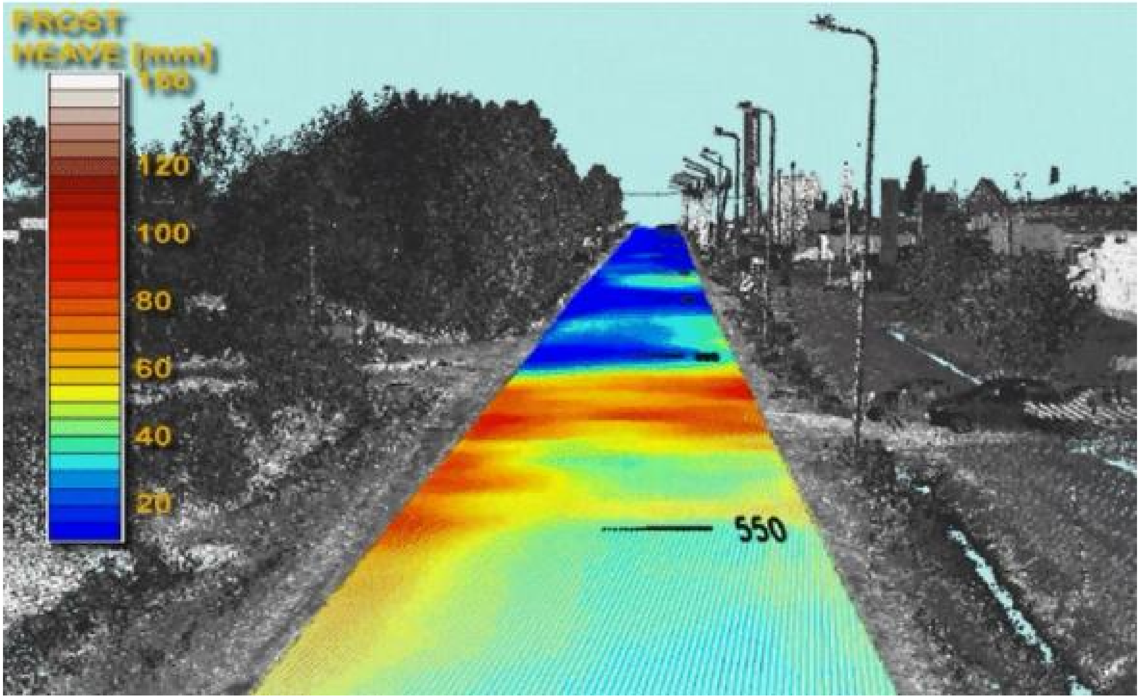

FIGURE 22. Frost heave from 3D point cloud (Roadscanners 2012)

5.5 Monitoring rutting using mobile laser scanning

Mobile laser scanning is widely used in rutting analysis. Due to the latest developments in the field of laser scanning, the information that is extracted from laser point cloud can be used to reliably determine the depth of ruts.

Roadscanners has developed the Road Doctor Laser Scanner (RDLS) technique in which the SICK LMS151 is installed at a height of 2.5-3 m on the back of the van used to measure the pavement surface at 2.5 degree intervals at 50 Hz frequency. When the result of a large number on points is averaged using proper algorithms, the outcome is rut depths with required accuracy to the millimetre. Another advantage of the method is that in addition to depth of ruts, it records the shape of ruts and makes it possible to compare the two parallel ruts of the same carriageway to determine the reason of rutting. For example, if the parallel ruts are approximately the same, the reason could be normal wear out due to usage or due to studded tires whereas uneven wearing could suggest other type of structural defects such as drainage or deformation due to insufficient bearing capacity. MTLS could also be useful in monitoring the formation of ruts and their development over time in new pavements. Figure 23 is a graphical comparison of actual rut depths to those extracted from point cloud.

