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COMBINING MLS & ALS POINT CLOUD DATA

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The combination of Mobile Laser Scanning and Airborne Laser Scanning point cloud data at the municipality of Rotterdam

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ABSTRACT

LiDaR point clouds can serve a wide range of applications. Generally speaking, point clouds can be obtained in two ways: Mobile Laser Scanning (MLS) or Airborne Laser Scanning (ALS). However, for certain applications using one of these two techniques is not sufficient. For some applications, the resolution of ALS point clouds is not sufficient. A disadvantage of MLS is that its positioning accuracy decreases significantly in urban areas, because the GPS signal is blocked by buildings. Apart from that, ALS provides little information on building façades, while MLS provides little information on roof tops.

Therefore, the combination of ALS and MLS data offers interesting opportunities for new applications and the improvement of existing applications. In order to combine the two data sources, three operations have to be undertaken. The first step is to align the two point clouds. This process is also called registration. However, little is known about which of the known registration methods best suits the practical needs and applications of an organisation. The second operation is to integrate the two point clouds. Undoubtedly overlap of points will occur. It is important to decide which points are then removed, and which point cloud is regarded as ground truth. The third step is to make the data available in an accessible way.

The municipality of Rotterdam, especially the department of Basic Information, that manages the municipality’s geographic information, is interested in point clouds developments and have an ALS point cloud of the city obtained every two years. They have also done two MLS pilots. This research focuses on finding out which point cloud combination methods suit the applications of the municipality the best.

Two groups of point cloud users are identified: advanced users and basic users. These two groups are involved in a wide range of applications of point cloud data. Advanced users actively use point cloud data themselves and greatly benefit from the added value of a combined ALS-MLS point cloud. Advanced users would like to have full control over their point cloud data. On the other hand, basic users would benefit more if the data was made available to them in a more simplified form. This research proves that a combination of Airborne Laser Scanning and Mobile Laser Scanning data is of great added value.

PREFACE

Before you lies the Master's thesis "Combining MLS & ALS point cloud data". The research set out to investigate how mobile laser scanning data and airborne laser scanning data should be combined, in order to be of added value for the municipality of Rotterdam. This thesis has been written to fulfil the graduation requirements of the Master of Science programme "Geographical Information Management & Applications" of the University of Utrecht, Technical University of Delft, Wageningen University & Research and ITC faculty of the University of Twente.

The research took place from September 2018 to March 2019 at the municipality of Rotterdam. The research has not always been a smooth ride, but in the end it has given me valuable insight in the activities at the municipality of Rotterdam and in the world of laser scanning. Laser scanning is a very valuable technology that brings the worlds of surveying, civil engineering and geo-information.

I would to thank four groups of people for assisting me in my research. Firstly I would like to thank my parents and my friends, who have helped with their motivating words. Secondly I wish to thank all of my respondents at the municipality of Rotterdam, who gave me valuable answers. Thirdly: thank you Alexander Boersema for welcoming me at the municipality. I would also like to thank my supervisor Dennis Franken for sharing his knowledge and experience on mobile laser scanning and my supervisor Michiel Boelhouwer for sharing his knowledge and experience on airborne laser scanning. Lastly I would like to thank Edward Verbree and Peter van Oosterom for the insightful discussions with them and the feedback I received from them.

I hope you enjoy reading!

Derek van Bochove

Rotterdam, February 28th, 2019

LIST OF FIGURES

LIST OF ABBREVIATIONS

2D	_Two-**d**imensional_
3D	_Three-**d**imensional_
AHN	_**A**ctueel **H**oogtebestand **N**ederland (Current DEM of the Netherlands)_
ALS	_**A**irborne **L**aser **S**canning_
ASPRS	_**A**merican **S**ociety for **P**hotogrammetry and **R**emote **S**ensing_
BAG	_**B**asisregistraties **A**dressen en **G**ebouwen (Key registry buildings and addresses)_
BGT	_**B**asisregistratie **G**rootschalige **T**opografie (Key registry large scale topography)_
BIM	_**B**uilding **I**nformation **M**odel_
CCD	_**C**harge-**c**oupled **d**evice (digital camera)_
CityGML	_**City** **G**eography **M**arkup **L**anguage (for 3D models)_
EDL	_**E**ye **D**ome **L**ighting_
FME	_**F**eature **M**anipulation **E**ngine_
GCP	_**G**round **C**ontrol **P**oint_
GDOP	_**G**eometric **D**ilution of **P**recision_
GIMA	_**G**eographical **I**nformation **M**anagement and **A**pplications_
GIS	_**G**eographic **I**nformation **S**ystem(s)_ or _**G**eographic **I**nformation **S**cience_
GNSS	_**G**lobal **N**avigation **S**atellite **S**ystem_
GPS	_**G**lobal **P**ositioning **S**ystem_
GPU	_**G**raphical **P**rocessing **U**nit_
ICP	_**I**terative **C**losest **P**oint algorithm_
IMU	_**I**nertial **M**easurement **U**nit_
LAS	_**Las**er file format for lidar point data_
LiDaR	_**Li**ght **D**etection **a**nd **R**anging_
LOD	_**L**evel **o**f **D**etail_
MLS	_**M**obile **L**aser **S**canning_
MMS	_**M**obile **M**apping **S**ystem_
MSc.	_**M**aster of **Sc**ience_
NCC	_**N**ormalised **C**ross **C**orrelation_
RGB	_**R**ed, **G**reen and **B**lue_
RANSAC	_**Ra**ndom **Sa**mple **C**onsensus_
TLS	_**T**errestrial **L**aser **S**canning_
UAV	_**U**nmanned **A**erial **V**ehicle_
WCS	_**W**eb **C**overage **S**ervice_
WebGL	_**W**eb **G**raphics **L**ibrary_
WFS	_**W**eb **F**eature **S**ervice_
WOZ	_**W**aardering **O**nroerende **Z**aken (Valuation of immovable property)_

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1. INTRODUCTION

In this chapter, the research will be introduced. Firstly, in Section 1.1, the context will be given. Secondly, in Section 1.2 the underlying motivation for this thesis will be explained. Thirdly in Section 1.3, the problem statement will be given and finally in Section 1.4 the scientific and societal relevance will be discussed.

1.1 CONTEXT

In recent years there has been more attention for three-dimensional geographical information, or 3D geo-information in short. This development has not gone unnoticed within the city of Rotterdam, which has led them to decide to develop a detailed 3D model of the city. The team GIS & Consulting, of the department of Basic Information of the municipality of Rotterdam is one of the leaders in this development.

There are several ways to obtain 3D geo-information, one of which is by using Light Detection and Ranging (LiDaR). LiDaR is a laser scanner, which, in the case of Rotterdam, was attached to a plane. This method is called Airborne Laser Scanning (ALS), of which the output is a point cloud, a 3D representation of the measured points in space. However, a drawback of Airborne Laser Scanning is that for some applications, the output's resolution is not high enough. ALS point clouds also usually contain little information on the ground level. This concerns mainly building facades, that are of course omnipresent in a city like Rotterdam.

Another method to use LiDaR to collect point clouds is called Mobile Laser Scanning (MLS). Instead of being attached to a plane, the laser scanner is attached to a ground vehicle. As opposed to ALS point clouds, MLS point clouds generally have a higher resolution. They also have a lot of information on building facades. However, MLS point clouds often suffer from poor positional accuracy because the measuring vehicle's GPS signals are blocked by buildings.

The use of point cloud data within an organisation such as the municipality of Rotterdam is a topic that has been researched rarely. On top of that, this research is unique because the combination of ALS and MLS has also been very underexposed.

1.2 MOTIVATION

The City of Rotterdam has an ALS dataset that covers its entire territory. However, for certain applications, the ALS point cloud's resolution and perspective may not be suitable. For these kinds of applications, a combination with MLS point clouds would provide a good solution. The first reason is perspective: the ground perspective of MLS and aerial perspective of ALS are complementary. The second reason is resolution: MLS point clouds have a higher point density than ALS point clouds, which allows them to show more detail. The third reason is positional accuracy. The positional accuracy of urban MLS point clouds is relatively poor, because GPS signals often are blocked by buildings, but this issue could be corrected by using ALS point clouds. For these reasons, the combination of ALS and MLS point cloud data could offer very interesting opportunities.

However, combination, or in other words, integration of the two data sources is not an easy assignment. The aforementioned different perspectives, different resolutions and difference in positional accuracy also cause challenges. There are many different methods to combine the data, each with its own advantages and disadvantages. The city of Rotterdam will most likely have specific needs for the eventual combined output. Thus, not every combination method is suitable for Rotterdam.

In order to combine two point clouds, there are two major steps. The first step is two bring the point clouds in a common coordinate frame. This process is also known as registration. The second step concerns the integration of the data. When combining two point clouds, the issue of duplicate points arises, because the point clouds have overlap. It is then the question which of the duplicate points will be ignored. So far, a lot of research has been done on different registration methods. However, little is known about the practical application and the mentioned combination issues.

1.3 PROBLEM STATEMENT

For a lot of applications ALS point cloud data is not suitable, or better results can be achieved with MLS data. The combination of ALS and MLS point cloud data offers interesting opportunities because the complementing features of ALS and MLS. However it is unknown which combination method is the most suitable for the city of Rotterdam, considering their data and their needs.

1.4 RELEVANCE

The relevance of this research can be divided in scientific relevance and societal relevance.

Considering scientific relevance, this research aims to fill in the knowledge gap about the practical application of the combination of ALS and MLS data. A lot has already been written about point cloud registration. However, the research has mostly focused on improving the geometric accuracy of the results, while there is little knowledge on which method and workflow best suits the data and needs of a real-world organisation, such as the municipality of Rotterdam. There is also little knowledge on the integration and supplying of the combination of ALS and MLS data. Issues arise, such as how to deal with duplicate points that will definitely appear, how to deal with a varying point density within one point cloud and how to ultimately offer the combined data to the end user, in a way that suits their activities. Therefore, this thesis focuses on the combination of ALS and MLS point clouds, aimed to suit the applications and purpose of point clouds that the municipality of Rotterdam has in mind.

This being said, the scientific relevance corresponds with the societal relevance. This research can be very useful for the municipality of Rotterdam. While this organisation already has a lot of knowledge of and practical experience with GIS in a broad sense and point clouds in particular, this research can contribute to that. An earlier pilot with MLS data has shown that before assigning a specialised company to collect MLS data, the specific purpose of the data should be known beforehand. Experts have also underlined this. This research therefore aims to increase the municipality's knowledge on point clouds, in order to give them a better position when they publish a tender for the collection of MLS data.

Lastly, the research will increase the municipality's knowledge on the combination of MLS and ALS data, in order to open up possibilities for new applications and to make current applications more efficient. With this knowledge, they can ultimately increase the level of detail of their 3D model. New fields of applications can open up for the municipality, because by using MLS data, the point density will increase, which will facilitate the identification of more objects. They will also be able to do analysis faster and with more recent data.

2. RESEARCH OBJECTIVES

In this chapter, firstly the research objectives will be discussed. Secondly, the research questions will be provided and lastly the research scope will be discussed.

The main objective of this research is to find out which considerations there are when combining Airborne Laser Scanning and Mobile Laser Scanning point cloud data, and to find out what the best way to do this is for the municipality of Rotterdam. Combination in regard to point clouds can mean two things: 1) simultaneous utilisation of ALS and MLS point clouds and 2) the combination of two point clouds, in this case an MLS and an ALS point cloud, to create one integrated point cloud. Both versions are discussed in this research.

The main objective is subdivided into three sub objectives. These are the following:

- Create an overview of considerations when combining ALS and MLS data
- Find out the needs of the municipality of Rotterdam regarding the combination of ALS and MLS point clouds
- Assess which of the available methods suits the needs and the data of the municipality of Rotterdam the best

2.1 RESEARCH QUESTIONS

The research questions are designed to be in line with the research objectives. The main research question for this thesis is the following:

Which way to combine Airborne Laser Scanning and Mobile Laser Scanning point clouds suits the municipality of Rotterdam the best?

The main question is subdivided into three sub questions:

1. Which methods to combine Mobile Laser Scanning data and Airborne Laser Scanning data are known in the scientific literature?
2. What possible applications of the combination of Mobile Laser Scanning data and Airborne Laser Scanning data exist within the municipality of Rotterdam?
3. What is the best way to combine Mobile Laser Scanning data and Airborne Laser Scanning data for the municipality of Rotterdam?

The first sub question tries to find an answer to the question which methods to combine ALS and MLS data there are available. The second sub question will investigate what possible applications there are for the combination of MLS and ALS point clouds within the organisation of the municipality of Rotterdam. The possible applications are based on the needs of the organisation. The third sub question will integrate the answers from the first and second sub questions. This means that from the overview of methods that was the result of the first sub question, the best method will be determined. This method will be based on the possible applications within the municipality (sub question 2).

2.2 RESEARCH SCOPE

So far, many challenges that could be faced when working with Mobile Laser Scanning and Airborne Laser Scanning data have been discussed. However, there are also many new interesting possibilities to be explored. Nonetheless, it is important to limit the scope of this research. This is mainly due to time constraints, but also because the research should not focus on too many issues, in order to be valuable. Therefore, the scope of this research will be identified in this section.

The goal of this research is to investigate how mobile laser scanning data can be combined with airborne laser scanning data. This combination should be done in a way that suits the applications of the municipality. While many previous research has focused on the accuracy of the results of point cloud registration, this research will focus more on the practical application of registration and combination. To ultimately do this, there are several steps to be taken. These steps together form the scope of this research. The first step is a literature review on methods to combine MLS and ALS data. This begins with the registration of the point clouds, and ends with the visualisation of the point clouds. The second step is to find out what the needs of the municipality are, regarding the combination. The last step combines the knowledge of the first two steps and consists of advising the municipality what to do.

Apart from point clouds that are obtained using laser scans, it is also possible to generate point clouds based on photogrammetric imagery. It was specifically chosen to work with point clouds based on laser scans, instead of point clouds based on photogrammetry. There are two reasons for this choice. The first reason is that the municipality has a good laser point cloud dataset available. There is no point cloud dataset available that is based on photogrammetry that has a comparable scale and quality. Additionally, generating a point cloud based on photogrammetry is too time-consuming to include in the time planning of this research. The second reason why photogrammetry is not included in the scope of this thesis, is that LiDaR point clouds are generally of better quality than photogrammetric point clouds. Therefore, photogrammetric point clouds are not included in the scope of this research.

Lastly, the research does not focus on terrestrial laser scanning data (TLS). TLS data is obtained with a static laser scanning, while MLS data is obtained using a moving laser scanner. Because of its static nature, TLS data has a better positional accuracy and a higher point density. However, the spatial resolution of MLS data is far better. MLS is capable of scanning a larger area in a shorter amount of time. MLS is more efficient. Therefore, terrestrial laser scanning is considered outside the scope.

3. LIDAR POINT CLOUDS

There are several methods to generate point clouds. Usually these methods fall in two categories: using LiDaR or using photogrammetry. For a lot of purposes, such as detailed 3D city modelling, LiDaR is preferred, because it is more accurate and less prone to errors (GIM International, 2018).

LiDaR is a surveying method that emits laser beams to measure the surroundings of the scanner. By measuring the return time and strength of the reflections of the beams, the distance to the reflected surfaces is calculated. By combining this with the scan angle, for each reflection point the position is calculated, resulting in x, y, z coordinates. This results in a 3D point cloud, with points representing the positionss of the reflecting surfaces. In Figure 3.1, an example of a LiDaR system is shown, with a drawing showing its different components. This particular system, the Velodyne HDL-64E, has a rotating unit with eight groups of eight laser emitters (64 emitters in total) and two groups of 32 laser receivers (64 receivers in total).

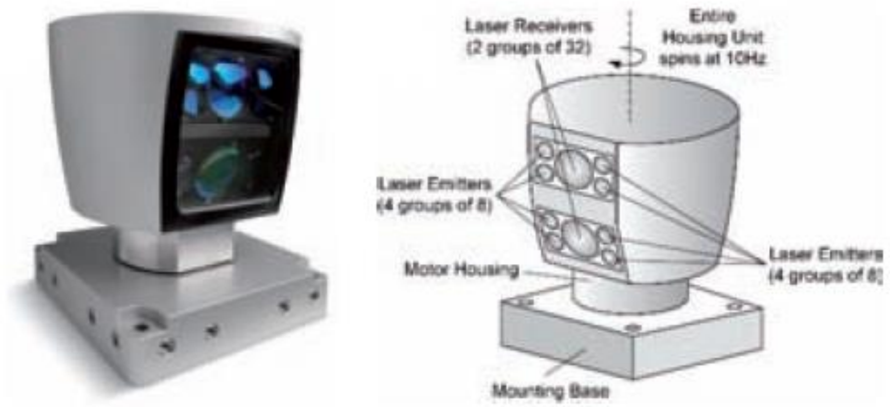


Figure 3.1: On the left an example of a LiDaR system: the Velodyne HDL-64E (source: Velodyne). On the right a drawing showing the main features of the HDL-64E rotating laser scanner. It has multiple laser rangefinders (drawn by Mike Shand) (Petrie, 2010)

3.1 POINT CLOUD DATA FORMATS

The most common file format for point cloud data is the LAS file format, which is the de facto standard. For each point a LAS file can store information about the x, y, z position, intensity, number of returns, RGB values, classification, GPS time and scan angle (ASPRS, 2011). Because LAS files tend to be very large, the LAZ (LASzip) file format was developed, which is a compressed version of the LAS file (Isenburg, 2013).

