CZECH TECHNICAL UNIVERSITY IN PRAGUE

F6

Faculty of Transportation Sciences
Department of Forensic Experts in Transportation

Master's Thesis

Linear Feature Extraction from Mobile Laser Scanning

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May 2023
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MASTER'S THESIS ASSIGNMENT

(PROJECT, WORK OF ART)

Student's name and surname (including degrees):

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Study programme (field/specialization) of the student:

master's degree – DS – Transportation Systems and Technology

Theme title (in Czech): **Extrakce liniových prvků z mobilního laserového skenování**

Theme title (in English): **Linear Feature Extraction from Mobile Laser Scanning**

Guidelines for elaboration

During the elaboration of the master's thesis follow the outline below:

- Describe the method of data collection along with the required steps before further processing.
- Describe existing solutions for extraction, vectorization and classification of linear features from the point clouds, such as road elements, kerbs, road markings, etc.
- Define the necessary processing steps and apply them to a test sample of data.
- Compare the outputs from selected approaches or tools. Analyze and assess the results.
- Design a workflow for further use of selected approach.

Graphical work range: not declared

Accompanying report length: 55 pages as minimum (including images, graphs and tables which are part of the thesis)

Bibliography:

OLSEN, M. J.: Guidelines for the Use of Mobile LiDAR in Transportation Applications. National Academy of Sciences, Washington, DC., 2013. ISBN 978-0-309-25914-9.

PAVELKA, Karel.: Mobile Laser Scanning. Prague: Czech Technical University, 2014. ISBN 978-80-01-05261-7.

Master's thesis supervisor: **Ing. Zdeněk Svatý, Ph.D.**

Ing. Pavel Vrtal

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(date of the first assignment of this work, that has be minimum of 10 months before the deadline of the theses submission based on the standard duration of the study)

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a) date of first anticipated submission of the thesis based on the standard study duration and the recommended study time schedule
b) in case of postponing the submission of the thesis, next submission date results from the recommended time schedule

L. S.

doc. Ing. Tomáš Mičunek, Ph.D.
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prof. Ing. Ondřej Přibyl, Ph.D.
dean of the faculty

I confirm assumption of master's thesis assignment.

Bc. Tadeáš Bartoš
Student's name and signature

Prague ....June 15, 2022

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I would like to also thank to my family and friends for their emotional support and my parents and grandparents for their materialistic support as well, which was provided during my studies.

Declaration

I hereby declare that the presented thesis is my own work and that I have cited all sources of information in accordance with the Guideline for adhering to ethical principles when elaborating an academic final thesis.

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Abstrakt / Abstract

Cílem této diplomové práce je najít efektivní proces extrakce liniových prvků z mračen bodů získaných mobilním laserovým skenováním a ukázat možné výhody a nevýhody. Mračna bodů jsou dobrým zdrojem širokého spektra informací o okolí, ale kvůli jejich charakteru je náročné s nimi pracovat, což může neefektivním přístupem zapříčinit ztrátu jejich potenciálu. Tato diplomová práce představuje přístup, jak extrahovat liniové prvky silniční sítě a zároveň se vyvarovat informačnímu zahlcení během zpracování mračen bodů. Práce je doplněna aktuálními přístupy z vědeckých článků, které představují problematiku extrakce liniových prvků z jiných pohledů. Představená komerční řešení jsou otestována na mračnech bodů, které byla k dispozici pro účely této práce a budou zpracovány ústavem v budoucnu. Výstupy jsou hodnoceny sadou vlastních kvantitativních a kvalitativních metrik, které jsou následně ukázány v radarových grafech. Finální proces hodnocení a workflow jsou podrobně vysvětleny na konci této práce, aby pomohly ústavu nebo komukoliv jinému s implementací tohoto typu dat.

Klíčová slova: laserové skenování, extrakce prvků, mobilní skenování, klasifikace

The aim of this master's thesis is to find an effective solution for linear feature extraction from point cloud obtained by mobile laser scanning and highlight its benefits and drawbacks. Point clouds are valuable sources of information, but their character can make them challenging to process, which could lead in lost potential by processing them ineffectively. This thesis proposes an approach for extracting linear features from road infrastructure point clouds while avoiding information overload. This is complemented by a several research articles to explore the problematic from different perspective. The commercial solutions presented were tested on point clouds available for the purpose of this thesis and will be processed by the department in the future. The outputs are assessed using a custom set of quantitative and qualitative metrics, which are then presented visually using radar charts. The final workflow chart and assessment steps are thoroughly explained at the end of the thesis to assist the department or anyone interested in implementing this type of remotely sensed road infrastructure data.

Keywords: laser scanning, feature extraction, mobile scanning, classification

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Chapter 1
Introduction

The last decade has seen significant technological advances that have also benefited survey systems and their modifications, reducing their size and increasing their functionality and affordability. As a result, sensing systems have become more widespread and accessible for a variety of engineering needs. This has had a positive impact on fields such as geomatics, geographic information systems and other related fields by providing a rich source of information that can be used effectively.

The amount of information provided, coupled with advances in geoinformatics, has enabled the handling of large but accurate amounts of data in subdisciplines such as photogrammetry, spatial analysis, web mapping, remote sensing and others. This has resulted in a more affordable and accessible type of survey information.

The wide range of information has a variety of applications, from inventorying current conditions to planning and estimating future projects. Documenting and inventorying can include detecting and locating various objects or performing basic censuses. Planning and estimation applications may include new water engineering projects such as lakes, rivers and coastlines, landscape projects such as parks, forests, mines, transportation infrastructure projects and more. Transportation infrastructure applications include cubature calculations, reconstructions, utilities localization, obstacle identification, standard landscape analysis, safety inspections, road mapping and lot more.

Engineering aspects have a significant impact on project costs from the beginning to the end. Fundamentals such as surveying or as-built mapping can produce incorrect results, which can have a cascading effect on other aspects of the project. The presence of incorrect information can be critical and lead to minor or major difficulties. As technology advances, surveys and general data collection become easier and more affordable. However, the abundance of data can lead to information overload, making it difficult to identify the correct and trustworthy source of information.

1.1 Elementary Challenges in this Thesis

This master's thesis is formed based on need and activities of the Department of Forensic Experts in Transportation. The aim is to find an effective way how to extract linear features such as road markings, any type of road edge including curbs or pavement, guardrails, handrails and noise barriers from point clouds. One of the requirements was to have the potential to scale to point-like feature extraction in the future. All of this is done in an effective way and prepare the incoming data for subsequent use in terms of safety inspections, road analysis and other possible applications for road infrastructure.

The beginning of the thesis outlines the basic theory by explaining the fundamentals. This is followed by a detailed description of the survey technology used and the point clouds provided. These introductory chapters provide a solid theoretical foundation for the subsequent chapters, including how to determine the required point cloud quality, how to set the survey conditions and how to evaluate the incoming data. While the survey and data preprocessing phases are not explicitly part of this thesis, their impact on the final outcome is significant, so they are explained in great detail. The clear demarcation of this thesis is showed in Figure 1.1.

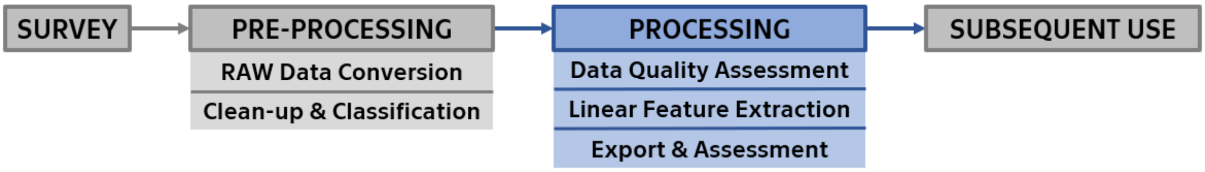


Figure 1.1. Thesis Demarcation

A commercial software solution is presented as a sensible solution after identifying a few reliable options. These solutions were tested on specific data sets and the results were evaluated using the commonly used numeric metrics introduced in the research papers. The research papers provided valuable insight into the problem from multiple perspectives and helped to establish achievable results that set the desired output quality level.

The calculated metrics obtained during testing the identified software were complemented by a number of quantitative and qualitative aspects. These were combined to create a radar chart that allows the reader to easily understand the strengths and weaknesses of each software solution.

By detailing the various steps involved, this thesis provides the reader with an understanding of the necessary requirements, advantages and disadvantages associated with using mobile laser scanning. Armed with this knowledge, readers can make informed decisions about how best to proceed with the implementation of this valuable technology.

This master's thesis proposes a workflow tailored to the data provided by the department's contractor, who conducts the survey and performs initial preprocessing to generate outputs. Although the workflow was designed for the specific needs of the department and tested on their data sets, it can be adapted to other data sets and produce comparable results with proper interpretation.

Chapter 2
Mobile Mapping Systems in Theory

Mobile mapping system (MMS) technology were used to gather the survey data for this thesis, resulting in a large amount of highly accurate data sets. The following sub-chapters provide the basic theory of MMS, covering topics such as it's general definition, possible configurations and data outputs. This is followed by an introduction to key components in this topic. The specific technology, along with its overall accuracy[1], quality and other pertinent considerations are described in the next chapter. All of this is crucial to understand in order to be able to propose an effective workflow, which is the main objective of this thesis.

2.1 Mobile Laser Scanning and Mobile Mapping Systems

The MMS is a superordinate term for the technology of collecting geospatial data from a moving vehicle and mobile laser scanning (MLS) is one option that includes vehicle or airborne laser scanning. Mobile mapping systems are gaining significance as a valuable 3D measurement technology that can quickly capture a significant volume of precise geospatial data. These systems usually accommodate supplementary sensors like cameras, reflectometers, laser crack measurement systems or inertial profilers to collect more data simultaneously with LiDAR[2] data acquisition. [2–3]

Obtaining substantial amounts of data from mobile mapping systems is a valuable but complex resource. A key advantage of MMS technology is that a single data set can serve multiple purposes. Moreover, the data may also yield additional information beyond the intended focus of the original acquisition. Despite it has broad applicability, MMS technology is best considered a "tool in the toolbox", as it may not always be the most effective solution. It is therefore advisable to conduct a cost/benefit analysis to determine if MMS represents the optimal technological approach for a particular project, such as for accident investigation or land use planning. [2]

MMS technology does not uniformly demand the same degree of data accuracy and density for all applications. Depending on the specific use case, local accuracy of the resulting point cloud may be more crucial than network accuracy requirements. For instance, when MMS data is obtained for bridge clearance calculations, stringent local accuracy is essential, while network accuracy to determine bridge location may be less critical. Due to the high survey speed and level of detail, there is a risk of information overload that could potentially compromise the effectiveness of the process. [2]

One possible method to determine an appropriate level of detail is the Data Collection Category (DCC) approach outlined in NCHRP Report 748. This approach utilizes a matrix consisting of 9 categories organized in a 3x3 grid. The column numbers indicate varying orders of accuracy (1 = High, 2 = Medium, 3 = Low), which significantly impact survey costs. The row letters correspond to point density levels (A = Coarse, B = Intermediate, C = Fine) on the targets of interest, which can be achieved through slower driving or multiple passes. This approach ensures that data set is utilized in a suitable manner. For example, category 1A denotes

[1] Accuracy is measurement of correctness and refers to how close a measured or predicted value is to the true or expected value. Precision refers to how consistent or reproducible a set of measurements or predictions are.

[2] LiDAR (Light Detection And Ranging), LADAR (Laser Detection And Ranging), Laser radar or Laser Remote Sensing are terms that stands for the same technology. [1]

data with a point density greater than 100 pts/m^2 and accuracy less than 0.05 meters, which can be used for highly accurate tasks such as bridge clearance analysis. Conversely, category 3C indicates data with coarse density of less than 30 pts/m^2 and accuracy greater than 0.20 meters, which is ideal for planning and bridge positioning purposes. [2]

2.2 Types of Mobile Laser Scanning

The technology and vehicle utilized for a survey must align with the specific survey objectives. For instance, a survey aimed at locating multiple bridges on a highway will differ from one focused on analyzing structure clearance, not only in terms of the required level of detail, but also in the necessary data collection time, equipment and post-processing. [2]

While terrestrial laser scanning (TLS) devices provide high point accuracy and density, they are limited by their smaller coverage and low time efficiency. For landscape or infrastructure surveys, it is essential to cover large areas in a relatively short amount of time, which can be achieved through mobile laser scanning, either through vehicle-mounted or airborne setups. MLS offers a wider coverage area in a shorter survey time compared to TLS, making it a more efficient option for these types of surveys. [2]

A mobile laser scanning typically consists of two essential components: a laser scanner and a GNSS+IMU unit. These units are further complemented by power and control units, as well as storage drives. To ensure they can operate effectively in outdoor conditions, mobile laser scanning systems are designed to meet water-proof certification standards. While airborne scanning systems have been around for some time, vehicleborne scanning systems have emerged more recently, using vehicles such as cars, trains for railway infrastructure surveys, or boats for bathymetry surveys as carriers. [3]

Figure 2.1 illustrates how airborne laser scanning (ALS) can cover larger areas in less time by utilizing aircraft to carry the laser scanner. ALS technology is capable of providing a faster coverage of areas and has a larger footprint compared to terrestrial-based scanning techniques. Additionally, ALS is not limited to areas visible from the roadway. However, the trade-off for this broader coverage and quicker surveys is that ALS sacrifices some level of detail. Due to the lower level of detail provided by ALS, it is best suited for applications such as planning, asset or vegetation management. [2–3]

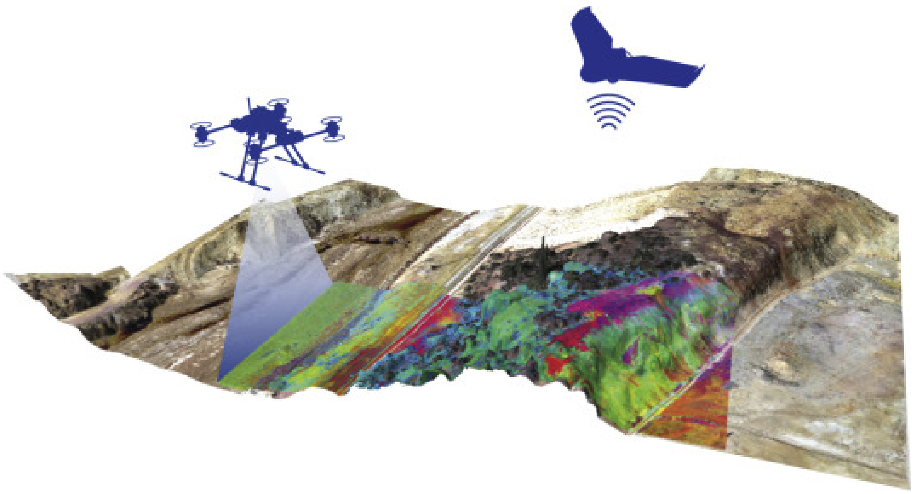


Figure 2.1. Airborne Laser Scanning [4]

Vehicle-based laser scanning is advantageous as it provides a closer view of the infrastructure, including the pavement and linear features. This is due to the fact that the survey is conducted at a slower speed with smaller footprints, but resulting in a higher point density and accuracy. To further increase accuracy and reduce overlaps with surrounding vehicles, the car can be driven multiple times through (MTA principle) the same survey area. This approach can increase point density, point cloud accuracy and reduce noise and vehicle overlap by combining multiple point clouds from the same area. [2]

Advancements in technology have resulted in the development of more compact devices, allowing surveys to be carried out in hard-to-reach areas by individuals wearing a backpack mounted system. This compact mobile mapping system is equipped with multiple laser scanners, capable of reaching up to 200 meters, five 4 Mpx cameras for optimal imagery coverage, GNSS antenna, SLAM Scanner and IMU. The collected georeferenced images are stitched together to provide an immersive panoramic experience and to aid in navigation and colorization of the point cloud. The device is powered by batteries, providing approximately 1 hour of operational time, with the option to extend this time by using multiple batteries. The Leica backpack device is illustrated in Figure 2.2. [5]

Figure 2.2. Leica Pegasus Backpack [5]

Choosing the right survey method is critical to obtaining accurate results. The Leica Backpack Wearable Mapping System, which is carried by a person and has a limited survey speed, provides a smaller coverage area and an accuracy of about 5 centimeters. It is mainly used for surveys in tunnels, subways or indoor buildings. On the other hand, the Riegl VMX-2HA mobile mapping system equipped with Riegl VUX-1HA laser scanners has an accuracy of 5 millimeters and is designed for linear infrastructure surveys such as road and rail projects. Therefore, it is important to carefully consider the survey objectives before selecting a particular method and system. [5–7]

2.3 LiDAR Technology

LiDAR was first developed in the 1960s and initially used for terrain mapping in the aeronautics and aerospace fields. In the 1970s, LiDAR was primarily used for airborne mapping of various natural features, including forests, oceans, ice sheets and the atmosphere. One lesser-known application of LiDAR is its use by NASA in the Apollo 15 mission for mapping the surface of the moon. In past yew years LiDAR became a widespread technology and now can be found in cars or cell phones. [8]

LiDAR is a remote sensing technology that uses laser light to measure the distance to objects and surfaces. The LiDAR systems consist of a laser, a scanner and a receiver (depicted in Figure 2.3). The top part of LiDAR rotates its axis to spread out the points all around and increase the coverage area. The time of flight between the emitter and the receiver is recorded, same as other attributes. Based on time of flight and speed of light the distance of the objects that reflected the laser beam back is calculated. Creating and recording nearly millions of laser beams each second, LiDAR is generating huge amount of data representing objects as a inconsistent and indistinguishable point clusters. This allows LiDAR to create highly detailed 3D maps of the environment, which are hard to manage and process. [9]

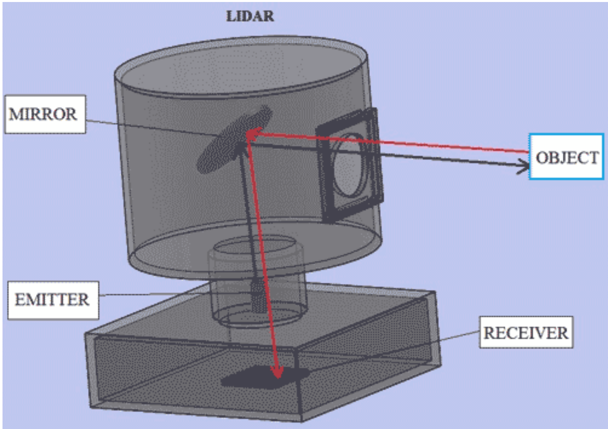


Figure 2.3. A LiDAR Device [9]

This technology is very powerful and precise in locating things in nearby surroundings. This function also serves well in other applications. Currently biggest application of this technology can be found in self-driving cars. LiDAR can create detailed 3D maps of the surrounding environment in real-time, allowing self-driving cars to navigate securely and precisely. The use of LiDAR increases based on the modifications, static LiDAR can be used for example in traffic engineering as an occupancy sensor. Another advantage of LiDAR is it's high level of accuracy and can produce highly precise measurements of the distance to objects and surfaces. This makes it an ideal technology for applications where precision is critical. [9]

2.4 Point Clouds

Point clouds are the outcome of mobile laser scanning, comprising a three-dimensional coordinate system, in which each point denotes a specific spatial location and is defined by its x, y and z coordinates, alongside other properties, such as color, angle and intensity. Typically, point clouds are produced through LiDAR or structured light scanners, which detect surface geometry of objects or environments. Furthermore, other sensors can be employed to acquire supplementary information on the surrounding environment. Since LiDAR scanners can record only limited information and are unable to record object color, a camera can be utilized to capture aerial imagery, thereby enabling the coloring of individual points to have better understanding of scanned environment. [10]

Point clouds are characterized by hundred million points, which pose challenges for storage, inter-device operations and processing. High-performance desktop computing systems with graphics capabilities can be leveraged to process point cloud data efficiently. They can be saved in different file formats that differ in the information they store and their compression rate for efficient storage and transfer. The choice of file format can also depend on the type of scanner or software used. The most commonly used file formats are .ply, .xyz, .pcd and .las.

Chapter 3
Provided Point Clouds

This chapter provides a comprehensive overview of the technology used and the steps involved, starting with the data collection process, the vehicle and equipment used. This is followed by a comparison of the mobile laser scanner used with the typical total station through an assessment of the vertical accuracy. The survey itself is then described, along with the processing of the raw data while maintaining the accuracy and classification to increase overall effectivity. A crucial aspect is to take a critical approach to the data provided, identifying typical quality issues in point clouds and recognizing them in our data sets. This step is crucial as it allows us to determine whether or not the data is suitable for our purposes.

3.1 Vehicle

The objectives of this thesis is to process the provided data from Geodetic Office Nedoma & Řezník and their specialization is to provide survey mainly for transportation infrastructure. Back in 2020, they made the decision to obtain and equip a survey car with an adequate survey machine for conducting surveys while on the road. [10]

The vehicle that matched all requirements like shallow height to allow installation of the mobile mapping system, possibility to drive on unpaved road, higher chassis and price budget was at that time hatchback the Škoda Yeti (all wheel drive). This car succeeded mainly because of better drive-ability and more powerful alternator, which is important for charging battery of mobile mapping system and on-board control unit. [10]

Even after matching all requirements vehicle still have to be modified. The appropriate modifications included installation of warning and advertising stickers, safety beacon and slight software modification. Mobile mapping system is assembled to the aluminum roof rack and is easily detachable after all cables are disconnected and safety lock release. These features allows car to be parked outside without expensive device on top. [10]

Power and data connection between the scanner and the camera outside with the computer and the storage drives inside is secured by multiple cables through slightly modified side window. The odometer is fixed to car's wheel. Engine, chassis or bodywork modification were not required. Survey technology is not mounted to car permanently and can be moved to another one if required. Car with all the equipment is depicted in Figure 3.1. [10]

3.2 Mobile Mapping System

Based on comparison done by Mr. Grešla in his thesis there were several options on the market for this particular situation. Comparison was primarily done between three main suppliers from Leica, Trimble and Riegl. Trimble did not provided an offer. Riegl offered the two scanner machine (VMX-2HA) with same precision for a price of single scanner machine from Leica (Pegasus:Two). The scanner offered by Riegl has more than 3 times longer reach, faster beam distribution allowing higher survey speed with same quality output and is more durable than machine offered from Leica. Regard to all these aspects Geodetic Office decided to buy Riegl VMX-2HA depicted in Figure 3.1 and 3.2. [10]

Figure 3.1. Škoda Yeti with mounted Riegl VMX-2HA and FLIR Ladybug Camera [11]

3.2.1 Riegl VMX-2HA System

Top part of scanner machine Riegl VMX-2HA is composed of two laser scanners VUX-1HA (described separately in following subchapter) assembled onto VMX-HA measuring head. The alignment and placement of these laser scanners keeps a simultaneous forward/backward looking to reduce scan shadows. The platform carries both - LiDAR sensors and a high grade GNSS/IMU units to provide an accurate and long-term stable system calibration. [6]

There is a cable interface located under the sensor units for the main cable and external devices, as well as a trigger and time stamping unit. The scanner head VMX-HA is equipped with slots for external Riegl cameras with adjustable positioning to capture images of the surroundings. These cameras can be used to take additional image records. For instance camera on left in Figure 3.2 points downwards for pavement analysis or crack indexing.

The record units and some other components are sealed and covered to protect them. The scanner machine has IP 64 certification, which means it is fully protected against dust and splashing water from all directions. This increases the overall operability of the scanner and allows it to be used in temperatures ranging from -20 to +40 degrees Celsius. [6]

All these components including external camera in front of Riegl mapping system is mounted on Riegl reinforced roof mount. This makes the mapping device easily transferable and compatible with standard roof racks. [6]

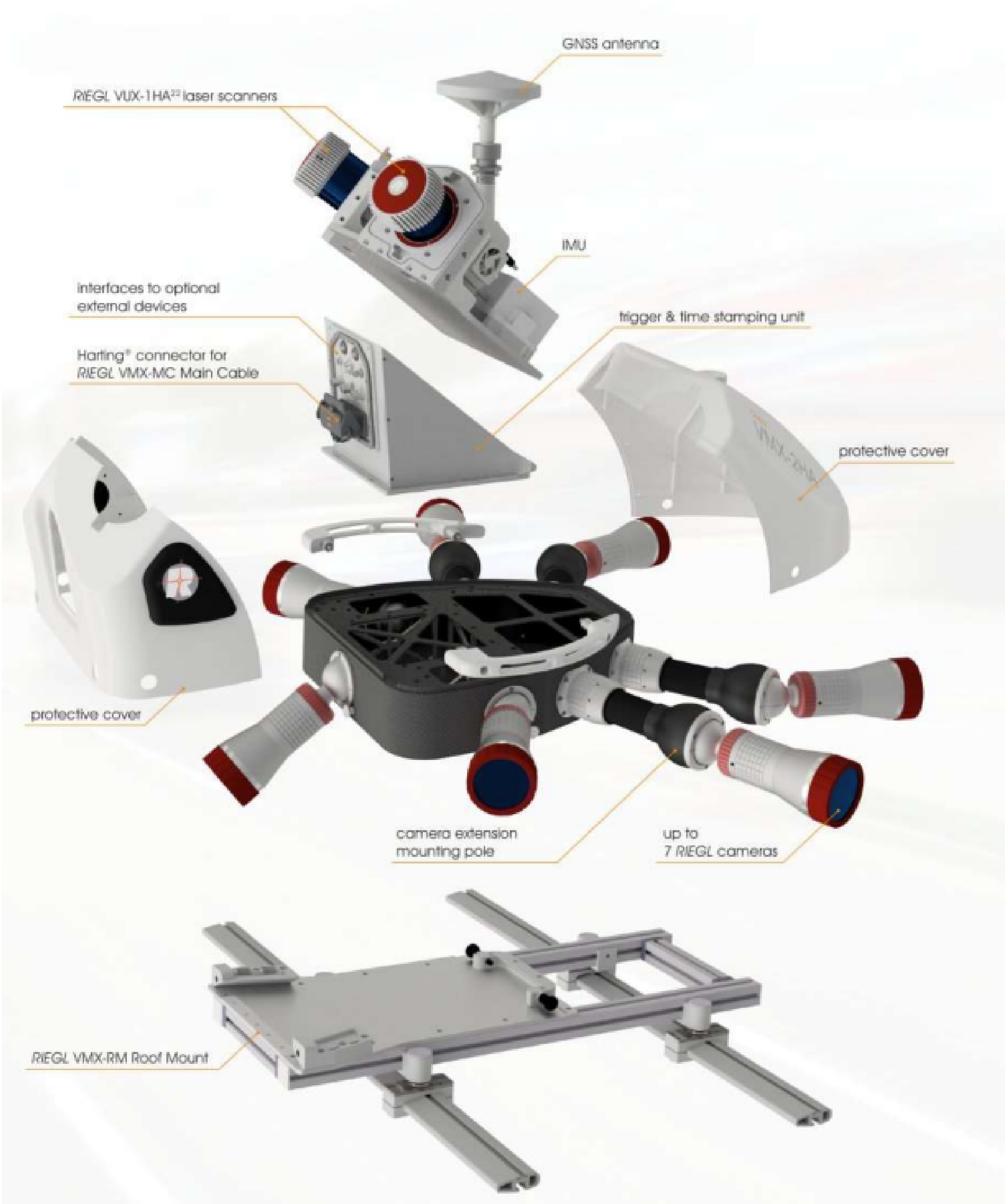


Figure 3.2. Composition of Riegl VMX-2HA [6]

3.2.2 Riegl VUX-1HA Scanner

The Riegl VMX-2HA mobile mapping system is equipped with 2 laser scanners Riegl VUX-1HA depicted on Figure 3.3. The scanners are mounted with 70 degrees horizontal and 39 degrees vertical rotation in relative to scanner machine and themselves. Scanners with this alignment are able to minimize scan shadows and maximize coverage around the vehicle. [10]

Figure 3.3. Riegl VUX-1HA Laser Scanner [7]

This particular scanner has a frequency of 1 MHz and is able to provide an accuracy of 5 millimeters and a precision of 3 millimeters. These specifications have been verified by the manufacturer and are effective up to a distance of 30 meters, with the ability to process up to 250 scan profiles per second within the field of vision. Each of the scanners produces rows of points that appear parallel due to the rotation speed. When the lines from the two rotated scanners intersects, a rhombic grid is formed as depicted on Figure 3.4.