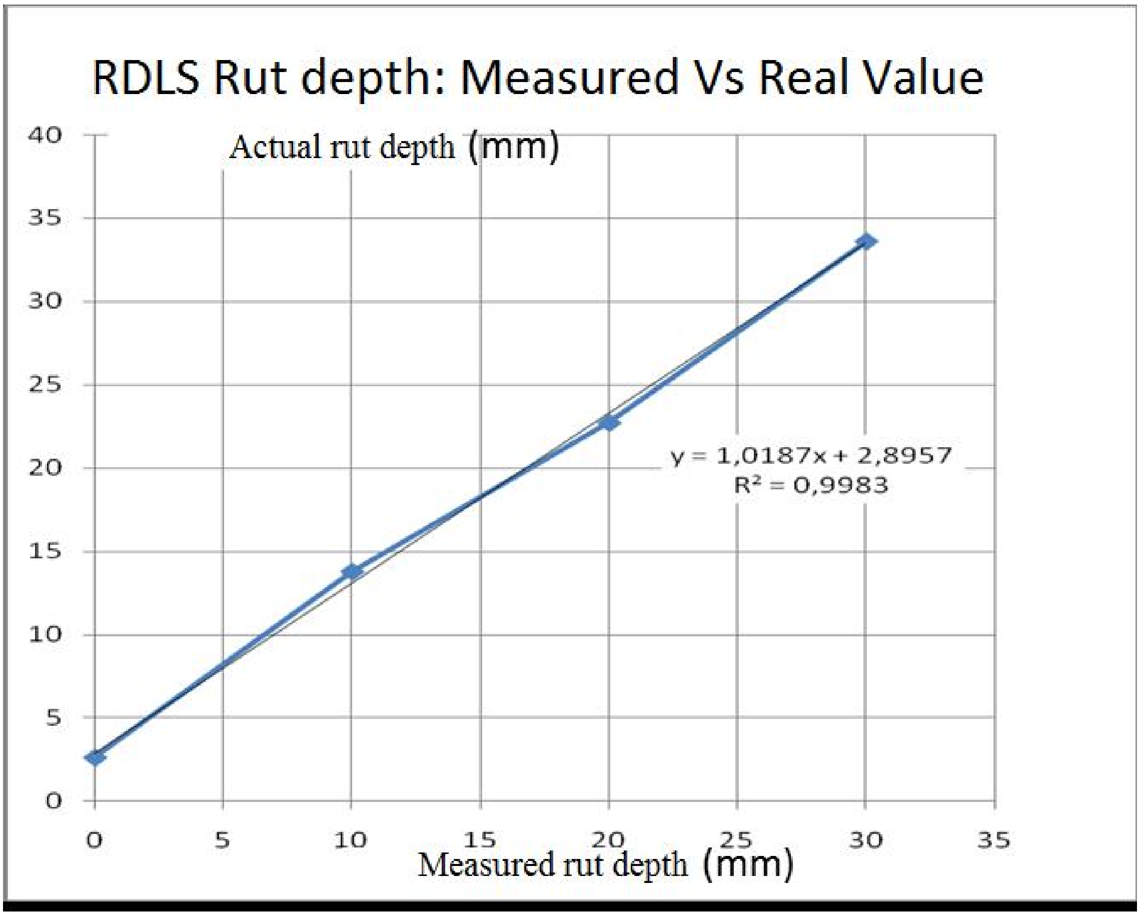

FIGURE 23. Comparing measured rut depth to actual value. Blue line illustrates the real value and grey line the measured value. (Roadscanners 2012)

The point clouds obtained by Lynx Mobile Mapper could be used to form rut-video in which the area lower than the optimum level (ruts) will be coloured blue while the optimum level will be yellow and areas in between will use the proper color of spectrum between the two colors depending on their distance. This makes it visual friendly and easy to compare. Figure 24 of point cloud shows wearing of pavement near a traffic light in Rovaniemi caused by studded tires of vehicles when accelerating after the traffic light. On the right top of the picture the dark blue spot shows deformation because of lack of drainage.

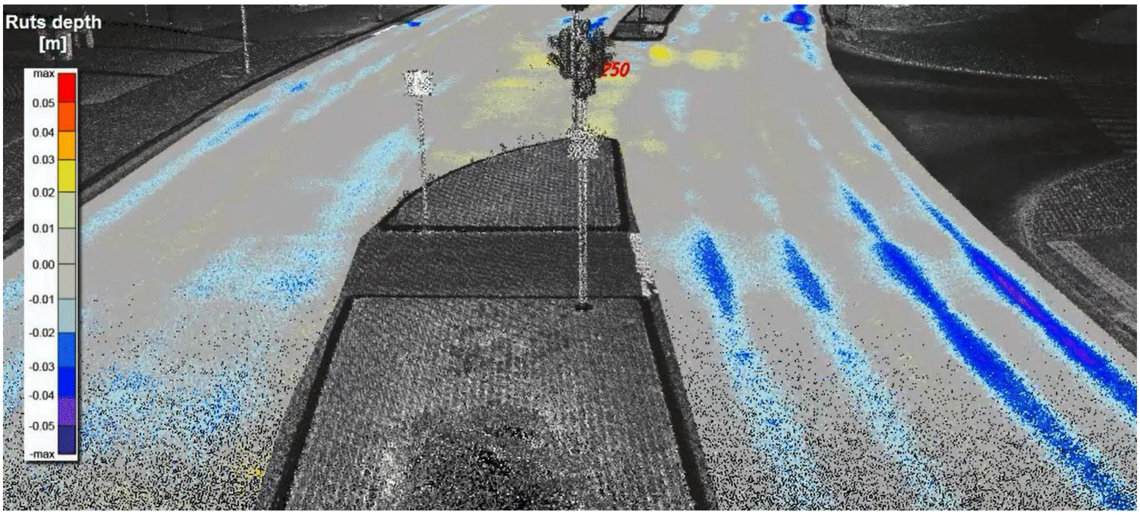

FIGURE 24. Hallituskatu in Rovaniemi (Roadscanners 2012)

5.6 Mobile laser scanning in Road and track geometry survey

Mobile laser scanning has proven to be an excellent tool in surveying road and track geometry in terms of both speed and accuracy of acquired data. MTLS survey yields a dense point cloud of the road or track and its environment. Essential geometric parameters of road and track such as curvature, height, longitudinal and transversal slope can be extracted from the point cloud. This can be used for a number of purposes such as quality assurance, as-built survey and aqua planning. It could also be combined with existing information to derive properties for future roadmap databases and car navigation (Hatger & Brenner 2002, 5). The longitudinal geometry of road, extracted from scanned data, can be used to set speed limits and thus increase driver safety and comfort. Figure 25 below shows quantum 3D mapper of geovap placed on a railcar for track survey.