3.2 QUALITY OF POINT CLOUDS

The quality of a point cloud dataset is usually determined by two properties. The first property is the absolute accuracy of the point cloud and the second property is the relative accuracy of the point cloud. The relative accuracy is related to the resolution of the point cloud.

The accuracy is the level of conformity of a measured distance with the distance in reality. The accuracy says something about the offset of an individual point within an imaginary sphere. In other words: the accuracy represents the possible offset between measured position of a point and the actual position of a point (PelserHartman, 2016). A division is made between absolute accuracy and relative accuracy.

Absolute accuracy concerns the shift of points relative to the real-world (absolute) position. It is determined by the quality of the positioning systems on board the scanning platform and the geometrical position of the satellites (Kukko, Kaartinen, Hyyppä, & Chen, 2012). The geometric position of satellites compared to each other is measured as Geometric Dilution of Precision (GDOP). The lower this value, the more accurate the positional accuracy of the satellites (Langley, 1999). The availability of a satellite signal is also of influence on the absolute accuracy. This can especially be problematic in the case of mobile laser scanning in urban areas, where satellite signals are obstructed by concrete buildings. This is the reason that usually ALS data has a better absolute accuracy than MLS data.

Relative accuracy concerns the shift of points relative to each other. The relative accuracy can be influenced by different factors. Firstly, the object that is measured is of influence because certain materials are less visible because of their colour, structure, transparency or level of reflection. Secondly, the environment can be of influence. Rainfall and fog can cause the laser beam to deviate. And lastly, the instruments that are used are of influence. It depends of course on the quality of an measuring instrument, but also on the scanning frequency, the speed of the scanning platform (e.g. vehicle or airplane) and the scanning distance to the target (Kukko et al., 2012). However, an internal compensator, such as an Inertial Measurement Unit (IMU), can compensate for shifts (PelserHartman, 2016). When the distance to the target decreases, the relative accuracy decreases as well, because the laser footprint increases as the distance to the target increases. This is due to laser beam divergence (Puttonen et al., 2013). The laser beam divergence is also the reason that MLS usually has better relative accuracy than ALS data. The relative accuracy is related to the resolution of a point cloud. The resolution can also be expressed as point density, which is usually measured as number of points per square meter. The higher the point density, the higher is the data's level of detail. However, having more points is not better in every case. A point cloud with a lot of points that was obtained with a lower quality instrument will most probably contain a lot of noise. Noise is formed by points that are spread out, but should be within the same surface (PelserHartman, 2016).

Generally speaking, there are two categories of methods of obtaining point clouds using LiDaR. The first method is called Airborne Laser Scanning (ALS), and was used to make the 3D model of the city of Rotterdam. The second method is called Mobile Laser Scanning (MLS). The next two sections will dive deeper into these two methods.

3.3 AIRBORNE LASER SCANNING

Airborne Laser Scanning uses a LiDaR scanner that is attached to an airborne vehicle, such as a airplane, a helicopter or an Unmanned Aerial Vehicle (UAV). It acquires mostly points from rooftops and object surfaces (Teo & Huang, 2014).

In comparison with mobile laser scanning, ALS data provides an overview of locations that are inaccessible for mobile laser scanning platforms. In most cases mobile laser scanners are attached to cars, which means that for instance backyards are outside of the scanning range. A major drawback of this method however, is the limited resolution of the resulting point clouds. The limited resolution is caused by a limited number of points per square meter, which in turn is caused by the speed of the plane and distance to the ground. Another disadvantage is that building façades are not clearly visible (Yang, Zang, Dong, & Huang, 2015).

ALS data is quite difficult to acquire. There are multiple factors of influence. In order to collect the data a plane, equipped with lidar sensors, has to fly. Not only are planes and LiDaR instruments expensive, weather conditions can also hinder air traffic. Apart from that, the Dutch airspace is quite busy, which makes obtaining a flight slot difficult.

3.4 MOBILE LASER SCANNING

In recent years, interest in mobile mapping systems (MMS) has increased. Mobile mapping is conducted as a vehicle moves, while a navigation system tracks the vehicle's movement and scanners or cameras capture the vehicle's surroundings. Mobile Laser Scanning is an approach that uses a LiDaR scanner that is attached to a vehicle to capture point cloud datasets. This vehicle is usually a car (Petrie, 2010), but there are also examples of the use of a trolley, a boat, a backpack (Kukko et al., 2012) or a train (S. Zhang, Wang, Yang, Chen, & Li, 2016). An MLS system always consists of three elements: a positioning system, a laser system and digital imaging devices. In Figure 3.2, an overview of a Mobile Laser Scanning system is shown.

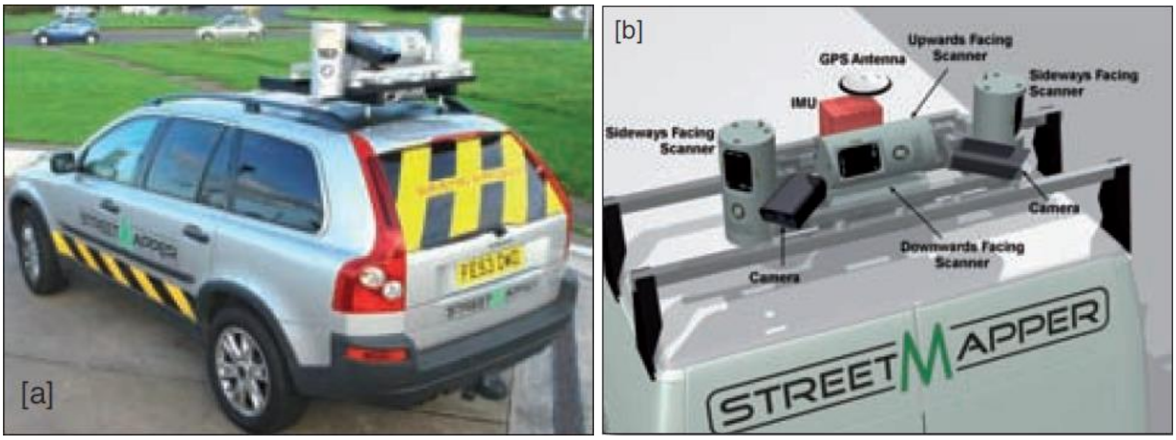


Figure 3.2: overview of a Mobile Laser Scanning system. [a]: Streetmapper vehicle with MLS attached to the roof. [b] The MLS itself, showing the locations of the LiDaR scanners, GPS, IMU and camera's. Source: 3D Laser Mapping (Petrie, 2010)

To determine the vehicle's position, usually a number of Global Navigation Satellite Systems (GNSS) is used. An example of a GNSS is the worldwide Global Positioning System (GPS). Because the GPS's accuracy is restricted due its dependence upon satellites, usually the GNSS works in combination with an Internal Measurement Unit (IMU). An IMU calculates its position based on the displacement from an initial known position (Levi & Judd, 1996).

Compared to ALS point clouds, MLS point clouds have a much higher resolution, because of their better point density. Therefore, MLS can greatly improve the precision of the collected data. MLS is attractive for specific tasks because its sensor lay out can easily be adjusted, and mobilization is relatively easy (Kukko et al., 2012). MLS point clouds are also for many applications cheaper than airborne solutions (S. Zhang et al., 2016). This mainly depends on the scale and goal of the application. An example of an MLS dataset is shown in Figure 3.3.

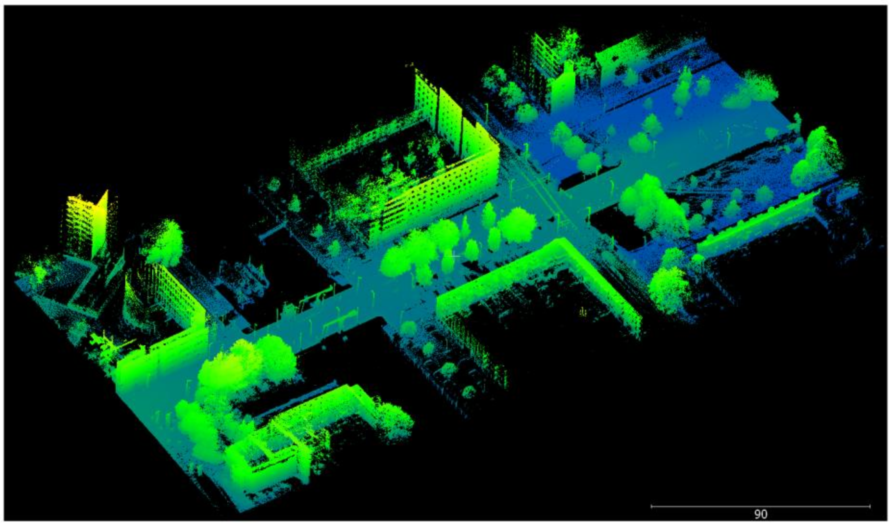


Figure 3.3: an example of an MLS point cloud (Murali, 2018)

However, a major drawback of this method is the fact that its accuracy is highly dependent on the performance of the vehicle's positioning. Especially in a city such as Rotterdam, large and high concrete buildings, metal objects and other radio waves can block the GNSS signal or cause the signal to reflect. This is visualised in Figure 3.4.

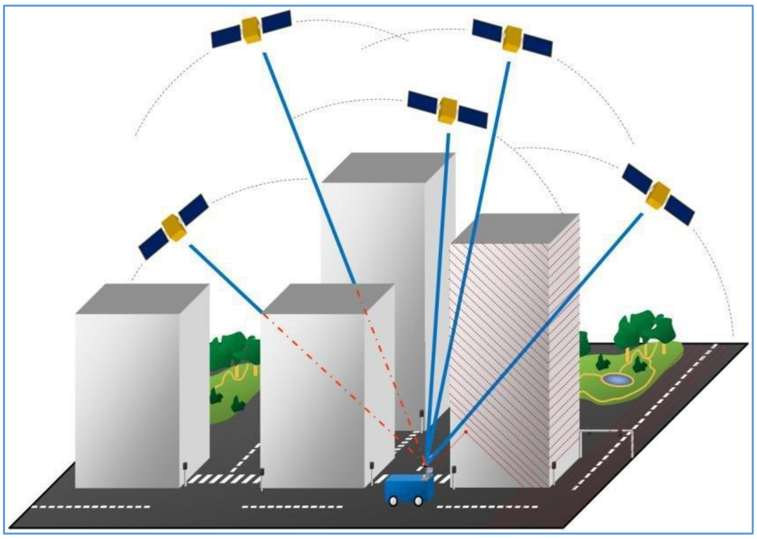


Figure 3.4: Blockage of GNSS signal in urban areas (Kukko et al., 2012)

Even with the help of an IMU the accuracy is often still not sufficient. Speed bumps may cause strong vibration, which has a bad influence on the IMU's accuracy (Peng, Zhi, Wang, Liu, & Zhang, 2014). Methods to overcome this problem are well-known, such as manually identifying Ground Control Points, but these are time-consuming and labour-intensive (Javanmardi, Javanmardi, Gu, & Kamijo, 2017). Therefore, the positioning of the output data is a major challenge.

3.5 APPLICATIONS OF AIRBORNE LASER SCANNING DATA AND MOBILE LASER SCANNING DATA

Airborne Laser Scanning data have been applied in all sorts of domains. A very notable example is elevation modelling. When compared to photogrammetry, ALS achieves a 5 to 10 times better elevation model accuracy. Other advantages are a higher grade of automation and lower costs (Virtanen et al., 2017). Other examples include forestry (Hyyppä et al., 2012) and city modelling (Nebiker, Bleisch, & Christen, 2010).

Mobile Laser Scanning data as well have been used for a large variety of applications, for instance: building modelling (Zhu, Hyyppä, Kukko, Kaartinen, & Chen, 2011), archaeology (Vozikis, Haring, Vozikis, Kraus, & Greece, 2004), geomorphology (Alho et al., 2011), outdoor mapping (Petrie, 2010), road inventory studies (Pu, Rutzinger, Vosselman, & Oude Elberink, 2011), topography changes (Vaaja et al., 2011) and extracting street furniture (Lim & Suter, 2009; Ordóñez, Cabo, & Sanz-Ablanedo, 2017). A last possible application of combined ALS and MLS data is visibility analysis.

3.6 COMBINATION OF AIRBORNE LASER SCANNING DATA AND MOBILE LASER SCANNING DATA

ALS and MLS datasets can complement each other. There are multiple reasons why the combination of ALS and MLS datasets is interesting.

The first reason is that ALS data has a lower level of detail compared to MLS data. Being hundreds of meters away from the objects that are captured, the resolution of ALS data could be at meter or decimetre level (Cheng, Tong, Wu, Chen, & Li, 2015).

The second reason is that ALS data provides information about buildings' rooftops, while MLS data provides information about buildings' facades (Teo & Huang, 2014). ALS point clouds are obtained from the air, and thus contain a lot of (roof)top information, but on the other hand, the façade and side information of objects is limited. MLS point clouds however, are obtained from the ground, and therefore contain a lot of façade information, while top information is usually missing (Cheng, Tong, et al., 2015). This is also shown in Figure 3.5-Figure 3.8. As seen, when ALS and MLS data are compared, ALS has more roof top information, while MLS has more façade information. The two datasets have ground information in common. It was shown already very early that the combination of ALS and MLS can be very useful for generating detailed 3D scenes (Iavarone & Vagners, 2003).

ALS

Figure 3.5: ALS: more roof top information of the Noordereiland (source: own work / Gemeente Rotterdam)

Figure 3.6: ALS: little façade information of the Noordereiland (source: own work / Gemeente Rotterdam)

MLS

Figure 3.7: MLS: little roof top information of the Noordereiland (source: own work / Gemeente Rotterdam)

Figure 3.8: MLS: more façade information of the Noordereiland (source: own work / Gemeente Rotterdam)

Furthermore, several studies have already shown that aerial data can be used to improve the quality of ground data (Javanmardi et al., 2017). By doing this, a combined point cloud with a high position accuracy, a high level of detail and a complete coverage could be created. Some authors argue that, considering the disadvantages and advantages of both MLS and ALS, the integration of these two sources has become inevitable (Heritage & Large, 2009).

Airborne laser scanning and mobile laser scanning can complement each other. To support this statement, in Table 3.1 ALS and MLS are compared on various aspects.

Table 3.1: Pros and cons of ALS versus MLS point cloud data

	ALS	**MLS**
Point of view	Top view	Side view
Spatial resolution	Relatively low	Relatively high
Positioning accuracy	Relatively high	Relatively low

3.7 APPLICATIONS OF THE COMBINATION OF AIRBORNE LASER SCANNING DATA AND MOBILE LASER SCANNING DATA

There are a lot of potential applications for the combination of airborne and mobile laser scanning data. Until recently, point clouds have been solely regarded as source for more simplified products, such as rasters or 3D models (Verbree & Van Oosterom, 2015). For the municipality of Rotterdam it is true that current 3D efforts mainly focus on CityGML models, and that the use of point clouds themselves is very limited. Within the organisation point clouds are available however, among derivative raster files and CityGML 3D models. Verbree and Van Oosterom (2015) mention that the use of point clouds is limited partially because of their enormous file size. While mass data storage and software capabilities have become more efficient in the last few years, this could remain an issue. Apart from this, specialised software and knowledge is also necessary to work with point clouds. In the last few years, there have been developments that contribute to a more effective use of point clouds. The first one is that computer power is increasing. This is in support of both better techniques for the analysis, data management and also visualisation of point clouds. As opposed to CityGML 3D models, point clouds have the advantage that they can be collected faster and do not require processing time to create 3D polygon meshes. More importantly, a point cloud is closer to reality than derivative products, such as a 3D polygon mesh. The point cloud is a 1-on-1 representation of the reality at the time of recording and not a simplification. Therefore, there are several future applications of combined point clouds to be explored.