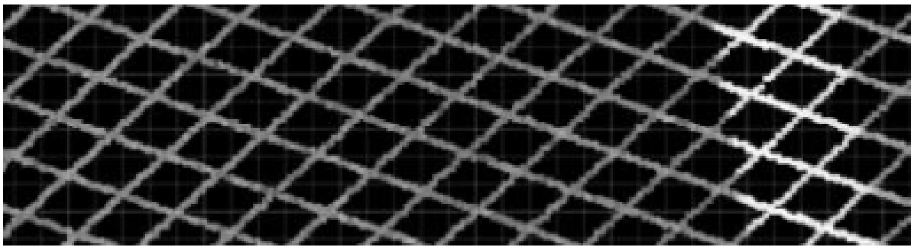


Figure 3.4. Rhombic Grid in Point Clouds [10]

By changing the speed of the vehicle and the scanner frequency, the distance between the lines in the grid is adjusted. The 1 MHz scanning frequency provides a line spacing of 56 millimeters at 50 kph, 89 millimeters at 80 kph and 133 millimeters at 120 kph. Point density depends on vehicle speed and distance from scanner head. At speed 50 kph and 3 meters distance from sensor 7640 pts/m^2 are recorded, 2300 pts/m^2 in 10 meters and 458 pts/m^2 in 50 meters distance. The number of points decreases with increasing vehicle speed. At a speed of 80 kph 4774/1432/286 pts/m^2 are recorded and at speed of 120 kph 3184/954/190 pts/m^2 are recorded respectively at the same distance increments as above. The area of primary interest for further processing is 5 to 10 meters from the scanner sensors on either side. [10]

3.2.3 On-board Equipment

The Riegl VMX-CU control unit is a computer system, housed in a rugged suitcase, that is designed to control all components. It is powered by two 12 V car batteries (on-board + back-up) and is equipped with an Intel processor and eight SSDs with a total capacity of 8 terabytes. The storage drives can be removed to quickly transfer the data after the survey is completed. The control unit is controlled by a separate computer running Linux and the RiACQUIRE software. This software allows the co-driver to adjust the scan frequency and the interval between records, among other things. System block diagram is depicted on Figure 3.5. The data transfer and power between control unit and sensor head is conducted via 10 GigE cable. Odometer and FLIR Ladybug camera are connected directly to the control unit via USB. The control unit is equipped with 4 separate fuses for extra safety. [10]

The GNSS unit serves as the primary recorder for the trajectory. In the event that the observation conditions significantly change during the survey, the IMU along with odometer serve as a backup with absolute precision 20 - 50 millimeters. [6, 10]

Scanner head is equipped with 7 camera ports to connect up to 8 Riegl cameras (with addition of using fork in rear port if precise pavement analysis is required). This fully modular setup allows to point these cameras as required. Beyond these Riegl cameras the sensor head allows to connect external thermocamera or spherical camera (FLIR Ladybug e.g.). This allows to color points based on true color or temperature (when using thermocamera) and have better understanding of surroundings in post-processing. [6, 10]

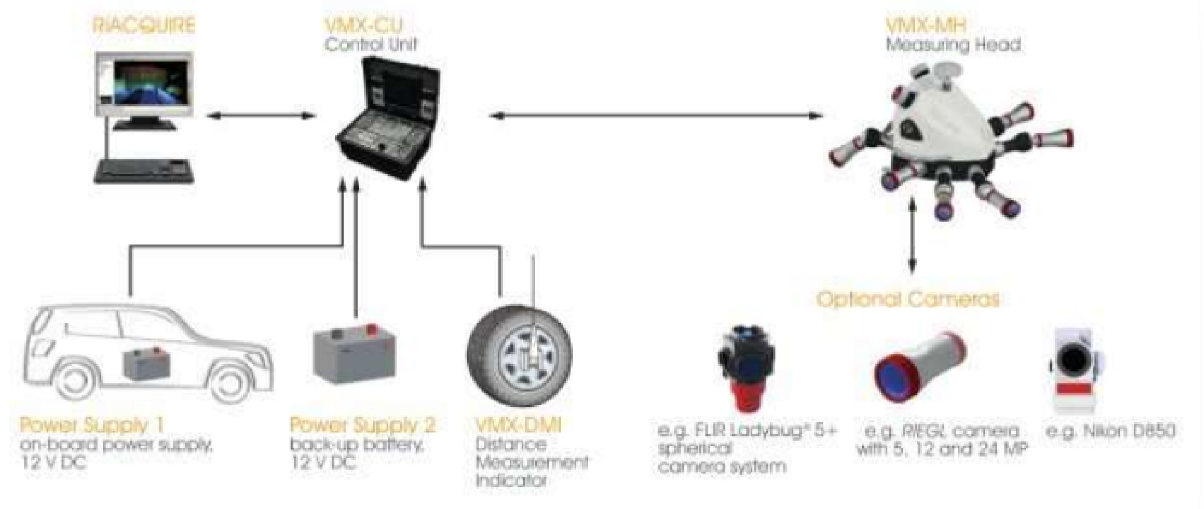


Figure 3.5. Riegl VMX-2HA System Block Diagram [6]

3.2.4 Accuracy of the Used Technology

Important difference is between a reference and non-reference point cloud quality assessment. If there is no reference to compare a point cloud data with, the point cloud quality could be tagged as sufficient or adequate, even though the data does not collide with reality. For this situation reference data are not available for a reference point cloud assessment. However the point cloud data for this thesis were provided by Geodetic Office Nedoma & Řezník with use of the mentioned technology.

The overall quality and accuracy of this particular machine was assessed by Mr. Grešla in his bachelor's thesis comparing the vertical reference deviation to the traditional total station. The methodology used involved obtaining six point clouds at three different time periods and comparing them. Five of them were obtained from LiDAR scans using Riegl VMX-2HA and one from measurement using the Leica NOVA MS50 total station. [10]

Comparison of two point clouds was carried out using the 2.5D triangulation method. This method selects k-closest points to the points being compared from the reference point cloud. These points are then used to create a triangulated irregular network, to which vertical deviations are calculated. The results from the 2.5D triangulation comparison consist of two components - the mean deviation between the TIN created from the selected number of k-closest points and its standard deviation. The root mean square error of these two components is subsequently calculated. [10]

Table 3.1 displays the results of Mr. Grešla's investigation. The point clouds obtained from LiDAR are compared to the point cloud obtained from total station measurement, which was considered as the base model for this experiment. Sample number 2 yielded the poorest result because it was not aligned with either MTA or control points. The deviation in sample 3 was significantly reduced by using only MTA, while sample 4 utilized MTA and control points. The same approach was taken with sample 5 (control points followed by MTA) and sample 6 (only control points). Samples 4 and 5, which employed both aligning procedures in opposite order, were the most accurate to the base model, as it greatly reduced the final deviation. [10]

Table 3.1. Vertical Deviation Analysis of LiDAR Compared to Terrestrial Measurements [10]

Sample	Machine	Date	MD[1]	SD[2]	RMSe[3]
1	MS50	06.11.2021	-	-	-
2	VMX-2HA	17.11.2021	16.7	9.8	19.4
3		17.11.2021	4.7	3.1	5.6
4		17.11.2021	-0.5	2.7	2.8
5		25.06.2021	2.3	3.1	3.9
6		25.06.2021	4.1	5.9	7.2

The data utilized in this thesis are similar to that of sample number 3, because all were aligned between scans from the same area (MTA principle). Numerous organizations and research studies around the world agree that a RMSe of around 20 millimeters is adequate to analyze road surface. For example the Idaho LiDAR Council has specified that their accuracy standards require RMSe of less than 125 millimeters and their construction specifications allow for a maximum RMSe of 30 millimeters. [12–14]

3.3 Course of the Survey

The survey always starts with installing the measuring head back on roof rack, pulling up the spherical camera, connecting necessary cables and software initialization. This procedure is then followed with static and dynamic auto-calibration of GNSS/IMU near the surveyed area. After the calibration is done, scanners are turned on and car finally approaches the surveyed area. Once the car enters the surveyed location recording of scanners and Ladybug camera starts. Due to presence of other cars in records the surveyed area can be scanned multiple times by passing through more than once (MTA principle). [10]

During a survey, data records are divided into 1 kilometers sections unless the operator intervenes through the control screen. The operator is also responsible for maintaining the smooth operation of the survey in the event of changes in observation conditions for example. After the survey is finished, recording is stopped and the vehicle leaves the survey area for dynamic and static auto-calibration. The measuring head is then disconnected, dismantled and stored in the office building. The data hard drives are transferred from the control unit to the in-house data center to make the data accessible to all company employees. [10]

[1] MD - Mean Deviation [mm].
[2] SD - Standard Deviation [mm].
[3] RMSe - Root Mean Square Error [mm].

3.4 Raw Data Processing

The survey data taken directly from the hard drives could not be used in point cloud processing. The recorded trajectory is calculated from the raw GNSS/IMU data in POSPac software with the addition of ephemeris and observation data from virtual reference stations. All these data need to be combined to calculate the final trajectory and error rate. [10]

The final trajectory is then exported to existing project in RiPROCESS software. This project is created before each survey and data collected during survey are already saved here. Point position is then calculated from time stamp of each point. [10]

Another step that is desirable to increase point cloud accuracy is to align the data relative to control points (manually or automatically). This can be a problem if the control point has moved between each car pass. In location with insufficient observation condition this could create a several meters error. Last step to increase a point cloud accuracy is to align scans from different passes between themselves, known as Iterative Closest Point method. This step can be done together with control point aligning in RiPRECISSION. [10]

All other subsequent steps, unlike the previous ones, are not related to modifying point position but to adding details to point clouds. Points can be colored based on pictures from Ladybug or any other spherical cameras.

3.5 Classification

Working with point clouds requires the use of software that can handle vast amounts of point cloud data and robust hardware. To optimize efficiency, it is essential to maximize the length of the section and reduce the number of points while maintaining the necessary level of detail. LiDAR scanners capture the entire environment, including our desired targets, in a single scan. To establish an effective workflow, it is essential to eliminate unnecessary data from the surrounding or nearby areas.

Currently, there are several different approaches to classify points and clear point clouds. The results may vary depending on inputs, conditions and individual steps. The data sets obtained from the Geodetic Office are classified with use of their own procedure and know-how. This particular procedure insists on cleaning the point cloud based on the properties of each point, for example limiting the range of values on a feature. This is a very difficult task as these values can vary from scan to scan. Using this approach, it's possible to filter points based on their reflectivity, for example to distinguish points reflected from wet or dry surfaces.

The very first step in this particular procedure is to delete the redundant points and clean up the previous classification, if any. Isolated points (e.g. less than a certain number of points in a given area) are then deleted and the normal of each point is calculated, as the direction of each point is important for the next steps. The ground layer is created based on the high point density at the lowest elevation. This is then used to create the hard surface layer, which represents a narrow pavement. The height from one of these base layers is then used to create low, medium and high vegetation classes or any other specific point class. These steps are part of basic classification. The more advanced classification comes next and consists of merging point clouds in the same location but from different car passes, extraction of power lines, or distinction between trees and vertical traffic signs, e.g.

Table 3.2 demonstrates the significance of employing classified point clouds, as evidenced by the following instance that comprises roughly 78.4 million points. For example if only two classes (number 2 and 35) are required to represent pavement, that enables us to diminish the number of processed points from 78.4 to roughly 26.8 million. This represents a reduction to nearly 34% of the original data set, while allowing us to add another two similar sections and process nearly 3 times longer region of road at once. All of this without significantly increasing the number of points or compromising detail nevertheless using same computational power.

Table 3.2. Point Count by Class [TerraScan]

Class Number	Description	Count	Color
0	Class 0	42 208 385	Black
2	Ground	16 068 289	White
4	Medium vegetation	1 210 085	Light Green
5	High vegetation	902 302	Green
16	Tree	1 976 440	Light Green
18	Pole	2 542	White
19	Car	910 913	Magenta
21	Wire	2 192	Yellow
35	Hard surface	10 692 349	Orange
36	Medium road	23 602	Red
37	High road	4 433 113	Purple
-	all	78 430 212	-

Figure 3.6 exhibits a clear distinction between the amount of information conveyed on the left side, where the complete data set is color-coded by class and the right side, where the information is limited to only hard surface and ground data. The left side of the data includes various types of information, such as cars (in magenta), medium or high vegetation and trees (shades of green) and guardrails (in red). The majority of the road data (nearly 54 %) is classified as Class 0 (in black)[4], as this class include points that did not fit into Class 2 or 35 algorithm filter.

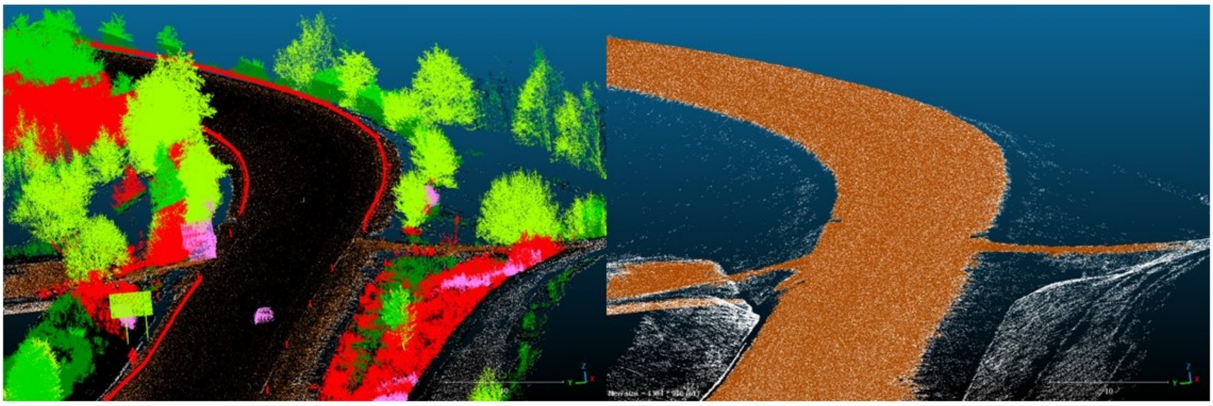

(a) (b)

Figure 3.6. Classification: (a) all classes; (b) ground + hard surface classes [CloudCompare]

Although implementing classification would undoubtedly improve the overall efficiency of the workflow, it must be done at a sufficient level to avoid misclassifying features in the data sets. Therefore, this thesis will not utilize classification, as the primary objective is to propose a productive workflow that maximizes the number of extracted features and explores the full potential of the software. It is likely that some features will be labeled differently across the samples, such as guardrails being classified as low/medium/high vegetation or road. This discrepancy could result in eliminating features before they can be extracted, which is not acceptable.

[4] According to the Geodetic Office's advice and further investigation, this class could be employed when there is insufficient data available in certain areas. Classes 2 or 35 are taken as the main source of information and Class 0 can serve as an addendum if required.

3.6 Quality Assessment

Assessing the quality of a point cloud is an important step in many applications of 3D modeling and data analysis. The quality of a point cloud refers to how accurately it represents the underlying object or environment and how well it can be used for further analysis or visualization and to describe the importance of the technology used.

There are several factors that can affect the quality of a point cloud, including the density of the points, the accuracy of the individual points and the presence of noise or artifacts. In order to assess the quality of a point cloud, it is necessary to look at each of these factors and determine how they affect the overall accuracy and usefulness of the data.

The accuracy of individual points in a point cloud can also be assessed by comparing them to the reference model. This can be done by calculating the average distance between each point in the point cloud and the nearest point on the reference model. A point cloud with a low average distance is likely to be of higher quality than one with a higher average distance.

Finally, the presence of noise or artifacts in a point cloud can be assessed by visual inspection. Noise can cause points to be randomly distributed, rather than forming a clear and coherent representation of the object or environment being scanned. Artifacts can take the form of false points or other distortions that do not accurately represent the underlying object or environment. In both cases, the presence of noise or artifacts can reduce the quality of the point cloud and make it difficult to use for further analysis or visualization.

In conclusion, assessing the quality of a point cloud is an important step in ensuring that the data is accurate and useful for further analysis or visualization. By assessing the density, accuracy and presence of noise or artifacts, it is possible to determine the overall quality of the point cloud and make informed decisions about how to use the data. The visualization of each named quality issue is depicted in Figure 3.7. The sample (a) is free from any quality distortions, while the sample (b) exhibits 8 % position noise. The following sample (c) has a point density that has been decreased by almost 99 %. Finally, the sample (d) lacks up to a quarter of the original data, resulting in a non-continuous data sample. [15]

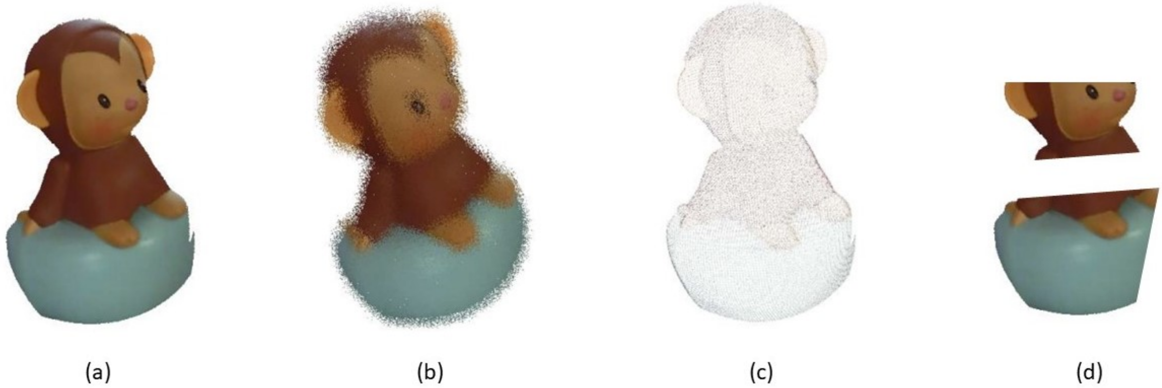


Figure 3.7. Common Point Cloud Defects [15]

The MTA principle, a widely used method for improving point cloud quality without requiring technology upgrades, involves using a vehicle to survey the same area multiple times. This process generates multiple scans of the area from different perspectives and at different times, which can be merged into a single scan. By incorporating data from multiple scans, gaps in the data can be filled, resulting in increased accuracy and reduced noise. Redundant elements, such as cars or other noise, can be identified and removed as they may appear unique in one scan but not in others.

The quality of point cloud data can greatly affect the usability and reliability in their applications. Therefore, it is important to assess the quality of the point cloud data before using it. It is a complex task that involves multiple aspects, including point density, point cloud completeness and noise presence. By assessing these aspects of point cloud data, users can better understand the quality and overall accuracy of the data and make informed decisions about how to use it.

3.6.1 Presence of Noise and other Redundants

The presence of noise is a critical aspect of point cloud quality assessment. Noise can arise from various sources, including measurement errors and environmental factors and can manifest in the point cloud data as outliers or spurious points. The presence of noise can negatively impact the accuracy of downstream applications and needs to be mitigated.

As explained in subchapter 3.5, the initial stage of point cloud classification involves reducing noise. Various methods can be used for this purpose and in the data sets utilized in this thesis points are discarded when they do not meet a certain density requirement within a given volume unit. Specifically, points within a cube with a side length of 25 centimeters are removed if their count is less than 10. These values are approximate and are based on long-term knowledge and expertise. It is important to note that they may vary from sample to sample.

The recognition of other types of redundants, such as of car overlaps, high voltage lines, or other irrelevant data that is considered redundant for certain purposes is included in the point classification as well. However, these points are not immediately discarded, but instead are moved to a different classification class. It is up to the user then to decide whether or not to utilize this class. An illustration of this concept can be found in the Figure 3.6.

Precise implementation of classification and noise reduction techniques is critical to improve the usability and overall effectiveness of point clouds. It is important to understand that any errors in these procedures can result in a lower point density by removing appropriate points instead of inappropriate ones for example. Therefore, it is essential to execute these processes precisely.

3.6.2 Density

Point density refers to the number of points per unit area in the point cloud data. A high point density can provide more accurate and detailed representations of the object or scene being captured, while a low point density can result in loss of detail and accuracy.

The scanner point density given by the manufacturer is a two-dimensional distribution of points per square meter, but point clouds are three-dimensional. One way to describe this process is that a scanner head produces a “shrink-wrap” with a certain number of point density represented in points per square meter. This “shrink-wrap” is overlaid onto the actual object and it conforms to the object’s spatial shape. This consideration enables us to make comparisons of density using different units, such as points in certain area and number of neighbors in certain range. [6]

Target point density range varies depending on the scanner’s capabilities, ranging from 3000 to 7500 pts/m^2 for close distances and 900 to 2300 pts/m^2 for far distances, as explained in subchapter 3.2.2. Figure 3.8 illustrates that the point density in the center of the road fluctuates between 2000 and 8000 pts/m^2 (light green to orange) with all classes turned on and between 1500 and 2750 pts/m^2 only with classes 2 and 35, which falls within our target range. Multiple other samples and sections demonstrate comparable or even greater point density.

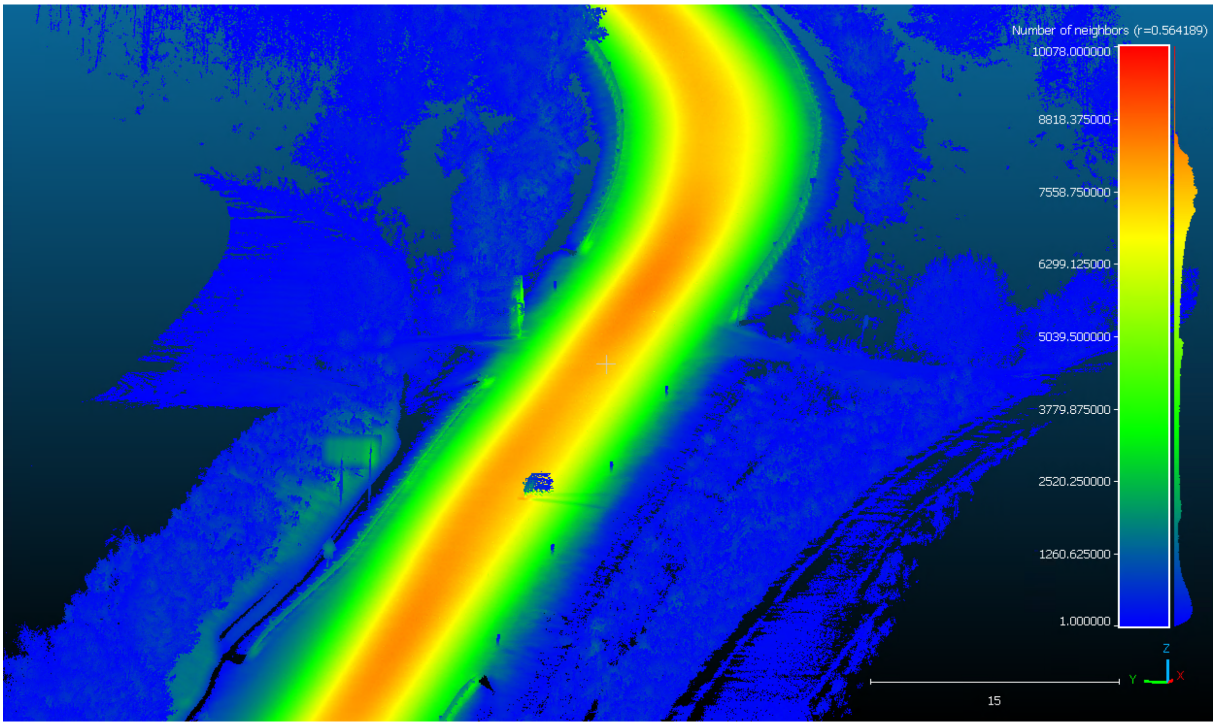


Figure 3.8. Point Cloud Colorized by Number of Neighbors[5] [CloudCompare]

Enhancing comprehension of the topic of point density can be achieved by drawing a parallel with the LiDAR scanner incorporated in the iPhone 12 Pro. This device utilizes a VCSEL that emits an array of 8x8 points that are diffracted into 3x3 grids. This results in a potential density of 7225 pts/m^2 at a distance of 0.25 meters and 150 pts/m^2 at a distance of 2.5 meters, measured from a static position. When compared to the point clouds depicted in Figure 3.8, this translates to a 10-meter wide corridor with a very low density that falls near the bottom of the density bar. A more relevant comparison is the Leica RTC360 terrestrial laser scanner, which offers three resolution options. The middle option provides a density of tens or low hundreds of thousands of points per square meter within 5 meters of the scanner. However, it is important to note that the static nature of this scanner makes it unsuitable for the specific application, as described in the 2.2 subchapter. [16–17]

3.6.3 Point Cloud Completeness

Point cloud completeness is another important aspect of point cloud quality assessment. Continuity refers to how well the point cloud data captures the continuous surfaces and shapes of the object or scene around. Poor continuity can result in gaps and holes in the point cloud data, which can affect the overall accuracy as depicted in Figure 3.7.

At present, there is no definitive method for assessing point cloud completeness within software during processing. Nevertheless, various techniques may be employed, including visual inspection by the user or detecting a significant decrease in point density, which may indicate a gap in the point cloud. In our particular situation, we will rely on visual inspection during the initial software import. This approach suffices for our objectives since our primary focus is on linear features, which is relatively simple to search for gaps or inaccuracies.

[5] The number of neighbors is calculated in a sphere of r=0.564189m, as this corresponds to a circle with an area of 1m^2.

3.7 Output

The above subchapters illustrate the significance of the employed technology and introduce the fundamental principles involved in the initial stage of point cloud preprocessing, as well as point clouds in general. The mentioned steps are not intended to reduce the number of points or overall accuracy, rather, they serve to enhance the overall usefulness of the point clouds by utilizing only the necessary amount of data.

Table 3.3 demonstrates that the decrease in point count is consistent or even more significant across multiple samples, indicating that this approach is not limited to just one sample. By implementing this technique, larger sections can be processed simultaneously or additional classes can be deployed to achieve better outputs.

Table 3.3. Point Count Decrease by means of Classification [CloudCompare]

Sample ID	Length [m]	All points	Classes 2 & 35	% Decrease
1a	200	8 966 217	3 703 357	59
1b	980	78 430 214	26 760 638	66
1c	1000	97 765 051	26 945 204	73
2a	370	40 689 779	5 253 144	87
2b	440	43 013 524	6 391 658	85

Data sets for this thesis are in .las format, which is an open binary format developed by the American Society for Photogrammetry and Remote Sensing (ASPRS) that supports different data types such as coordinates, RGB color and intensity in different bit depth. The user must be careful to use the correct value and setting as it may lead to incorrect data interpretation as shown in Figure 5.14. [18]

The major advantage of .las files is their optimization for working with point clouds and their high compression rate, which is beneficial for storage and data transfer. However, this compression can also make editing the data within the file difficult. There are several more file formats, but they are mostly derived from these basic formats or are exclusive to particular software or machine.

Chapter 4
Existing Solutions

This chapter provides an overview of various solutions that are currently available, including those presented in research papers or commercial solutions. The solutions are categorized into different chapters, each addressing a specific existing solution.