FIGURE 25. Mobile Mapper survey of railway (Geovap 2013)

Figure 26 illustrates 3D model of railway yard extracted from point cloud. The measurement was conducted by Geovap in 2013. Over head utilities and other railway furniture are easy to locate from this point cloud picture.

FIGURE 26. Railway yard point cloud (Geovap 2013)

5.7 Mobile laser scanning in tunnel monitoring and survey

Mobile laser scanning can be a very effective tool in tunnel survey. Tunnel surveys are generally divided in to three major application tasks. The first one is positioning, alignment, dimensions and shape during the construction and excavation work. The second one is as-built survey and the third one is the monitoring and condition survey over time. Mobile laser scanning has proven be useful for all the above mentioned survey tasks. (Boavida, Oliveira & Santos 2012, 1-3.)

During the construction of tunnels mobile laser scanning can be used to monitor the cross section and compare this to the cad drawings to see if drill and blast has been achieved as planned. Mobile laser scanning is an excellent method for this phase of tunnel construction for many reasons. Laser scanners can be fitted on a robot to scan the tunnel. Since ventilation takes time, this way the survey personnel can execute the mission remotely avoiding poisonous fumes of the recent blast, the unsupported rocks from tunnel ceiling, unstable walls and save time.

For as-built surveys mobile laser scanning is a fast and accurate method that can capture enormous amount of 3D data that can be used to reconstruct model of the tunnel and compare it the construction plans and drawings. The point cloud can then be used to extract all the necessary information such as tunnel cross section, horizontal and vertical clearance (inner dimension) and even the condition of tunnel walls and ceiling. (Boavida, Oliveira & Santos 2012, 2.)

The third type of survey where MTLS can be taken advantage of is the monitoring of road and railway tunnels. Since tunnels undergo enormous amounts of pressure from both dynamic loads of traffic and other types of loads such as water pressure, rock/earth pressure, thermal expansion and shrinkage and earthquakes, it is essential to monitor them for any possible changes or damages to ensure safety. Tunnel cross-sections, openings and condition of the rock can be measure and monitored. Figure 27 illustrates point cloud model used for clearance analysis.