A promising application is change detection. Change detection concerns the automatic detection of changes happening both in public space and private space, and is done using multi-temporal point clouds. Examples in the public space include detection of backyards that are illegally expanded into the public space, street furniture and road surfaces. Examples in the private space include detection of illegally built backyard sheds or dormers. Change detection on a small scale using either solely ALS or solely MLS datasets is already quite common (Rieg et al., 2014). However, a disadvantage of the sole use of ALS, is that these datasets are collected relatively infrequently, because they tend to be very expensive and difficult to collect. Thus, because ALS datasets are not recent, changes that are detected might have changed again in the meantime. MLS datasets can be used instead, because MLS data is cheaper and faster to collect. MLS can for instance be used for the change detection of trees. A study was done using an MLS dataset of Rotterdam, that showed that the growth and pruning of trees can successfully be (semi-automatically) detected (Xiao, Xu, Oude Elberink, & Vosselman, 2012). A disadvantage of the sole use of MLS datasets for change detection, is that information is only available for the street level. A combination of MLS and ALS data could overcome these challenges. ALS and MLS from different moments in time could be compared to each other. It is expected that in the coming years, change detection can be performed on a larger scale (Virtanen et al., 2017). This kind of application could also play a role in informing the public about, for instance, construction projects. By combining different datasets from different moments, a time-lapse animation could be created, that can be used to give the public an overview of the construction progress.

Another application concerns increasing the level of detail of building facades. While ALS contains little information on facades, MLS data does. It has already been shown many years ago that superimposing TLS data on 3D models can improve the level of detail of facades, with low costs. The TLS data was used to increase the level of detail from LOD1 to LOD3 (Böhm, 2005). It is believed that MLS data can yield the same results. A dense MLS point cloud in combination with ALS data or 3D meshes can produce very realistic images. However coarse polygon meshes as opposed to detailed polygon meshes will stay important, because for certain applications, a high level of detail is not required. Sometimes only basic features, such as the plain roof or wall surface are required (Böhm & Haala, 2005).

The modelling of tunnels and underpasses is also a possible application. The ALS point cloud does not contain any information of tunnels, underpasses or the space below a bridge. The MLS point cloud could be used to provide information about these locations, or to enhance the 3D model of the city.

Furthermore, a possible application is the inventory of the state of roads. This includes road furniture and road surface. The inventory of the state of roads could make use of techniques like automatic segmentation of pole-like objects and the earlier mentioned automatic segmentation of trees. There are multiple methods for the segmentation and classification of pole-like objects, for instance using different algorithms (Ordóñez et al., 2017) or using a so-called knowledge-based feature recognition method (Pu et al., 2011). Both methods use MLS data, but an approach that combines ALS and MLS data could yield better results. Road inventory can be performed for both safety analysis and maintenance purposes, in order to save a lot of valuable time.

A major innovation that is related to the already mentioned road inventory and change detection is a further automation of updating topographic information. Work has been done on updating information on rivers using MLS (Vaaja et al., 2011). This approach uses a scanning platform that is attached on a boat and is focused on rivers, but in practice it can be used for all topography change mapping. A combination of MLS and ALS data is promising, because an MLS dataset can be obtained much faster and more frequent than an ALS dataset. The combination would allow for more up-to-date topographic and partial updating of the ALS dataset. For instance, when a new building is being built that is not included on maps yet, an MLS survey can be performed to include the new building on an earlier ALS dataset.

Apart from complete integration of ALS and MLS datasets, partial integration is also possible. For instance, the ALS dataset can be enriched with the more detailed trees from MLS data. The trees, or other objects, would first be extracted from the MLS dataset and then be added to the ALS dataset. The combination could improve the level of detail of 3D models.

A last application is noise removal assisted by a combination of ALS and MLS datasets. Point cloud data often contains a lot of unwanted noise, such as cars. Cars are unwanted because they tend to move (and are thus partially shown) and not needed for the point cloud’s application. Algorithms could be developed that detect whether a car-shaped object is present in one of the two datasets. If there is no overlap, then the car is removed.

In conclusion on this section, the combination of ALS and MLS data has the ability to create visual 3D models that can be gradually extended, enhanced and enriched, in order to ultimately create a so-called rich point cloud or smart point cloud (Poux, Hallot, Neuville, & Billen, 2016). This model will be able to support more applications, will have better coverage, will have a higher degree of realism and will be more up-to-date than ever before (Nebiker et al., 2010).

4. METHODOLOGY

In this chapter, the methodology for this research will be discussed. In Section 4.1, the research approach will be discussed, including the conceptual model. In Section **Fout! Verwijzingsbron niet gevonden.**, the research methods will be discussed: the data collection and data analysis.

4.1 RESEARCH APPROACH

The strategy for this research consists of a qualitative approach. The approach consists of a theoretical part and a practical part, and a third part in which the first and second part are linked together.

For each research objective, a specific research approach was chosen. The first objective of the research is to create an overview of the considerations when combining ALS and MLS data. In order to address this objective, a literature review is conducted, that results in an overview of combination methods. The second objective is to find out the needs of the municipality regarding the combination of ALS and MLS point cloud data. The method to address this objective is conducting interviews. The third and last objective is to assess which of the available methods for combination is the best for the municipality of Rotterdam. This objective is based on the needs and the data and is addressed with the third research question, concerning the best way to combine MLS and ALS data. The findings are based on an integration of the literature review and interviews. The literature review provides all available methods, and using the findings of the interviews, the best available method for the municipality of Rotterdam is found.

Table 4.1 summarises the research objectives, research questions and their corresponding research methods.

Table 4.1: Overview of research methods per research question and objective

Objective	Research question	Research method
Create an overview of considerations when combining ALS and MLS data	Which methods to combine MLS and ALS data are known in the scientific literature?	Literature review
Find out the needs of the municipality of Rotterdam regarding the combination of ALS and MLS point clouds	What possible applications of the combination of MLS and ALS data exist within the municipality of Rotterdam?	Interviews
Assess which of the available methods suits the needs and the data of the municipality of Rotterdam the best	What is the best way to combine MLS and ALS data for the municipality of Rotterdam?	Integration of literature review and interviews

In Figure 4.1, the conceptual model for this research is shown.

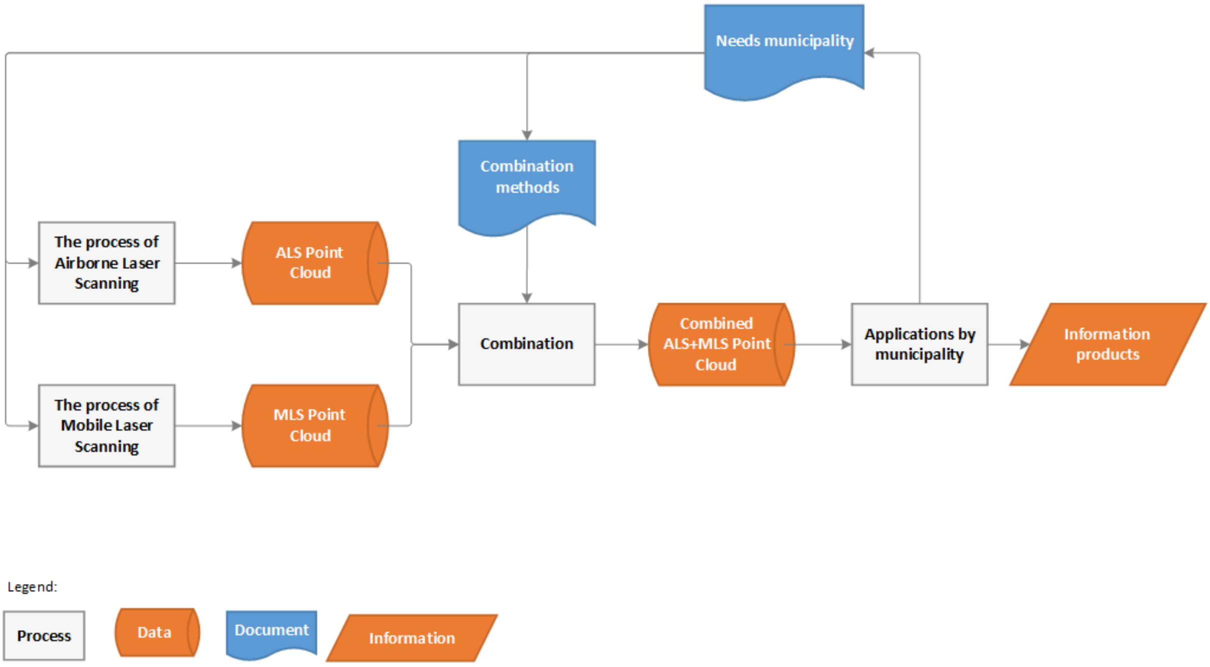


Figure 4.1: Conceptual model

The research methodology consists of two parts. The first part is the data collection and the second part is the data analysis.

4.2 DATA COLLECTION

As already mentioned, a literature review was performed and interviews were conducted. Data collection is the most important part of the research.

4.2.1 LITERATURE REVIEW

The literature review was performed using the snowball method. Articles were initially found using relevant keywords. Subsequently, other relevant articles were found through the articles that were already found, via the reference list.

4.2.2 INTERVIEWS

The interviews were conducted using a semi-structured approach. Respondents were asked about possible applications of combined MLS and ALS datasets within the municipality of Rotterdam.

RESPONDENTS

Respondents were found inside and outside the municipality of Rotterdam. The respondents are advisors, experts or engineers who work with point cloud data for their main duties. The list of respondents was formed with the help of the network of the researcher's supervisors at the municipality. Among the respondents are:

- 3D engineers/modellers at the municipality's engineering office
- Project managers
- Surveyors
- BAG/WOZ process managers
- Managers

Initially, the idea was to only interview users of point clouds. However, it turned out that this resulted in a very narrow view. It was then decided to interview more respondents. These would not necessarily use point clouds. Involving more people resulted in a broader overview and less one-sided.

TOPIC LIST

A key element of the semi-structured approach is the topic list. The topic list consisted of questions, that form the structure of the interview. The word "semi" points out that the conversation can flow freely without the need to stick a strict order of questions. This allowed the respondent to elaborate more on a certain topic. When the respondent talked about a theme that is relevant for the research, but was not included in the structured topic-list, the structure of the interview automatically changed. The interviewer would then drop the topic list for a while and ask the respondent about the newly introduced theme. The use of a semi-structured topic list also allowed to include probing questions. The function of probing is to motivate the respondent to tell more about the subject, and give more detailed answers.

Since the topics that are discussed during the interviews are often practical, these are often better expressed in a visual way, rather than exclusively via text or verbally. Therefore, interactivity was an important part of the interviews. Images of point cloud visualisations were used to support the questions in the topic list. These are shown in Figure 4.2, Figure 4.3 and Figure 4.4. Figure 4.2 shows combination of MLS and ALS data, Figure 4.3 shows the different perspectives of ALS and MLS and Figure 4.4 shows the effect of different point densities. During the interviews, respondents were also encouraged to share examples of their work. These examples include 3D datasets and screenshots of 3D software and 3D data.

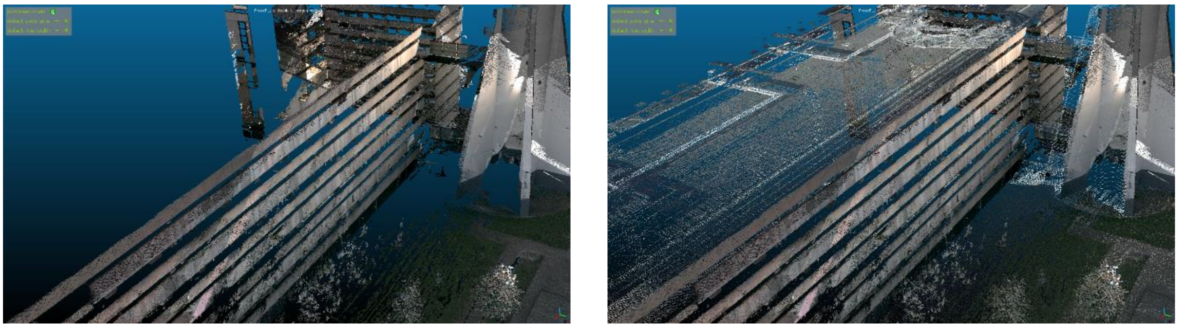


Figure 4.2: Examples of point cloud combination, used in the interviews. On the left only MLS data, on the right ALS and MLS data combined

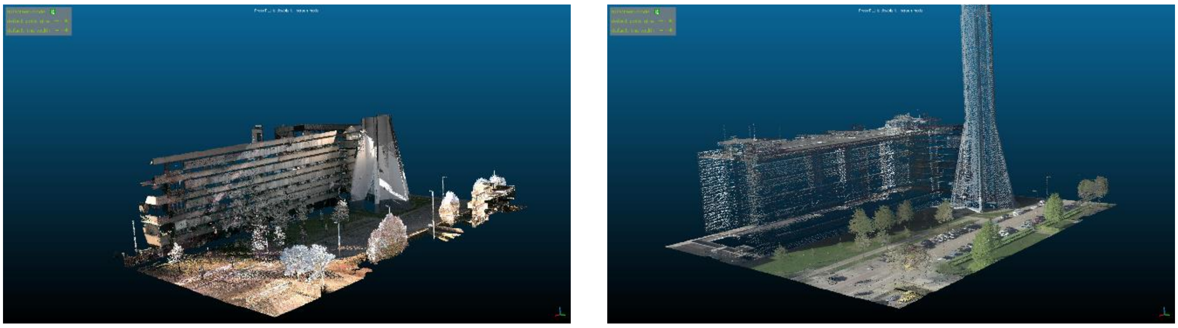


Figure 4.3: Examples of point clouds, used in the interviews. On the left only MLS data, on the right only ALS data.

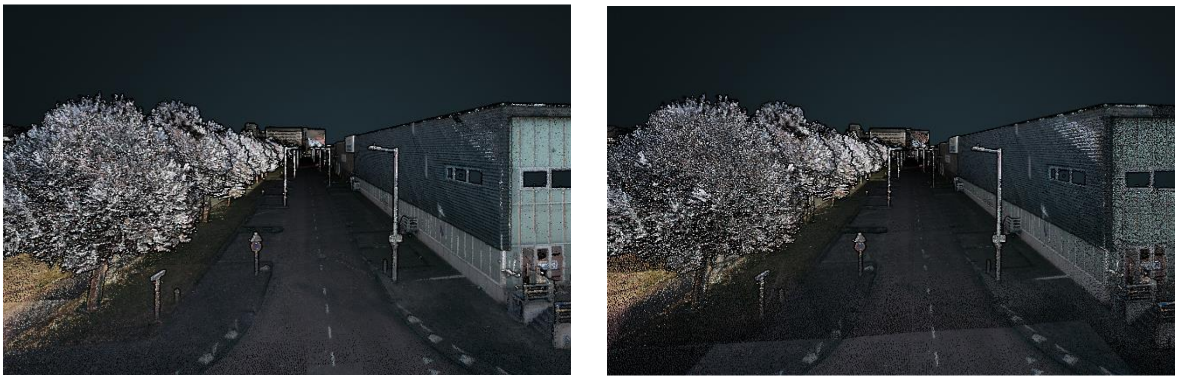


Figure 4.4: Examples of point density, used in the interviews. On the left a high point density, on the right a low point density

The interviews were recorded, for which the respondents gave their full consent. The recordings were used for the transcription of the interviews, in combination with written notes, taken during the interviews. The transcripts were used for the data analysis.

In Appendix 12.1, the topic list can be found.

4.3 DATA ANALYSIS

Data analysis consisted of three steps: literature analysis, interview analysis and an integrated analysis of the results of the literature review and the interview results.

4.3.1 LITERATURE ANALYSIS

The literature review consisted of an overview of combination methods, and therefore did not need any advanced data analysis methods.

4.3.2 INTERVIEW ANALYSIS

The results of the interviews were analysed in multiple steps. The first step was transcribing the interviews. Transcribing means that literal text versions of the interviews were produced. The second step consisted of re-reading the interviews. This way, the researcher gets more familiar with the topics that were discussed during the interviews. The third step consisted of coding the interviews. Coding means that everything that is said during the interviews is categorised. Using these categorisations, an analysis can be made which applications are mentioned the most. Analysis is the fourth step. Using these as themes, per theme the different opinions of each respondent are compared. This comparison is the fifth step and also forms the final result of the analysis.

4.3.3 INTEGRATED ANALYSIS

The interview results were integrated with the findings of the literature review. The findings of the interviews consist of possible applications, and the requirements of these applications to the combination method. This information is used to find the best suitable combination method among the results of the literature review.

5. SOFTWARE AND DATA

In this chapter, the software and data that will be used for this research will be discussed. In Section 5.1, the research area will be discussed. Section 5.2 will discuss the visualisation software, Section 5.3 will discuss the processing software and Section 5.4 will discuss the datasets that will be used.

At the moment, the usage of open source software is on the rise. However, the municipality’s IT and legal department are supposedly not too happy with this development because of liability concerns. For this reason and because of limited graphical processing capabilities, most point cloud analyses are done on stand-alone desktop computers or laptops.