For the research papers, the focus is on summarizing the underlying theories, principles and technologies used to test and compare the results of the solutions, as well as the data sets used. In terms of commercial solutions, these are divided into two categories - “manual” or “semi-automated” options. Although the “manual” options have been tested, they have not been thoroughly investigated due to the primary focus of this thesis on automated and effective workflow. The “semi-automated” options from Atlas Computers Ltd., Application in CADD Ltd. and TopoDOT were explored and assessed in more detail in the next chapter and demonstrated on provided data sets, because they mostly fit the objectives of this thesis.

4.1 Existing Research Papers

Wide range of academics articles are focused on the MMS in general, point cloud processing and feature extractions, while some are not directly aligned within this thesis, they present a valuable source of information and provide a wider context to the problematic. However, several are closely related to the scope of this thesis and therefore reviewed. [19–36]

Others only serves as a proof to the specific topic. Some of the research papers may also include subtasks that are not explicitly addressed in the thesis, such as preprocessing or point classification. [37–47]

4.1.1 “Safety Inspection”

The first article discussed in 2011 is part of a broader research effort to create an automated route corridor mapping solution that includes a risk assessment process to identify unsafe roads. The primary motivation behind this research was to provide a solution that could replace the laborious task of conducting visual safety inspections. The list of extracted road components highlighted in the article is consistent with the objectives of this thesis, with a few exceptions. [19]

The connected articles can divided into two categories based on whether it focuses on the extraction of road edges or pole-like features. The first source discussed is the work of McElhinney et al. (2010), which involves extracting cross-sections from point cloud data and selecting only ground points. A 2D cubic spline is then fitted to the cross-sections and the peaks and valleys of the pavement are detected. Points are further filtered based on intensity and echoes before edge strings are connected to form the final road contour. The next two sources, by Jaakkola et al. (2008) and Manandahar and Shibasaki (2002), outline a workflow for delineating roads, curbs and road markings by filtering points based on their properties, such as intensity, reflectance, density, point dispersion and variation between these. The fourth source, by Brenner (2009), focuses on the extraction of pole-like features. This paper proposes a method to identify the cylindrical features of vertical poles through a kernel region containing pole points and an outer ring with fewer or no points. The pole is then divided into several horizontal stacks, each of which is analyzed independently. If the conditions for a pole are met in a certain number of stacks, the point cloud is recognized as a vertical pole object and extracted accordingly. The fifth source, by Lehtomäki et al. (2010), applies a scan line segmentation approach to extract short line segments and cluster them by projecting in the XY plane to identify poles with more than three adjacent segments. The detected poles are classified into different types based on their height or thickness. Finally, the last theory-based source by Munoz et al. (2008) involves classifying point clouds by analyzing the point distribution and labeling them as linear or surface of scattering and categorizing them into different groups. [19–25]

The recognition method proposed in this paper is based on the theory of knowledge-based feature recognition introduced by Pu and Vosselman (2009). The method presented in this paper uses a hybrid model that combines forward chaining, which is data-driven and used for more complex features where sufficient data is available and backward chaining, which is model-driven and used for low-quality data for less complex features. Geometric features are first extracted by forward chaining, specifically by planar seed surface detection, while semantic features are identified by backward chaining, which involves knowledge-based recognition by searching for known shapes through geometry fitting and recognizing basic shapes or poles. Feature characterization takes into account geometric attributes such as size, position, orientation, shape, color, or material difference, as well as topological relationships between features such as intersection or angle. Using these attributes and their combination, most road features can be defined and extracted. For example, a generic definition of ground might sound like "a large plane that is located at the lowest part of the scene and is nearly horizontal". [19, 26]

Although the proposed methods have only been assessed on two data sets for the extraction of pole-like features, which is beyond the scope of this thesis, the underlying concept of merging attributes to describe features provides valuable insights into the general process of feature extraction. [19]

4.1.2 "Road Extraction in Remote Sensing"

This paper is a detailed summary of road extraction techniques using 2D earth observation imagery and 3D LiDAR point clouds. However, it does not propose a specific solution. The review is based on recent literature published in the last decade, covering different methodologies, data types, challenges and trends. [27]

This thesis focuses on the extraction of road features from point clouds acquired by vehicle-mounted mobile laser scanning. While this particular article provides a comprehensive overview of road extraction methods using various data types and it is not necessary to describe all 28 MLS, 10 ALS, 1 TLS and up to 50 2D remote sensing methods. Many of these methods focus only on road extraction, not other features, which is not the primary objective of this thesis. Instead, only the most effective methods for MLS with the highest completeness, correctness and quality ratios are reviewed. Table 4.1 shows the articles that contain these results and it is worth noting that all results were demonstrated using self-collected samples. A detailed explanation of the calculation methodology for these values is provided in the subchapter 5.3.1. [27]

Table 4.1. Quantitative Performance Summary of MLS Feature Extraction Articles [27]

Article	Completeness	Correctness	Quality
MO by Rodríguez-Cuenca et al. (2015)	97.7%	98.3%	**96.1%**
GVF&BPACM by Kumar et al. (2013)	98.5%	**100%**	-
RBNN-CA by Zhao et al. (2021)	**99.8%**	99.7%	-

The first article, by Rodríguez-Cuenca et al. (2015), presents a six-step workflow for extracting street curbs from MLS data. The first step involves georeferencing the data using navigation and IMU data, followed by trimming the data by removing points above the GPS antenna.

The next step is to rasterize the 3D point clouds into 2D images, followed by segmentation using a thresholding technique to search for height differences. Linear element search is then performed by grouping pixels and detecting linear features and edge detection is performed by identifying large angular changes. Finally, undetected boundaries are estimated. The proposed method has been tested on two point clouds obtained from the Lynx Mobile Mapper system of Optech Inc. The initial data set consisted of an 800-meter two-way road with both straight and curved segments, as well as ambient noise from vehicles, trucks and various obstructions such as fences and poles. The resulting point cloud data consisted of more than 45 million points and was used to assess the ability of the proposed method to detect curb edges. In the second data set, a 250 meter long road in an urban area with structured road boundaries in the form of curbs, ramps and crosswalks was used. This data set contained 18 million points and was used to assess the performance of the proposed method in estimating boundaries that were not originally detected. The computed quality of the results obtained using the MLS data was 96.1% (95.31% for curbs and 96.8% for boundaries). However, the time required to obtain these results was not specified. [27–28]

The second paper, by Kumar et al. (2013), used snake energy analysis for road edge detection and achieved 100% correctness. In this method, a controlled spline curve was used to explicitly represent the snake, with internal energy used to control the elasticity and stiffness of the curve and external energy used to pull the snake curve toward the object boundary. The motion of the snake curve was controlled by balancing the internal and external energy terms until an energy minimization condition was satisfied. The results of the snake energy analysis were impressive, using three different point clouds from three different mobile mapping systems. Samples ranged from 50 to 105 meters in length and processing time ranged from 10.5 to 23 minutes on a typical laptop. The resulting correctness rate was 100%, with a completeness rate of 98.5% (quality was not assessed). [27, 29]

The third paper by Zhao et al. (2021) presents an algorithm for the extraction of road curbs in urban areas. The procedure involves three steps: first, classification is used to extract vegetation, followed by the use of elevation, echo intensity and slope change characteristics to detect road curbs from the point cloud. Finally, the k-NN clustering algorithm is applied to cluster the extracted boundary points. The approach resulted in an impressive 99.8% completeness rate. The data samples used in this study were collected using the ROBIN high-precision laser scanner measurement system. The complete data set covered a length of 1693.41 meters, consisting of a total of 35 million points. The algorithm used took approximately 45 minutes to generate these results on a standard laptop. [27, 30]

4.1.3 "Extraction of Road Boundary from MLS"

Other article from Sui et al. (2021) have used the spatial distribution of point clouds to estimate the scanner ground path and determine the location of roads. Their results show a remarkable correctness of over 99.2% in determining road boundaries in two experimental scenarios. The articles reviewed in this study have used different strategies to address the problem at hand. For example, some have used techniques such as converting 3D point clouds to 2D images, applying multiple image processing algorithms and constructing 3D raster map with a unit volume called voxel (volume pixel). These approaches are particularly helpful in simplifying high-density point clouds. [31]

This study proposes a three-part approach to efficiently extract road boundaries from point clouds. First, the scanner ground track is estimated from the raw data using point density and slope. Second, the road edge is identified using blocks composed of several points that continuously fluctuate upward on either side of the estimated tracks as depicted in Figure 4.1. Third, a simple linear model is developed based on the proximity and collinearity of boundary feature points to quickly detect and track boundary points. It is important to note that the height of the boundary block must be tailored to the location and region, as curb heights may vary from country to country. In addition, frequent lane changes are not allowed during scanning to limit the variation in the distance between the road boundary and the scanner track. Finally, the post-processing step involves vectorizing the extracted boundary. [31]

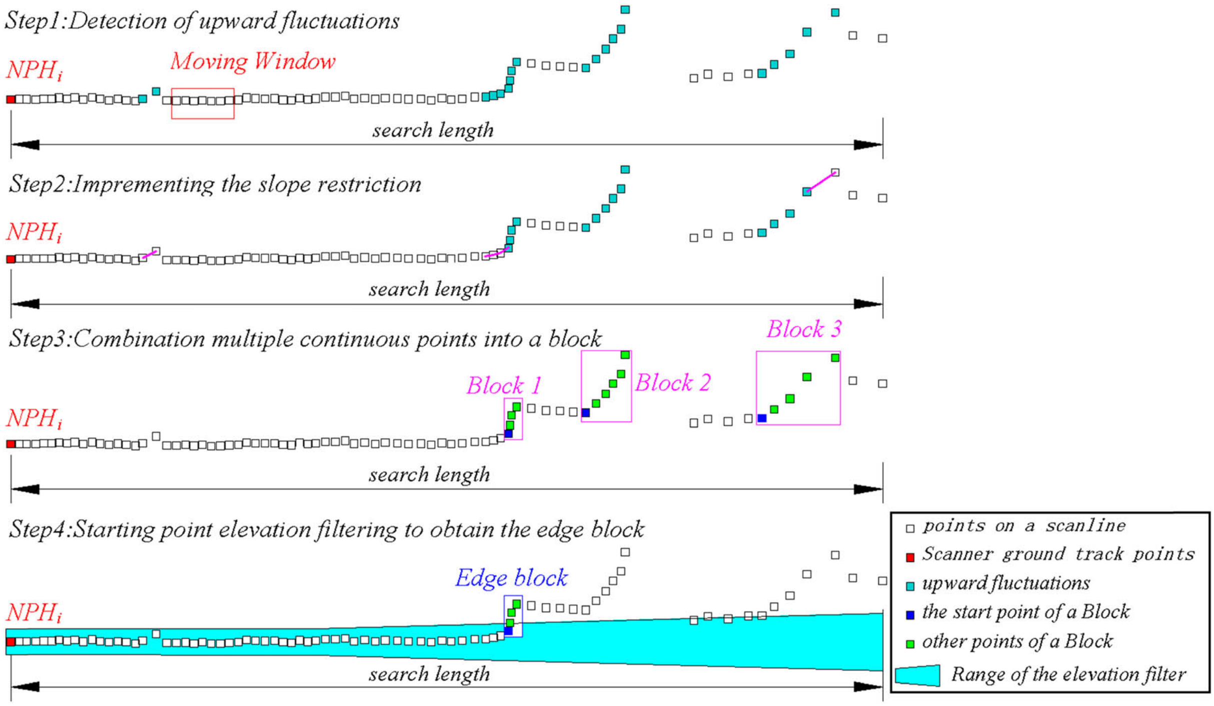


Figure 4.1. Procedure of Detecting Edge Block by Moving Window [31]

The proposed approach was demonstrated using two data sets collected with the SSW-IV vehicle developed by the Chinese Academy of Surveying and Mapping. The laser is positioned at the right rear of the vehicle and the scanning plane is perpendicular to the driving direction. The first data set contains 5.7 million points and covers a distance of 308 meters in an urban area with multiple road lanes, high-rise buildings, trees, poles and wires. It includes both straight and curved roads, as well as two types of curbs (rectangular and S-shaped). The second data set has 4.8 million points, spans 300 meters and is located on a winding highway surrounded by towering mountains, several trees, sidewalks, fences and overhead power lines. [31]

The results of this approach are impressive, with 100% completeness and correctness for road edge block detection on the left side of Sample 1 and the right side of Sample 2. The completeness of the left edge of Sample 2 was 99.88%, while the right edge of Sample 1 was the noisiest with 57 noise records and a completeness of 99.62%. The lowest completeness obtained during the boundary tracking step was 99.2%. Importantly, the results of the algorithm are not affected by the shape of the road, as demonstrated by the successful extraction of a T-intersection (completeness not mentioned). The algorithm also does not require that the road boundary be strictly parallel to the direction of travel of the vehicle, nor does it depend on the shape of the road boundary. The main advantage of this approach is that the extraction process can be performed in real time during data collection, although this obviously requires the vehicle trajectory data to be available in real time. The authors stated that future research will focus on improving the tracking model's ability to detect lateral branch boundaries with a small number of edge points, which is currently a limitation. The computer used to process this was not mentioned. [31]

4.1.4 "Automatic Detection and Vectorization"

This paper from Barçon et al (2021) developed two approaches to reduce the processing time of road MLS data. The first approach involves the automatic identification of pole-like objects, while the second approach focuses on the detection of linear objects. The workflow presented attempts to automatically extract a 3D position for each object from the MLS data. These deliverables typically include linear or point objects such as curbs, lane markings, guardrails, walls or building facades. The related literature is categorizes based on the type of extracted feature, whether it is linear or point-like. Several articles, such as Jaakkola et al. (2008), Kumar et al. (2013) and Lehtomäki et al. (2010), have already been reviewed. In addition, a compelling article on the implementation of neural network called PointNet, as introduced by Qi et al. (2017), will be examined separately in subchapter 4.1.6. [32]

In this paper, the methodology was tested using point clouds captured by a Riegl VMX450 mounted on the roof of a vehicle together with a FLIR Ladybug LB5+ panoramic camera equipped with IMU+ DMI. These point clouds were obtained from different sections of the highway, covering a total length of 14 kilometers for road markings and 10 kilometers for guardrails. To facilitate processing, the point clouds were divided into smaller clusters of 400 points called "patches" and indexed and stored in a PostGIS and PostgreSQL database. This technique greatly simplifies the data without loss of information and allows quick access to specific and localized areas without the need to handle large files. [32]

The paper presents two different algorithms. The first algorithm proposes an automated approach to segment pole-like objects in point clouds and compute their 3D insertion points. Further investigation revealed that the best solution for this task is a hybrid method using both point clouds and panoramic images. However, the focus of this thesis is to find a solution for extracting linear features from point clouds only. Therefore, the hybrid method is not discussed further in this review. [32]

The second aspect of this research focuses on the detection and vectorization of road markings and guardrails in highway point clouds. The authors used an image-oriented approach to obtain 3D polylines that accurately represent the location of these elements. The approach involves converting point clouds into an enhanced elevation grid. In this process, the point clouds are first classified into ground and non-ground points. To detect road markings, intensity images are used, as these linear features usually have a higher reflectance due to their visibility to drivers. Road markings are extracted using an adaptive thresholding method introduced by Bradley and Roth in 2007. This method is particularly adept at handling changes in road color or light exposure. In addition, since road markings may have different widths according to traffic regulations, the filtering process takes this into account. Vectorization is performed using either the least squares method or the Random Sample Consensus (RANSAC) method. [32]

Guardrails (curbs in urban area) are the first feature that breaks the flat pavement surface vertically. Therefore, elevation images were used to detect them. This was accomplished by taking advantage of the fact that points describing virtual surfaces create areas of high point density when projected vertically onto a plane, as shown in Figure 4.2. Detection of vertical surfaces is achieved by applying a threshold to the point density in the image. [32]

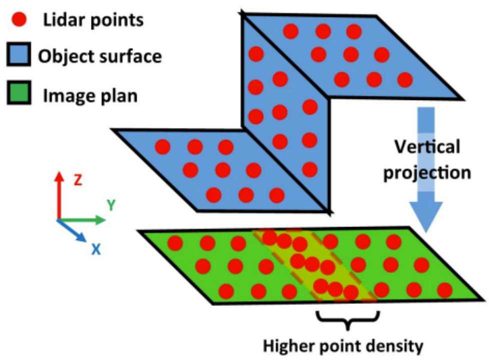


Figure 4.2. Point Plane Projection [32]

The paper categorizes its results in comparison to manually vectorized features, which are considered as ground truth. The maximum tolerance assumed in this thesis is 10 centimeters, which means that all measurements exceeding this limit are not relevant. The results are presented in the Table 4.2. [32]

Table 4.2. Linear Object Detection and Vectorization Results [32]

Object	Tolerance	10cm	5cm	3cm
Road Marking	Completeness	92%	84%	67%
	Correctness	- [1]	69%	94%
	Quality	90%	82%	66%
Metallic Guardrail	Completeness	78%	69%	53%
	Correctness	68%	60%	49%
	Quality	73%	64%	49%
Concrete Guardrail	Completeness	88%	74%	50%
	Correctness	83%	70%	48%
	Quality	85%	72%	49%

The authors claim that a decrease in correctness percentage indicates that objects are correctly detected, but their vectorization requires manual improvement. At 10 centimeter accuracy, the completeness values are greater than 80% for all objects, only 66% of road markings and 49% of guardrails are vectorized at 3 centimeter accuracy. Several factors have been identified that contribute to this, such as the transition between a concrete and a metal guardrail, which causes the program to fail due to the need for special management. In addition, the manual vectorization process is not always perfect and sometimes simplifies the trajectory. The template matching procedure could be improved to avoid false positives. In terms of processing time, the execution speed from a point cloud to a .dxf file is between 0.5 and 1 kph on standard computer. The pre-processing step, which is the most time-consuming, has been optimized by parallelization. The authors say the other steps have not yet been optimized. [32]

4.1.5 "Robust Approach"

The article by Nurunnabi et al. (2022) focuses on solving the challenge of extracting road surface features from point clouds acquired by MMS, which are often contaminated with noise and outliers. The authors propose a robust algorithm that can extract pavement, curb, islands/dividers and shoulders. In addition, the article references previous work by Zhao et al. (2021), Kumar et al. (2013), Rodriguez-Cuenca et al. (2015), that were already reviewed. It is also worth mentioning that this author contributed to the article discussed in the subchapter 4.1.2. [27–30, 33]

In this paper, the authors present a methodology that includes a Robust Locally Weighted Regression (RLWR) based road surface filtering method (Nurunnabi et al., 2016) to remove non-ground points. The ground surface points are then classified into different categories such as pavement, curb and roadside. To account for noise and outlier-contaminated data, the algorithm uses a combination of robust and diagnostic regression (Nurunnabi et al., 2008) and robust statistical approaches to ensure great results. The proposed algorithm follows a 5-step process to extract road surfaces. First, the entire data set is divided into multiple parts or stripes and road surfaces and their components are extracted strip by strip, as shown in Figure 4.3. Finally, all the stripes are combined to obtain the complete results of the road point cloud data. [33–35]

[1] This cell is empty as the result was nonsensical.

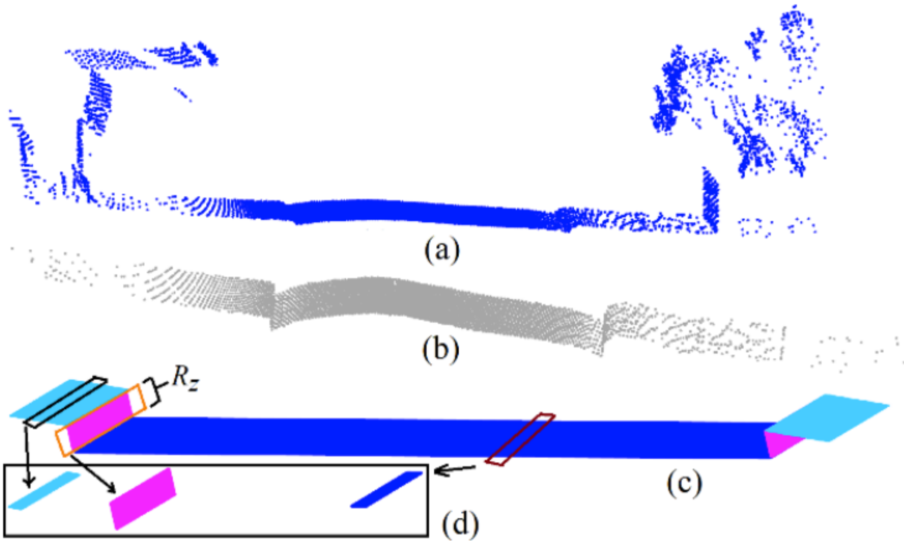


Figure 4.3. Stripes Illustration: (a) an individual road stripe; (b) extracted ground; (c) vectorized stripe; (d) three patches corresponding to sidewalk, curb and pavement [33]

Hadi et al. (2009) and Rousseeuw et al. (2018) introduced the statistical principle for computing Rz values. This principle serves as the basis of this paper and aims to identify outlier cases of Rz values, which are then considered as potential candidates for curbs (CC). The Rz values are calculated as [33]

$$CC(Rz) > median(Rz) + c * MAD(Rz)$$

$$MAD(Rz) = 1.4286 * median|Rz - median(Rz);$$

a constant value, "c", can be set to either <2, 3, or 4>, or customized by the user. This allows the equation to be adjusted for different curb heights. The Figure 4.4 shows road patches determined based on the calculated Rz values. [33]

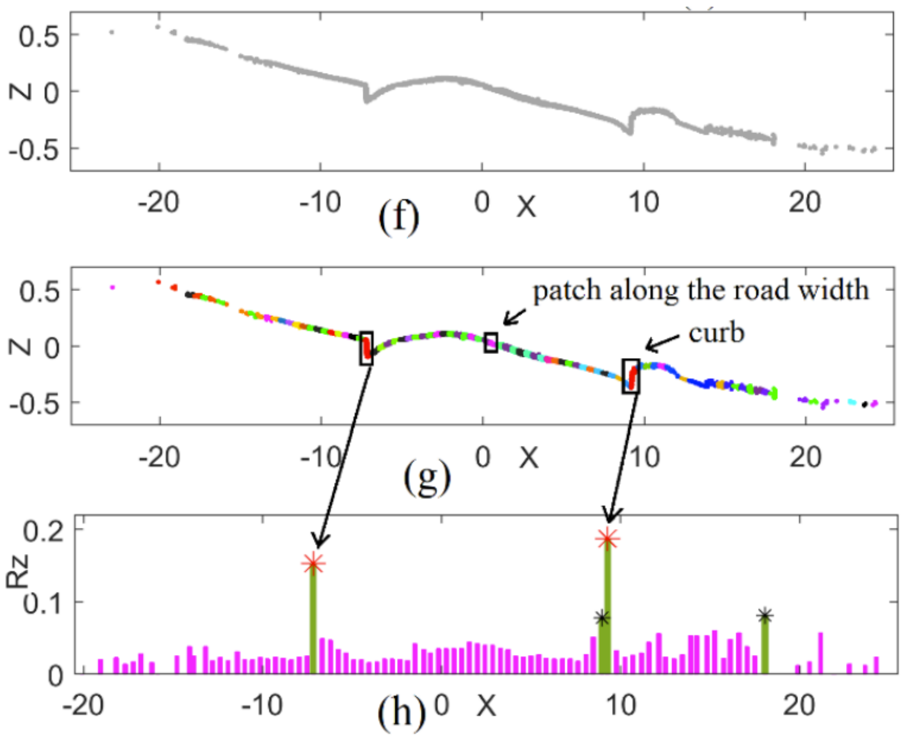


Figure 4.4. The Correlation between Z and Rz Values: (f) filtered ground points as in 4.3.a; (g) patches along the road width; (h) bar diagram of RZ values [33]

Both of the samples used in this study were captured by a mobile laser scanning (MLS) system, although no specific system is mentioned. The first sample covers an urban road of approximately 53 meters, including pavement, curbs, sidewalks and non-ground objects such as trees and buildings. The proposed algorithm achieved a completeness rate of 99.56% and a correctness rate of 97.28% for curb extraction. The performance of the proposed algorithm was assessed by comparing its results with the algorithm proposed by Zhao et al. (2021) on the same data set. The results showed that the proposed algorithm outperformed the old algorithm. Specifically, the proposed algorithm achieved significantly better results in terms of completeness and correctness compared to the old algorithm, which achieved 81.05% completeness and 72.61% correctness on the same data set. [33]

The second example covers a road section of approximately 31 meters, including pavement, curb, roadside and road islands. The proposed algorithm achieved a completeness rate of 97.5% and a correctness rate of 91.9% for curb extraction. All results were compared with manually labeled ground truth and the quality of the results was not reported. Furthermore, the processing time and the computer used were not specified in the article. [33]

4.1.6 "PointNet: Deep Learning"

The purpose of this brief review is to highlight the innovative solutions presented in the article that address the challenge of implementing rapidly evolving techniques. Specifically, the paper proposes a unified architecture that takes point clouds directly as input and generates either class labels for the entire input or labels for each point. The basic architecture of the network is surprisingly simple, with each point being processed identically and independently in the initial stages. The representation of each point in the basic setting consists only of its three coordinates (x, y, z). The use of a single symmetric function - max pooling[2] - is a key feature of the approach. Through this function, the network learns a set of optimization functions that select interesting or informative points in the point cloud and encode the reason for their selection. The final fully connected layers of the network then aggregate these learned optimal values to produce a global descriptor for the entire shape (for shape classification) or to predict per point labels (for shape segmentation). [36]

This article presents a deep learning framework that can handle unordered point clouds as input. A point cloud is represented as a set of 3D points Pi| i = 1, ..., n, where each point Pi is a vector consisting of its (x, y, z) coordinates and other features. However, for simplicity and clarity, the algorithm uses only the (x, y, z) coordinates as the point's channels unless explicitly stated otherwise. For the object classification task, the input point cloud can be either directly sampled from a shape or pre-segmented from a scene point cloud. The proposed deep network generates k-values for all k-candidate classes. For semantic segmentation, the input can be a single object for part region segmentation or a sub-volume of a 3D scene for object region segmentation. The model produces $n \times m$ scores for each of the n points and each of the m-semantic subcategories. [36]

The network architecture is inspired by the properties of point cloud in space. The input is a set of points from a Euclidean space with the following properties First, they are unordered, a point cloud is a set of points with no particular order. Second, the points interact with each other, i.e., they are not isolated and neighboring points form a meaningful subset. Finally, the representation of the point cloud learned by the network should be invariant to certain transformations due to its geometric nature. For example, rotating and translating points together should not change the global point cloud category or the segmentation of the points. [36]

The principles outlined above have been successfully demonstrated to segment typical objects such as tables, cups and guitars. The ability to achieve segmentation of these objects highlights

[2] Max pooling is a type of operation that involves taking the maximum value of a set of values from a feature map and using it to create a down-sampled feature map of the greatest value.

the potential of this approach for application to other domains. In particular, if the code or other framework focused on point clouds is adapted and trained on segmented road data, it could be implemented to analyze and segment transportation infrastructure, such as roads and bridges, in a manner similar to generic objects. [36]

4.1.7 Conclusion of the Literature Review

The reviewed articles provide a comprehensive overview of the procedures, algorithms, equations and approaches that yield the best results when extracting features from point clouds. By examining these approaches, we can gain an understanding of the level of accuracy that can be achieved with different algorithms. A common solution has been to treat point cloud data by converting it to 2D volume images or slicing it into smaller patches. These methods do not affect the point cloud data itself, but can significantly facilitate its handling and processing. The majority of the reviewed articles presented their algorithms using their own data sets and standard computer hardware. This demonstrates the feasibility of implementing these algorithms in various settings without requiring specialized hardware or resources. [19, 27–33, 36]

The primary focus of the first article reviewed was to streamline and reduce the cost of safety inspections. The proposed solution primarily addressed point features, but also provided valuable insight into the extraction of linear features. For example, the article suggested that the ground could be transformed into a set of conditions and then extracted, highlighting a novel approach to identifying features in point cloud data. [19]

The second article reviewed is a comprehensive study of over 200 articles covering a wide range of topics. It provides a 10-year summary and highlights the top three methods applicable to mobile laser scanning data. These methods were then reviewed individually. One of the methods converts the 3D point cloud to 2D images, which is an important step because it reduces the amount of data to be processed, but it also drastically changes the subsequent steps. The second method proposed in the article is a snake energy analysis for edge detection, which uses a controlled spline with internal and external energy to achieve 100% accuracy and 98.5% completeness. The final method referenced in this extensive article uses elevation change, echo intensity and slope to detect curbs from point clouds. These detected features were then clustered using a k-NN algorithm and achieved 99.8% completeness. Overall, this study provides valuable insight into the most effective methods for processing and analyzing mobile laser scanning data. [27–30]

The third paper reviewed proposed a method for detecting curb blocks using a moving window approach that detects significant changes in both block height and width. The proposed procedure achieved impressive correctness of 100%/100%/99.88%/99.62% when applied on 1.2 kilometers of curbs in four separate samples. The fourth article reviewed presented two different algorithms. The first algorithm was designed to detect point-like features, but was not fully assessed in the paper. The second algorithm focused on the detection of road markings and guardrails. To detect road markings, intensity images were used, assuming that road markings have a higher intensity than the surrounding infrastructure. Guardrails, on the other hand, were detected by projecting the 3D point cloud onto a 2D plane and searching for high-density areas corresponding to the ends of planar surfaces. The article provides a detailed breakdown of the results obtained, which can be found in the Table 4.2. [31–32]

The fifth article presents a robust approach for detecting linear features such as curbs and road islands using statistical principles. This approach has been developed over a long period of time and has shown very good results. The last paper presents a deep learning network for direct processing of point clouds. While this algorithm has been tested on different types of data, it is plausible to assume that if the network is trained on road-specific segmented data, it could also be used to detect linear features. [33, 36]

4.2 Commercial Solution

It is probable that this thesis will propose a software or commercial solution, as a number of reliable options have been identified and categorized as either “manual” or “semi-automated”. While the “manual options” have been tested, they have not been extensively explored, as the main objective of this thesis is to introduce an efficient solution where manual methods are not ideal. Nevertheless, they are briefly outlined in the following subchapters.