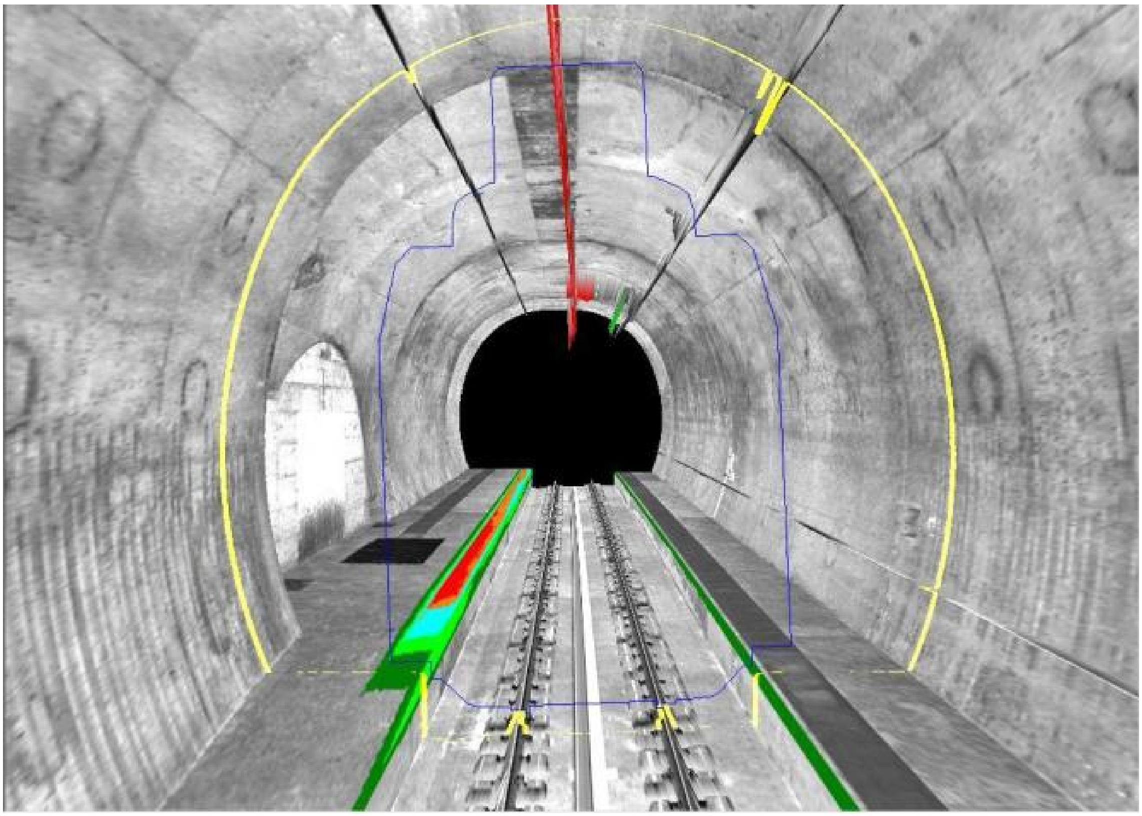

FIGURE 27. Clearance analysis using MTLS point cloud (Cronvall 2011, 13)

Figure 28 shows the effect of seasonal changes in the wall of railway tunnel where water infiltration has caused swelling in the rock of the tunnel wall. The turquoise lines show the winter measurements and red lines show the summer measurements. Seasonal changes can be monitored in tunnel survey comparing point cloud data sets from winter and summer time surveys (Cronvall, Krånkäs & Turkka 2012, 31).

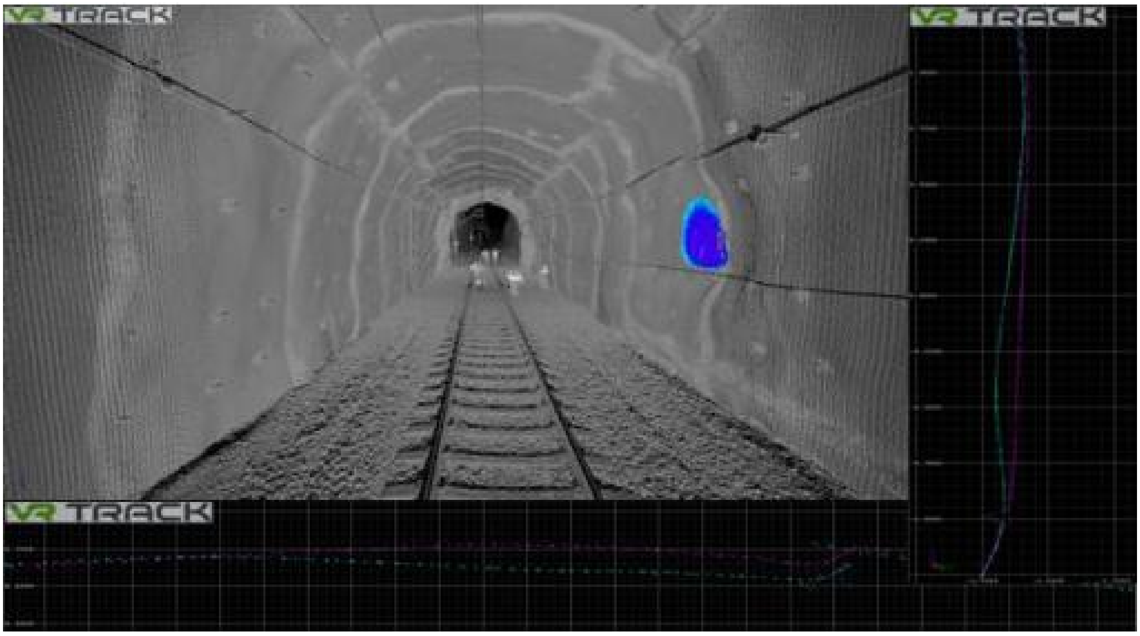

FIGURE 28. Tunnel cross-section with swelling on the right shown in color (Cornvall, Krånkäs & Turkka 2012, 34)

In case of a catastrophe a fresh MTLS survey can be conducted quickly and safely using remote controlled robot. Obtained data can be compared to previously acquired scans to determine condition of tunnels and whether they are safe to use. In addition, the scanned data can be used to precisely define the location and type of problem and focus repair on the correct locations. MTLS can also be an excellent tool in surveying mines and caves for seasonal changes, load effects and stability.