5.1 RESEARCH AREA

As the result of this research will be used by the municipality of Rotterdam, it is only logical that the study area is Rotterdam. Rotterdam is the second biggest city of the Netherlands, with approximately 640.000 inhabitants (Statistics Netherlands, 2018).

Both ALS and MLS datasets, situated within the study area, will be used. There is an ALS dataset for the complete area of the municipality, which is shown in Figure 5.1. There are MLS datasets available for two areas. The first area is the Noordereiland, which is an island with mainly housing in the river Maas, in between the southern and the northern part of the city. The second area is the Waalhaven business park, situated next to the Waalhaven port in the south of the city. These two areas and their location within the city are shown in Figure 5.2.

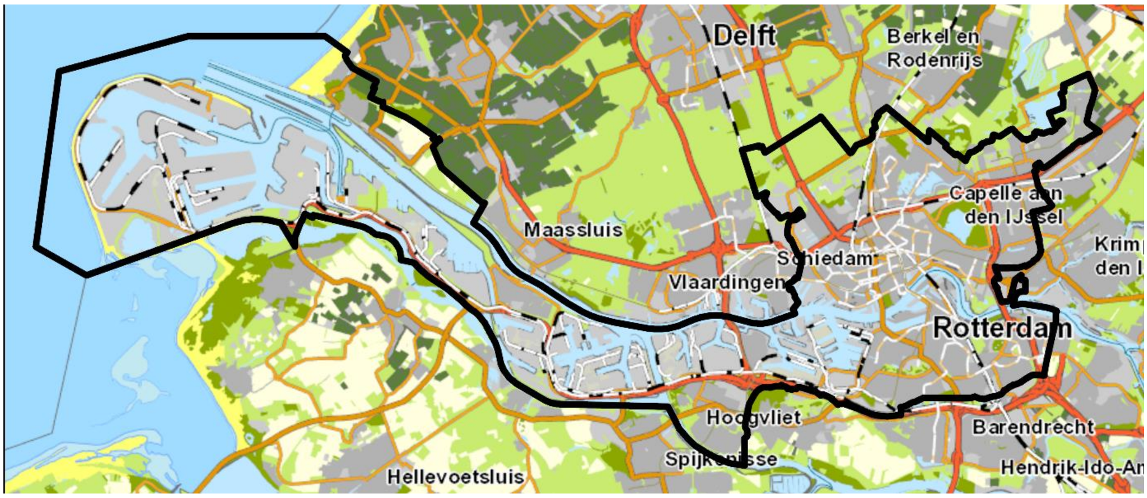


Figure 5.1: Complete area of the municipality (source: TOP10NL / own work)

Figure 5.2: Study area for the MLS datasets (source: TOP10NL / own work)

5.2 VISUALISATION SOFTWARE

In this section, several software products for point cloud visualisation will be discussed. Processing is not possible with this software, so these products will mainly be used as reference or for visual inspection. Their relevance for this research will also be discussed. These are the following:

- Potree (Section 5.2.1)
- Plas.io (Section 5.2.2)

5.2.1 POTREE

Potree is a web-based point cloud renderer, based on WebGL technology (Schuetz, 2016), that can be used to visualise point clouds in a web browser. It is free and open source, and is being developed at the Institute of Computer Graphics and Algorithms at the TU Wien (Potree, 2018). Some of Potree's possibilities are:

- Visualisation of multiple point clouds in one viewer
- Visualisation of point clouds together with shapefiles, lines, polygons, animations
- Change the visualised size of points
- Change the visualised point density
- Do measurements
- Use different navigation methods and camera projections
- Change lighting settings
- Use different classification filters

Both the Pointer platform and the AHN2 point cloud viewer (http://ahn2.pointclouds.nl/) use Potree's visualisation engine, with some slight modifications. The AHN2 point cloud viewer was developed in 2013-2015 at the TU Delft with several partners, in order to visualise the AHN2 point cloud dataset. This point cloud dataset is the input for the Digital Surface Model (DSM) that spans the entire country of the Netherlands.

WEBGL

WebGL is a variation of OpenGL (Open Graphics Library), which allows web pages to use GPU (Graphical Processing Unit) rendering capabilities, on a wide variety of devices, such as desktop PCs, laptops and mobile phones. WebGL allows Potree to use hardware acceleration, for faster rendering on devices with a better GPU. One important aspect of WebGL is Eye dome lighting (EDL). EDL is a method that creates illuminated surfaces and outlines along silhouettes, which helps to perceive objects. Another feature to increase the visual quality is splatting. Splatting is the use of squares and circles with depth, instead of primitive points (Schuetz, 2016).

VISUALISATION PARAMETERS

The visualisation parameters that can be changed in the Potree viewers are shown in Table 5.1.

Table 5.1: Potree visualisation parameters

Visualisation parameter	Explanation
Point budget	The maximum number of points shown at a time (in millions)
EDL	Eye dome lighting on or off
EDL radius	The radius of the eye dome lighting
EDL strength	The strength of the eye dome lighting
Splat quality	Standard or high quality of the splats
Min. node size	The minimum size of the splats

USAGE WITHIN THE MUNICIPALITY OF ROTTERDAM

Within the municipality, Potree itself is not used. However, it is used as foundation for the Pointer platform that is used within the organisation.

USAGE FOR THIS RESEARCH

For this research Potree could be used for small visual comparisons.

5.2.2 PLAS.IO

Plas.io is also a web-based point cloud renderer. It supports both LAS and LAZ files. It is free and open source and developed by Uday Verma and Howard Butler (Plas.io, 2019). Some of its functionalities are:

- Change the visualised point density
- Use different navigation options
- Do measurements
- Use different colorisations

Its main advantage, as opposed to Potree, is that there is no need to set up anything when the user wants to view a particular LAS dataset. Datasets can just be dragged and dropped into the Plas.io viewer. Just like Potree, Plas.io is based on WebGL (Plas.io, 2018).

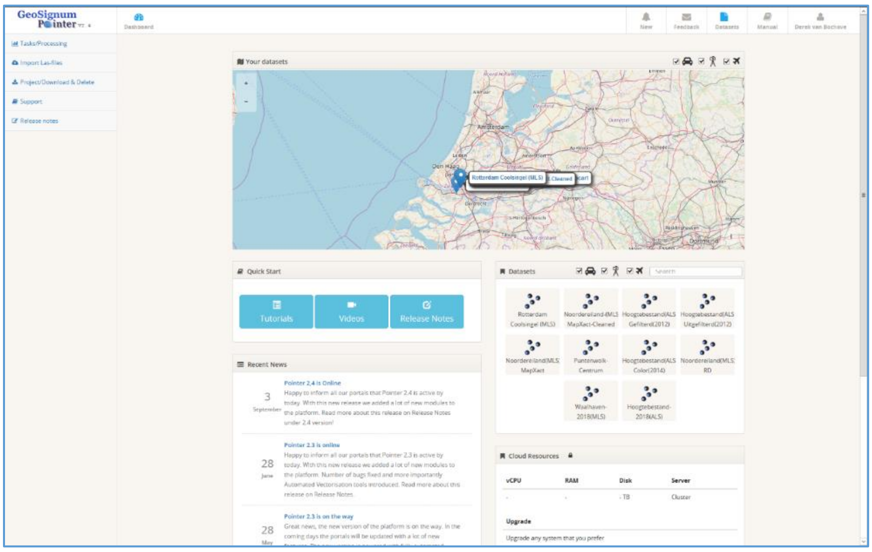
5.3 PROCESSING SOFTWARE

In this section, point cloud processing software will be discussed. These software packages can be used for the processing of point cloud datasets and for the registration of datasets. Their relevance for the research will also be discussed. These software products are the following:

- GeoSignum pointer (Section 5.3.1)
- CloudCompare (Section 5.3.2)
- FME (Section 5.3.3)
- LAStools (Section 5.3.4)

5.3.1 GEOSIGNUM POINTER

The municipality of Rotterdam uses the so-called “Pointer” web-platform. This is a Software as a Service (SaaS) that works in a web browser, and was developed by GeoSignum B.V. The current version is 2.5. It can be accessed through https://rotterdam.pointer.cloud/ with an account. A screenshot is shown in Figure 5.3.



3 September

Pointer 2.4 is Online

Happy to inform all our portals that Pointer 2.4 is active by today. With this new release we added a lot of new modules to the platform. Read more about this release on Release Notes under 2.4 version!

28 June

Pointer 2.3 is online

Happy to inform all our portals that Pointer 2.3 is active by today. With this new release we added a lot of new modules to the platform. Number of bugs fixed and more importantly Automated Vectorisation tools introduced. Read more about this release on Release Notes.

28 May

Pointer 2.3 is on the way

Great news, the new version of the platform is on the way. In the coming days the portals will be updated with a lot of new

vCPU	RAM	Disk	Server
-	-	- TB	Cluster

Upgrade

Upgrade any system that you prefer

Figure 5.3: Screenshot of Pointer’s dashboard (source: GeoSignum / own work)

Some of its possibilities are the following:

- Hosting of LiDaR data
- 3D point cloud visualisation, based on Potree
- Exporting to LAS file
- Overlay of 2 different point clouds to check differences
- Measurement tools
- Automatic extraction of features
- Automatic classification of features
- Automatic noise filtering (GeoSignum, 2018)

A new version (2.6) is expected to be released in February 2019. This new version will likely also contain a registration feature (Personal communication, 2018).

An interesting feature is the possibility to overlay different point cloud datasets. At the moment this functionality can only be used for visual inspections and only with two datasets that have already been separately registered. This is shown in Figure 5.4: Overlay of ALS and MLS point clouds in Pointer (source: Gemeente Rotterdam / own work). In this figure, the Waalhaven 2018 MLS dataset is combined with the Rotterdam Hoogtebestand 2018 ALS dataset.


Figure 5.4: Overlay of ALS and MLS point clouds in Pointer (source: Gemeente Rotterdam / own work)

VISUALISATION PARAMETERS

The visualisation engine of Pointer is based on the Potree point cloud renderer. There are several parameters that can be modified, in order to change the visualisation in Pointer. These are shown in Table 5.2.

Table 5.2: Pointer visualisation parameters

Visualisation parameter	Explanation
Points (m)	The maximum number of points shown at a time (in millions)
Point size	The size of the points shown
Opacity	The opacity of the points shown
Material	The colour of the points: RGB (taken from ortophoto), colour, depth, height (classification)
EDL	Eye dome lighting on or off
Visible	Make the point cloud visible or not
Clip mode	Unknown
Dataset overlay	Choose another dataset as overlay, its colour, point size and opacity

USAGE WITHIN THE MUNICIPALITY OF ROTTERDAM

Within the GIS & Consulting Team of the municipality’s Basic Information department and within the municipality’s engineering office, the Pointer platform is used by several people, in order to automatically extract features, visualise point cloud data and run tests.

USAGE FOR THIS RESEARCH

For this research, the Pointer platform can be used for visual inspections, obtaining the data, testing registration methods (using the upcoming functionality), pre-processing and automatically detecting features.

5.3.2 CLOUDCOMPARE

CloudCompare is an open source 3D point cloud processing software package. It was originally developed in 2003 to detect changes between point clouds, but evolved towards a more general and advanced 3D data processing software. The current stable version is 2.9.1. It is able to handle many file formats.

Some of its functionalities are:

- Registration (for instance ICP)
- Distance computation
- Statistics computation
- Segmentation
- Geometric features estimation (CloudCompare, 2018)

CloudCompare is also able to display multiple point clouds at once. This is shown in Figure 5.5, with the same objects as in Figure 5.4.

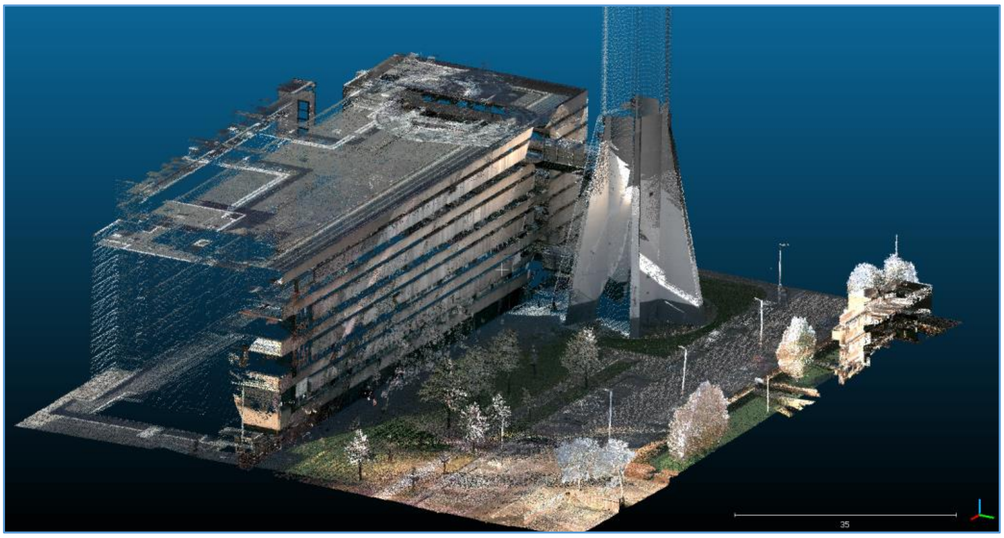


Figure 5.5: Overlay of different point clouds in CloudCompare (source: Gemeente Rotterdam / own work)

USAGE WITHIN THE MUNICIPALITY OF ROTTERDAM

At the moment, CloudCompare is used at the municipality fairly often to run tests and analysis on a small scale. However, it is not available within the municipality's network environment, and is thus used on stand-alone laptops.

USAGE FOR THIS RESEARCH

CloudCompare could be used to do direct registration of point clouds with its built-in feature. CloudCompare could also be used to inspect results.

5.3.3 FME

FME (Feature Manipulation Engine) is a so-called ETL (Extract, Transform and Load) application, developed by Canadian software company Safe Software. It was first published in 1994. It can handle almost any GIS file format. Its main component is the Workbench, which has 3 components: Readers, Transformers and Writers. These can be used convert from one file format to another or to do certain analyses (Safe Software, 2018). Some useful point cloud transformers are:

- PointCloudCoercer
- PointCloudCombiner
- PointCloudStatisticsCalculator
- PointCloudThinner
- PointCloudMerger
- PointCloudSplitter
- PointCloudSimplifier

An example of an analysis in FME is shown in Figure 5.6: two point cloud LAS files are combined into one LAS file.

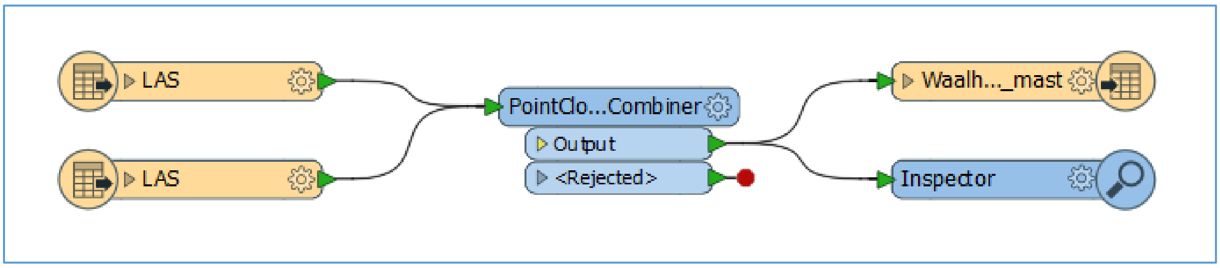


Figure 5.6: Example of an FME workspace in which two point clouds are combined into one LAS file (source: own work)

USAGE WITHIN THE MUNICIPALITY OF ROTTERDAM

Within the Basic information department of the municipality of Rotterdam, FME is used for several processes and analyses. However, for analysis and processing of point clouds, it is not being used.

USAGE FOR THIS RESEARCH

It is unclear whether FME could be used for the registration of point clouds. It can however be used to combine two point clouds into one point cloud, and small tests could be done with this. However, it does not have direct registration tool or transformer. FME can be used for the inspection of point clouds and test results.

5.3.4 LASTOOLS

LAStools is a software package, consisting of large amount of separate applications specialised in processing LiDaR data. These are both available as GUI or command-line tool. It is developed by Martin Isenburg of the company rapidlasso GmbH, and its first version came out in 2007. The current version is 181119. According to their website, the program is “a collection of highly efficient, batch-scriptable, multicore command line tools” (rapidlasso GmbH, 2018).

Some of its functionalities are:

- Compress LAS files
- Raw data geocoding
- Calibration and strip adjustment
- Model adjustment and ground control
- Classification
- Point cloud thinning

- Point cloud clipping
- DEM creation

USAGE WITHIN THE MUNICIPALITY OF ROTTERDAM
At the moment, the paid version of LAStools is sometimes used at the municipality of Rotterdam on stand-alone laptops.