The “semi-automated” alternatives require some degree of human input, such as determining the starting point, direction and validating the results. These options have been explored, experimented with on the mentioned data sets and elaborated in the following subchapters of this thesis (specifically 5.4, 5.5 and 5.6).

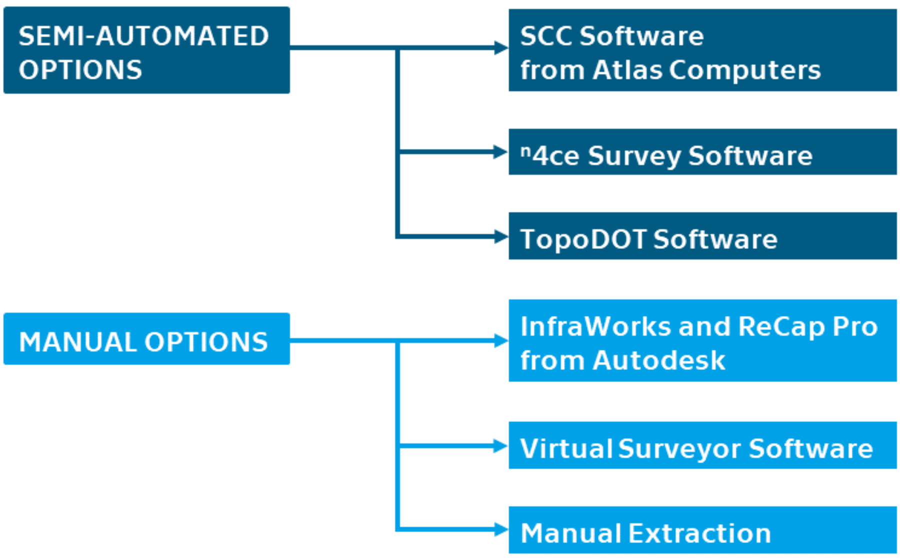
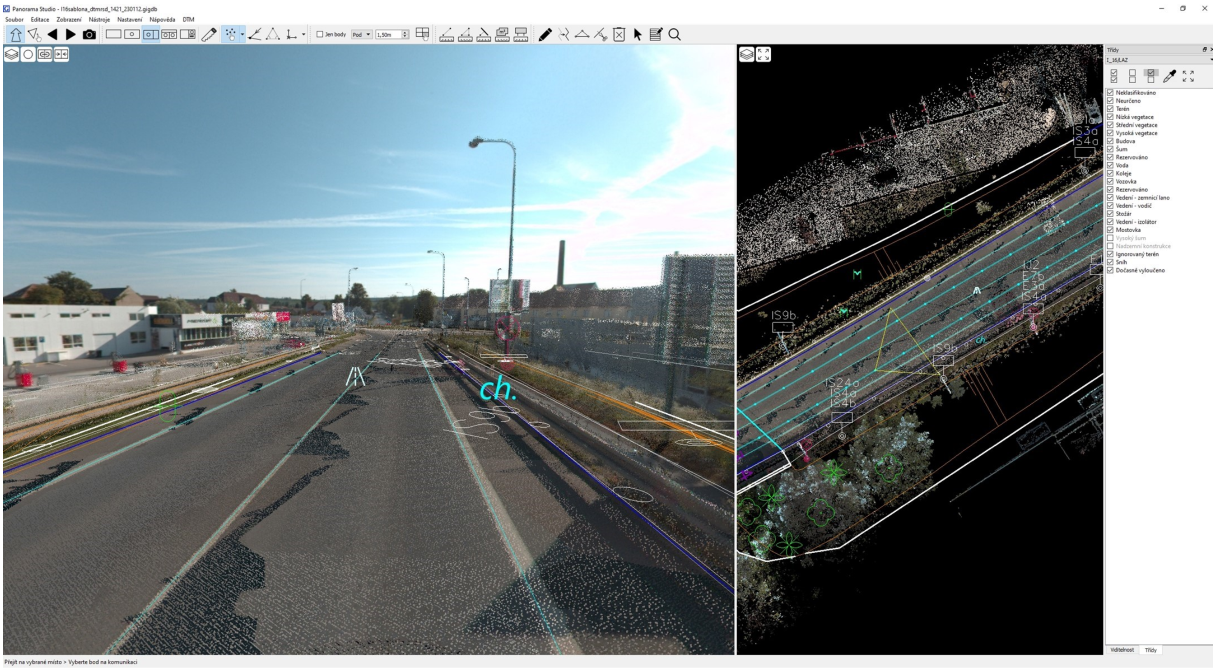


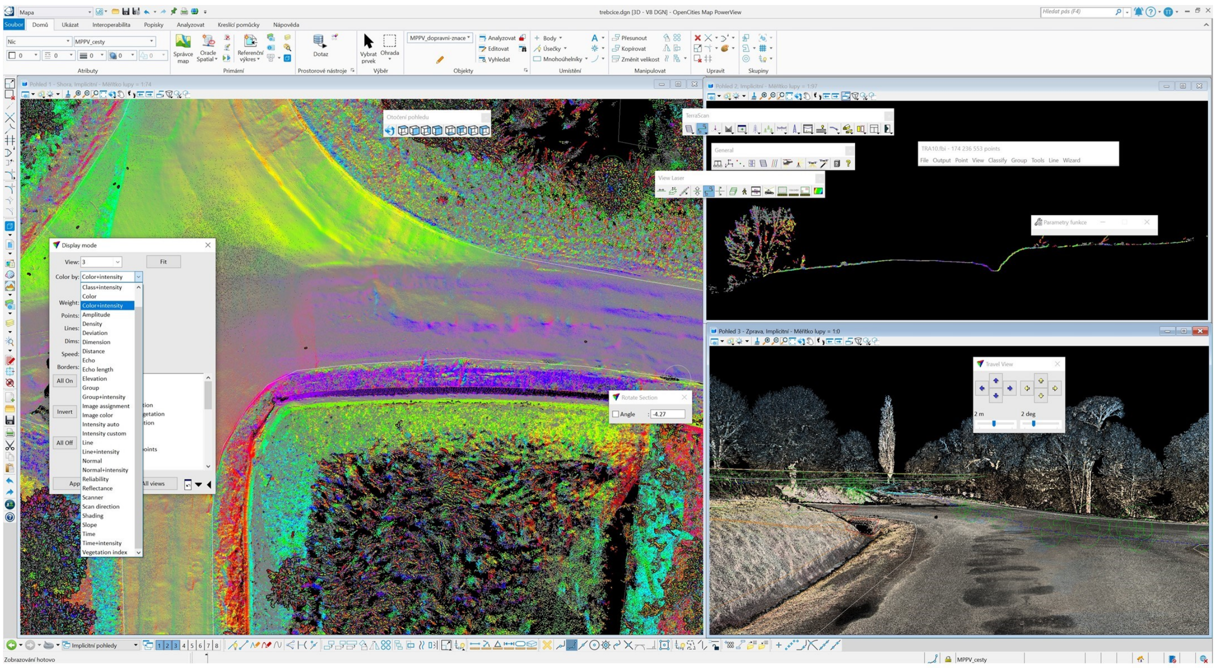
Figure 4.5. Chart Representation of Reviewed Software

4.2.1 Fully Manual Approach

The fully manual approach is currently a widely used option in practice, where any CAD software can be utilized by using the point cloud as a reference and manually placing vertices to extract linear features. Figure 4.6 shows an example of this approach where the base software is Panorama in (a) and TerraScan in (b). The vertices are manually placed on the point cloud features. This process is the most time consuming and the output quality is highly dependent on the person performing the task. To propose an effective and competitive workflow, this type of work needs to be automated as much as possible, with human input reduced to a minimum for minor adjustments and output verification.



(a)

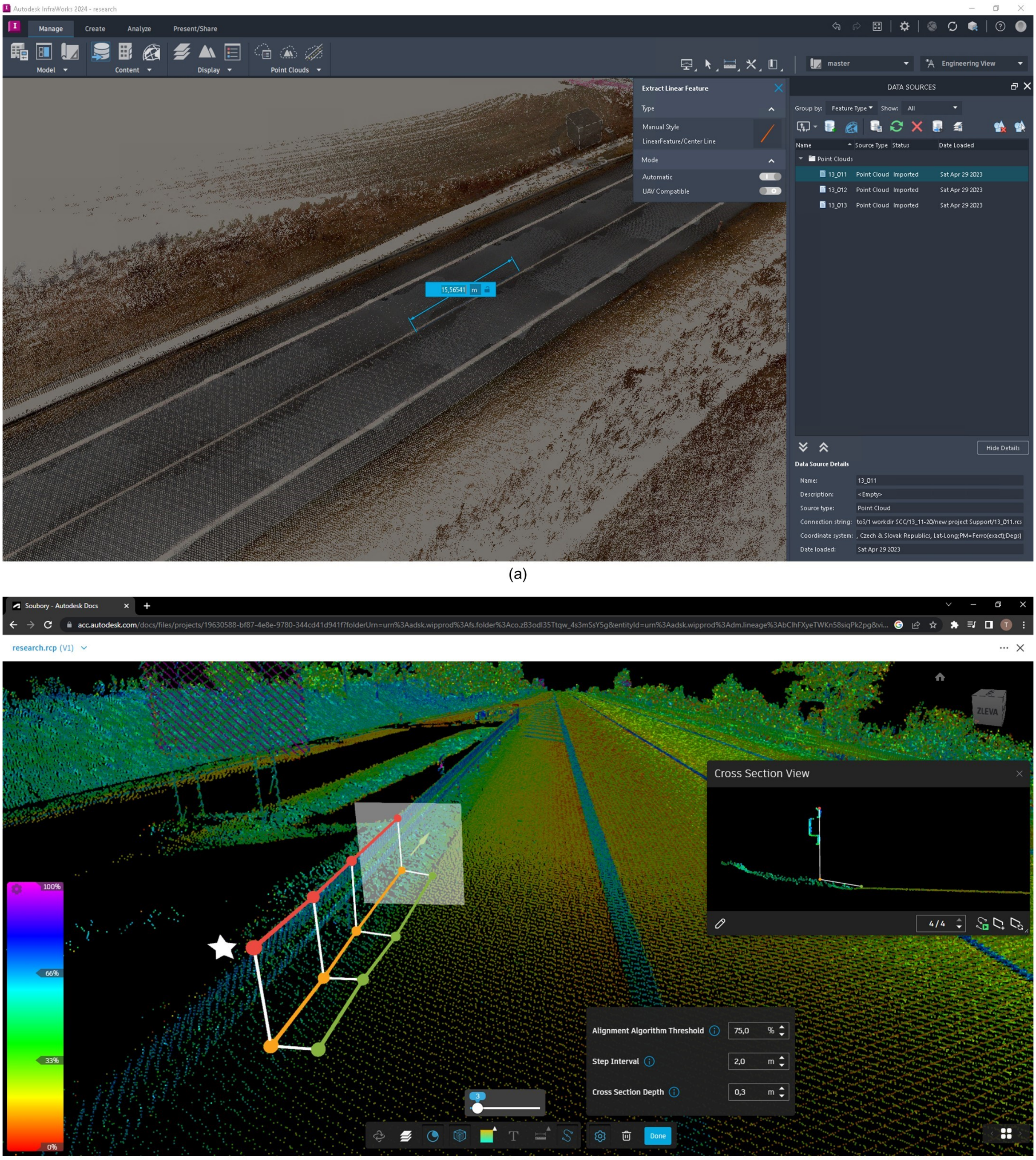


(b)

Figure 4.6. (a) Panorama Software; (b) TerraScan Software

4.2.2 InfraWorks and ReCap Pro from Autodesk

At this time, Autodesk's only point cloud processing tools are InfraWorks and ReCap Pro, both depicted in Figure 4.7. InfraWorks is primarily targeted at engineering applications and facilitates the rapid creation of highway or rail models on case study level. Recently, the software has been enhanced in terms of infrastructure and structural design, with the goal of complementing other Autodesk tools and serving as a powerful optioneering platform. [48]



(a)

(b)

Figure 4.7. Autodesk: (a) InfraWorks 2024.0, Release 24.0.0.21; (b) ReCap Pro 2024 - browser-based ReCap Viewer, Release 24.0.0.240

The extraction tool provided by InfraWorks, illustrated in Figure 4.7.a, is relatively basic and suitable for small tasks or one-time extractions. It is likely that this tool will be phased out in the near future as InfraWorks shifts its focus toward design applications. Autodesk has been working on a standalone point cloud processing software called ReCap Pro, which now includes first version of the "Feature Extraction Tool". This tool is part of the browser-based "ReCap Viewer" platform, as shown in Figure 4.7.b. [49]

This tool enables the simultaneous extraction of two or more features, where the user input is required as the automatic detection feature proved unreliable when applied to road markings and guardrails, giving incorrect results on numerous occasions. Nevertheless, as a first glimpse of a more sophisticated point cloud processing and extraction tool from Autodesk, it has the potential to compete with advanced tools from other companies in the future, provided it is further developed. A notable advantage of this tool is that it is browser-based, meaning that linear features can be extracted as long as the web browser is installed and an Internet connection is available. The tool runs on the Autodesk Construction Cloud and was accessed using the university's Autodesk license.

4.2.3 Virtual Surveyor

Virtual Surveyor is another standalone point cloud processing tool that provides core extraction capabilities with a focus on digital terrain modeling, editing, volume calculation and topographic processing. It provides a limited number of CAD tools that are primarily geared toward manual, but precise, linear feature extraction, such as curbs in parking lots, road islands, or other small segments. Figure 4.8 shows the Virtual Surveyor environment with one of the imported samples. The Virtual Surveyor team provided the highest level "Peak" license for the purposes of this thesis for a limited time. [50]

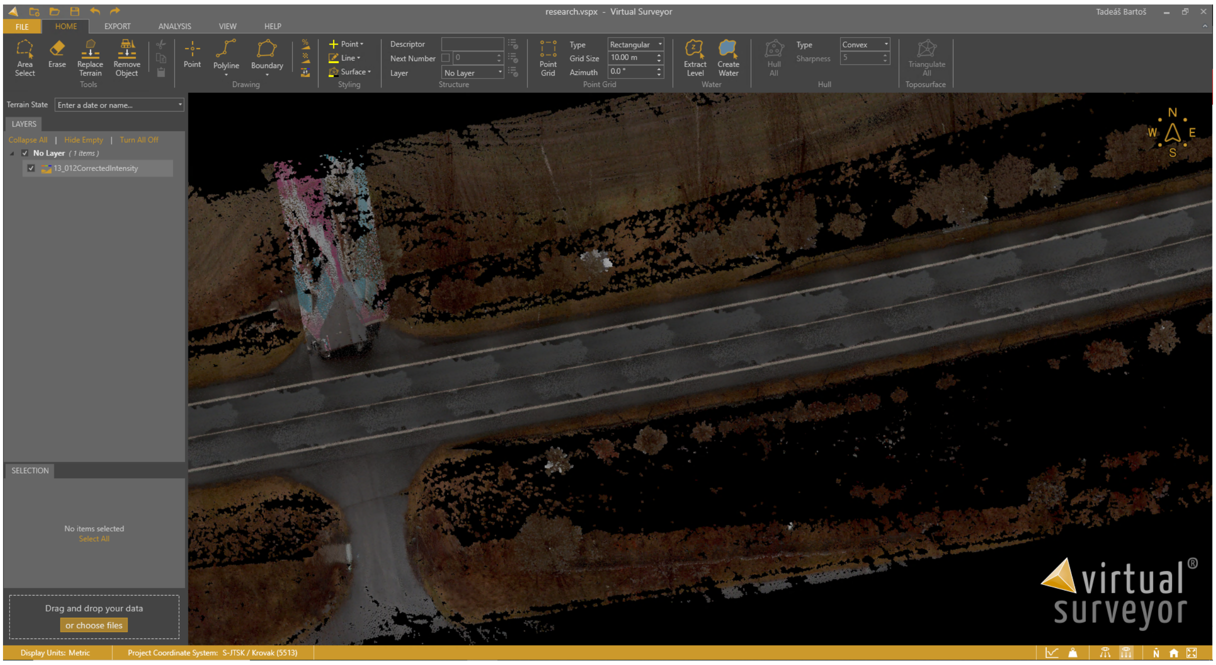


Figure 4.8. Virtual Surveyor Software Environment, Version 8.7.1

Chapter 5
Data Processing

This chapter provides an overview of the hardware and data sets used to test three "semi-automated" commercial solutions discussed in the 4.2 subchapter. It details the entire investigation from a technical perspective and presents each software through a structured review that includes a large banner consisting of smaller figures, as well as a detailed description of the scores in each aspect. The chapter concludes with the final score for each software and the overall score.

5.1 Hardware Used for Test

The software described in the 4.2 subchapter was installed and tested on a single computer, the faculty's server machine. A second computer (standard laptop), was used mainly for processing and assessing the exports from the software, specifically Autodesk Civil 3D and Navisworks. A detailed specification of both computers can be found in the Table 5.1.

Table 5.1. Utilized Computer Hardware

	Server	Laptop
CPU	2x AMD EPYC 7F52 16-Core	1x Intel i7-9750H 6-Core
GPU	3x NVIDIA RTX A5000	1x NVIDIA GTX 1650
RAM	512 GB 3200 MHz	16GB 2667 MHz
HDD/SSD	-	512 GB SSD

Although the faculty server has non-standard hardware that provides impressive computing power, the software should produce identical results on standard computers and laptops. The server was used primarily to ensure that testing was not limited by insufficient computing power. In the future, this high computing power could prove advantageous, as using this powerful server could speed up data processing or allow multiple point clouds to be loaded simultaneously. VPN and Remote Desktop from Windows were used to access the server.

5.2 Data Sets Used for Test

In order to thoroughly demonstrate and assess the capabilities of the software, two very different samples were selected. Since this thesis aims to propose a solution tailored to a specific country with specific transportation infrastructure and standards, these factors were taken into account in the sample selection process. Both samples were collected using the survey car and mobile mapping system previously described in the 3.1 and 3.2 subchapters. Based on the aspects mentioned in the subchapter 3.6 about the general quality, all of the used point clouds are sufficient for these purposes, since all the data sets have been processed with great MMS and using the MTA principle. According to the NCHRP Report 748, the DCC matrix identifies these data sets as 1A type, which denotes the highest level of density and accuracy. [2]

The initial sample consists of an undivided highway known locally as "First Class Road No. 13", which is the second highest road category in the Czech Republic (the highest being the multilane motorway shown in Figure 5.1.b). First class roads are typically equipped with a narrow breakdown lane, mandatory road markings and traffic signs, may also include guardrails and noise barriers. The maximum speed limit on this type of road is typically 90 kph to facilitate rapid travel between communities and cities. However, local ordinances may require lower speed limits, such as 50 kph, particularly within urban areas, as these roads often pass through such areas. This extravilan highway is typically organized as shown in Figure 5.1.a, with one lane of width “a” for each direction, a narrow breakdown lane consisting of elements “c” and “e” and sidewalks in urban areas. Intersections on recently constructed/reconstructed roads of this type are achieved by ramps, while older or urban roads may use both ramps and conventional intersections. [51]

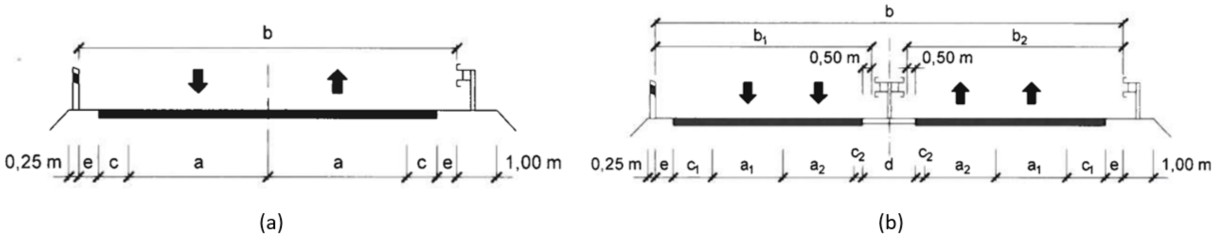


Figure 5.1. Standard Cross Section of Highway and Motorway in Czech Republic: (a) two-lane highway, (b) four-lane divided motorway [51]

This particular sample consists of approximately 2.2 kilometers of road, complete with continuous or dashed edge and center lines along its entire length. Guardrails, noise barriers and overhead power lines are present in certain sections. This road is partially bordered by low, medium or high vegetation and few buildings. The sample was generated by combining samples 1a, 1b and 1c described in Table 3.3, resulting in approximately 185 million points. A comprehensive breakdown of the classified sample 1b can be found in Table 3.2 and this particular sample is also shown in Figures 3.6 and 3.8. The second sample is a fusion of samples 2a and 2b presented in Table 3.2. Together they cover about 800 meters and contain around 84 million points. The first sample consists primarily of guardrails and road markings, while the second sample, selected to represent urban local roads in the Czech Republic, includes curbs, road markings and handrails. Together, these two samples provide comprehensive coverage of the majority of road types found in the country.

Local regulations usually dictate that the maximum speed on this road should not exceed 50 kph and it is usually designed as a two-lane or multi-lane road when passing through urban areas. The road is often surrounded by varying levels of vegetation, overhead power lines, street lights, traffic islands and railings. It is usually marked with road markings, traffic signs and bordered by curbs. Figure 5.2 shows a typical cross section of this type of road. In addition, these examples include sidewalks and bus stops, which may be either pull-out or in-lane. [52].

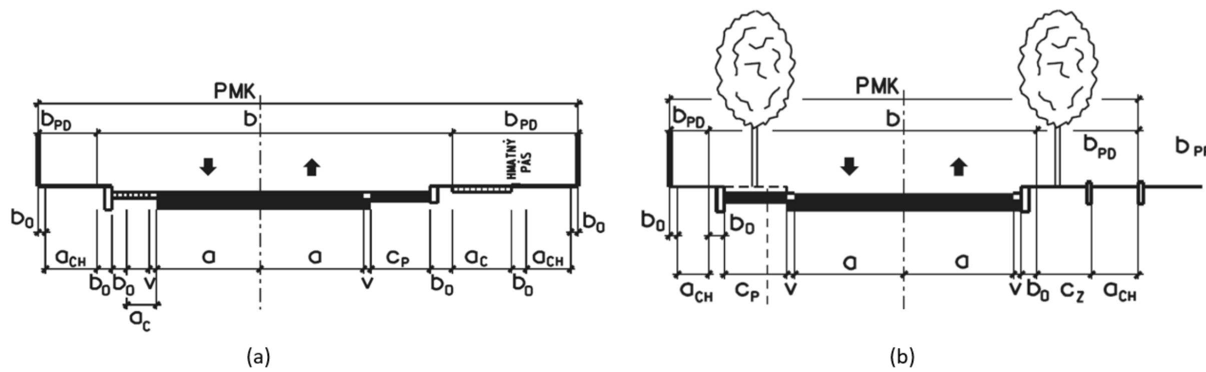


Figure 5.2. Standard Cross Section of Urban Road in Czech Republic: (a) two-lane local road with two bike lanes “a_c”, two sidewalks “a_{ch}” and one parking lane “c_p”; (b) two-lane local road with two sidewalks “a_{ch}” and one parking lane “c_p” [52]

The primary goal of this work is to extract as many linear features as possible from road infrastructure - such as road markings, guardrails and noise barriers. Sidewalks are closely related and may be separated by handrails. The goal is to extract these linear features, along with any type of pavement edge, with sufficient accuracy to calculate road and lane widths, slopes and guardrail/handrail distances from the lane. These extracted features and calculated values are used for safety inspections, general inventory and documentation of road infrastructure. In addition, point-like features such as trees, streetlights and culverts could also be extracted to identify hazardous obstacles near the road. This could be the next step towards fully automated workflows for safety inspections and other use cases involving both linear and point features.

5.3 Assessed Metrics

The metrics used to assess the deliverables from all three software are divided into two primary categories. The first category is referred to as "Calculated Metrics" and is designed to assess the outputs from an objective and unbiased perspective. These metrics are defined by equations 1, 2 and 3 below and very common in the reviewed articles (subchapters 4.1.2 - 4.1.5). Equation 4 complements the previous equations and provides an explanation of the underlying principles behind these values.

The second category of metric is expected to be less objective, since the numbers in this category are derived from the author's personal experience in testing and comparing all three software. The author has carefully selected these aspects to reflect the results obtained in terms of time and skill required, licensing and final outputs.

It is important to note that some of the metrics included in the second category may reflect the author's personal perspective. Factors such as "Overall Time Efficiency," "UI & UX" and "Software Support" are subjective and may vary from person to person. However, the author will make adjustments to these metrics and use a modified point allocation by setting the base at 10 points, to ensure that the software rating is minimally affected by the author's subjective view. Conversely, metrics such as "Data Exchange" and "Number of Features Extracted" along with "Further Adjustments" reflect the software's capabilities without any human subjective input. Each of these primary metrics is described separately in the following text to provide a full understanding of the author's approach and perspective.