5.8 Mobile laser scanning in infrastructure assents management

The use of MTLS technology has been broadened in recent years to include the mapping of infrastructure assets. This means the TMLS survey technology is applicable in highway, rail road and street assets mapping. This has revolutionized the fast mapping of road and track furniture and over head utilities (Li 2011). MTLS can be used to perform inventory task for

- Road and track surface condition
- Road markings like centrelines, lane markers and limits
- Position and condition of rumble strips
- Traffic signs
- Bridges, their position and vertical clearance

- Light poles
- Traffic portals and their vertical clearance
- Noise barriers
- Under ground and over head utilities such as power cables
- Fire hydrants
- Manholes
- Culverts
- Guard rails
- Median strips and greenery

The recent advances in the field are the creation of algorithms that can extract all the above mentioned assets automatically from an obtained point cloud. In addition to number of assets, the data records their condition and position along the surveyed stretch thus making it easy to spot and fix the assets in need of repair. The survey personnel can perform the tasks without having to leave the vehicle, hence reducing the risks factors involved in traffic surveys. In addition, MTLS is applied without blocking the traffic flow or causing delays assuming the speed limit is 70 km/h maximum (Li). The obtained data is diverse and can be used for multiple purposes. The ability to perform such surveys fast and the degree of automation in data processing make the updating of databases and repetitive surveys of this type possible and affordable. The technology can, furthermore, be used to monitor speed and parking violations. Figure 29 demonstrates damaged traffic signs. It is possible to extract such signs from point cloud data automatically to inspect aspects like aesthetic damage of the reflective pain or bents and folds from accidents and vandalism (Gonzalez-Jorge, Riveiro, Armesto & Arias).

FIGURE 29. Examples of damaged traffic signs (Gonzalez-Jorge, Riveiro, Armesto & Arias)

Figure 30 illustrates model created from point cloud acquired by Mobile Mapper of Geovap during the survey project of highway 4 Kemi where road furniture is well depicted.

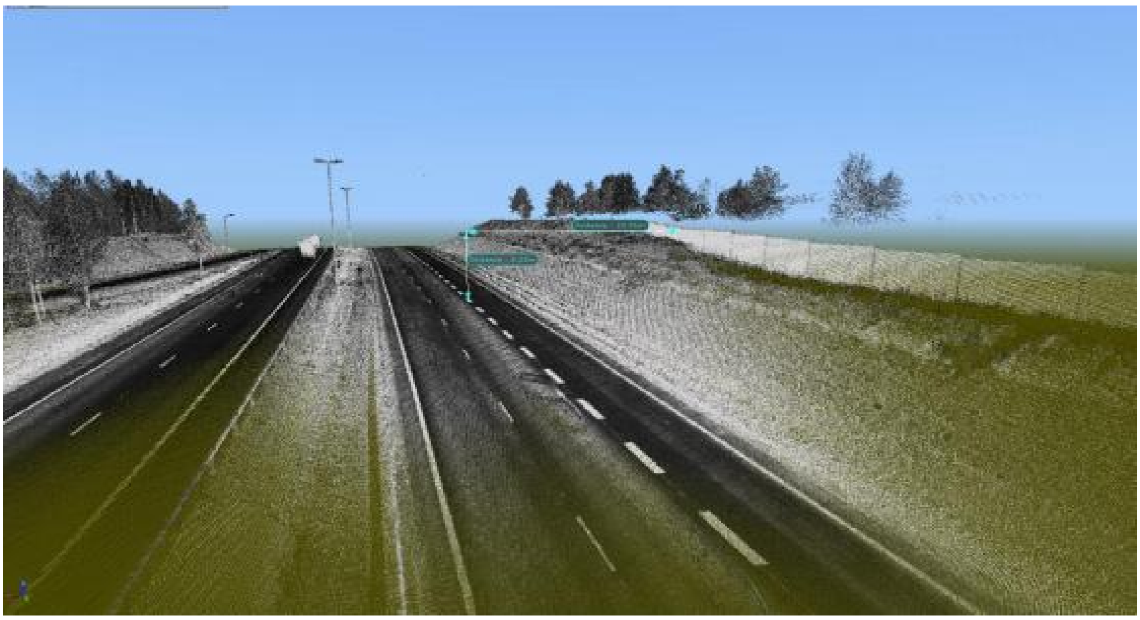

FIGURE 30. Road furniture and environment visible from point cloud image (Geovap 2010)

6 SUSTAINANBLE INFRASTRUCTURE AND BUILDING INFORMATION MODELING

Building information modeling (BIM) is a process that involves the generation and management of digital illustration of physical and functional aspects of places. BIMs are files which can be exchanged or networked to help the process of decision making about a place. BIM software is used by individuals or agencies that plan, build, operate and maintain diverse infrastructure from roads to utilities and buildings (Wikipedia). An important aspect of researching transport infrastructure is collecting data from physical locations of objects that form the infrastructure. This data collection process needs to be precise, accurate and efficient. MTLS has the potential to deliver such data. It is essential to ensure the sustainability of current and future transport networks by considering energy efficiency, climate change and other such challenges. (Babić, Pribičević & Đapo 2012, 96-97) The development of greener, safer and more energy efficient transport solution is the goal. Transport infrastructure is an essential factor for operation and growth of economy.

6.1 Future of mobile laser scanning

The use of MTLS is going to increase in future because of the advantages this technique offers compared to more conventional methods (Mandenhall 2011, 3). Example would include

- Speed of data acquisition
- Diversity of data
- Increased accuracy
- Reduced disturbance to traffic flow
- Possibility to conduct night survey
- Reduction of field-work related risks
- Multiple use of data
- 3D features of data
- Substantial cost saving
- Expediting the project
- Wide variety of end uses

The increase of precision laser scanners and development of new software programs to further automate the feature extraction from point clouds combined with the production of more potent computers drive this technology to the next stage (Hohner 2009, 2). We are yet to identify the full potential of MTLS as new survey tool. This technology has what it takes to become the next standard technique for professional survey. (Perry 2010.)