USAGE FOR THIS RESEARCH
LAStools can be used point cloud thinning, which makes it essential for the combination of point clouds.

5.4 DATA

In this section, the datasets that this research focuses on will be discussed. In Section 5.4.1, the Airborne Laser Scanning dataset, the "Hoogtebestand Rotterdam", will be discussed. In Section 5.4.2, the MLS datasets will be discussed.

5.4.1 AIRBORNE LASER SCANNING DATASET

The Airborne Laser Scanning Point Cloud that will be used is the Hoogtebestand Rotterdam 2018. This is a LiDaR point cloud that was acquired in 2018. It is acquired once every two years, of which the first time was in 2008. The Hoogtebestand Rotterdam is comparable to the Actueel Hoogtebestand Nederland (AHN). However, the Hoogtebestand Rotterdam differs in multiple aspects from the AHN.

The first aspect is that the Hoogtebestand has a higher point density. The Hoogtebestand Rotterdam has an average point density of 15 points per meter in the port area and 30 points per meter in the urban area, while the AHN dataset has an average point density between 6 and 10 points per meter. The visual implications of this difference are shown in Figure 5.7 and Figure 5.8.

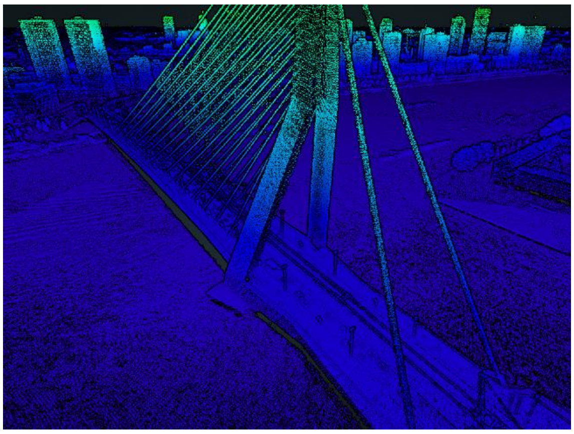


Figure 5.7: Erasmusbrug in Hoogtebestand Rotterdam point cloud (source: Gemeente Rotterdam own work)

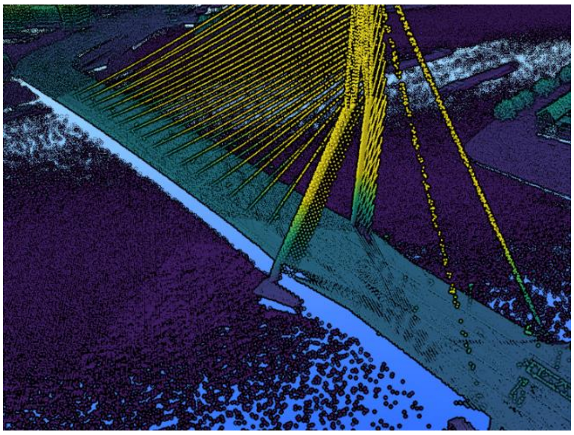


Figure 5.8: Erasmusbrug in AHN2 point cloud (source: AHN / own work)

On the left the Erasmusbrug, a famous landmark in Rotterdam, is shown in the Hoogtebestand Rotterdam point cloud, that was collected in 2018. On the right the Erasmusbrug is shown in the AHN2 point cloud, that was collected in 2008-2012. The same visualisation parameters were used in both visualisations, which are shown in Table 5.3.

Table 5.3: Visualisation parameters used for Figure 5.7 and Figure 5.8

Visualisation parameter	Setting

Number of points	10
Point size	0.5
Color by	height
EDL	Yes

The second aspect is that the Hoogtebestand is more recent. While the AHN is not collected in a set frequency, the Hoogtebestand Rotterdam is collected once every two years. The last version of the Hoogtebestand is from 2018, which makes it far more recent than the AHN.

The third and last aspect is that the Hoogtebestand Rotterdam is limited to the territory of the municipality of Rotterdam, while the AHN covers all of the Netherlands.

The AHN dataset did not suit the municipality's requirements, and therefore they decided to collect their own dataset. Especially the higher point density and the fact that the data is more recent, make the dataset more useful for the municipality's analyses.

The extent of the dataset is shown in Figure 5.9. The outline corresponds to the municipality's borders.

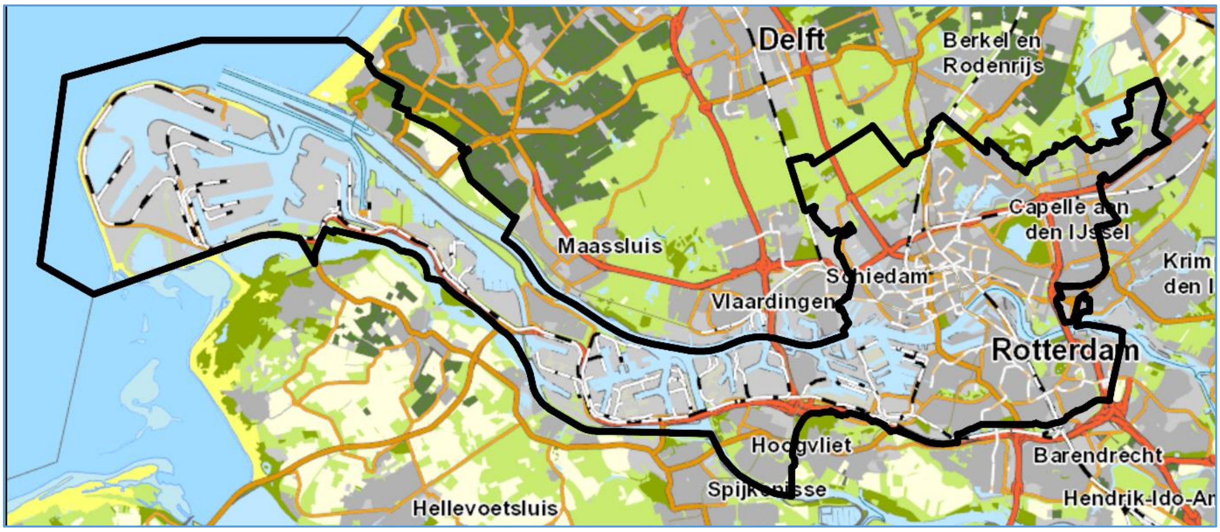


Figure 5.9: Extent of Hoogtebestand Rotterdam 2018 point cloud dataset (source: TOP10NL / own work)

In Figure 5.10, a top-down view of the point cloud itself is shown.

Figure 5.10: Top-down view of Hoogtebestand Rotterdam 2018 point cloud dataset (source: Gemeente Rotterdam / own work)

An extensive quality audit has been carried out. In Figure 5.11, the point density is shown. The point density is calculated as points per square meter. The area was divided in grid cells of 1 by 1 meter. The municipality demanded that for the port area, at least 95% of the cells should have a point density of 15 points per m^2. For the living areas, at least 95% of the cells should have a point density of 30 points per m^2. Water is excluded. It was concluded that in the port area 97.12% of the cells had a density > 15 pt/m^2 and in the living area 97.47% of the cells had a density > 30 pt/m^2.

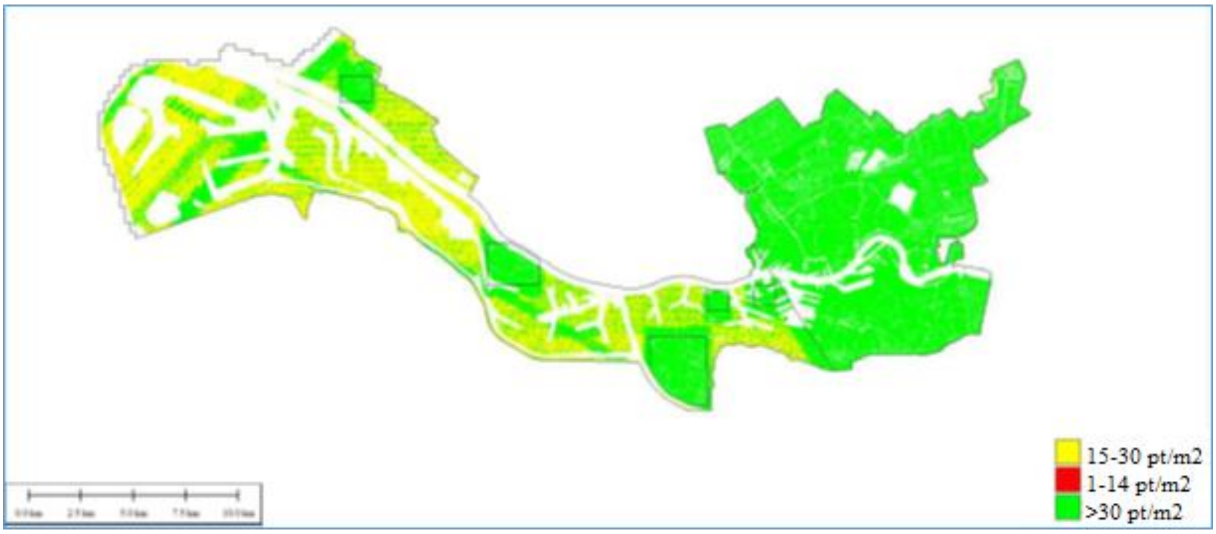


Figure 5.11: Point density of Hoogtebestand Rotterdam 2018 (source: Gemeente Rotterdam)

The Hoogtebestand Rotterdam 2018 is available as LAS file in separate tiles. It is also available in the GeoSignum Pointer platform. A clip of the ALS dataset was downloaded for the Waalhaven area, as LAS file, consisting of 39,368,246 points, and 1,24 GB in size.

DERIVATIVE PRODUCTS

The ALS dataset has multiple derivative products, apart from the ALS point cloud (LAS file) that is available through the GeoSignum Pointer platform. The most important ones are the 3D model and 3 raster files. The most well-known and most accessible way the 3D model has been made available is through a web viewer, 3drotterdam.nl. The 3D model is accessible as LOD1 and LOD2 model, with and without texture.

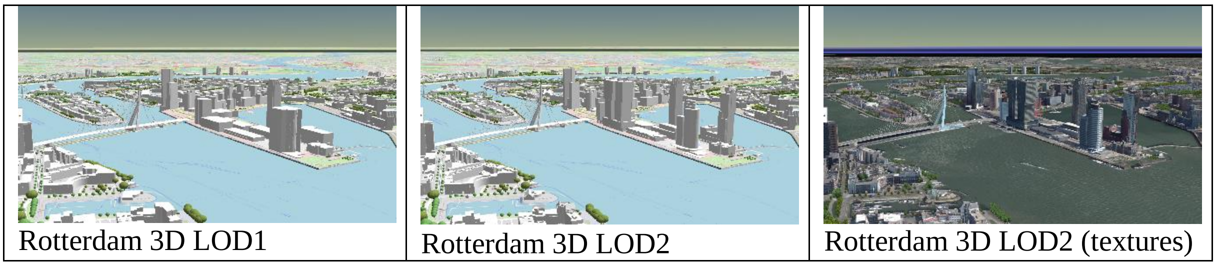

Rotterdam 3D LOD1
Rotterdam 3D LOD2
Rotterdam 3D LOD2 (textures)

Figure 5.12: Rotterdam 3D model version

The three most important raster versions are 1) the total ALS file (in 1 meter resolution); 2) the ground level raster (in 0.5 and 1 meter resolution) and 3) all objects at ground level (in 1 meter resolution).

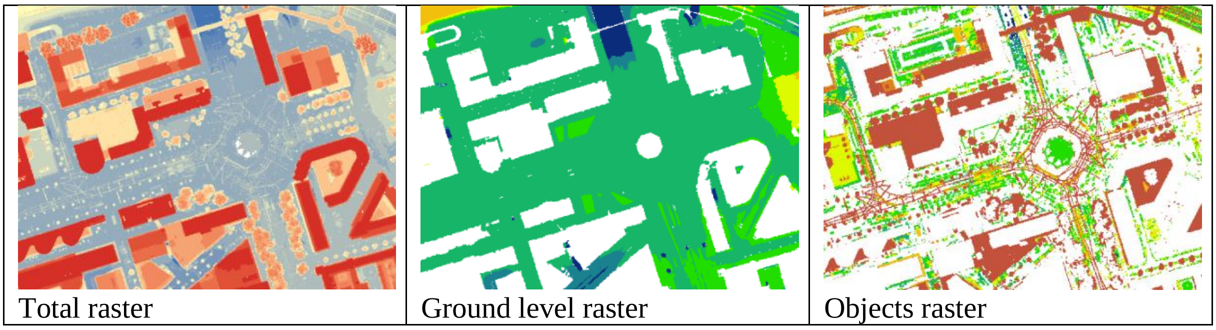

Total raster
Ground level raster
Objects raster

Figure 5.13: Raster versions

5.4.2 MOBILE LASER SCANNING DATASETS

The municipality has two MLS datasets that are available to use. The first one is the Noordereiland area and was obtained in 2016. The second one is the Waalhaven area, and was obtained in 2018. The two areas are shown in Figure 5.14.

Figure 5.14: Waalhaven and Noordereiland areas (source: TOP10NL / own work)

NOORDEREILAND

In 2016, an MLS pilot was done on the Noordereiland area by the company MapXact. The pilot showed that accuracy and positioning are very important, because the accuracy turned out to be insufficient for the foreseen applications and there was also a large shift in height in the dataset. This shift was later corrected.

In Figure 5.15, the area is shown highlighted, on a 3D image obtained from the 3drotterdam.nl viewer. In Figure 5.16 the Noordereiland area is shown on a map.

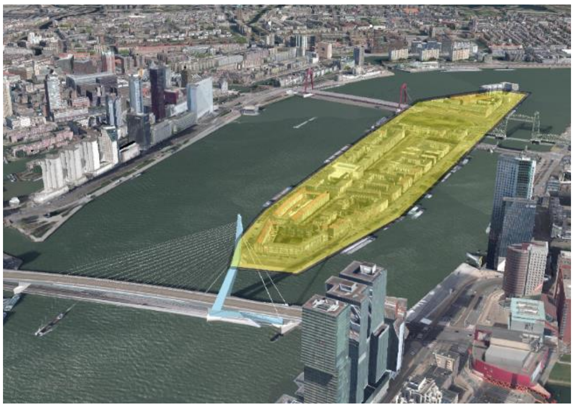


Figure 5.15: Noordereiland area (highlighted) (source: Gemeente Rotterdam / own work)

Figure 5.16: Noordereiland area (source: TOP10NL / own work)

In Figure 5.17, an example of the Noordereiland MLS dataset on street level is shown.

Figure 5.17: Example of the Noordereiland MLS dataset on street level (source: Gemeente Rotterdam / own work)

The Noordereiland MLS dataset is available in the Pointer platform.

WAALHAVEN

In February 2018, a few streets in the Waalhaven area were measured using Mobile Laser Scanning. The goal of this project was to map the exact locations of entrances. There were road maintenance works, but companies had to stay accessible. By using MLS point clouds, money was saved because errors were prevented. Registration was done using manually set ground control points. This was especially necessary for correction of the height. The absolute horizontal accuracy was around 1 cm and the absolute vertical accuracy was around 0.5 cm.

In Figure 5.18, the area is shown highlighted, on a 3D image obtained from the 3drotterdam.nl viewer. In Figure 5.19 the area is shown on a map (TOP10NL).

Figure 5.18: Waalhaven area (highlighted) (source: Gemeente Rotterdam / own work)

Figure 5.19: Waalhaven area (source: TOP10NL / own work)

In Figure 5.20, an example of the Waalhaven MLS dataset on street level is shown. RGB data is added from aerial photographs.

Figure 5.20: Example of the Waalhaven MLS dataset on street level (source: Gemeente Rotterdam / own work)

The Waalhaven dataset is available in the Pointer platform. It was also downloaded from the Pointer platform. In total, this dataset consists of 898,770,714 points. The LAS file is 28,4 GB.

Eventually only the Waalhaven dataset has been used. The Noordereiland dataset was only a pilot, and it turned out that within the organisation most of the knowledge on the project had been lost. The Waalhaven dataset however has recently been used.

6. COMBINATION OF AIRBORNE LASER SCANNING AND MOBILE LASER SCANNING DATA

In this chapter, the first sub question will be answered:

> "Which methods to combine MLS and ALS data are known in the scientific literature?"