5.3.1 Calculated Metrics

The calculated metrics are used to assess the capabilities of the software and typically measure the success rate of the algorithm in detecting features, the percentage of errors in the final output and the amount of the detected data. These calculated metrics serve as the basis for the quantitative parameters and include the following:

$$Completeness = \frac{\text{length of matched reference}}{\text{length of reference}} = \frac{\text{TP}}{\text{TP+FN}} \tag{1}$$

$$Correctness = \frac{\text{length of matched extraction}}{\text{length of extraction}} = \frac{\text{TP}}{\text{TP+FP}} \tag{2}$$

$$Quality = \frac{\text{length of matched extraction}}{\text{length of extracted + unmatched reference}} = \frac{\text{TP}}{\text{TP+FP+FN}} \tag{3}$$

$$\text{GT} = \text{TP} + \text{FN} \tag{4}$$

The parameters in calculated metrics include "GT" (ground truth), which represents the actual feature length, "TP" (true positive), which represents the detected feature length that matches the ground truth, "FP" (false positive), which represents the detected feature length that does not match and "FN" (false negative), which represents the total length of undetected features present in the ground truth. These parameters are assessed separately for each extracted feature of each software and these results defines the final ground truth length in both samples, because they were manually labeled by the author. These metrics are commonly used in research articles and will help the author and audience understand how well the software performs compared to other approaches. It is important to note that the "Completeness, "Correctness" and "Quality" metrics are equivalent to the commonly used 2D metrics of "Recall", "Precision" and "IoU", respectively. The mean of all "Quality" will serve as the basis for the "Further Adjustments" in order to minimize the author's subjectivity. The lengths of the individual features classified into "TP"/"FP"/"FN", as well as the calculated metrics, can be found in the subchapters B.2; C.2 and D.2. [27–30]

5.3.2 Quantitative and Qualitative Metrics

Software performance in each discipline was scored on a scale of 0 to 20 using carefully defined quantitative and qualitative metrics. A score of 20 indicates that the software perfectly meets the required objectives, while a score of 0 indicates that the software is unusable in that particular field.

The first quantitative metric, called "Further Adjustments", measures the need for additional adjustments to the data or any human input required after export from the program. A score of 20 indicates that no further adjustments are required, while a score of 0 indicates that manual adjustments are required. This aspect is determined by the mean of "Quality" of all features, which takes into account all three parameters and provides the final score. The translation between the two metrics is done using a slightly modified direct proportionality. The modification ensures that any output with a "Quality" score of 50% or less does not meet the objectives of the thesis and is reflected in the final score by receiving 0 points. The standard proportionality rating bar in Figure 5.3.a shows that the "Further Adjustments" rating bar is the same length as the "Quality" rating bar, meaning that a 10% decrease in "Quality" corresponds to a 2-point decrease in "Further Adjustments", for example. The modified rating bar in Figure 5.3.b ensures that the lowest translated score from "Quality" to "Further Adjustments" is 50% or higher.

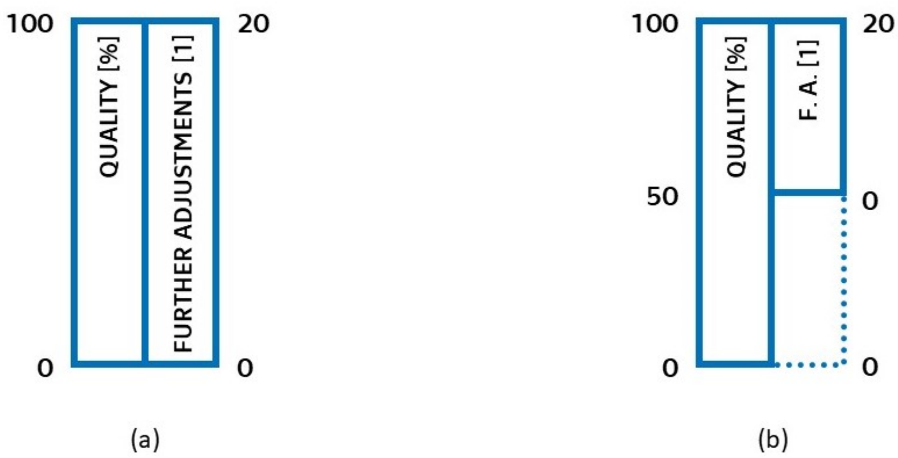


Figure 5.3. Direct Proportionality: (a) standard; (b) modified, "F.A." represents "Further Adjustments"

The second quantitative metric, called "Features Extracted", measures the number of features extracted by the software. The objectives of this work include the extraction of road markings, guardrails, handrails, noise barriers and any type of road edge (both curbs and edge). Any useful feature not included in this list can be considered a benefit and potentially earn additional points. The first and second metrics are correlated; for example, if one feature is completely missing from the sample, both metrics (and others) will be affected. Since it is intended to expand this workflow to include point-like features and others in the future, there is 4 point range for any additional features that the software may offer, in addition to the listed features. Each feature is worth 4 points, divided in half because most of the final outputs should contain (at least) 2 geometries as shown in Table 5.2.

Table 5.2. Point Allocation for Number of Extracted Features

Points	Features	Details
20 17	Additional Features	-
16	Curbs / Road Edge	2 pts per feature top point, 2 pts per feature ground projection
	Guardrails / Handrails	
	Noise Barriers	
4	Road Marking	2 pts for center, 2 for edge
0	-	-

The third quantitative aspect, known as "Data Exchange", reflects how user-friendly the software is in terms of data formats. It measures whether the software provides native point cloud file import and direct export to standard CAD files. The primary focus is on the import of standard .las files, as these are received from the faculty contractor and are part of this thesis. For exports, any type of CAD file such as .dwg/.dxf/.dgn will suffice, as these can be easily edited if needed and most companies are familiar with this type of file. Any export to .csv/.txt files with a reasonable structure is considered an unrated benefit. A score of 20 indicates full compatibility with all possible formats.

The fourth aspect, named "Overall Time Efficiency", is the first qualitative measure included in this metric. It slightly incorporates the first two aspects mentioned above, but is considered a separate measure. The goal is to assess how easily and quickly satisfactory results can be obtained. This aspect will reflect whether highly accurate results (assessed in the first aspect) were obtained at the expense of time or by extracting fewer features, for example.

The next aspect on the list is the "UI & UX" environment, which is critical for long-term use. It describes how easy the software is to learn and control and how intuitive it is to search for new tools or seek help. This is a qualitative and subjective aspect that can vary between users based on their experience with the software.

Another aspect that is assessed is "Software Support". This is important for troubleshooting any issues that may arise on the job and can greatly impact effectiveness. It will be assessed based on communication, additional paid service offerings, available forums and online solutions. As with the 2 previous aspects, all qualitative aspects will be scored starting from 10 points and any changes will be made only slightly to maintain objectivity.

The last aspect to be assessed is called "Overall Usage", which combines all the previous quantitative and qualitative aspects. It slightly incorporates the author's perspective and could be taken as a recommendation of how valuable and suitable the software is in meeting the requirements.

Each software's metrics are presented in a separate software radar chart and all software is then compared in a single chart shown in Figure 5.19. The metrics are designed to form a complete circle when excellent results are achieved and the opposite when they fall short. Figure 5.4 shows an example of a radar chart, where dark orange indicates robust software results and light orange indicates decent software results.

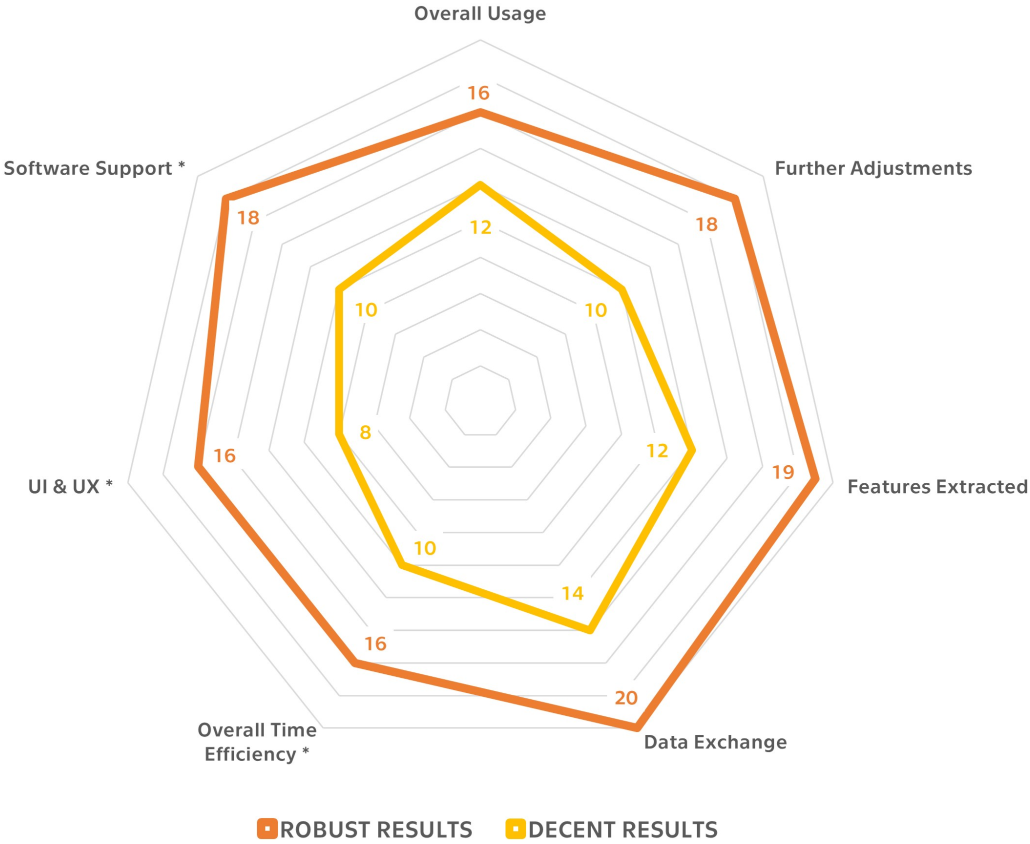


Figure 5.4. Radar Chart of Fundamental Metrics

The qualitative metrics will be placed on the left side of the radar charts and will be marked with an asterisk "*" because their base is set at 10 points. This distinction will emphasize that the points for these metrics were assigned differently than for the quantitative metrics. The notation used in all radar charts is consistent and the distinction between scoring criteria is shown in Figure 5.5. The full-score bar, represented by (b), applies to quantitative aspects and uses the entire score range from 0 to 20 points. The bar in (a), on the other hand, shows the point allocation for qualitative aspects, with a range that is more concentrated in the center of the graph, figuratively starting at 5 points and ending at 15 points, where 15 points indicates excellent results.

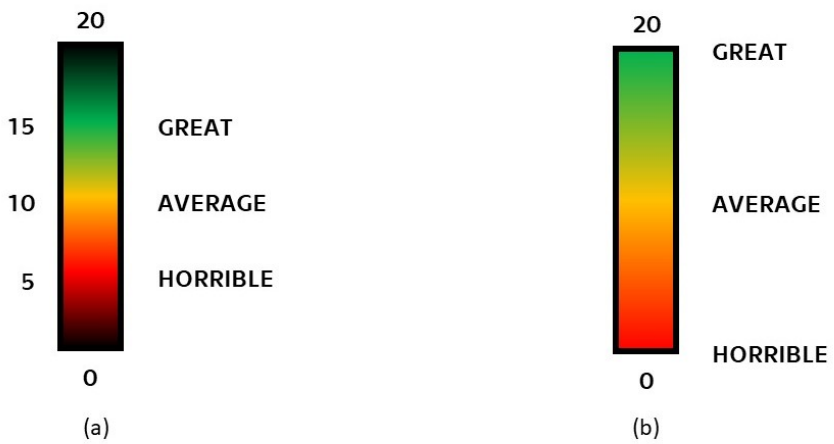


Figure 5.5. Point Allocation Bars: (a) qualitative aspects; (b) quantitative aspects

5.4 Survey Control Centre Software from Atlas Software Ltd.

The first software to be reviewed is Atlas Computers' Survey Control Centre[1], hereinafter referred to as SCC. It is a standalone geomatics software designed specifically for survey offices. It provides a wide range of capabilities including data collection, point cloud analysis, 3D visualization, setting out, quality assurance and other tools required for survey work. SCC can handle a variety of tasks, including those involving point clouds, TIN models and industry-specific tools for any type of topographic survey. Developed over 26 years and with 13 major releases, SCC combines advanced tools and is compatible with legacy software as well as the latest industry standards and tools. The Atlas Computers team provided a temporary license for the purposes of this thesis and for a limited time. [53]

5.4.1 Initial Procedures

The process of installing SCC on a Windows system is similar to installing any other software. Once installed, SCC allows you to assign each job to a "project", which serves as a general template for the specific task at hand. After creating a project, users can import any type of file they wish to process. In our case, .las point cloud files were imported from the "Cloud" drop-down menu. SCC is compatible with all point cloud formats and also has the ability to import native Leica/Faro/Riegl files. It's important to be familiar with point cloud properties, such as how image information is stored (8-bit, 16-bit or 24-bit), in order to properly access point colors and intensities. SCC can also access point cloud classification in LAS version 1.4 R13 or any other standardized form. The import window and supported formats are shown in figures 5.6.a and 5.6.b. [18]

5.4.2 Tools

Once the initial process is complete, the point clouds are imported into the SCC environment. Similar to most software applications today, all tools are located in the top bar of the screen and are categorized according to their purpose. This is illustrated in Figure 5.6.c.

SCC provides a number of tools and options for handling and processing survey data. Users can create and manage survey projects, define project areas, add survey data and adjust project settings. It also provides tools for processing and analyzing survey data, such as extracting linear features, performing coordinate transformations or running statistical analyses. To ensure accurate and reliable survey data, SCC includes quality control tools that identify and correct errors, verify data consistency or validate survey measurements. Users can also generate customized reports that include maps, graphs and other visualizations.

[1] Survey Control Centre version v14.6.0, 64-bit

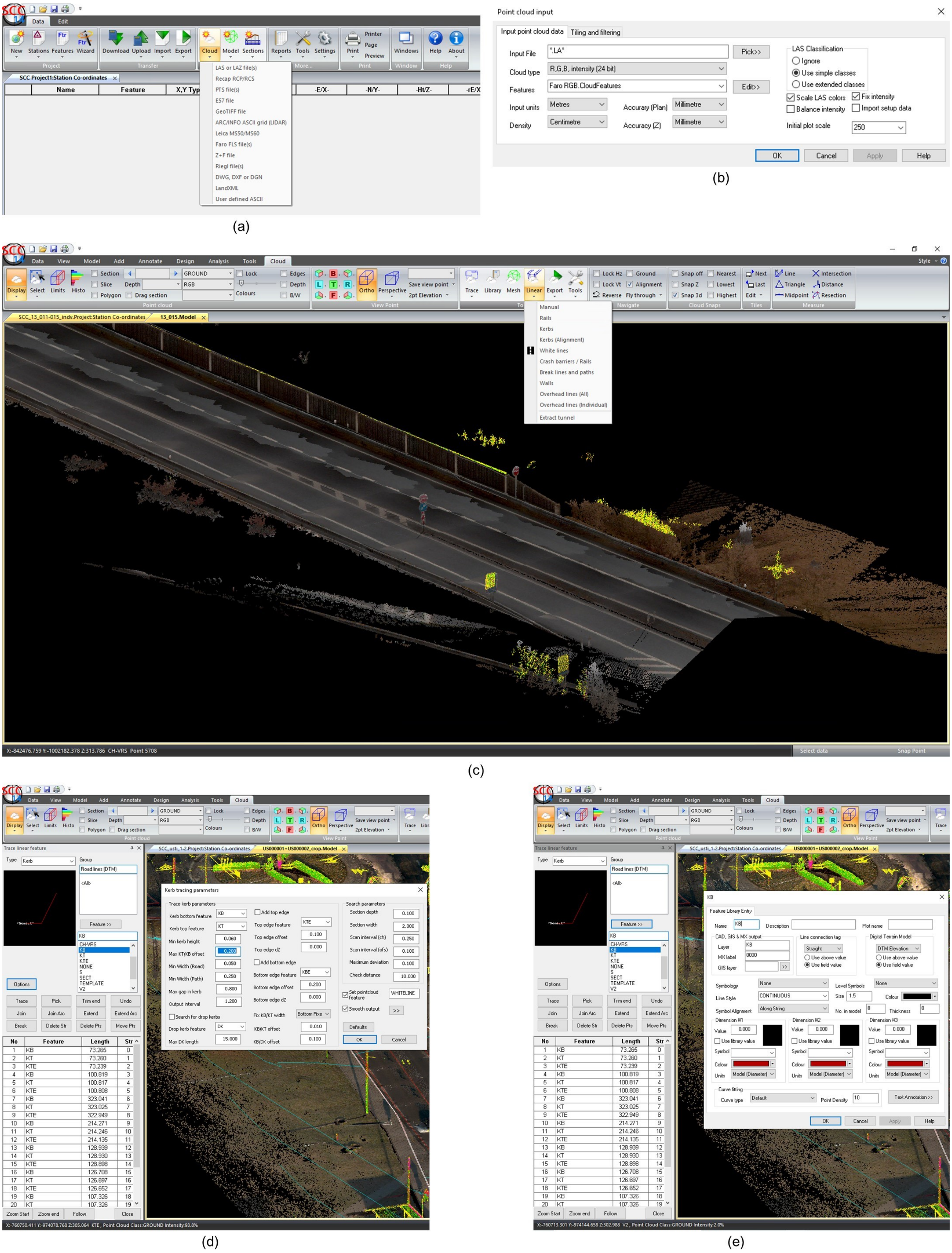


Figure 5.6. SCC: (a) initial import settings; (b) detailed import options; (c) SCC environment with "Linear" extraction tools drop-down; (d) "Tracing parameters"; (e) "Feature Library" settings

5.4.3 Feature Extraction

Primary focus of this thesis is on point cloud data and the process of extracting linear features from it. For this purpose, SCC provides a tool called "Linear", shown in Figure 5.6.c. All the options for linear feature extraction can be accessed through this tool. Clicking on it will open a second window called "Trace Linear Feature", located on the left side of the screen, where other tools are also displayed, as shown in Figures 5.6.d and 5.6.e. Within this window, users can easily navigate between tools such as "Trace", "Pick", "Join" and "Delete Str" to extract and adjust the string output. In addition, users can switch between extracted features using the drop-down menu at the top of the window.

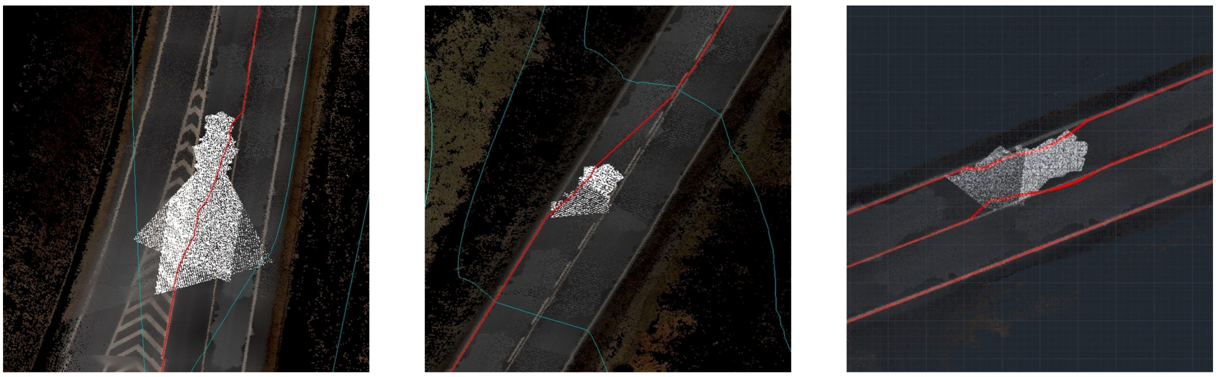
The main point of interest is on the point cloud and how to extract linear features from them. For this case, SCC offers the tool called "Linear" as shown in Figure 5.6.c. All the options for linear feature extraction are located here. This prompt will open a second window called "Trace Linear Feature", located on the left side of the screen where all other tools are located as depicted in Figures 5.6.d and 5.6.e. In this window, user can easily navigate between tools like "Trace", "Pick", "Join", "Delete Str" to extract the string and adjust the output. User can also switch between the extracted feature class through the drop-down on the top.

Before performing any type of extraction, users must define the "Feature" settings shown in Figure 5.6.e. This step is primarily for classification and export purposes, as users can define the layer name, color, line type, symbols, or any type of text annotation that will be included in the export file. Once users have set up these settings in the pop-up window, it's important to select the defined feature in the list, as this will ensure that the exports have the desired settings.

Clicking the "Options" button brings up a window (as shown in Figure 5.6.d) that contains settings related to the technical perspective of the extraction process, such as maximum/minimum width, height, offset and more. This allows the user to fine-tune the algorithm inputs, as curb height and lane width can vary from country to country. All extracted features are listed in the "Trace Linear Feature" window, along with their number, feature name and length. This feature is very helpful because it gives the user an idea of how many features have been extracted and whether the length matches the expected results.

To perform any type of extraction, users must select the export feature class and press the "Trace" button. They must then define the starting point, direction and verify or adjust the output. The time required for this process, from defining the starting point to verifying the extracted feature, depends on the complexity and length of the detected feature, but typically takes only a few seconds.

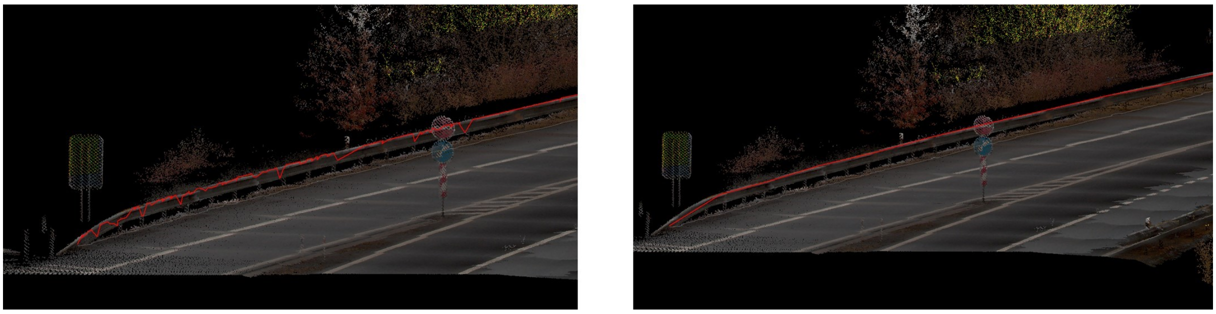
As shown in the Figures below, it is critical to have good quality point clouds, as even a small color glitch can cause the algorithm to break down. Such errors are typically not caused by the software and the output need to be manually adjusted to correct them.



(a) (b) (c)

Figure 5.7. Multiple Errors During Extraction in SCC

SCC allows users to define very precise algorithmic steps for detection, resulting in detailed and high quality outputs. However, these outputs often require smoothing, which in SCC can be done during the extraction process or as a separate step afterwards. Figure 5.8 illustrates the difference in the example of guardrails, but smoothing may also be required for road markings and noise barriers, among others.



(a) (b)

Figure 5.8. SCC Extractions: (a) before smoothing; (b) after smoothing

5.4.4 Export

SCC uses its own .model file format to process and store point clouds. Nevertheless, it can export to formats such as .dwg, .dxf, .dgn, .xml, .shp, .kml, .ifc and more. Although the .dwg format is commonly used, the exported file is not a native Autodesk drawing file and is not recognized by AutoCAD applications. To solve this issue, users must copy and paste the objects from the exported file into a blank new template file in AutoCAD, making sure that the units and coordinate systems are correct. This practice of copying and pasting into a new file is often necessary because some companies require their own templates. This extra step does not affect the points in the “Data Exchange”. In addition, all defined lines, layers, line types and colors are exported correctly and the extracted features are usually saved as 3D polylines.

5.4.5 Output Analysis

The workflow shown in Figure B.1 was used to assess the outputs. Appendix B.2 contains a detailed analysis of the length of the classified features and the metrics described in subchapter 5.3.1. The data is structured in the following manner:

- The results for the highway sample:
  - Total length of the extracted features: Table B.1
  - Completeness/Correctness/Quality: Table B.2
- The results for the urban road sample:
  - Total length of the extracted features: Table B.3
  - Completeness/Correctness/Quality: Table B.4

The mean value of the calculated “Quality” is 78%, which translates to a score of 11 points in the first quantitative metric “Further Adjustments”. This indicates that a significant amount of manual input is required to achieve satisfactory results. In addition, SCC lacks a solution for extracting pavement edges, resulting in a loss of approximately 4 points in this aspect. However, the software was successful in detecting road markings in both samples, with a few minor exceptions. Similarly, the detection of curbs and handrails was generally successful, with some difficulty in detecting small sections of curbs and road markings, particularly in complex urban areas where multiple features were close together. For example, in one case, SCC was not successful to detect four curb edges on the central islands of a roundabout.

SCC scored 14 out of 16 base points in the “Features Extracted” aspect, with 2 points deducted for the inability to extract the pavement edge in the highway sample. However, 2 additional points were awarded for the ability to extract both dashed and continuous lines in a single extraction iteration and for other point cloud processing options. A detailed breakdown of the point allocation for this aspect can be found in Table 5.2. SCC received the maximum amount of points in the "Data Exchange" aspect as it did not require additional conversion and supports all well-known formats.

In terms of processing time, it took about 6-7 hours to process the data for the highway and 11-12 hours for the urban road, from importing the .las to exporting the .dwg. This time included some one-time tasks such as learning the software and determining the correct algorithm settings for the extractions. It should be noted that once these initial tasks are completed, the processing time for future samples will decrease. The software's interface is intuitive and follows the methodology of other CAD software, with the main tools located on the top ribbon and tool windows on the sides. However, it would be helpful to have a text window with more details when hovering over parameters with the mouse to aid understanding. In terms of software support, email communication and available support materials were at a good level.

SCC receives in all three qualitative aspects: "Overall Time Efficiency", "UI & UX" and "Software Support", earning 12 points for each. Using SCC reduces the time required for linear feature extraction, whether used as a starting point or as a standalone tool. Its intuitive and easy-to-learn software interface makes it easy to work with. The team behind SCC is supportive and responsive, providing helpful assistance to users.

The "Overall Usage" aspect takes into account the previous sections and reflects the author's experience and opinion after thorough testing of all three programs. SCC is awarded 15 out of 20 points for providing a comprehensive set of tools for processing point clouds that largely met the objectives of this thesis, although not in all aspects. However, it is an excellent starting point for point cloud processing, a tool for managing survey data from multiple sources and a starting tool for processing point clouds and linear feature extraction. In total, 98 out of 140 points, or about 70%. A separate radar chart depicting these aspects and scores is available in Figure 5.9 and a common radar chart is available in Figure 5.19.

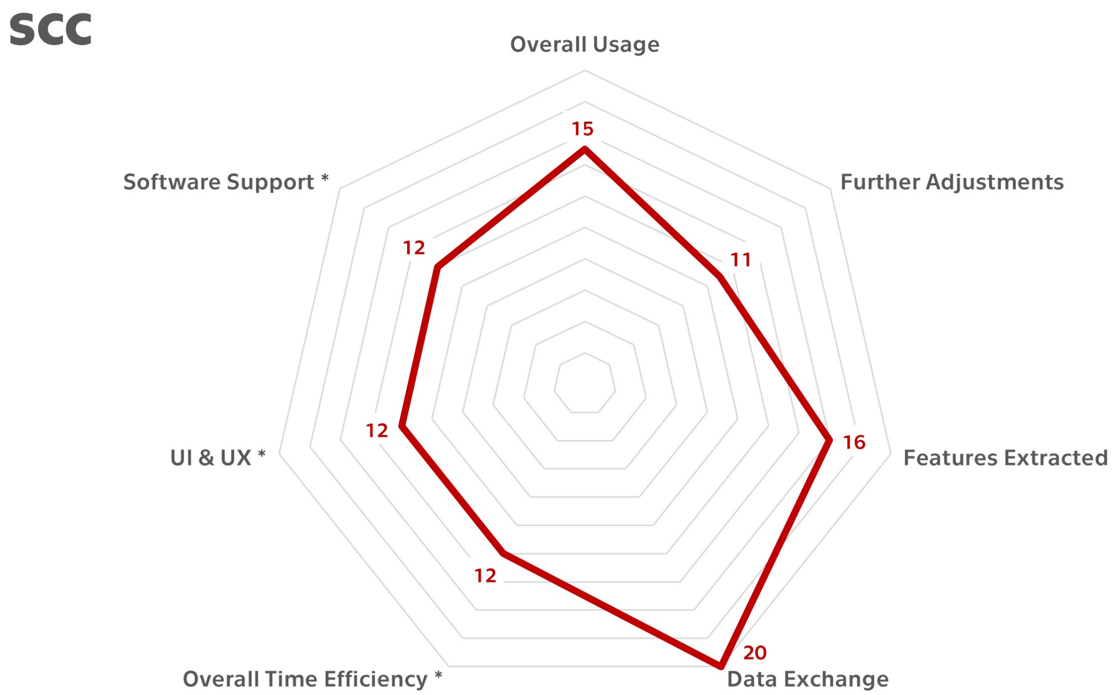


Figure 5.9. SCC - Radar Chart with Final Score

5.5 ^{n}4ce Software from Applications in CADD Ltd.