6.2 Return on investment

It has been difficult to assign Return on Investment (ROI) value to laser scanning. This is for two main reasons: the data and results derived from laser scanning are difficult to compare to traditional data and deliverable because of their great difference; and because laser scanning offers a whole new world of opportunities in terms of its capacity compared to previous solutions. They are often used on projects where more conventional techniques have not been attempted. (Autodesk 2012, 6)

One reason that gives laser scanning great value is the fact that it delivers for more value in much less time using less manpower. Another reason is safety. The last reason is hard to quantify in terms of capital. Laser scanning can be used to perform remote survey on dangerous areas such as toxic mine tailings, unstable lands or rocks and places where traffic, electric or other utility might pose danger to surveyors. Using laser scanning can significantly reduce number of work related injuries and it can positively affect insurance rates.

One source of quantified ROI is California department of transportation (Caltrans) that published a cost-benefit analysis (Mobile Scanning- Cost and benefit Analysis Caltrans District 4 Doyle Drive Project San Francisco CA) in December of 2009. The project was a high accuracy survey of a 20 mile stretch of high traffic four-lane freeway. After accounting for mobilization of costs of mobile laser scanning equipment, the department had made a direct saving of $65,800. When cost of freeway shutdown was factored in, the estimated saving reached a total of $167,800. These figures do not include the value of so called left-over data that could be used in other projects, additional data used in visualizations or the increase in safety level of field survey by minimizing traffic exposure.

7 CONCLUSION

Field survey is an unavoidable and essential part of civil engineering. In order to be able to conduct surveys effectively and cost efficiently, it is necessary to stay abreast of the latest developments in technology to provide clients with timely and affordable solutions. Technology is a key component to the success in engineering profession.

Mobile terrestrial laser scanning is a relatively new technology that has opened a whole new world of opportunities in professional survey world. Although the experience with MTLS is still very limited and only a handful of pioneer companies have realized the great potential of this method and adopted it, its full potential and spectrum of applications in different survey tasks is yet to be discovered.

MTLS is a non-invasive state-of-the-art technique that combines the most advanced terrestrial LIDAR sensors, cameras and IMUs to collect survey grade data quickly and accurately. The usage of this technology has expanded to cover a vast area of survey spectrum from tunnel to railway and highway corridors.

Like every new technology, MTLS has created concerns among surveyors whether this technology will do more harm than good for the survey business by replacing conventional survey methods. On the contrary, what was realized during the research process of this thesis was that a closer look at this technology reveals its potential applications and integration of MTLS can complement the existing methods.

Just as GPS has not replaced total stations, MTLS is not going to replace conventional methods of topographic data collection. However, the efficiency you can gain using MTLS must not be overlooked. It is important to choose the right method of survey. For example, for the survey of a long stretch of highway where the uninterrupted flow of traffic is unconditional and high precision is needed, MTLS is the method of choice and refusing this technology will put the surveyor and client at a decided disadvantage.

Providing that MTLS is the right method of choice for the project it offers numerous advantages over more conventional methods of survey. MTLS could offer efficient acquisition of millions of 3D design points per minute and higher point density compared to other survey methods. The survey is conducted remotely thus avoiding contact and reducing risk of exposure to traffic, difficult terrain and damage to the environment. The survey is not time dependent which enables the surveyors to conduct night surveys or plan work hours so that it creates minimum disturbance to traffic flow (avoiding diversions) and achieve best results.

Many sources referred to MTLS as best method of survey. I believe that is it is a very bold statement. It was noticed that although MTLS is an excellent survey method, it is not necessarily suitable for every project. It is a line-of-sight survey method which means if you cannot see it, you cannot capture it. In certain cases laser data needs to be supplemented by more conventional data collection methods. Reference points need to be measured using total stations or predefined control points are used to complement point cloud data.

Another example of inconsistency, which was observed during the research process for the thesis, is the percentage of accuracy that MTLS offers in different survey tasks. The figures were at odds. Some sources, for example, agreed that while surveying pavement conditions automated extraction of cracks from point cloud data and classification of their type can reach 90% accuracy while other sources promised accuracies of up to 95%. Those percentages could still be true due to the usage of different equipment, software and methodology since these methods have been developed by private contractors or institutions for commercial use. Some research has been conducted at universities in Europe and America where scanners from different manufacturers have been compared and their accuracies, advantages and disadvantages in survey tasks documented. Yet still, the usage of different methodology, software and algorithms might account for different precision percentages. The worst case scenario would be that the higher precision percentages offered might be sales pitch.