This chapter will therefore discuss which aspects are important when combining MLS and ALS data. The actual combination of ALS and MLS datasets or simultaneous utilisation of ALS and MLS datasets is actually a very underexposed topic. Not only is the combination of ALS and MLS data a very unexplored area within the academic literature on laser scanning, also in practice, the combined use of ALS and MLS point clouds is very limited. There are only a few surveying companies that offer it as a product. One of these companies, industry leader in data collection, mentioned the following, when talking about the challenges of co-registration, data integration and making the data available:

> "The issues that you mention are exactly the issues that we struggle with"

Combining data means that choices will have to be made. These choice can be seen as turning buttons, and each slight difference in the way these buttons are turned have impact on the end result. In this case the end result is a combined point cloud. The choices are categorised in the following three categories:

- Co-registration
- Data integration, which consists of removing overlap and down sampling the point density
- Making the data available

Co-registration is the process of aligning the positions of the points in two point clouds, which is essential because two points of the same location in reality can have different positions in the data, due to GPS errors. In this research, the term "data integration" refers to two operations: the removal of overlapping duplicate points and the down sampling of the point density. The integration of the data itself is necessary when combining two data sources. The term "making the data available" can be defined as making sure the users have access to the data in an efficient way and a way that suits the way they intend to use the data.

Generally speaking, there are two methods of combining ALS and MLS data. The first method is active combination and the second method is passive combination. Whether the combination is active or passive also has influence on the way the data is registered, integrated and made available. This generalisation is based on typical use of point cloud data. Active combination of ALS and MLS data will be discussed in Section 6.1, while the passive combination of ALS and MLS will be discussed in Section 6.2. This will be followed by Section 6.3 on (co-)registration. Section 6.4 will discuss data integration and finally Section 6.5 will discuss making the data available.

6.1 ACTIVE COMBINATION

In this research the concept of "active combination" is introduced. Active combination of point cloud data involves the full integration of ALS and MLS point clouds. This means that the end product is a single point cloud with information on both roof tops and facades of buildings.

To make an active combination possible, the data should be accurately co-registered and integrated. A high point density and high absolute accuracy are very important. An active combination point cloud should be made available as raw as possible, in order to make advanced use possible and to make automatic processes possible.

6.2 PASSIVE COMBINATION

In this research the concept of "passive combination" is introduced. Passive combination of point cloud data involves the overlay of multiple point clouds. Passive combination will not produce a single integrated ALS-MLS point cloud.

To make passive combination possible, a simple point cloud web viewer with an overlay function will suffice. Accuracy and point density are less important, since passive combinations will only be suitable for manual visual inspection. Registration will be performed separately. The following sections will mostly apply to active combination and be less relevant for passive combination.

6.3 (CO-)REGISTRATION

When integrating data from different sources, it is essential to have all data in a common coordinate frame. The process of aligning point clouds from different observation points and different moments is also known as registration. When carrying out registration, an important decision is to choose which source will be adjusted to fit the other source. In this case MLS or ALS data. The adjustment is important to maintain the point cloud's quality.

Registration of ALS and MLS point clouds often comes with challenges, for several reasons. First of all, because of the earlier mentioned GPS errors, the positioning accuracy of MLS data is poor. One method to overcome this issue is to manually extract Ground Control Points (GCPs), but this is very labour-intensive and time consuming (Javanmardi et al., 2017). Secondly, MLS data and ALS data are very different in nature. They have different perspectives and different covering areas, which means that there is not a lot of commonality. Thirdly, another difference between ALS and MLS data is the difference in spatial resolutions. The distance from a mobile scanner to the target could be tens of meters, but the distance from an airborne scanner to the target could be hundreds of meters. Therefore, the point density differs massively. This makes point to point matching very difficult. A one-to-one relationship becomes a one-to-many relationship (Cheng, Tong, Li, & Liu, 2013).

In general, there are two different subdivisions possible for automatic point cloud registration methods. The first one is the subdivision between local and global registration methods (A Christodoulou & Oosterom, 2018). The second subdivision is between auxiliary registration methods and data-based registration methods (Cheng, Wu, Tong, Chen, & Li, 2015).

6.3.1 LOCAL VERSUS GLOBAL REGISTRATION METHODS

Local registration, also known as relative registration, is the process of relative alignment of two point clouds. Local registration is necessary because an airborne or mobile laser system continually collects points at a set time interval, for instance every second. Therefore, many points will represent the same location, but because of GNSS errors, these points will not be in the same position. This is shown in Figure 6.1. With local registration, the overlapping point clouds will be aligned, in order to create one scene with a good relative precision.

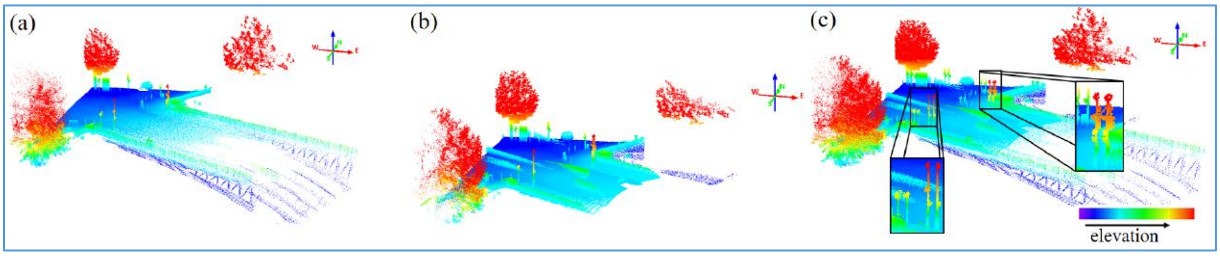


Figure 6.1: (a) and (b): Two point clouds representing the same scene but captured at different times. (c): an overlay of (a) and (b), showing the offsets between (a) and (b). (A Christodoulou & Oosterom, 2018).

Global registration is the process of aligning the point cloud with the rest of the world (Sanchez, Denis, Checchin, Dupont, & Trassoudaine, 2017). Global registration is necessary in order to use point clouds for purposes that require a larger scale than only the point cloud scene itself, or for instance to measure distances. With global registration, the coordinate of every point will be known in a global reference system.

6.3.2 AUXILIARY VERSUS DATA-BASED REGISTRATION METHODS

In auxiliary registration methods, auxiliary data are used to match the point clouds. Examples of auxiliary data are spectral images, GPS data and artificial targets. An example is a study where 2D points where extracted from a 3D point cloud. These points where then projected in the 3D point cloud to be matched. From the 2D-3D correspondences, the transformation parameters were estimated (Weinmann, Weinmann, Hinz, & Jutzi, 2011). Other studies use GPS data to directly georeference the LiDaR point clouds, but in urban and forest areas, GPS receivers are often not accurate enough because they lose signal (Cheng, Wu, et al., 2015).

Data-based registration methods focus on registration without the use of auxiliary data. The most common method is the iterative closest point (ICP) algorithm, developed by Besl & McKay (Besl & McKay, 1992). Later, many different variants were developed. A drawback of the ICP algorithm, is that it needs a good initial alignment of the point clouds that need to be matched (Cheng, Wu, et al., 2015). When there is no initial alignment, the benefits of ICP being an automated method then disappear.

Usually, auxiliary methods are used for global registration, because the auxiliary data already contains absolute positions. Data-based methods are generally used for local registration.

6.3.3 POINT CLOUD REGISTRATION STRATEGIES

There are multiple strategies for registration. A possible strategy is direct registration at the moment of data acquisition, by using a calibrated GPS device (Rönnholm, 2011). However, as already mentioned, MLS' positioning quality is relatively poor because in urban areas, the GPS signal is often blocked. Therefore this strategy will not be considered further.

The first possible strategy is the separate global registration of the data in a common coordinate system.

The second possibility consists globally registering ALS data first, and adjusting the MLS dataset to the ALS dataset secondly.

The third possibility is globally registering MLS data first and adjusting the ALS dataset to the ALS dataset secondly.

Local registration is always included, because it is always necessary to register the different MLS or ALS strips to achieve relative positioning within a dataset. Because MLS datasets usually have a good relative positioning but bad absolute positioning and ALS datasets usually have bad relative positioning but good absolute positioning, the choice for which dataset will be chosen as ground truth is an important one. The three strategies result in three different workflows, which are shown in Figure 6.2.

The registration strategy strongly relies on the available data and on the desired absolute accuracy in the end.

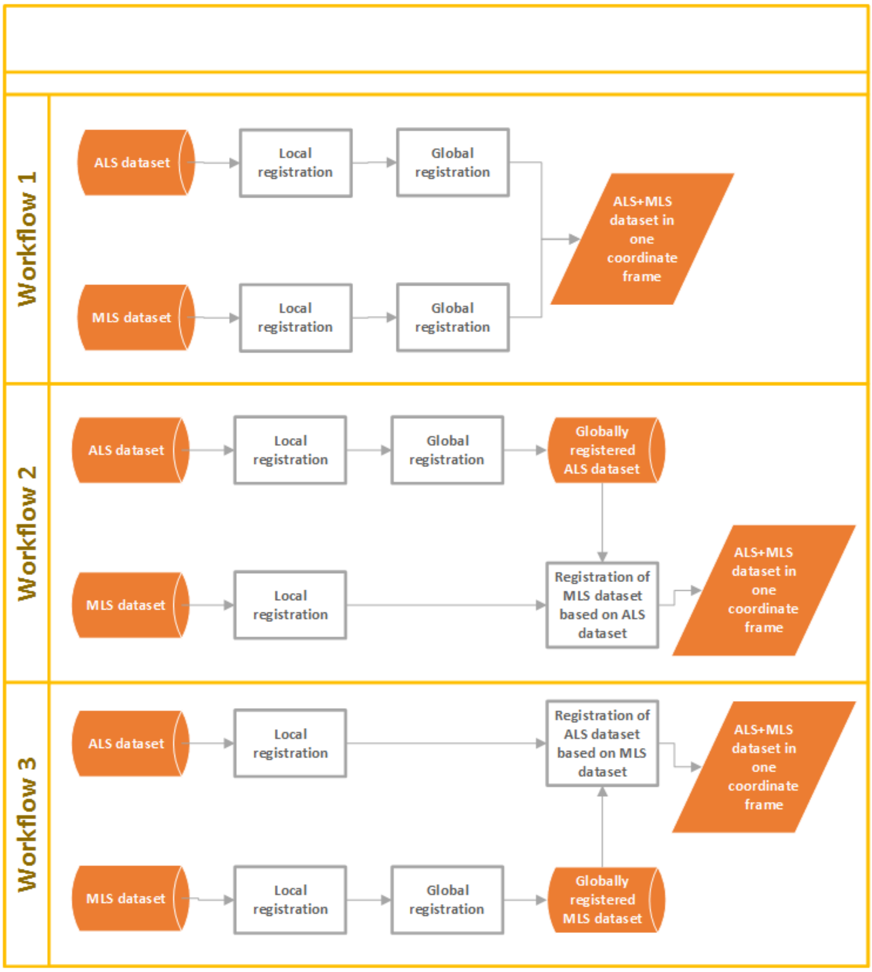


Figure 6.2: Different possible ALS + MLS registration workflows

The best option seems Workflow 2. Because this workflow is based on a global registration of the ALS point cloud, this workflow will save a lot of time and effort, compared to the other workflows. The global positioning of an ALS point cloud is initially already quite good. The global registration of the MLS dataset of Workflow 1 would therefore be unnecessary, and the global registration of Workflow 3 is less efficient than Workflow 2’s global registration of ALS data.

6.3.4 OVERVIEW OF DATA-BASED REGISTRATION METHODS

To overcome the challenges at the beginning of this section, a wide range of registration methods has been developed. Within the data-based methods, a subdivision is made between point-based, line-based and plane-based methods (Cheng, Wu, et al., 2015). Apart from these three, data-based registration is also possible based on images (A Christodoulou & Oosterom, 2018). The different data-based registration methods are shown in Figure 6.3.

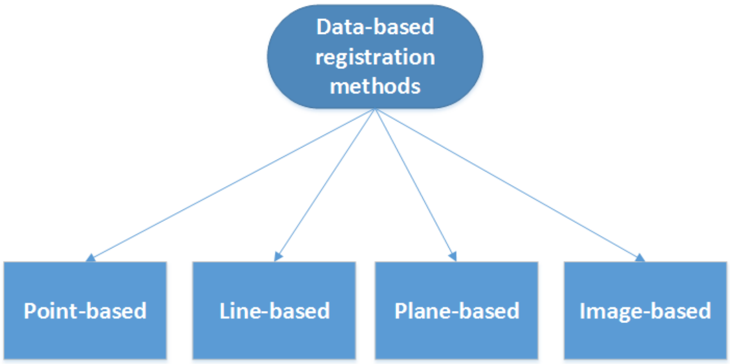


Figure 6.3: Data-based registration methods

POINT-BASED REGISTRATION METHODS

The most common point-based registration method is the iterative closest point (ICP) algorithm (Besl & McKay, 1992; A Christodoulou & Oosterom, 2018). This is essentially an algorithm that uses a target and a source point cloud. The source point cloud is fitted to the fixed positions of the points in the target point cloud. This iterates until the distance between the corresponding points is not decreasing anymore or when the maximum number of iterations is reached (C. Zhang et al., 2016). There are also examples of studies where 3D building corners were extracted from the intersection of 3D building boundaries, from both airborne and terrestrial LiDaR data. These points were then matched through an automatic iterative process. The first step of this approach was to extract boundary segments from both the terrestrial and airborne data. A so-called boundary self-extending algorithm was then used to segment and recover the extracted boundaries, of which the intersections formed the 3D building corners. These corners were then registered. The boundaries were used as reliability check of the result (Cheng et al., 2013). Another example is the use of a so-called shiftable leading point method. In this approach, the first step is to extract building corners from airborne LiDaR data and terrestrial data, by using building contours. Then an initial matching of airborne and terrestrial building corners takes place. The authors use a matching technique based on “maximum matching corner pairs with minimum errors”. The last step is to improve the geometric accuracy of the registration, by generating leading points from corners in the airborne data, and taking the terrestrial corners as reference. The leading points are then shifted from their original positions to their corresponding terrestrial corners. It resulted in a registration with quite a high accuracy. However, it was mentioned that the method would have difficulty in non-urban areas, because it depends on geometric buildings. Another limitation is that the method would not achieve ideal results with buildings with eaves (Cheng, Tong, et al., 2015).

LINE-BASED REGISTRATION METHODS

According to (Cheng, Wu, et al., 2015), lines can also serve as features to base the registration on, at least in areas with sufficient man-made structures (such as buildings). (Eo, Pyeon, Kim, Kim, & Han, 2012) in (Cheng, Wu, et al., 2015) suggest that better registration results could be achieved with lines than with points, if these lines are available.

(Jaw & Chuang, 2008) propose an automatic registration method for ground-based lidar data based on 3D line features. Their workflow consists of three steps and is shown in Figure 6.4. The first step consists of extracting the 3D line features from the point clouds. The second step consists of the feature matching of these lines, using constraints on angles and distances. The third and last step consists of a simultaneous adjustment of the point clouds. While the results were fairly accurate (22.4 mm accuracy), the authors note that a line-only approach might not be effective, and therefore it should always be complementary to a point-based or surface-based method. This is also due to the fact that straight features are not always available.

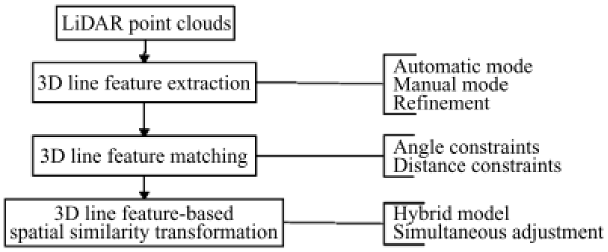


Figure 6.4: Workflow by (Jaw & Chuang, 2008)

PLANE-BASED REGISTRATION METHODS

The same authors of the 3D building corners (Cheng et al., 2013) and the shiftable leading point method (Cheng, Tong, et al., 2015) published a study where they tried a hierarchical plane-based strategy. The first step in this method is coarse registration using 3D road networks. A 3D road network is extracted from airborne LiDaR data using an existing method (Clode, Rottensteiner, Kootsookos, & Zelniker, 2007). The 3D road network is then matched with the vehicle trajectory lines. The second step is fine registration using 3D building contours. First, vertical 2D building contours are extracted from the vehicle LiDaR data. Then, horizontal 2D building contours are extracted from the airborne LiDaR data. These are then registered together. With this method, they reached an accuracy of 0.73 meters in the horizontal direction and 0.39 meters in the vertical direction (Cheng, Wu, et al., 2015). Their workflow is shown in Figure 6.5.