The second software under review is called ^{n}4ce[2], hereinafter referred to as ^{n}4ce. Produced by Applications in CADD Ltd. during last 40 years, starting as one of the first survey data processing tools for tasks such as terrain modeling, quarry design, infrastructure planning and road and drainage design. Over time, the tool has undergone significant development, culminating in the release of ^{n}4ce in the early 2000s, which required a complete redesign due to changes in operating systems. [54]

^{n}4ce introduced a new set of capabilities and is now a great option for handling survey data generated by today's total stations and GNSS. This software is designed to facilitate building surveys, data transfer, local and free station network adjustments, complete with error detection and reporting. It is a standalone software program that runs on Windows and is available in three different versions: "Lite", "Professional" and "Designer". [54]

5.5.1 Tools

In addition to the three main versions of the software, there is an additional feature available for the top two editions, known as "^{n}4ce Point Clouds". This tool can process point clouds of almost any size, the only limitation being the user's hardware. The "Designer" version, which is the highest level of the software, can be extended with a paid subscription to the "Feature Extraction" toolset. In the case of this thesis, the author received the "Designer" license along with the "^{n}4ce Feature Extraction Tools" by the Applications in CADD Ltd. team for a limited time for purposes of this thesis. [54]

The "Lite" version of the software provides basic functionality such as minor survey data editing and the ability to perform some rudimentary modeling tasks. It can also handle terrain surface modeling, generate sections, import point clouds and calculate volumes. The next level up, the "Professional" edition, offers a broader range of tools, including some advanced features such as string densification, terrain import from .xml or .dwg and terrain merging. It also includes key plans, fly-through, 3D measurements and basic point cloud operations. The "Designer" license is the most comprehensive and can be considered a professional toolbox. It includes all the features of the previous licenses plus additional capabilities such as point cloud sectioning, shape recognition, ortho elevation imaging of sections and specialized rail tools such as cant and gauge reports, rail overlaps and planar offsets. This top-of-the-line license also provides advanced tools for designing alignments both horizontally and vertically. [54]

5.5.2 Initial Procedures

The ^{n}4ce software follows an unconventional but intuitive and efficient organization scheme. When the software is installed and started, the user is presented with a main project window, as shown in Figure 5.11.a. This window provides an overview of all data imported into the current project. On the left side of the window is a project tree that organizes data into folders based on their type. For example, under the "Models" folder, the author has created two models named "extravilan" and "intravilan". This structure allows the user to quickly distinguish between different data sets and switch between them without need to reopen or reload other data. Once a model is selected, such as "extravilan", more detailed information about its points is displayed on the screen without having to open the model.

Using the base project window, the user can access another window called "Graphics", as shown in Figure 5.11.b. Here, the user can finally see a visual representation of the objects. This window contains a full set of standard CAD tools and serves primarily as the editing window. The user can work with CAD features, create standard or tunnel sections, annotations, digital terrain models and manage boreholes, create layouts and much more. From this window, the

[2] n4ce Designer 4.40b with Feature Extraction Tool

user can also open another window called "3D View", as shown in Figure 5.11.c. This window contains all of the advanced point cloud processing tools. All extracted features from the 3D View window are immediately sent to the "Graphics" window, where the CAD tools are located.

To import point clouds into the ^{n}4ce software, the user use the "Convert to Octree" button shown in Figure 5.11 to map point cloud files or folders. Once imported, the user can specify the color storage method, view the maximum and minimum coordinate values and remove duplicates if necessary. The point clouds are easily accessible through the Octree structure. User can check the intensity by switching the display mode in the left pane. After these initial steps, the user can proceed with the point cloud extraction using the extraction tools found on the top ribbon as shown in Figure 5.11.d. The "Model" and "Tool Properties" are on the sides of the screen.

5.5.3 Feature Extraction

The ^{n}4ce software provides several feature extraction tools designed for specific feature types, as shown in Figure 5.11.d. These tools include "Cable Extraction", "Rail Track Extraction", "Floor Plan Extraction", "Break Line Extraction" and the "Height and Stagger" tool. For the purposes of this thesis, the focus will be on two main tools, namely "Road Marking Extraction" and "Wall/Curb Extraction".

The feature extraction tool in ^{n}4ce follows a similar approach to SCC, where there is a single main extraction tool with numerous adjustable parameters. This level of customization allows users to fine-tune algorithm steps, including cluster radius, maximum distance, number of redirects, direction and horizontal tolerance, maximum gap and many others. As a result, users have precise control over the detection algorithm, even though it requires multiple iterations and different settings for each feature and sample. These settings can be saved or exported for sharing with other users.

The tools used to extract the necessary data for this thesis were the "Road Marking Extraction" and the "Wall/Kerb Extraction". The "Road Marking Extraction" tool uses the intensity values present in the point cloud data, which is advantageous because it eliminates the need for color calculations and improves the performance of the algorithm. The curbs, walls and guardrails were all extracted by using the same tool, but with different templates and settings. No other adjustments or smoothing were required for the output. The initial feature class settings were used for output classification.

A major advantage of ^{n}4ce is the ability to place multiple "seeds" (extraction start points and directions) and extract multiple features simultaneously. This feature saves time when extracting multiple long and simple features. Users can define multiple seeds, extract them at once and check multiple outputs simultaneously, as shown in Figure 5.11 and 5.10 in more detail.

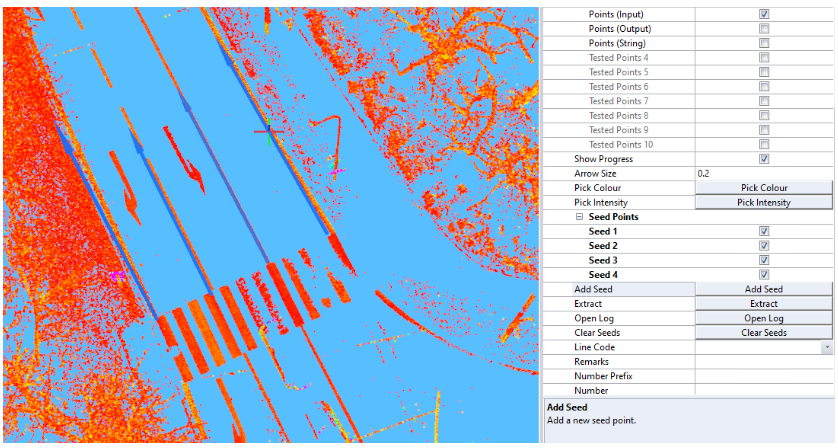


Figure 5.10. ^{n}4ce - Multiple Feature Extraction

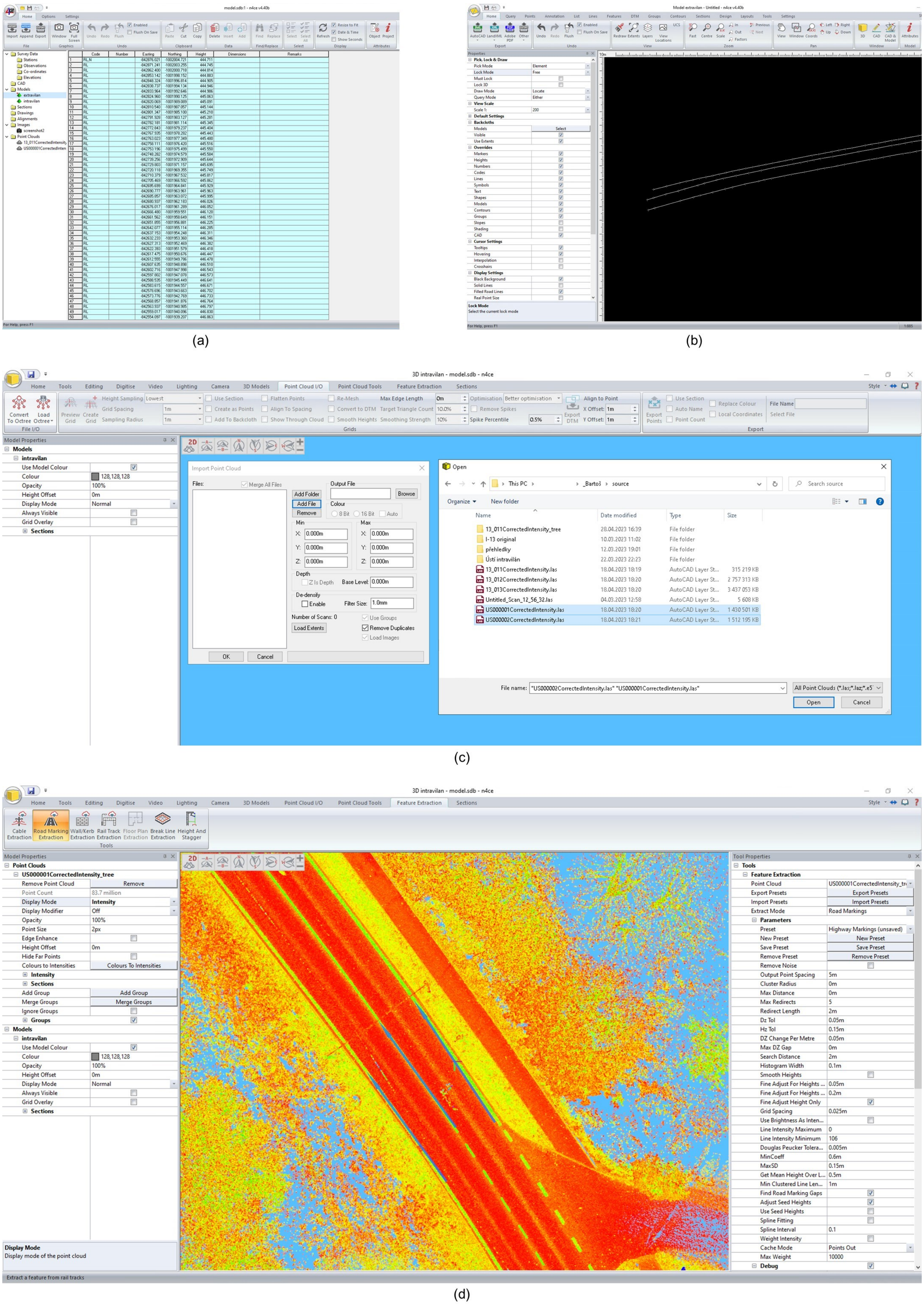


Figure 5.11. ^{n}4ce: (a) project data window; (b) “Graphics” window; (c) “3D View” window with “Octree Point Cloud Import”; (d) “Road Marking Extraction Tool”

5.5.4 Export

The objective of this thesis is to obtain any type of CAD file as output. In ^{n}4ce, all information accessed through the three window hierarchy is saved in a single .sdb file. Once the objects are extracted in the "3D View" window, they are then sent to the "Graphics" window. Here, users have access to an advanced tool for exporting to a variety of formats, including .dwg, .dxf, .xml, .pdf, .csv, .dot and even Genio/Trimble/Leica/Topcon native files. In addition, a basic format export option is available in the base window, allowing users to export the first six options listed above.

Exporting to .dwg was used for both samples. However, the output file was .dwg, but not in the native Autodesk drawing format and was not be recognized by AutoCAD applications. Therefore, an additional step was required, similar to the one described earlier for SCC in the 5.4.4 subchapter. The exported objects appeared as 3D polylines and matched the initial settings.

5.5.5 Output Analysis

The assessment of the outputs was carried out using the workflow presented in Figure C.2. A comprehensive analysis of the length of classified features and the calculated metrics described in subchapter 5.3.1 can be found in appendix C.2. The data is organized in the following format:

- The results for the highway sample:
  - Total length of the extracted features: Table C.5
  - Completeness/Correctness/Quality: Table C.6
- The results for the urban road sample:
  - Total length of the extracted features: Table C.7
  - Completeness/Correctness/Quality: Table C.8

The total "Quality" score for ^{n}4ce was determined to be 85% based on the average of all sub-aspects. This translates into 14 points for the "Further Adjustments" aspect. Similar to the SCC, 4 points were lost due to the lack of a pavement edge extraction tool in the highway sample. In addition, 2 points were lost due to a large error in the detection of the noise barrier and smaller errors in the road markings, curbs and handrails (with an error rate of less than 7% for the last three features). While ^{n}4ce had similar problems as the SCC in detecting multiple features behind each other, it performed better in detecting smaller sections of curbs and road markings. Overall, there results into a 3 point difference between ^{n}4ce and SCC.

In the second aspect, "Features Extracted", ^{n}4ce received 14 out of 16 base points due to the lack of a road edge extraction tool. However, it received 2 extra points for providing more detailed options for extraction, such as various road marking templates, including hatching, yellow boxes and yield markings. In the third aspect, "Data Exchange", ^{n}4ce received the full 20 points as there was no need for additional file conversion.

The first qualitative aspect considered is "Overall Time Efficiency". The processing time, from importing the .las file to exporting to .dwg, was approximately 5-6 hours in case of the highway sample and 9-10 hours for the urban sample, mainly due to the ability to extract multiple features simultaneously. The second qualitative aspect, "UI & UX", describes the intuitiveness of the software. The author appreciates ^{n}4ce's three-window layout, which provides quick at-a-glance access to the survey data. In addition, ^{n}4ce follows modern trends with a top ribbon and multiple side tabs. Both aspects scored 13 points each, indicating a good result, as shown in the bar chart in Figure 5.5.a.

The final qualitative aspect is "Software Support", where it is worth to mention the excellent communication from the Applications in CADD team. The team responds promptly to email inquiries and also provides support via a phone line where users can speak directly to a technician who can quickly resolve issues or demonstrate how to perform certain tasks on the user's machine through TeamViewer. As a result, the "Software Support" aspect received a score of 15 points, which is a great result.

The final aspect, called "Overall Usage", is a summary of all the previous aspects and includes the personal experience and opinion of the author, who has thoroughly tested all the programs. ^{n}4ce receives 16 points for its excellent performance in quickly processing point clouds and extracting linear features. While it met most of the goals of the thesis, it fell short in certain aspects, such as the lack of a tool for extracting road edges and additional tools for upscaling the workflow in the future. However, the licensing options for ^{n}4ce provide an excellent set of tools for managing survey data and users can purchase more advanced licenses for processing point cloud data and extracting linear features. ^{n}4ce is an excellent tool for extracting standard linear features such as road markings, curbs and walls from road infrastructure, as well as additional tools for rail infrastructure. The total number of points accumulated by ^{n}4ce is 107 out of 140, or 76%. The allocation of points for all aspects is shown in a separate radar chart in Figure 5.12 and a common radar chart is available in Figure 5.19.

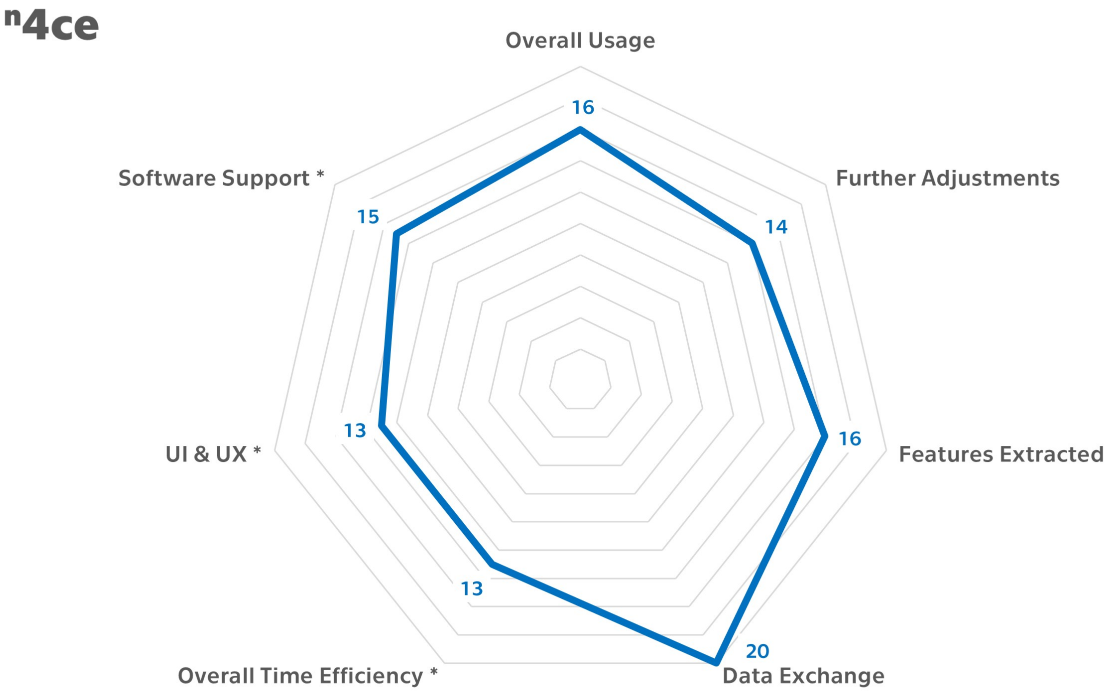


Figure 5.12. ^{n}4ce - Radar Chart with Final Score

5.6 TopoDOT / Certainty 3D Software

TopoDOT Software[3], formerly known as Certainty 3D, is a suite of software tools for extracting topography, 3D models and GIS assets from point cloud data. With TopoDOT, users can establish a highly efficient process for managing data, assessing quality and extracting CAD/GIS products. The main goal of this tool is to produce quality outputs from point clouds. TopoDOT provides a sophisticated set of common tools that allow users to manage, extract and store data. It is an add-in to MicroStation or other Bentley Systems software, which means it can be installed anywhere Bentley software is in use. TopoDOT itself has no inherent limitations and is limited only by the capabilities of the host software. For the purpose of this thesis and within a limited time frame, the license for TopoDOT was acquired directly from the TopoDOT team. The university license was used to install the “base” Bentley software. [55]

The company/product website for TopoDOT shows that they prioritize building and engaging with their community. They organize conferences, offer online training, share their own notes, maintaining a product blog and wiki page. Figure 5.13 provides a series of images of TopoDOT launch button in Bentley software, loading point clouds, the software environment and two basic extraction tools. This figure serves as a reference point and more details about each part of the figure are provided in the accompanying text. [55]

5.6.1 Tools

TopoDOT provides a comprehensive set of tools organized into a workflow that covers a wide range of tasks. The workflow begins with data management and organization, which is facilitated by TopoDOT’s ability to quickly lay out a tile system over an area and subdivide it into smaller tiles. The software also allows for easy storage of point clouds in its cloud service. The second step in the workflow is quality assessment, which involves comparing the point cloud to reality using image or relative point cloud alignment techniques. The third and final step is extraction, where users have access to a wide range of tools for feature extraction, vectorization and classification from point clouds. This is followed by quality assessment and control, which provides users with control over the extracted features compared to the original point cloud. In addition, TopoDOT provides more advanced analysis capabilities such as bridge clearance, pavement, sidewalk condition analysis and grade assessment.

[3] TopoDOT 64-bit 2023.1.1 on MicroStation CONNECT Edition 10.17.2.61

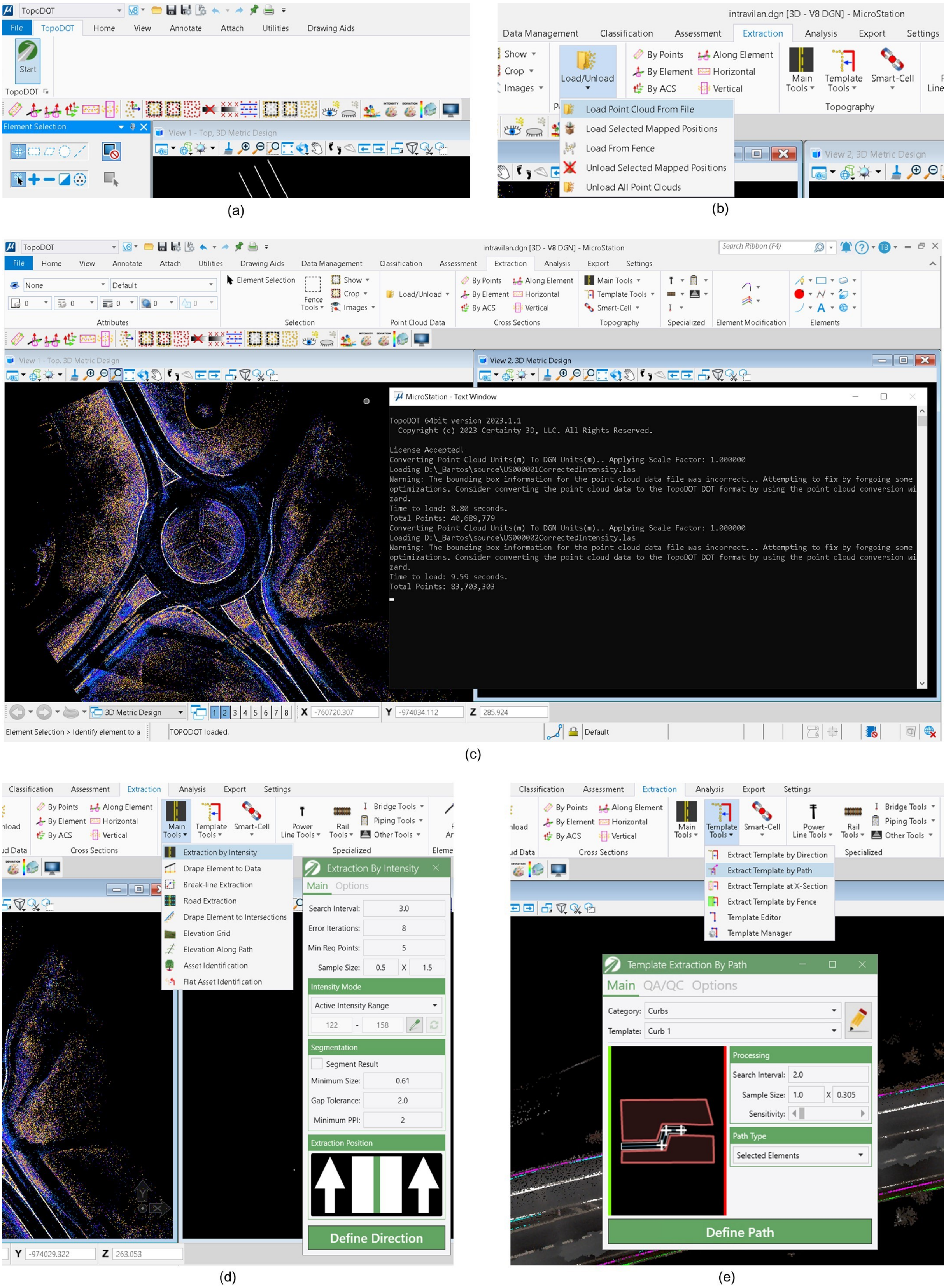


Figure 5.13. TopoDOT: (a) launch button in Bentley Software; (b) importing point cloud files; (c) software environment with "Text Window"; (d) TopoDOT "Main Tools" - "Extraction by Intensity" and detailed settings; (e) TopoDOT "Extract Template by Path" tool

5.6.2 Initial Procedures

As mentioned earlier, TopoDOT requires the installation of Bentley software. Once any type of Bentley CAD software has been obtained and successfully launched, TopoDOT is launched from the button located on the top ribbon, as shown in Figure 5.13.a. Upon launch, the user tool ribbon is expanded to include the “Classification”, “Assessment”, “Extraction”, “Analysis”, “Export” and “Settings” panels as shown in Figure 5.13.b.

The “Settings” allows the user to define the import for TopoDOT. This includes providing user information such as the method for storing image information (8-bit or 16-bit), units and whether to calculate intensity from RGB or use original values from the point cloud. This setting is crucial for processing, as it is essential that the intensities are imported correctly. Figure 5.14 shows a significant difference in the point cloud colors when the intensity values are calculated from RGB values, as seen in (b), compared to when they are obtained directly from the LiDAR scanner during the survey, as seen in (a). Sample (c) serves as a reference and shows some noise that has been translated into intensities in (b). The road markings in (a) are easier to see, even to the human eye, which means that accurate algorithms do not have to rely on calculated intensity values.

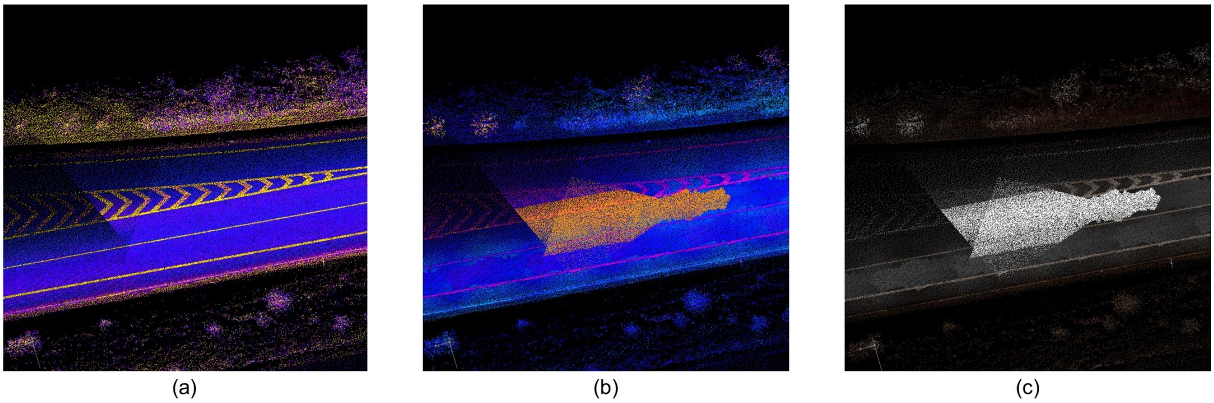


Figure 5.14. TopoDOT Intensity Settings: (a) original intensity values from LiDAR scanner; (b) intensity values calculated from RGB values; (c) RGB sample for reference

TopoDOT allows for the import of point clouds through the “Load/Unload” tab shown in Figure 5.13.b. This tab allows for the import of various standard point cloud formats, TopoDOT Data File .dot and .txt files or native Leica Cyclone, Riegl and Topcon files. Here is an example of TopoDOT as an add-in to engineering/CAD software - engineers or technicians working on a project with any type of modeling file open can launch TopoDOT on top of the currently running model, import the desired point cloud and extract any other information they need without having to open another piece of software. The extracted information is available directly in the .dgn file without the need for conversion/export.

The “Text Window” runs in the background of Windows, as shown in the middle of the Figure 5.13.c. This window keeps the user informed about ongoing background processes, such as loading the point cloud, the number of points and the time it takes to load them.

5.6.3 Feature Extraction

TopoDOT provides a wide range of tools, especially for extraction. In the “Main Tools” drop-down menu shown in Figure 5.13.d, there are several tools available, such as “Extraction by Intensity”. This tool allows the user to define an intensity range and then TopoDOT searches for linear features through the points with the desired intensity range. This tool was used to extract lane marking from both samples. Another tool - “Break-line Extraction”, allows users to manually or automatically extract and classify multiple features at once by providing a partial cross section of the point cloud. Users can adjust the position of the point and feature, as shown in Figure 5.15, which refers to the sample shown in Figure 5.1, which includes a noise barrier behind the guardrail.