Four aspects of MTLS that all sources agreed upon were the reduction of survey costs, increase in work safety, speed at which survey is conducted and return on investment. These were the most compelling arguments for MTLS. Base on these four points it is safe to assume that in future the use of MTLS as a survey tool is going to increase considerably. Other reasons for this increase are probably the high quality of data and the photo realistic viewer-friendly deliverables this method offers. The gradual tendency and trend of moving towards 3D modeling is probably another imperative force that will droves MTLS towards becoming a standard tool in future surveys.

Mobile laser scanning is probably going to infiltrate new areas of survey and its full potential will be exploited to ease the work and reduce the risks. Future developments could involve automation of heavy construction machinery using TLS and GPS together. Robot could be equipped with TLS for post catastrophe surveys to avoid dangerous and unstable areas and structures.

Figure 31 is a pie chart of MTLS work by project type from 2009. The survey data is from the United States of America. According to this survey the market for 3D laser scanning solutions has undergone a rapid growth going from $100 million in 2003 to $400 million in 2009. According to Spar Point Research the category including civil, transport and building projects is the second highest rated sector using this technology.

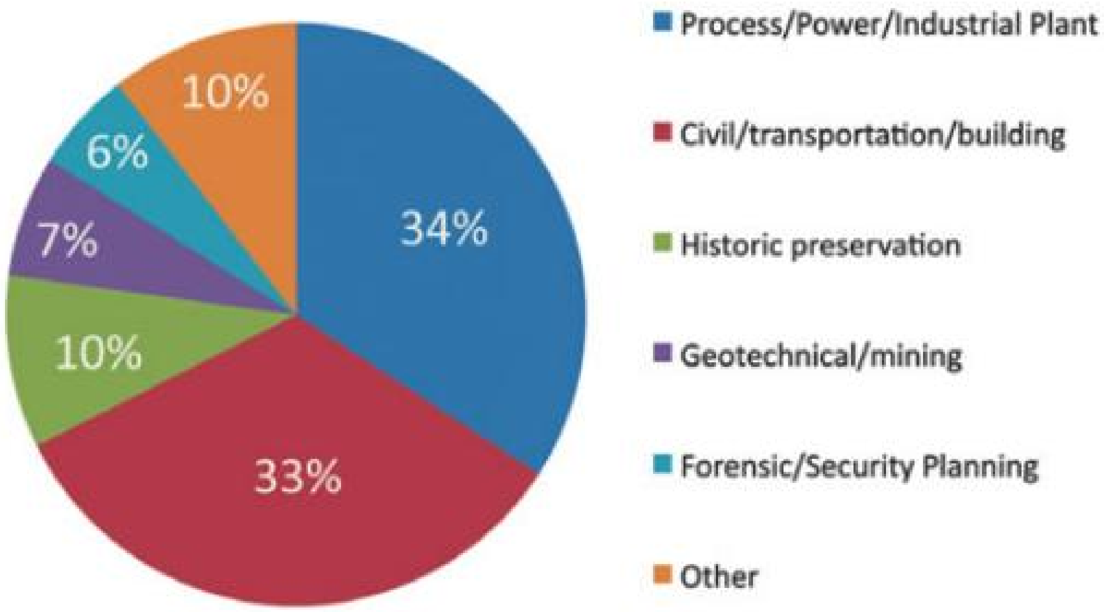

FIGURE 31. Laser scanning work by project type. (Spar Point Research 3d Laser Scanning User Satisfaction survey 2009)

Over all MTLS offers better return on investment by providing very diverse and accurate data sets. It offers not only a more viewer friendly picture but also a more complete picture of the intended project. Combined with other non-destructive survey methods like ground penetrating radar, thermal camera image and high resolution video capture it can form an entirety that provides virtually all the needed information about the surveyed object upon which engineers could plan construction or rehabilitation.

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APPENDICES

Appendix 1. LMS151 Laser Measurement System

Sick Ag. 2009. Germany, Waldkirch.

LMS151 Laser Measurement System

The light-weight for long range

The LMS151 at a glance:

- Small, light and economical
- Maximum scanning range of 50 m at object remission >75 %
- Supply voltage range from 10.8 V to 30 V DC
- Real-time measurement data output via Ethernet interface
- Number of switching outputs can be expanded by external module
- Scanning frequency: 25 Hz to 50 Hz
- Power consumption: typically 8.4 W to 12 W
- IP 67 and integrated heating for outdoor use

Target applications

- Automated guided vehicles (AGV)
- Anti-collision

Future capabilities

- Synchronization of several LMS151
- Advanced CAN functionality

Safety note:
LMS151 laser measurement systems are not devices for personal protection within the sense of valid safety standards for machines.

SICK
Sensor Intelligence.