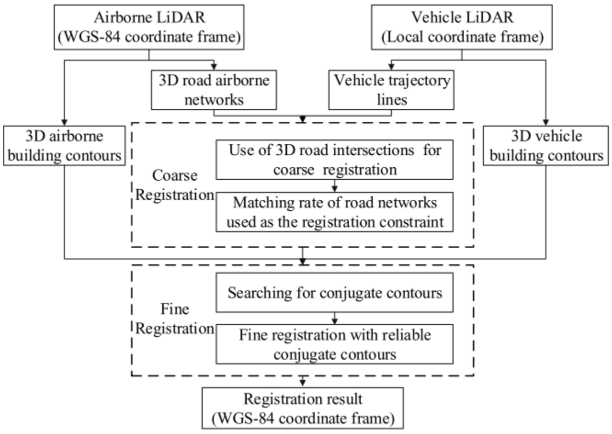
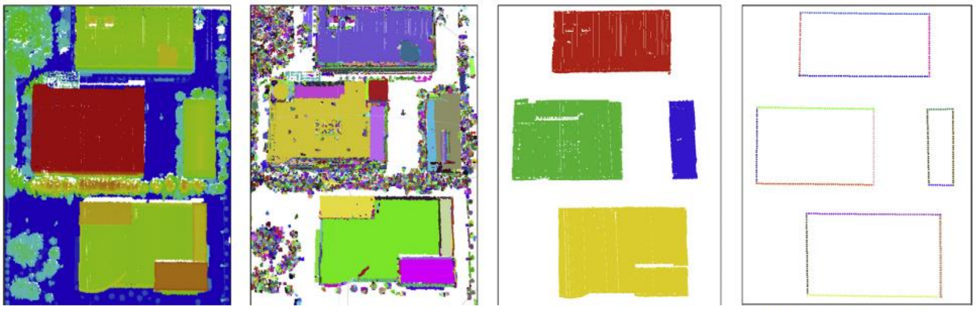


Figure 6.5: Workflow of the registration method of (Cheng, Wu, et al., 2015)

A similar method was proposed by (Yang et al., 2015). This method consists of several steps. The first step is to extract building outlines from both ALS and TLS point clouds. For this, in the TLS data façade points are extracted, which are then used to construct the building outlines. In the ALS data points are clustered based on elevation and regions are created in multiple steps, which are then projected on a plane, using the method of (Ortner, Descombes, & Zerubia, 2007). This is shown in Figure 6.6.



(a) Raw laser scanning data (colored by height value).
(b) Result after initial segmentation.
(c) Result of segmentation.
(d) Building outlines extraction.

Figure 6.6: The extraction of building outlines used in (Yang et al., 2015)

The second step is the initial matching of building outlines, based on geometric constraints. To save computing time, the lengths and angles between the edges of the building outlines are taken as constraints. The third step is the modelling of building outlines, based on spectral graph theory. The fourth step is determining the optimal outline correspondences based on Laplacian matrix. The fifth and final step is calculating the transformation parameters. This workflow is also shown in Figure 6.7.

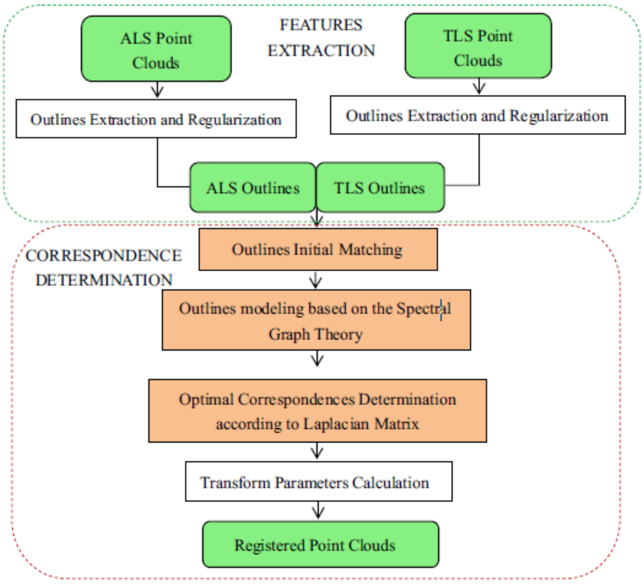


Figure 6.7: Framework proposed by (Yang et al., 2015)

Another example of a method to register ALS and MLS data together is presented in (Teo & Huang, 2014). ALS and MLS data is co-registered in order to increase the details of urban scenes. They developed a method that uses the least squares 3D surface technique, with successful results. The first major part in their approach is the registration of multi-strip MLS data and the second major part is the registration of ALS and MLS data. The least squares 3-D surface matching (LS3D) algorithm was used to minimise the Euclidean surface distance between the ALS and MLS point clouds. This algorithm, developed by (Gruen & Akca, 2005), minimises the 3D distance between surfaces, while the ICP algorithm minimises the Euclidean distances between points. Compared to ICP, LS3D needs less iterations. The following steps were undertaken: 1. Extracting planar features, 2. Matching criterion (search for the corresponding planes), 3. Mathematical modelling, 4. Solving transformation parameters and 5. Applying the parameters to the model data. Ultimately they were able to improve the maximum error from 1.6 to 0.02 meters and the standard error from 0.4 to 0.05 meters.

(Wu et al., 2014) also proposed a registration method based on building profiles for ALS and TLS data. First, they extracted the roof outlines from the Airborne and Terrestrial data. The next steps were estimating horizontal parameters and estimating vertical parameters. They achieved a horizontal accuracy of 0.15 m and a vertical accuracy of 0.20 m.

The results of a comparison of different plane-based methods demonstrate that plane-based are more accurate than point-based methods. Point-based methods however are faster and conceptually simpler (Cheng, Wu, et al., 2015).

IMAGE-BASED REGISTRATION METHODS

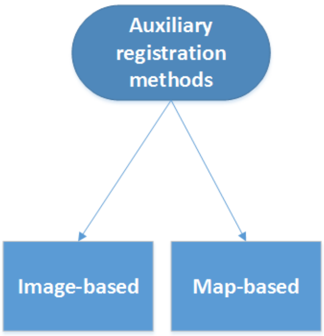
Data-based image-based registration methods use images that are derived from point clouds as source to match two different point clouds.

A common technique to match two images is template matching. It is the process of positioning an image (template) inside a larger image, which involves shifting the template over the larger area, creating search windows and storing the similarities for each position of the search window. The search window with the largest similarity is then most likely the correct position of the template within the larger area. The Normalised Cross Correlation (NCC) is a common method for template matching. It detects the correlation between two images, based on the grayscale of pixels (Lewis, 1995).

An example is (A Christodoulou & Oosterom, 2018). They propose an image-based method for the pairwise registration of MLS point clouds, as an alternative to ICP. Their approach works for the relative (local) registration of point clouds. In their approach, the point cloud is stored in separate tiles. For each tile, a normal vector is computed. The next step is to find which point cloud tiles overlap, based on their coordinates by assuming a buffer zone. Each point cloud tile gets a cell grid. Then the attributes of 3D points are used to generate 2D projections (images). These attributes are the density within each grid cell, the intensity, the depth, the gradient of the intensity, the gradient of the depth and the normal vectors. They were chosen to describe the point cloud’s 3D information in 2D. The images are then matched using template matching. This means that a template image shifts over the reference image, pixel by pixel. For this, a simple cross correlation statistical analysis is used to compare the brightness of the template image and the reference image. When the highest similar brightness is found, a match is found. The registration is based on matching pixels instead of matching points, and thus depends on the number of pixels instead of the number of points. This leads to their approach being more cost-efficient, when compared to ICP, because it performs relatively fast. The results were successful, even when the overlap between the point clouds was small or the offset large (Antria Christodoulou, 2018).

6.3.5 OVERVIEW OF AUXILIARY REGISTRATION METHODS

In this section, an overview of automatic auxiliary point cloud registration methods will be given. Using manually measured ground control points could also be seen as an auxiliary registration method, but this is not an automatic method, and is therefore considered as out of scope. So far, a distinction can be made between image-based auxiliary registration methods and map-based auxiliary registration methods. This is shown in Figure 6.8.



s

Figure 6.8: Auxiliary registration methods

IMAGE-BASED REGISTRATION METHODS

Auxiliary image-based registration methods use external imagery for the registration of MLS data.

In an article by Tournaire et al. a method to georeference ground-based mobile mapping imagery using aerial imagery is presented. They propose a strategy to extract road marks from the ground-based imagery (Figure 6.9) and to extract road marks from aerial imagery (Figure 6.10), and use these as ground control points, in order to improve the georeferencing of the mobile mapping imagery to a sub-decimetre level. The authors took zebra crossing as automatically extracted ground control points, and rather called these "ground control objects". Zebra crossings are not present everywhere, but the authors argue that other road marks could also be used (Tournaire, Soheilian, Paparoditis, & Descartes, 2006).

Figure 6.9: Road mark extraction from ground-based imagery. A one meter cube is shown for scale (Tournaire et al., 2006)

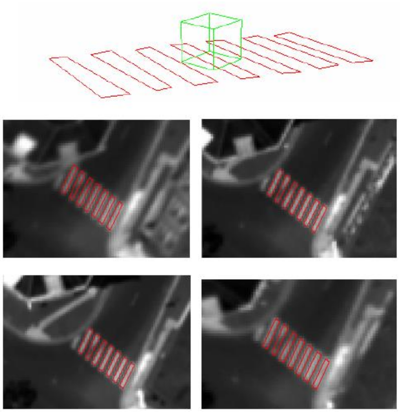


Figure 6.10: Road mark extraction from aerial imagery from different perspectives. A one meter cube is shown for scale (Tournaire et al., 2006)

A similar approach was used by (Javanmardi et al., 2017) to georeference MLS point clouds based on aerial imagery. However, this study focused on imagery obtained with CCD (digital) cameras rather than on point clouds obtained with laser scanners. They also use zebra crossings. Their approach is specially designed for urban areas, where the quality of GNSS measurements is significantly degraded due to blockage of the satellite signals and where road marks are widely available. Therefore, their method is not workable when there are no road marks. However, this is usually outside urban areas, where satellite signals are usually better. It should also be mentioned that their approach performs a 2D registration, because they use 2D aerial imagery. They mention however that in the future they intend to extend their approach to 3D registration using a combination of aerial imagery and ALS point clouds. Another drawback of the method, is that the time interval between the moments of acquisition of the different data should not be too large. This might result in road markings disappearing or being altered. The first step of the method is to extract road markings from the aerial imagery, based on a perspective occlusion map and adaptive thresholding. The perspective occlusion map is generated by perspective projection of a digital surface model. This way, it is known which parts of the road are occluded by buildings. Moving vehicles that could be mistaken as road marks were filtered out by comparing overlapping aerial photographs. The second step was extract the road marks from the MLS data, using road segmentation, laser intensity calibration and adaptive thresholding over intensity value. The last step was to perform the MLS registration, by using a dynamic sliding window (template matching) and a normal distribution transform (NDT). The results were good, and the method was able to decrease the average MLS data error from 99.7 cm to 11.6 cm and decrease the maximum error from 200 cm to 27 cm. This performance is even better than registration by using manually selected ground control points. Their results are shown in Figure 6.11.

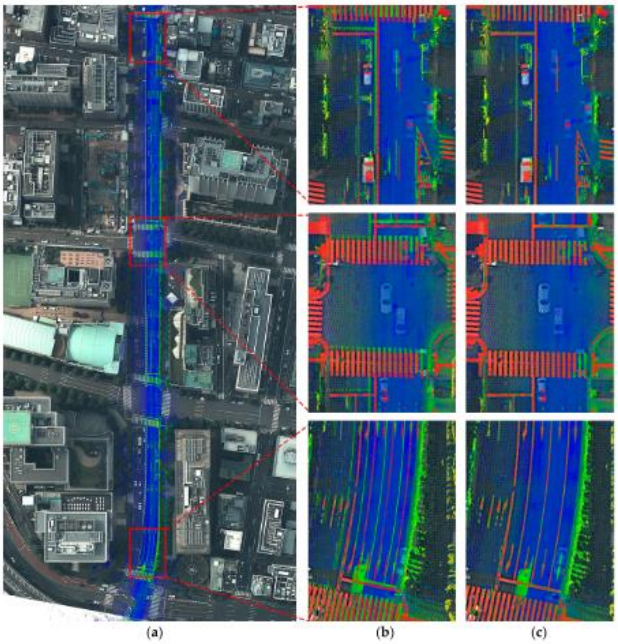


Figure 6.11: "Visual evaluation of the proposed method for survey No. 6: (a) survey route of the MMS on the aerial image (after registration); (b) enlarged view of the original MMS point cloud before registration (the red points are aerial road markings); and (c) enlarged view of the MMS point cloud after applying the proposed method (the red points are aerial road markings)" (Javanmardi et al., 2017)

(Jende et al., 2016) mentioned that existing methods to correct the absolute positioning of mobile mapping data usually only correct horizontal errors and do not consider vertical errors. They propose that positioning mobile mapping data, in the case of the article both imagery and mobile laser scanning data, could be corrected by using georeferenced aerial nadir and oblique imagery as horizontal and vertical reference. The performance of four different algorithms (SIFT, KAZE, AKAZE and LATCH) for low-level feature extraction is tested. Features are extracted and described (identified) from the georeferenced aerial and oblique imager, and are then matched to the same extracted and identified features in the laser data and in the imagery. Thus, there are two separate workflows, one for laser data and one for imagery. The test results showed that the KAZE algorithm was the most reliable extraction method, and that the techniques that were used performed better with MLS than with imagery.

MAP-BASED REGISTRATION METHODS

(Joosten, 2018) proposes a map-based registration method for MLS data. In this method, the first step is extracting building outlines from the Basisregistraties Adressen en Gebouwen (BAG) and Basisregistratie Grootschalige Topografie (BGT). The second step is to transform the building outlines to raster images. The third step is then to generate raster images from the MLS point clouds. Using template matching, the translation parameters for the point cloud are found, that are used for the registration of the MLS point cloud in the last step. The result is then a georeferenced MLS point cloud. The ultimate goal of to use this georeferenced point cloud for classification, in order to create a so-called smart point cloud, again using the BAG.

6.4 DATA INTEGRATION

In Section 3.6 it was stated that the combination of ALS and MLS point clouds is interesting, because the two data sources complement each other, which has interesting applications. The complementarity is especially expressed in the fact that ALS datasets predominantly have information on rooftops and MLS datasets predominantly have information on facades. However, ALS and MLS both have information on the terrain, especially of road surfaces. Simply integrating the two datasets without proper pre-processing or “post-processing” would result in a point cloud with a lot of more or less duplicate points. Data redundancy is of course an undesirable situation. Therefore, it is of vital importance to consider a good data integration process.

In literature, two important operations are known that concern the integration of ALS and MLS point cloud datasets. The first one is down sampling of the point clouds (Section 6.4.1) and the second one is removing overlap between the two point clouds (Section 6.4.2) .

6.4.1 DOWN SAMPLING

Down sampling entails the removal of points, or thinning of the point cloud. When down sampling is applied, the total point density of a point cloud is lowered. Down sampling can have two different aims: in order to achieve a lower point density or in order to achieve a point density that is consistent among the entire point cloud. However, a representative from a major scanning company mentioned:

> “The difficulty in down sampling lies in keeping the important features, whilst not erasing every detail that you want to see in your mesh”

The first reason, to achieve a lower point density, may be desired to allow for higher processing speeds or to ensure that the total point cloud takes up less storage space (Puttonen et al., 2013). To what extent the point density is lowered, of course highly depends on the eventual application of the point cloud data. For example, a lower point density will allow the generation of a polygon mesh based on a point cloud to be faster. However, when lowering the point density, it may be desirable that details are kept. Lower point densities mean in general that the range for detecting objects decreases (Puttonen et al., 2013). On the other hand, a point cloud with a lower point density would make a lighter file, which would allow it to load faster on most computers. This could make the point cloud accessible for a broader group of users.

The second reason is to achieve a point density that is consistent among the entire point cloud. When collecting ALS or MLS data, an irregular or inconsistent point density is inevitable in the raw data. An inconsistent point density is undesirable because it makes recognising patterns harder and because it makes building 3D polygon meshes harder. It would cause the computer to make unnecessary computations. The amount of points and irregularity of shapes would make automatic modelling an unnecessarily time-consuming process. In the case of ALS, irregularity in point density is present because of overlapping flight (or scan) lines. The areas that are scanned during each flight line overlap, sometimes up to 20 %, to allow for accurate co-registration. Where the overlap is present, a higher point density is present. In the case of MLS, a higher point density occurs for example on street crossings, that are crossed by the scanning vehicle multiple times. Apart from this, the point density of objects that are very near the MLS scanner, such as the ground surface and traffic signs, will also be very high. This is due to the fact that the scanner is within the geometry of the study area (in the case of ALS, the scanner is of course outside the study area) (Puttonen et al., 2013). In the post-processing stage, both in the case of ALS and of MLS, down sampling is required. This would result in a single point cloud with a consistent density (Virtanen et al., 2017). Not only is down sampling required before using ALS or MLS point clouds, it is also required when combining ALS and MLS point clouds. MLS point clouds have a rather high point density compared to ALS point clouds. MLS point density is usually between 800-2000 points per square meter, and ALS point is usually 10 – 70 points per square meter. When combining ALS and MLS point clouds, inadvertently overlap will occur, which will inadvertently lead to a high inconsistency in point density. As mentioned early, this inconsistency is undesirable. Therefore, down sampling is highly essential.