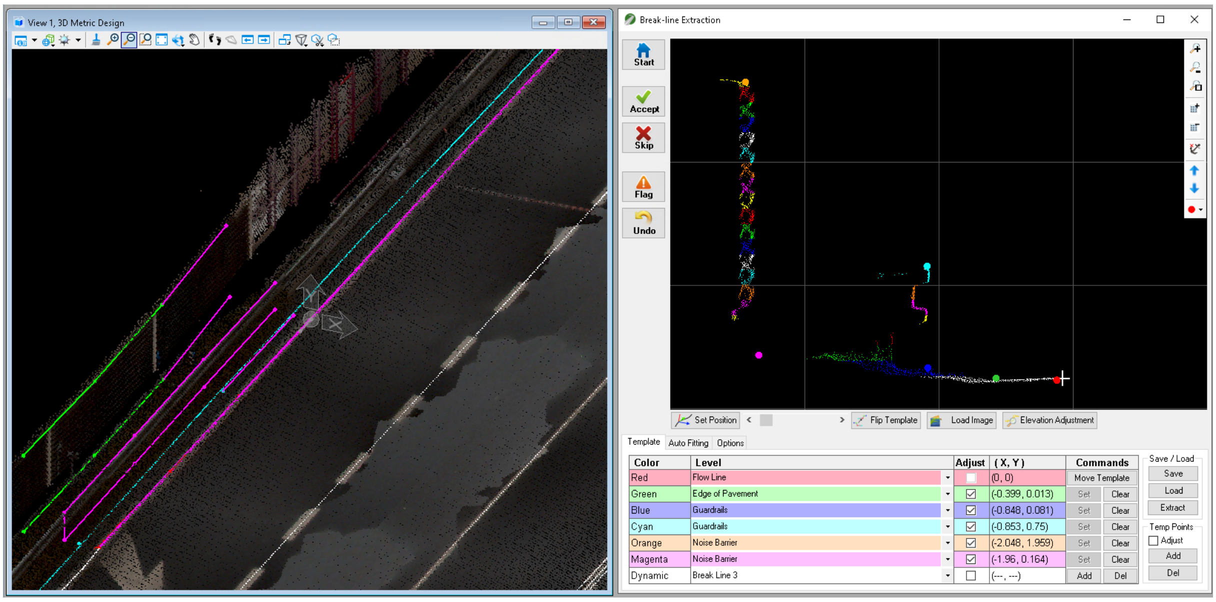
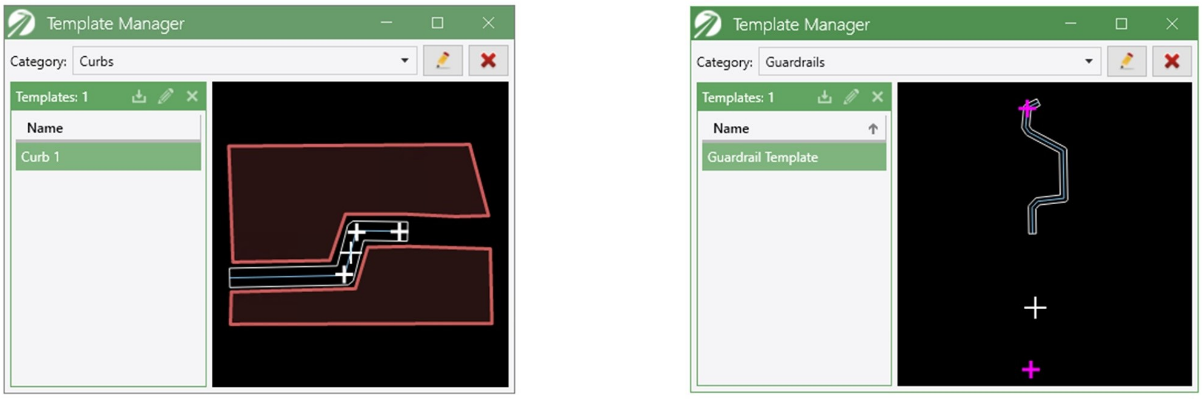


Figure 5.15. TopoDOT - "Break-line Extraction" tool: window on right shows the isometric view, window on the left shows the partial cross section with adjusted points

The "Break-line Extraction Tool" in TopoDOT allows multiple features to be extracted and classified at once by providing a partial cross section of the point cloud and adjusting the position of the points/features. It was used to extract five features at once, including the top and bottom points of the noise barrier, the top and bottom projection of the guardrail and the edge of the road, using the previously extracted lane markings as a guide. By defining the step distance, the outputs are precise and this tool is useful for manual extraction of complex features. It was also used to extract the central island of a roundabout with multiple curbs.

TopoDOT's "Template Tools" are often used to extract complex, but common shapes. Users can define their own shapes and choose whether the extraction follows a path or a user-defined direction. This tool was used to extract large sections of guardrail and curb from both examples. The user-defined shapes can be seen in Figure 5.16. Most of the extraction tools requires user to define the inputs, starting point, direction and verify the outputs. By using these semi-automated tools, users can extract long sections of guardrails or road marking in matter of seconds. The process of classifying is carried out using the MicroStation level system.



(a) (b)

Figure 5.16. TopoDOT - Extraction Templates: (a) curb template with 3 points representing the back, front and bottom curb edge, red zones around is the exclusion zone; (b) guardrail template with point at the top and ground projection

TopoDOT provides several advanced tools such as automatic calculation of feature height from ground, rail extraction, point feature extraction and analysis tools for bridge clearance, structures, bridges and beam extraction. Although these tools have not been thoroughly tested, the previously discussed tools were sufficient for the objectives of this thesis. Figure 5.17 provides a brief overview of these advanced tools, including extraction of power lines in light blue, analysis of pavement condition by dividing it into tiles, extraction of bare earth and road points and calculation of lane slope and width.

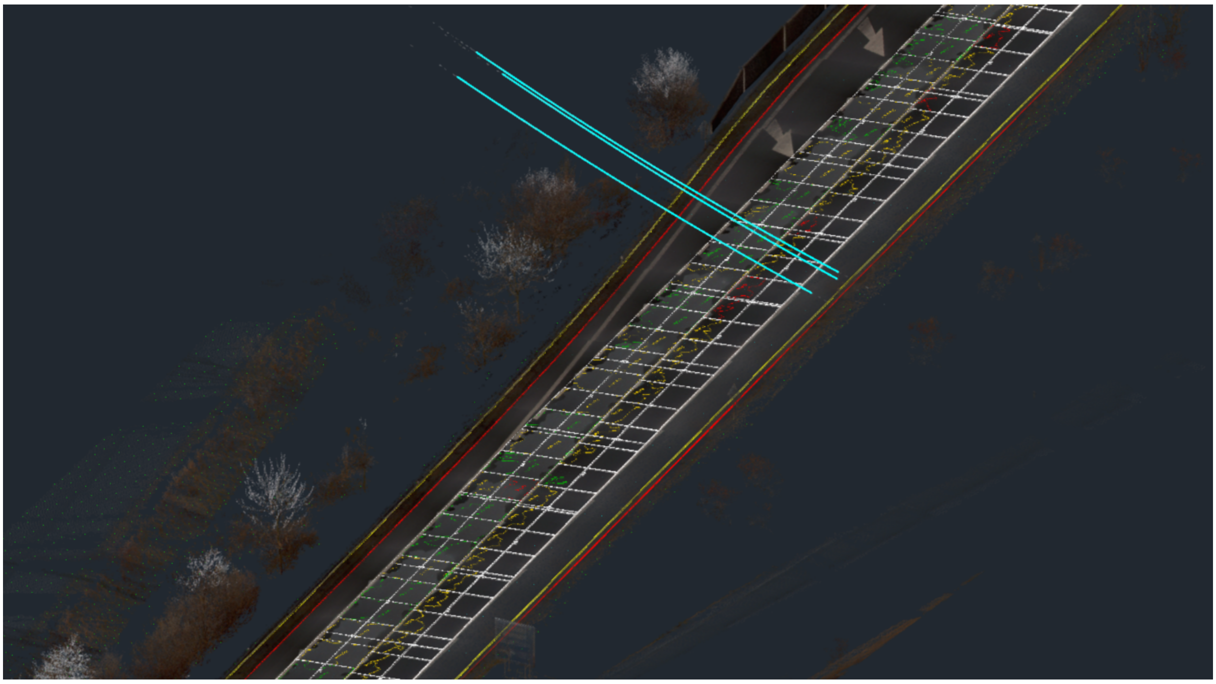


Figure 5.17. TopoDOT - More Advanced Tools

5.6.4 Export

TopoDOT's export tools are located at the top of the ribbon and provide a number of options. In addition to basic exports to images or .csv/.xml files, users can create a set of sheets or export to .json format. Because TopoDOT is an add-in to Bentley Systems, all extracted features are saved as lines or smart lines in the native .dgn format. This eliminates the need for additional export steps when working with Bentley software. If needed, other export options such as .dwg/.dxf/.fbx/.obj can be accomplished using the standard export tool in Bentley software. During testing for this thesis, the .dwg export function worked well and resulted in an AutoCAD-recognized drawing file with the correct layer, line types and colors. The extracted features are stored as 3D polylines.

5.6.5 Output Analysis

The assessment of the outputs followed the workflow depicted in Figure D.3. The appendix D.2 provides a detailed breakdown of the length of the classified features, as well as the calculated metrics described in the subchapter 5.3.1. The data is organized as follows:

- The results for the highway sample:
  - Total length of the extracted features: Table D.9
  - Completeness/Correctness/Quality: Table D.10
- The results for the urban road sample:
  - Total length of the extracted features: Table D.11
  - Completeness/Correctness/Quality: Table D.12

The mean of the partial quality scores for all features in both samples is 98.57%, which translates into a score of 19 out of 20 for the first quantitative metric, “Further Adjustments”. TopoDOT receives all points for the second quantitative aspect, “Features Extracted”, which allocates points based on the number of tools provided. The software exceeded the expectations of this thesis and all desired features were extracted with good quality using the basic tools. Consequently, TopoDOT received all 16 points from the base and all 4 points for the additional features. For the third quantitative aspect, “Data Exchange”, TopoDOT received the maximum points because it did not experience any slowdowns due to unsupported formats.

The time required to process the urban road sample from .las to .dwg using TopoDOT was approximately 5 to 6 hours, primarily due to the large number of curbs and one roundabout. The time required to process the roadway samples was about 2 to 3 hours, as the learning curve is relatively steep and fast. The TopoDOT add-in is easy to use and has an intuitive interface that is identical to Bentley’s CAD software. Additionally, TopoDOT provides comprehensive support to its users through their own wiki, blog, other supportive materials and communication at a good level. These factors contribute to a score of 15 points in each of all three qualitative aspects: “Overall Time Efficiency”, “UI & UX” and “Software Support”. With a base score of 10 points in these aspects, these points indicate that TopoDOT is a highly efficient and user-friendly software with good support.

The “Overall Usage” aspect is a summary of the previous sections and includes the author’s personal experience and opinion, as he has thoroughly tested all the programs. While TopoDOT is excellent software and could easily receive the maximum points in this aspect, two points were deducted due to licensing. TopoDOT is an add-in to Bentley software, which means that users must purchase licenses for both the base Bentley software (if they don’t already have one) and TopoDOT. While TopoDOT being an add-in is seen as a great advantage, it can also be a disadvantage depending on the job, company or situation. This must be taken into consideration when thinking about the software.

After assessing TopoDOT on various aspects related to point cloud processing, the tool scored 122 out of 140 points, equivalent to 87% of the final score. This makes it a highly recommended tool for feature extraction and point cloud processing. This assessment of TopoDOT was based on various aspects, which are represented by a radar chart in Figure 5.18. Common radar chart with results of all three software is in Figure 5.19.

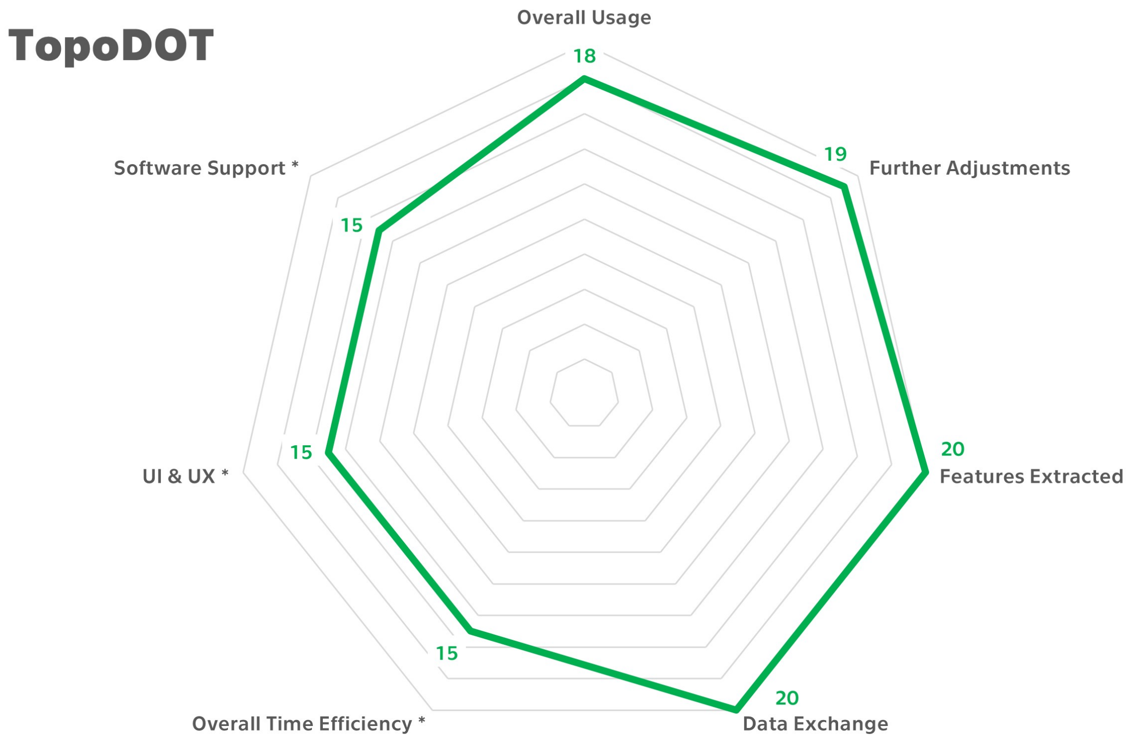


Figure 5.18. TopoDOT - Radar Chart with Final Score

5.7 Final Assessment

This final subchapter serves as a summary of the three commercial solutions explored. While the point results of each software have already been described, this subchapter provides a more detailed explanation and comparison of the results.

5.7.1 Investigation Results

The individual results for each software have been combined into a single radar chart, shown in Figure 5.19, allowing readers to easily compare the differences between the software in each aspect.

TopoDOT outperformed SCC and ^{n}4ce in the first two aspects. SCC had difficulty extracting short-length features, resulting in a significant loss of points in the "Further Adjustments" aspect. Although ^{n}4ce provided slightly better results than SCC, mainly due to its ability to extract short sections of curbs and road markings, neither software had an option to extract pavement edges. In contrast, TopoDOT provided this option and had significant scalability potential, meeting all objectives of this thesis and offering more tools for potential workflow extension. This was reflected in a four-point gap between TopoDOT and the other software in the "Features Extracted" aspect. All of the commercial solutions assessed were able to handle standard point cloud and CAD formats - 20 points for each in "Data Exchange" aspect.

TopoDOT scored higher than the other software options in the first qualitative aspect, "Overall Time Efficiency", because the tools were intuitive and easy to learn and use. The user did not have to figure out algorithm parameters and the learning curve for TopoDOT was steep in a positive way. SCC and ^{n}4ce scored similarly in this aspect, as both software gave the user full control over the detection algorithm parameters. However, some users may prefer this option for its level of control, which is time-consuming to figure out. ^{n}4ce received an extra point in this aspect due to its ability to extract and verify multiple strings in one hit, which can be a powerful option if set up correctly. In contrast, TopoDOT provides more generic and predefined tools with minimal user input.

TopoDOT is an add-on to Bentley's CAD software, which has both positive and negative aspects. On the positive side, TopoDOT's "UI & UX" largely mirror Bentley software, making it easy for companies familiar with Bentley solutions to integrate TopoDOT into their toolbox. However, on the negative side, the integration and licensing process can be challenging for companies using different types of CAD software. This negatively affects the "Overall Usage" aspect, resulting in a two point deduction.

SCC and ^{n}4ce are independent software solutions with their own user interfaces, but both follow modern design trends by having a main ribbon at the top and tabs on the sides. ^{n}4ce scores extra point in the "UI & UX" aspect for its non-standard, yet intelligent three-window layout.

Both ^{n}4ce and TopoDOT excel in the aspect called "Software Support", which includes available resources for troubleshooting while using the software. ^{n}4ce provides a "help" page with frequently asked questions and tool guides. Their team quickly responds to e-mails and has a phone line for direct communication with technicians who can resolve issues or provide demonstrations via TeamViewer. TopoDOT offers a "wiki" site with introductory videos, tutorials and a blog. The team communicates with users via email and the wiki page is easily accessible from within the software. Pressing F1 on the keyboard while selecting a specific tool opens the user "wiki" window with information about the selected tool.

In the case of ^{n}4ce and SCC, the last "Overall Usage" represents all partial aspects. The case of TopoDOT has been described before, in the last subchapter 5.6.5 or up here by the positive, yet negative aspect of implementation.

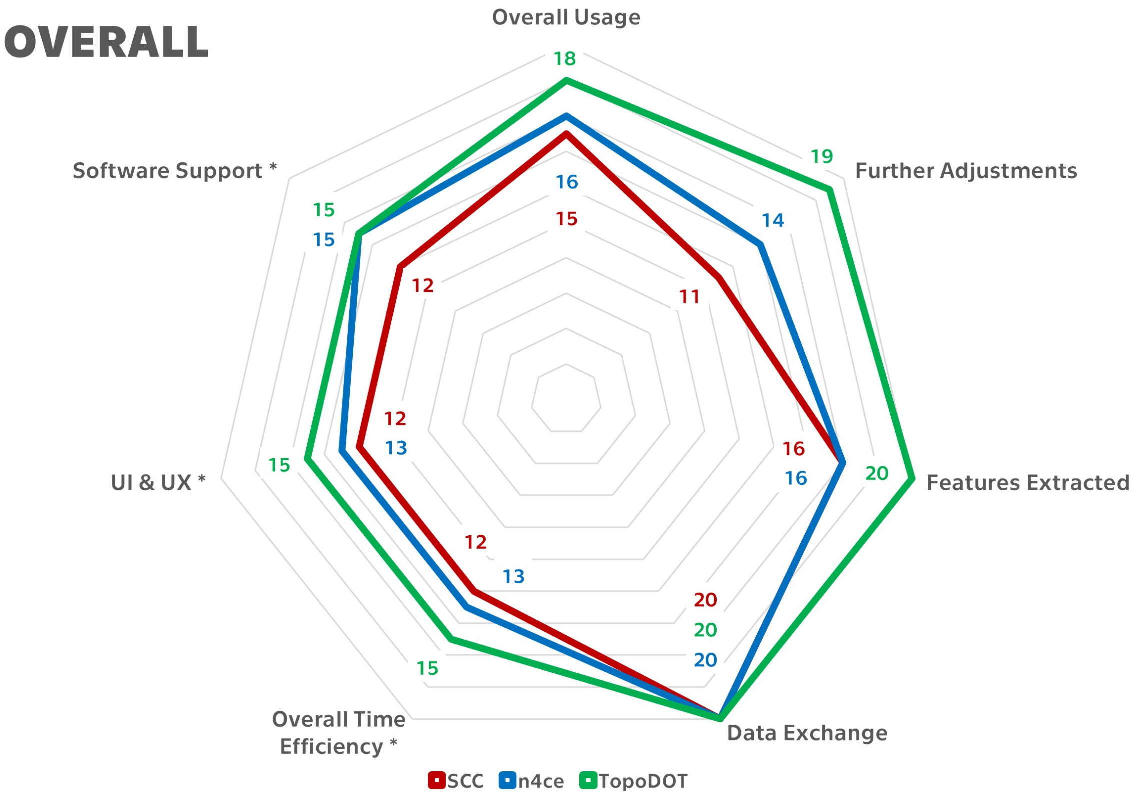


Figure 5.19. Common Radar Chart with Final Score

The three aspects, namely “Overall Time Efficiency”, “UI & UX” and “Software Support”, were scored differently, as explained in the subchapter 5.3.2 and illustrated in Figure 5.5.

All of the software reviewed in this thesis was installed on the faculty’s server machine described in Table 5.1 on the left. This ensured that the investigation was not hampered by a lack of computing power. It should be noted that this software should be able to provide the same results on standard laptops, although this claim from the manufacturer has not been verified.

The assessing of the outputs from each software followed a different procedure, tailored to the capabilities and export options of each software. Further details can be found in the appendices B.1, C.2 and D.3. The assessments were performed separately, resulting in different ground truth values for each feature from each software. A detailed comparison of the percentage differences is shown in Table 5.3, which is in the range of <-0.342%;+0.477%>. These small percentage differences, when scaled to kilometers, correspond to a difference of only a few meters. This can be seen as another indicator of the success rate of the extraction, since the differences between the software results did not exceed ±0.5%.

Table 5.3. Ground Truth Comparison[4] from All Three software[5]

Feature Type	Sample Highway	SCC/^{n}4ce [%]	^{n}4ce/TopoDOT [%]	TopoDOT/SCC [%]
Road Marking	Edge Lines	+0.409	-0.116	-0.292
	Center Lines	-0.149	-0.230	+0.380
Road Edge	(Both Edges)	-	-	-
Guardrails	(Both Points)	+0.477	-0.232	-0.244
Noise Barriers	(Both Points)	+0.350	-0.007	-0.342
Feature Type	**Sample Urban Road**	**SCC/^{n}4ce [%]**	**^{n}4ce/TopoDOT [%]**	**TopoDOT/SCC [%]**
Road Marking	Edge Lines	-0.080	+0.124	-0.045
	Center Lines	+0.051	-0.092	+0.041
Curbs	Top Edge	-0.188	+0.093	+0.096
	Bottom Edge	-0.333	+0.076	+0.259
Handrails	(Both Points)	+0.069	-0.014	-0.056

[4] Length of the particular feature from software “X” divided by length of the same feature from software “Y”.
[5] SCC: B.1 and B.3; ^{n}4ce C.5 and C.7; TopoDOT: D.9 and D.11.

Chapter 6 Workflow

The following text summarizes the necessary actions discussed earlier in this thesis and organize them into a comprehensive workflow diagram.

The workflow shown in Figure 6.1 on the right can be conceptually divided into three phases - I. Quality Check, II. Processing, III. Export Validation, which are demarcated and enclosed by boundaries. To process an unfamiliar data set, it is advisable to perform the first phase using any available free software, as it meet the requirements and potentially save money in case of a complete stop. The second phase is obviously done with the primer processing software, with only the export procedure being different. The final stage of "Export Validation" can be done with any type of CAD software, ideally with the point cloud as a reference in the background.

As familiarity with this workflow develops, it is more practical to integrate the first two steps and perform them only in the primer software. Although this may also apply to the third step, it is recommended to validate the export each time.

While the workflow is generally similar for all three software, it doesn't include detailed step-by-step instruction, as this may vary slightly depending on the software, the job and the user's preferences.

6.1 Quality Check

Upon receiving the data, the first step is to perform a "Quality Check" by looking for potential defects as described in the 3.6 subchapter. The completeness of the point cloud is assessed visually by searching for gaps. Density assessment can be performed simultaneously with the previous check procedure, but requires that the points be color-coded based on the number of neighbors, as shown in Figure 3.8. The third defect to be addressed is the presence of noise and other redundancies, which can be checked during classification validation. As described in the 3.4 subchapter, minor noise is eliminated during preprocessing and should not be present in the provided data sets. The major noise, such as surrounding vehicles, must be classified and can be easily removed or masked, as shown in Figure 3.6.

The classification validation is a critical process that can significantly improve the efficiency of the workflow by reducing the number of points and allowing longer sections to be processed together. However, the drawback is that incorrect classification, such as removing the low+medium+high vegetation classes, may also result in the unintentional removal of guardrails or noise barriers that were incorrectly classified in those classes. Removing essential features from the data sets prior to processing is unacceptable. For large jobs, aligning data from additional survey sources, such as a standard total station or other types of terrestrial survey methods, can supplement this process, as described in 3.2.4 subchapter. This approach provides a higher level of accuracy and can reduce any problems.

After the quality check, there are three options to choose from: use the classification (+), reject it (-) or stop processing altogether (/). The decision to stop processing could be due to insufficient point cloud quality, missing information or other reasons. It is up to the user to make an informed decision whether to continue or request additional data or information. For example, missing sections of guardrails, incorrect "bit" format for point intensity or color values, unidentifiable coordinate systems and other problems can result in unreliable output, which is unacceptable in terms of human, machine and software costs.

The first step, bordered by the dashed lines in Figure 6.1, is recommended to be performed outside the primer processing software. This is because some free software, such as CloudCompare, can provide an excellent service for these purposes. The recommendation is based on the possibility of a complete processing stop (/), as the primer software may charge for the open and initial import, even though the user has not used any of the advanced extraction tools. This step is essential when dealing with an unreliable data source. However, if the data sets are reliable or from a reputable provider, this step can be skipped and the quality check and classification validation can be performed within the primer software. [56]

6.2 Processing

After the initial inspection, there is the "Processing" step, which involves validating the extraction and exporting the data. In general, the processing step does vary slightly from software to software. Users typically use the available extraction tools within the specific software, reviewing and adjusting the output as needed. There is potential for scalability in this step as well, as it may include the extraction of pole-like features, pavement crack analysis and other required extractions in the future. This work has focused only on linear features, but can be adapted as needed based on the user's objectives.

The export process varies between different software programs, such as SCC (described in subchapters 5.4 and 5.4.4) and ^{n}4ce (described in subchapters 5.5 and 5.5.4), which store the extractions in their own unique format. Therefore, exporting to any type of CAD software is required. When exporting to .dwg format, it is necessary to migrate the data to a native Autodesk template and do unit and coordinate system checks. Although this step is not mandatory in TopoDOT (subchapters 5.6 and 5.6.4), it is recommended as a best practice to maintain full control over drawing settings.

6.3 Validation of Export

Although this last step may seem optional, it can actually be a critical source of errors in later use that may not become apparent until some time later. To ensure that the exports have the correct units, coordinate systems, layer settings and are compatible for later use, it is highly recommended to perform this step in any CAD software, using the source point clouds as a reference and verify the results. In the assessment procedures of all three software packages (as shown in Figures B.1, C.2 and D.3), this step was performed using Autodesk Civil 3D or Navisworks Manage, with the point clouds used as a background reference.

6.4 Workflow Chart

The workflow presented in Figure 6.1 represents the entire process for all three investigated software, starting from the input data and proceeding through the "Quality Check", "Processing" and "Export Validation" phases. This workflow fulfils the objectives stated in the beginning of this thesis and provides satisfactory results. Furthermore, it provides room for scalability by allowing the addition of more extracted features in some software.