Technical data

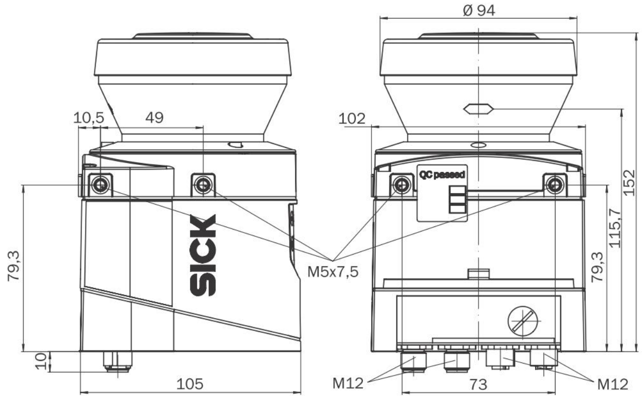
Type	LMS151-10100
Max. range	50 m (at >75 % reflectivity) / 18 m (at 10 % reflectivity)
Scanning angle	Max. 270°
Angular resolution	0.5°/0.25° adjustable
Scanning frequency; Response time	50 Hz / 25 Hz; 20 ms / 40 ms
Error	Statistical (1 s): typ. 12 mm; Systematic: typ. ±30 mm (temperature drift max. 0.32 mm / °C)
Sender	Pulsed laser diode; Divergence of the collimated beam (full angle): 15 mrad (equals approx. 15 mm/m or 0.86°); Light spot size at the optical hood: 8 mm
Switching inputs/outputs	2 / 3
Data interfaces	Ethernet 100 Mbit TCP/IP; RS 232
Supply voltage	Electronics: 10.8 V ... 30 V DC; Heating: 24 V DC
Laser Protection Class	Laser Class 1 (IEC 608251, corresponds to 21 CFR 1040.10 and 1040.11)
Enclosure rating; Protection class	IP 67 acc. to EN 60529, section 14.2.7; III acc. to EN 50178 (1997-10)
EMC test	Acc. to EN 61000-6-2 (2005-08), EN 61000-6-3 (2007-01)
Vibration test	Acc. to EN 60068-2-6 (1995-04); frequency range: 10 Hz to 150 Hz: Amplitude: min. 5 g RMS
Shock test	Acc. to EN 60068-2-27 (1993-03), EN 60068-2-29 (1993-04); single shock: 15 g, 11 ms; Cont. shock: 10 g, 16 ms
Housing alloy	Excellent weather resistance acc. to DIN/EN 1061988, table 3
Dimensions (W x H x D); Weight	102 mm x 162 mm x 105 mm; approx. 1.1 kg (without connection cables)
Operating temperature	–30 °C to +50 °C

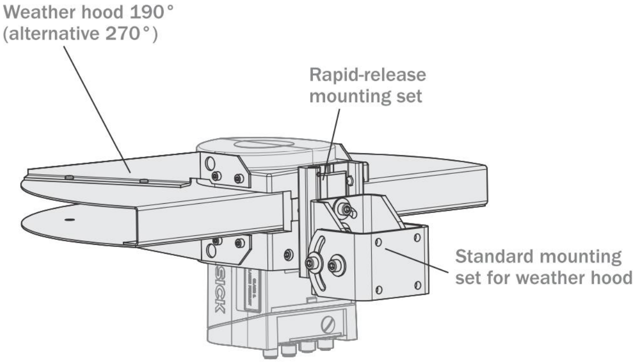
Order information

Part no.	Type	Description
Device		
1047607	LMS151-10100	Outdoor variant with heating, IP 67, system plug with 2 x M12 plugs (5-pin/8-pin) and 2 x M12 sockets (4-pin/8-pin), CD-ROM „Manuals & Software Auto Ident“
Accessories		
2034324	Mounting Set 1a[1]	Bracket for mounting to wall or machine from the back
2034325	Mounting Set 1b[1]	Bracket for mounting to wall or machine from the back, with cover protection
2039302	Mounting Set 2[1]	Bracket, only in combination with bracket 1a or 1b, adjustment possible around transverse axis
2039303	Mounting Set 3[1]	Retention plate, only in combination with bracket 2, adjustment possible around longitudinal axis
2046459 / 2046458		Weather hood, 190° / 270°
2046025		Standard mounting set for 190°/270° weather hood
2046989		Rapid-release mounting set for 190°/270° weather hood
6034415 / 6030928 / 6036158		Ethernet M12x4/RJ-45 connection cable for connection of LMS151 Ethernet interface to PC Ethernet interface, 5 m / 10 m / 20 m
6036159 / 6036160 / 6036161		Supply cable for LMS151-10100, M12x5, 4 open wires, 5 m / 10 m / 20 m
6036155 / 6036156 / 6036157		I/O-cable for LMS151-10100, M12x8, 8 open wires, 5 m / 10 m / 20 m
6036153 / 6028420 / 6036154		RS 232 cable for LMS151-10100, M12x8, 8 open wires, 5 m / 10 m / 20 m
6021195 / 2027649		Connection cable M8x4 / D-Sub 9-pin (DIN 41642) for connection of serial auxiliary interface with the PC serial interface, 2 m / 10 m
6038825		External CAN extension module for up to 8 additional outputs

[1] Including mounting materials

Dimensional drawings (all dimensions in mm)





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