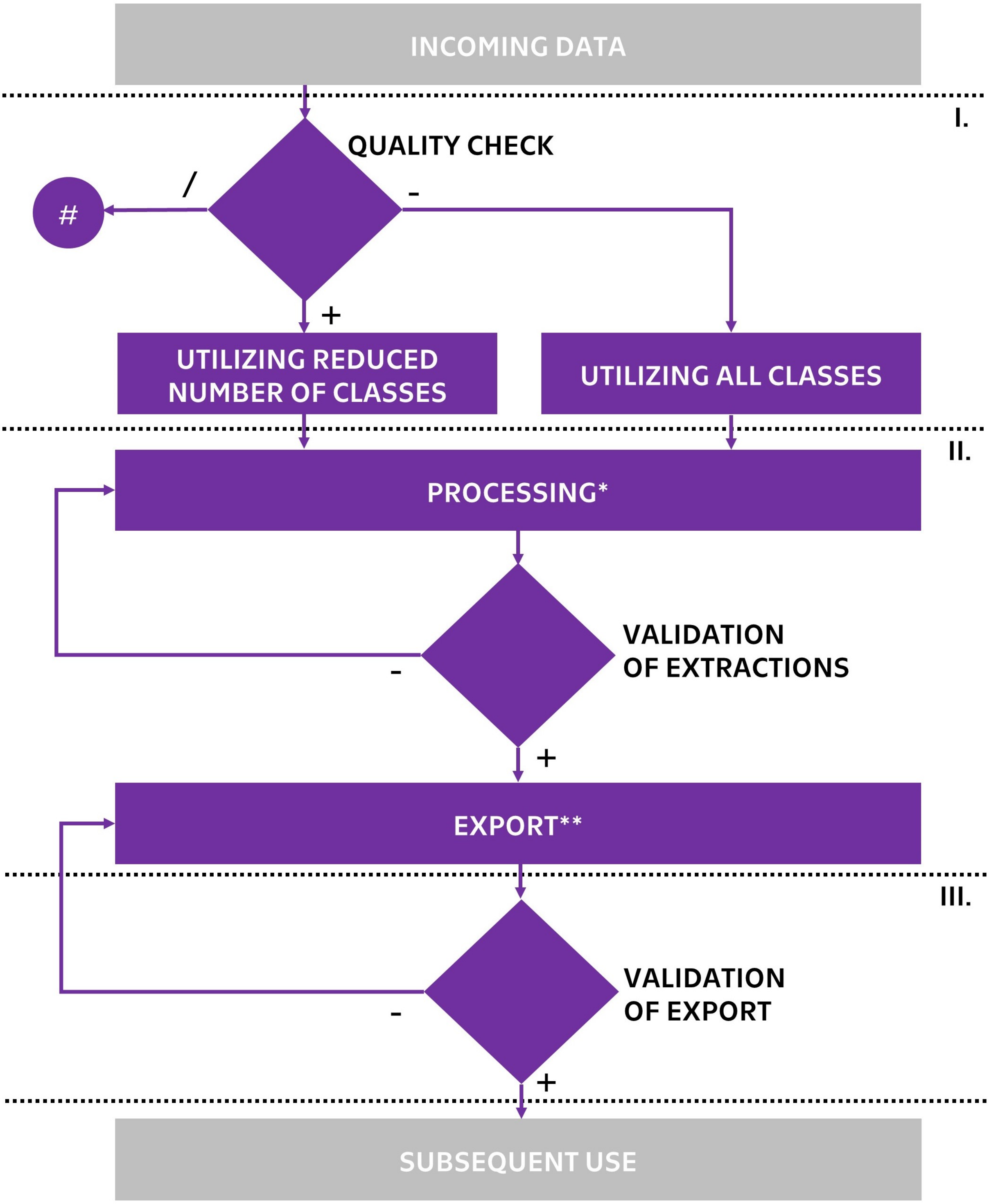


Figure 6.1. Final Workflow[1,2]

[1] * - Common to all three software.
[2] ** - Export procedure depends on the used software.

Chapter 7
Discussion

The main goal of this thesis is to find and assess the available methods for extracting linear features, in practical and effective way and to assess its performance on specific data sets. Currently, linear feature extraction is done manually, as described in subchapter 4.2.1, which is time consuming and costly. The department has a long-term contract for road safety inspections of the Czech road infrastructure and these specific data sets will be processed in the future. Therefore, it was essential to find a scalable solution that, in addition to the primary objectives, can also extract point-like features that are crucial for safety inspections.

When comparing the research papers discussed in the subchapter 4.1, it is apparent that the commercial solutions have outperformed them in terms of feature extraction, processing time, output quality, or a combination of these factors. Therefore, this thesis presents three highly competitive solutions that provide an efficient workflow for feature line extraction from point clouds.

The first two commercial options, SCC and ^{n}4ce, did not have a tool for automated point-like feature extraction. However, they can still be useful starting points, the department may consider upgrading later to the third option TopoDOT. This software did not only met the objectives of this thesis, but also provided a scalable solution with a set of tools for various applications. These solutions were tailored to the needs of the department and provided satisfactory results. However, in order to provide a more comprehensive benchmark, it would be good to test them on commonly used and publicly available data sets, such as the Vaihingen and Toronto data sets from ISPRS, but more preferably on the KITTI data set obtained through vehicle-mounted mobile mapping systems. [27]

Based on the author's experience with processing multiple samples, it is not recommended to load multiple samples at once to increase the overall effectiveness. This is due to the risk of losing control of the software, as many imported point clouds and extracted features can cause the software to freeze or crash, leaving the authors uncertain about the data. Therefore, it is recommended to process shorter sections, about 1 kilometer or even less in complex areas, to maintain good output quality. It is also suggested that consider splitting tasks, working on the long and easy sections and the short but complex sections separately.

After more than a year of investigation, this thesis offers a comprehensive solution to the needs of the department and potentially others by providing an overview of the technology used, along with a detailed description of available solutions from both research and commercial perspectives. This begins with basic theoretical information to introduce an approach for specifying survey terms, requirements and assessing the resulting output from a quality perspective. [2–3, 12–14, 19–36, 48–50, 53–56]

Chapter 8
Conclusion

Mobile laser scanning offers a variety of data collection methods, including airborne and vehicle-based, but all produces valuable information about the environment - point clouds. However, despite advances in the technology, working with this type of data can be challenging due to information overload, inefficient processing, resulting in potential loss. Therefore, the goal of this thesis was to find an effective solution to extract linear feature and avoid these issues. The increasing processing time incurs costs such as human labor and computing power, making automation a desirable solution.

Prior to any practical testing and processing, a description of the general issues surrounding mobile laser scanning, point clouds and their underlying theory was provided. Understanding these concepts is critical for proposing an effective workflow. This included a description of the recommended point cloud density and accuracy required from a survey, as poor decisions in this area can lead to inappropriate results for specific applications. This was followed by a review of existing solutions and approaches in available research papers to gain insight from different perspectives to benefit the processing and final workflow proposal. It should be noted that although the survey and initial processing were not part of this thesis, they are described in detail to complement the rest of the theory.

The theoretical knowledge gained was valuable in the research that followed. This involved obtaining licenses for four chosen software, communicating with five companies, installing and investigating all of them. The author considers this a significant accomplishment, as one of the licenses is likely to be purchased by the department and used in the future. The software programs were first tested to confirm their capabilities and based on that divided into two groups. Ultimately, only three options from the semi-automated group were selected for further testing on a specific data sets as they met the objectives of this thesis.

The subsequent research involved testing more of the software's capabilities on specific data sets, exporting and evaluating the results using commonly used calculated metrics. These were then expanded to include several custom quantitative and qualitative aspects. All results were organized into detailed tables or radar charts to provide an overview of the strengths and weaknesses of each software tested, making it easy for the reader to understand. Testing was performed on two different samples, resulting in three ground truth lengths for each feature, which is similar to measuring the length of a table with three different rulers. The results were then compared to verify their consistency between software features and samples, with deviations of $<-0.342\%;+0.477\%>$. This is a remarkable result, as deviations of $\pm 0.5\%$ is considered as acceptable. Therefore, these results confirm that the extractions reflect reality at a reasonable level.

Five out of six commercial solutions were installed and tested on the server machine, with the expectation that processing time would be reduced due to the atypical hardware. However, access to the server proved to be an unexpected bottleneck when processing data through remote access. While the hardware requirements for the commercial solutions suggest that standard computers or laptops are sufficient, the use of the powerful server did not provided the expected benefits. Despite having an internet connection to the server through an optical cable with an upload and download speed of about 1 Gbps and a laptop internet speed of about 0.2-0.3 Gbps through a standard ethernet cable, the latency when working on the server was high. The author often had to check to see if the software had frozen or if the connection was bad, resulting in multiple reconnects during the session. This had no negative impact on the output, but if the option to work locally instead of remotely becomes available, it may be preferable.

One way to take advantage of the power of the server machine is to split tasks between it and a local machine. Longer and less complex sections could be processed on the server, while shorter and more complex sections or final fine-tuning, could be done locally. It should be noted that some software may not support remote access, by limiting the available tools or requiring a special license to enable it. It is important to consider these factors when deciding on the optimal workflow.

The objective of this thesis was to find, test and assess effective solution for extracting linear features from point clouds that can be used for safety inspections, road documentation and more. The objective of the thesis was successfully achieved, as the semi-automated options significantly reduce the required human input and processing time, while providing at least as good, if not better, outputs. However, the semi-automated methods still require some human input, such as defining the starting point, direction and approximate information about the extracted features (such as curb height and lane marking points intensity range). In addition, all approaches require further verification of the exported data, so the overall difference between automated and semi-automated extraction is minimal. The difference between semi-automated and manual extraction is much more significant, as the time required for manual extraction increases linearly with the length of the section.

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Appendix A
Abbreviations List

a_c	■	Bike Lane
a_{ch}	■	Sidewalks
ALS	■	Airborne Laser Scanning
ASPRS	■	American Society for Photogrammetry and Remote Sensing
c_p	■	Parking Lane
CAD	■	Computer-Aided Drafting
DCC	■	Data Collection Category
DMI	■	Distance Measuring Instrument
GigE	■	Gigabit Ethernet
GNSS	■	Global Navigation Satellite System
GPS	■	Global Positioning System
IMU	■	Inertial Movement Unit
IP	■	Ingress Protection
ISPRS	■	International Society for Photogrammetry and Remote Sensing
LADAR	■	Laser Detection And Ranging
LiDAR	■	Light Detection And Ranging
MLS	■	Mobile Laser Scanning
MMS	■	Mobile Mapping Systems
Mpx	■	Megapixel
MTA	■	Multiple-Time-Around
NCHRP	■	National Cooperative Highway Research Program
RANSAC	■	Random Sample Consensus
RLWR	■	Robust Locally Weighted Regression
SLAM	■	Simultaneous Localisation and Mapping
SSD	■	Solid State Drive
TIN	■	Triangular Irregular Network
TLS	■	Terrestrial Laser Scanning
VCSEL	■	Vertical Cavity Surface Emitting Laser

Appendix B
SCC - Additional Data

B.1 SCC Assessment Procedure

Symbol “*” stands for the file name and symbol “#” stands for the feature class in the figure below.

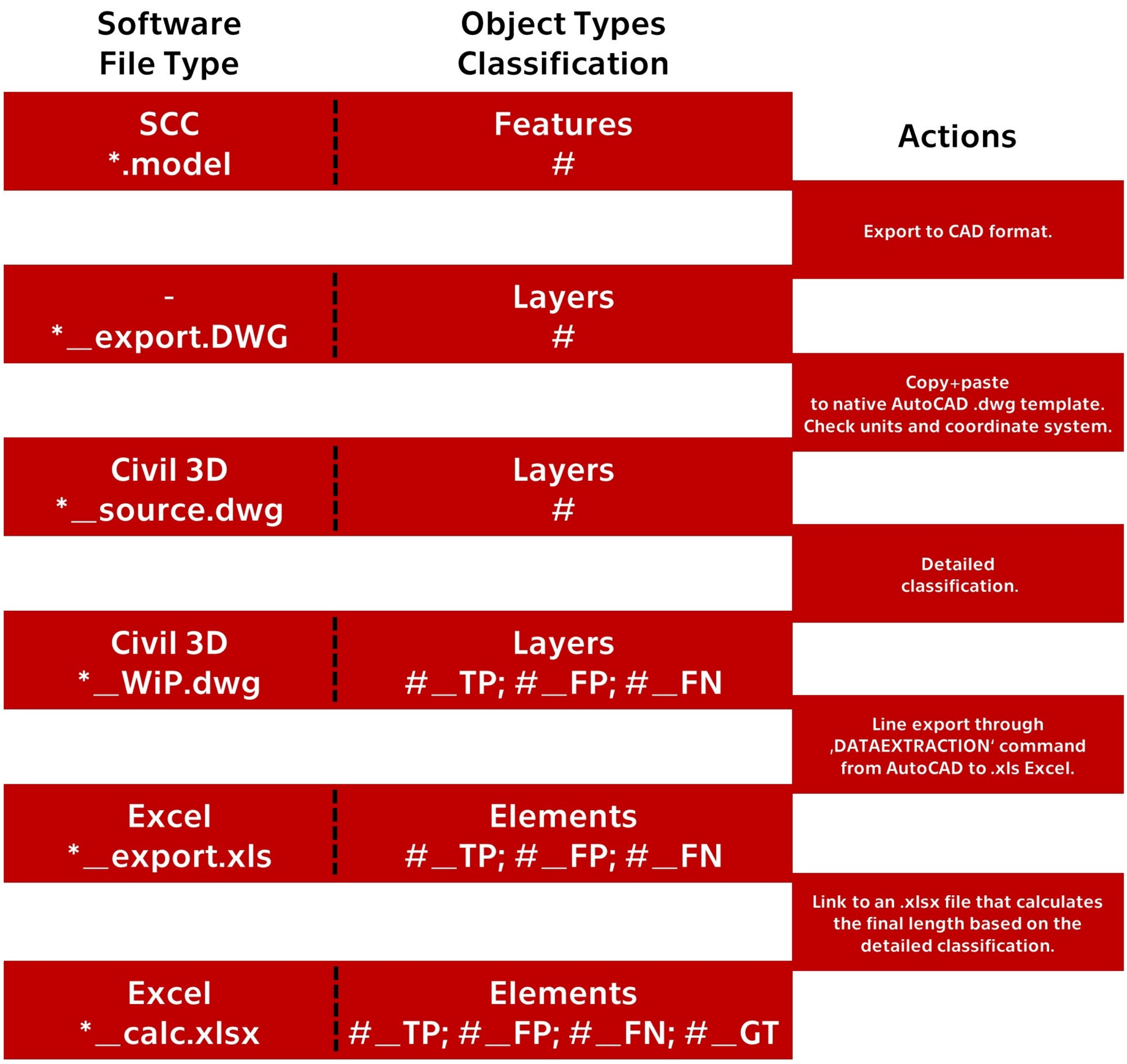

Figure B.1. SCC - Assessment Procedure

B.2 SCC Assessed Outputs

Table B.1. SCC - Final Length of Extraction in the Highway Sample

Feature Type		GT [m]	TP [m]	FP [m]	FN [m]
Road Marking	Edge Lines	4733.98	4738.98	0.00	0.00
	Center Lines	2389.20	2389.20	0.00	0.00
Pavement Edge	(Both Edges)	0.00	0.00	0.00	0.00
Guardrails	(Both Points)	3611.65	3456.79	0.00	154.86
Noise Barriers	(Both Points)	412.10	313.76	85.76	98.34

Table B.2. SCC - Calculated Metrics from the Highway Sample

Feature Type		Completeness [%]	Correctness [%]	Quality [%]
Road Marking	Edge Lines	100.00	100.00	100.00
	Center Lines	100.00	100.00	100.00
Pavement Edge	(Both Edges)	0.00	0.00	0.00
Guardrails	(Poth Points)	95.71	100.00	95.71
Noise Barriers	(Both Points)	76.14	78.54	63.02

Table B.3. SCC - Final Length of Extraction in the Urban Road Sample

Feature Type		GT [m]	TP [m]	FP [m]	FN [m]
Road Marking	Edge Lines	1654.00	1433.85	0.00	220.15
	Center Lines	862.92	736.21	0.00	126.71
Curbs	Top Edge	1661.63	1317.09	23.78	344.54
	Bottom Edge	1661.46	1316.91	23.76	344.54
Handrails	(Both Points)	59.08	56.33	0.00	2.75

Table B.4. SCC - Calculated Metrics from the Urban Road Sample

Feature Type		Completeness [%]	Correctness [%]	Quality [%]
Road Marking	Edge Lines	86.69	100.00	86.69
	Center Lines	85.32	96.34	85.32
Curbs	Top Edge	79.26	98.23	78.15
	Bottom Edge	79.26	98.23	78.15
Handrails	(Both Points)	95.35	100.00	95.35

Appendix C
^{n}4ce - Additional Data

C.1 ^{n}4ce Assessment Procedure

Symbol "*" stands for the file name and symbol "#" stands for the feature class in the figure below.

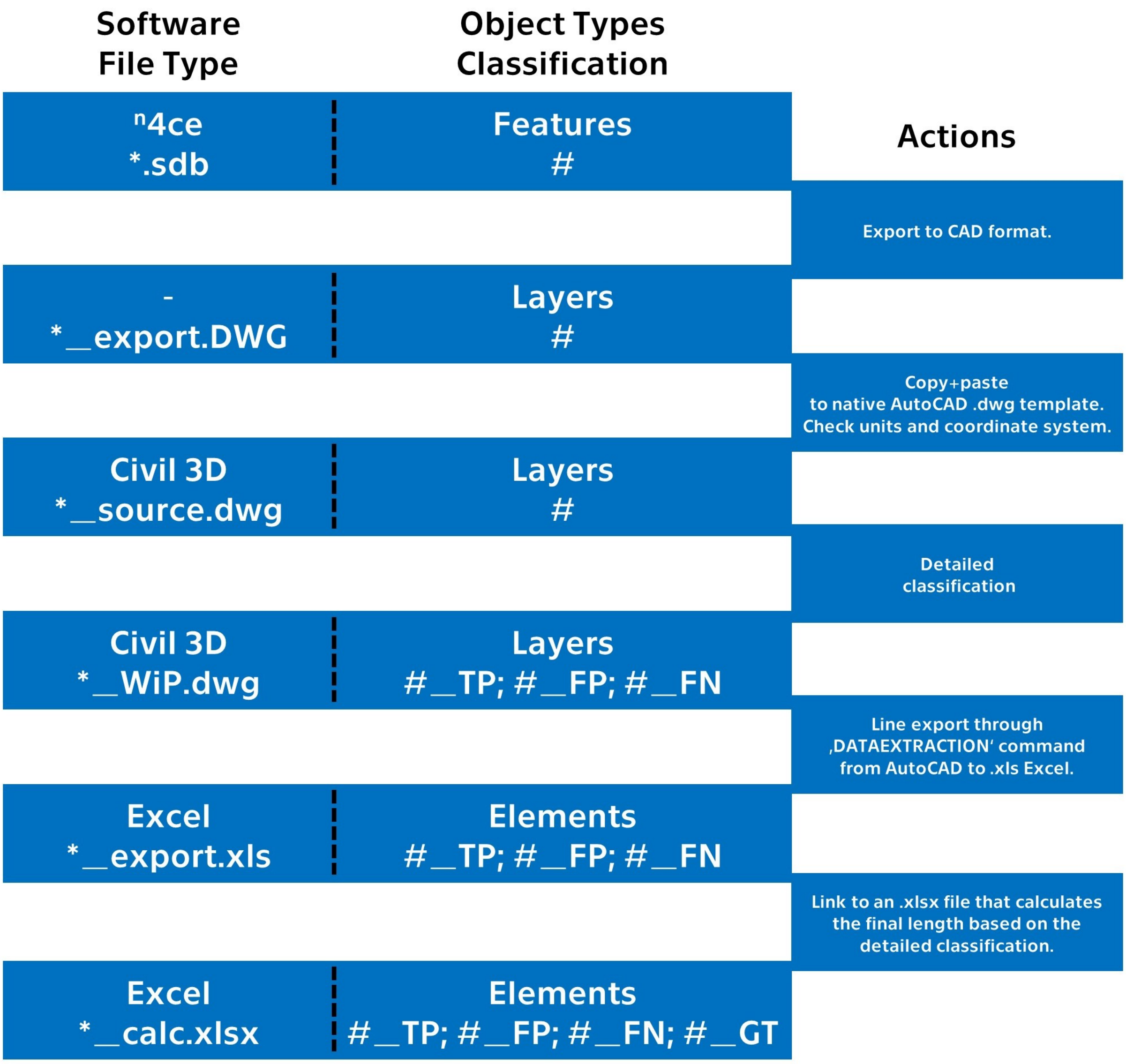

Figure C.2. ^{n}4ce - Assessment Procedure

C.2 ^{n}4ce Assessed Outputs

Table C.5. ^{n}4ce - Final Length of Extraction in the Highway Sample

Feature Type		GT [m]	TP [m]	FP [m]	FN [m]
Road Marking	Edge Lines	4714.69	4714.69	0.00	0.00
	Center Lines	2392.77	2392.77	0.00	0.00
Pavement Edge	(Both Edges)	0.00	0.00	0.00	0.00
Guardrails	(Both Points)	3594.51	3511.19	0.00	83.32
Noise Barriers	(Both Points)	410.67	266.74	0.00	143.93

Table C.6. ^{n}4ce - Calculated Metrics from the Highway Sample

Feature Type		Completeness [%]	Correctness [%]	Quality [%]
Road Marking	Edge Lines	100.00	100.00	100.00
	Center Lines	100.00	100.00	100.00
Pavement Edge	(Both Edges)	0.00	0.00	0.00
Guardrails	(Poth Points)	97.68	100.00	97.68
Noise Barriers	(Both Points)	64.95	100.00	64.95

Table C.7. ^{n}4ce - Final Length of Extraction in the Urban Road Sample

Feature Type		GT [m]	TP [m]	FP [m]	FN [m]
Road Marking	Edge Lines	1655.32	1639.71	0.00	15.61
	Center Lines	862.48	862.48	0.00	0.00
Curbs	Top Edge	1664.76	1556.55	0.00	108.22
	Bottom Edge	1667.01	1558.80	0.00	108.22
Handrails	(Both Points)	59.04	57.95	0.00	1.09

Table C.8. ^{n}4ce - Calculated Metrics from the Urban Road Sample

Feature Type		Completeness [%]	Correctness [%]	Quality [%]
Road Marking	Edge Lines	99.06	100.00	100
	Center Lines	100.00	100.00	100.00
Curbs	Top Edge	93.50	100.00	93.50
	Bottom Edge	93.51	100.00	93.51
Handrails	(Both Points)	98.15	100.00	98.15

Appendix D
TopoDOT - Additional Data

D.1 TopoDOT Assessment Procedure

Symbol "*" stands for the file name and symbol "#" stands for the feature class in the figure below.

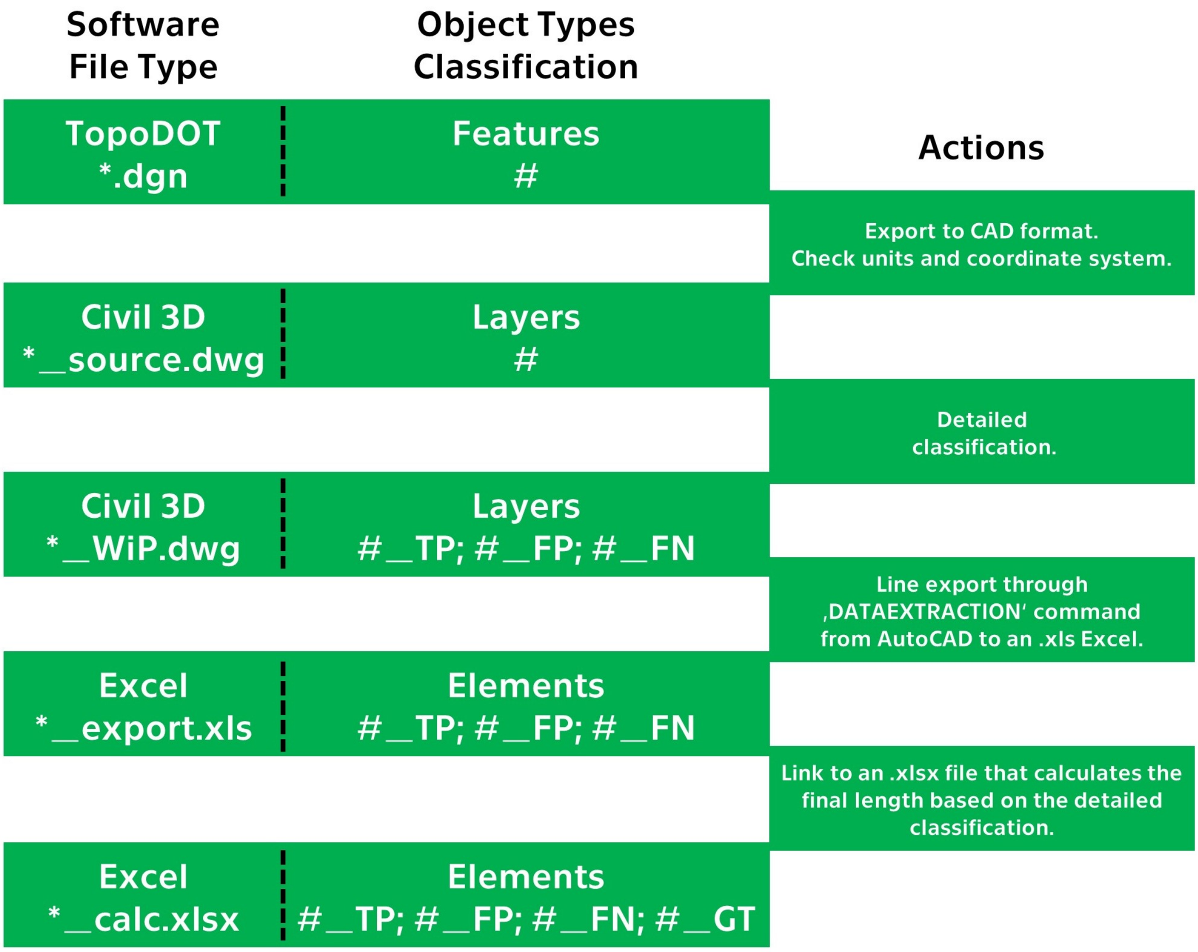

Figure D.3. TopoDOT - Assessment Procedure

D.2 TopoDOT Assessed Outputs

Table D.9. TopoDOT - Final Length of Extraction in the Highway Sample

Feature Type		GT [m]	TP [m]	FP [m]	FN [m]
Road Marking	Edge Lines	4720.12	4720.12	0.00	0.00
	Center Lines	2398.28	2398.28	0.00	0.00
Pavement Edge	(Both Edges)	4355.29	4355.29	0.00	0.00
Guardrails	(Both Points)	3602.85	3602.85	0.00	0.00
Noise Barriers	(Both Points)	410.70	0.00	0.00	0.00

Table D.10. TopoDOT - Calculated Metrics from the Highway Sample

Feature Type		Completeness [%]	Correctness [%]	Quality [%]
Road Marking	Edge Lines	100.00	100.00	100.00
	Center Lines	100.00	100.00	100.00
Pavement Edge	(Both Edges)	100.00	100.00	100.00
Guardrails	(Poth Points)	100.00	100.00	100.00
Noise Barriers	(Both Points)	100.00	100.00	100.00

Table D.11. TopoDOT - Final Length of Extraction in the Urban Road Sample

Feature Type		GT [m]	TP [m]	FP [m]	FN [m]
Road Marking	Edge Lines	1653.26	1653.26	0.00	0.00
	Center Lines	863.28	813.31	30.88	49.96
Curbs	Top Edge	1663.22	1619.73	0.00	43.49
	Bottom Edge	1665.75	1622.26	0.00	43.49
Handrails	(Both Points)	59.20	59.20	0.00	0.00

Table D.12. TopoDOT - Calculated Metrics from the Urban Road Sample

Feature Type		Completeness [%]	Correctness [%]	Quality [%]
Road Marking	Edge Lines	100.00	100.00	100.00
	Center Lines	94.21	96.34	90.96
Curbs	Top Edge	97.39	100.00	97.39
	Bottom Edge	97.39	100.00	97.39
Handrails	(Both Points)	100.00	100.00	100.00