There is a wide range of methods to perform down sampling. Two methods will be described. Uniform point sampling is a rather simple but could cause undesired loss of information. Another method that is investigated uses local geometry representations to remove redundant point from surfaces (Song & Feng, 2009). This technique uses the distances between neighbouring points and results in high quality object sampling, but is computationally heavy. Another method uses range-dependent median filtering along the scanning trajectory lines. This technique performs very fast.

6.4.2 REMOVING OVERLAP

When integrating ALS and MLS point clouds, undoubtedly overlap of the two datasets will occur. In other words, there will be duplicate points of (nearly) the same location. Not only do ALS and MLS complement each other, but they will also both have information of the same locations. This would occur at the following locations:

- Road surface
- Facades
- Street objects

The first location where overlap occurs is the road surface. This is also shown in Figure 6.12, and is most visible at the bottom of the image. The MLS dataset will probably have more information of the road surface than the ALS dataset, because of a higher point density.

Figure 6.12: Overlay of MLS and ALS dataset in Pointer. The two datasets complement each other but also partially overlap (Source: Gemeente Rotterdam / own work)

A solution to prevent overlap on the ground surface from happening in the first place, is to clip the facades from the MLS dataset, and integrate these points into the ALS dataset. The clip could be performed based on an additional source, such as the key registry of buildings and addresses (BAG) or the key registry of large-scale topography (BGT). Not only would this prevent overlap on the ground surface, but also would this save processing time and result in a more efficient workflow. However, such a strategy would have three major disadvantages. The first disadvantage is that the usefulness of the MLS dataset would be limited to building facades. The combination of ALS and MLS data will have applications that reach much further than only showing facades. The second disadvantage is that the

MLS data only has information on the façade from the ground perspective. This means that the upper side of balconies will not be visible in the MLS data. The third disadvantage is that sometimes, buildings are so high, that the entire façade is so high that it cannot be fully captured by an MLS scanner. This is also visible in Figure 6.12, at the upper side of the image. Therefore, building facades should have both ALS and MLS data as source.

The second category where overlap occurs are building facades. It was already mentioned that ALS data has a top view of the facades and MLS data has a ground view of the facades. In order to get the best detailed facades possible, a combination of the two sources is necessary. The MLS data will have a higher point density, but the ALS data will be necessary in order to see the upper side of balconies and small canopies, and for very high facades that are out of reach for MLS scanners.

The third category of overlap consists of street objects, such as lamp posts and traffic signs. The street objects are present in both data sources, but in ALS data they will have a very low resolution. Removing the ALS street objects seems like an obvious choice. Trees could also be treated the same way, because MLS trees are much more detailed. However, not every tree can be seen from the public streets, which means that not every tree can be reached by an MLS scanner, since the MLS trajectory usually follows public streets. An approach that includes ALS trees and includes MLS trees by using a buffer could be a solution but would result in a point cloud with trees of different levels of detail.

6.5 MAKING THE DATA AVAILABLE

The next step is to make the combined point cloud data available to the user. The different products that can be derived from the point cloud data will be discussed in Section 6.5.1. Visualisation will be discussed in Section 6.5.2 and data storage and management will be discussed in Section 6.5.3. The chapter will end with Section 6.5.4 on data formats.

6.5.1 PRODUCTS

The combined point cloud data can be offered to the user in the form of different products. The first form is the point cloud itself. The advantage of this, is that the point cloud is the closest representation of reality. Another way of making the data accessible is in the form of a 3D polygon mesh. There are other derivative products possible, such as only certain objects or with a down sampled point density.

6.5.2 VISUALISATION

Apart from usage for data analysis, point clouds can also be used when they are visualised. When viewed in a fluent 3D fly-through or walk-through, point clouds can visualise spatial structures in a both attractive and interactive way. It is also being argued that the visualisation of dense point clouds may contain less errors than the results of automated modelling in some cases (de Haan, 2009). Visualisation can also work in support of the analysis.

However, visualisation of massive point clouds is often an immense challenge, because of their enormous size. Downloading, in order to view the point cloud on a regular computer, could take hours or even days, and is therefore a big challenge. After downloading the next step would be rendering the point cloud. This would also take an enormous amount of time. The aforementioned challenges would become even bigger when the user is without any prior knowledge on point clouds and when the user does not have access to specialized tools. In order to view and use point clouds, specialized knowledge is required, otherwise the data files would remain enormous and intangible chunks of data. Related to this is the fact that point clouds usually require specialized software and hardware with rather high capabilities.

In order to enlarge the range of applications of combined point clouds, solutions that make the visualisation less of a challenge are highly required. The main challenge can be subdivided in three parts: 1) downloading point cloud data is difficult, 2) rendering point cloud data is difficult, 3) making point cloud data available to non-expert users is difficult.

For common geo-information formats, such as raster data or vector data, standards allowing requests have already been existing for years and are widely used. For the case of raster data, the Web Coverage Service (WCS) is a well-known example, and for the case of vector data, the Web Feature Service (WFS) is a well-known example. The standards both allow requests, querying, viewing and editing of data. While the LAS file format is widely regarded as standard for the distribution of lidar point cloud files, it does not have the same abilities as WFS or WCS. It is a file format and not a standard for web services, so it does not directly support the availability of data directly on the web.

However, software has been developed that allow the visualisation of point cloud data directly in a web browser. Two notable examples are plas.io and Potree, both of which have already been mentioned in Section 5.2. Both of these products can load and visualise LAS files in a web browser, in order to widen the audience (Schuetz, 2016). Prior knowledge or advanced hardware are barely required.

6.5.3 STORAGE AND DATA MANAGEMENT

Because of their enormous size, good data management is important for point cloud datasets. Good data management should answer two needs:

- Point clouds should not take up too much storage space
- Point clouds should be accessible and utilisable in a time-efficient way

Therefore, point clouds should be able to be stored in databases, on which spatial queries can be applied. Using the AHN2 dataset as test material, a benchmark was performed, that compared several solutions. These solutions (so-called point cloud data management systems) were Oracle, PostgreSQL, MonetDB and LAStools. The main finding was that LAStools offered the best performance for simple queries. One of the other findings was the suggestion for two new standardisations: an extension for point clouds for the Structured Query Language (SQL) to support efficient querying of point cloud data(bases) and a Web Point Cloud Service (WPCS) standard to support the transfer of point cloud data (Van Oosterom et al., 2015).

Another way to overcome the problem that point clouds are very large in file size, is to use a cloud computing solution. This means that the data is stored on “the cloud”, thus in an external internet location, that is accessible from every computer in the world. This improves the availability of the data, as the user is not dependent on his or her geographical location or available computer resources. It also improves and widens the processing and analysis possibilities, as the user is not dependent on available hardware anymore, since the “hard labour” is done at an external location.

A solution that combines the visualisation requirements from the previous section and the data management requirements from this section is Pointer. This is an online platform that facilitates the cloud storage, visualisation and analysis and processing tasks of point cloud data. Since its development is ongoing, its functionalities are continuously expanded. The platform is already in use at the municipality of Rotterdam.

6.5.4 DATA FORMATS

In Section 3.1, different data formats for point cloud data were mentioned. The most common data format is LAS. Point cloud data should be made available in a format that is widely used and is supported by the software within the municipality.

7. APPLICATIONS OF POINT CLOUDS IN THE MUNICIPALITY OF ROTTERDAM

In this chapter, the applications of ALS and MLS point clouds within the municipality of Rotterdam will be discussed. This will answer the second sub question:

> "What possible applications of the combination of MLS and ALS data exist within the municipality of Rotterdam?"

In the previous chapter, it was established that the combination of ALS and MLS point clouds can generally be classified in two categories: active combination and passive combination. It was also established that the combination depends on three factors: 1) (co-)registration, 2) data integration and 3) making the data available. This chapter will discuss the applications of ALS and MLS data within the municipality of Rotterdam, both active and passive. The combination of ALS and MLS data is essential for these applications. The combination of airborne and mobile data generates value because it provides a full overview of the real world, instead of one perspective. Objects are visible from multiple angles. Section 7.1 will discuss the two main groups of users that were found in the organisation, and Section 7.2 will discuss the applications these two groups use point clouds for.

7.1 USERS

The total group of users of point cloud data within the municipality of Rotterdam can be divided into two sub groups. These two groups differ in the way they use the point cloud data, and thus in the way the data is made available to them. The first sub group consists of advanced users, who benefit the most from raw point cloud data. The other sub group consists of basic users. These users benefit more from simplified and more abstract visualisation.

Basic users will be discussed in Section 7.1.2 and advanced users will be discussed in Section 7.1.1.

7.1.1 BASIC USERS

Basic users would like to access the point cloud data in way that is as simple as possible. They benefit from an abstract visualisation and from the omission of unnecessary details. Therefore, at the moment, they commonly use the derivative products and not the point cloud itself. Basic users often do not have the technical knowledge that is required to work with point cloud data. There is also a strong boundary between basic users of ALS data and basic users of MLS data.

Basic users benefit from simple web viewers.

7.1.2 ADVANCED USERS

Advanced users would like to access the point cloud data as raw as possible. This would allow them to be more in control of the data themselves. Within the municipality, data is often made available as derivative products, in which certain choices have already been made for the users. The advanced users would like to make these choices themselves, in order to make the data better suit their desired applications:

> "As 3D modeller you want to have more control on the filters and on what you use, so you want to make the choices yourself"

However, when it is possible, advanced users would also like to simplify the point cloud and leave out points that are unnecessary and replace the points for generic objects such as lamp posts and trees.

Advanced users heavily make use of 3D design software. They use a wide variety of these software packages, because each package has its own specialisations. Therefore, advanced users highly value interoperability.

Advanced users both use ALS and MLS data. These use the data separately but also combined. They use the data both in an active manner and in a passive manner.

7.2 APPLICATIONS

In this section, the different applications of ALS and MLS point clouds that were found within the municipality of Rotterdam will be discussed. These are the following:

7.2.1: Determination of ground level
7.2.2: Increasing the level of detail of the 3D model
7.2.3: BAG-WOZ inspection
7.2.4: Road design
7.2.5: Redevelopment projects
7.2.6: Management and maintenance of public space
7.2.7: Maintenance of monumental buildings
7.2.8: Renovation of monumental buildings
7.2.9: Detection of mutations in the BGT

7.2.1 DETERMINATION OF GROUND LEVEL

Both MLS and ALS data can be used to determine the height of the ground level in the city. The ground level is also known as “Maaiveld” in Dutch. Thus, the maaiveld is the plane on which the municipality designs roads and other infrastructure. For this application, especially the absolute accuracy of the z-value (height) is very important. Regarding resolution, the point density that is desired depends heavily on the eventual application, but for most applications, a low resolution ground level is sufficient.

The ground level lends itself perfectly for combination. A combination of ALS and MLS data from different moments can also be used to detect subsidence of the surface. This combination could both be passive and active. The ground level is also used by both basic and advanced users.

7.2.2 INCREASING THE LEVEL OF DETAIL OF THE 3D MODEL

The municipality of Rotterdam has a 3D model of the city, which is being used both in active manner and in a passive manner. The active use includes spatial planning, shadow analysis, wind models and air pollution models. The passive use includes communication and providing a more intuitive way of accessing the Key registration of large-scale topography (BGT) and the Key registrations of buildings and addresses (BAG). Currently, the model is offered in LOD1 and LOD2 and is based on airborne laser scanning data. This means that facades of buildings are flat and not detailed.

A combination with MLS data could make facades available in the 3D city model. When the ALS and MLS datasets would be actively integrated, a mesh could be generated that would be far more detailed than the current 3D city model. Especially the visualisation of detailed facades would benefit from this development.

In order to accurately record the building facades, a high point density and a high absolute accuracy are required. The end product could ultimately be used by advanced and basic users. Advanced users will be able to use the improved 3D model for more advanced air pollution and wind analyses. Basic users will be able to use the improved 3D model for a better understanding of the built environment. The improved 3D model can also be used to involve citizens in spatial planning in a more attractive way.

7.2.3 BAG-WOZ INSPECTION

The municipality of Rotterdam maintains and uses multiple key registries. Two of these are the Key registries for addresses and buildings (BAG, Basisregistraties Adressen en Gebouwen) and the valuation of immovable property (WOZ, Waardering Onroerende Zaken). These both contain a usable area for each building, however, these values do not correspond. The BAG value is often based on original construction plans and the WOZ value is often based on visual inspections. Both values should be accurate. The usable area value is important because it is used for tax collection. Therefore, it is important to know which of the two values corresponds with the reality the best. Both key registries are not up to date. Therefore, it is interesting to compare the values with a point cloud that is more recent. With a rather passive visual inspection differences between the different databases could be explained. A respondent, who is responsible for making sure that the BAG and the WOZ accurately represent the reality:

> “When I see a difference of 5 meters in the usable area of a building between the BAG and the WOZ, it could be a dormer window or some other small structure on the roof. So I go to my colleague with the point cloud, and then he shows me that there is actually a higher rooftop!”

While the point cloud data is available to the respondent, he still prefers to ask his colleague to show him the point cloud. This is likely caused by the limited technological knowhow of this person, or the fear that the use point cloud data is a process that is too complicated. For this occasional inspection of rooftops, a passive combination would be sufficient, to be used by basic users. The requirements for point density and positional accuracy would be rather low. However, the requirements for making the data available are rather high.

7.2.4 ROAD DESIGN

Within the municipality of Rotterdam, roads are designed with the help of laser scan data. The Waalhaven industry area is in redevelopment, which means that roads are being re-laid and heightened to the desired level. This level is also called the “uitgiftepeil”. A 3D modeller was asked about his activities:

> “My main activity is designing roads, so new infrastructure. This includes everything underground, for example sewage. We do everything outdoors, except for private areas”

Usually these activities are performed with the help of 2D data. For the Waalhaven area however, a successful pilot with 3D MLS laser scan data was performed. In a location such as the Waalhaven, it often occurs that buildings subside faster than the road. This could also happen the other way around. However, it is important that the loading doors of companies located in the area are connected to the road on the same level. At the same time, the road should be constructed in a way that rain water does not flow into the buildings. For these kinds of challenges, a mobile laser scan is an ideal solution. The point clouds can be used to determine the exact height of the doors and streets, which allows the designers to design the road in an ideal way. For this, height profiles are made, which is shown in Figure 7.1 and Figure 7.2.

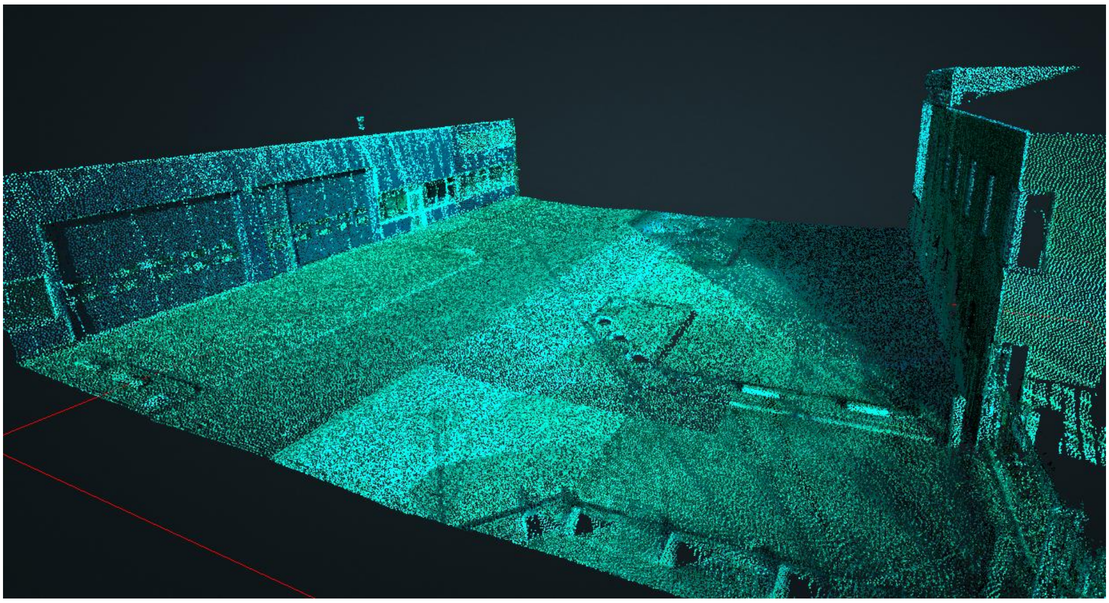
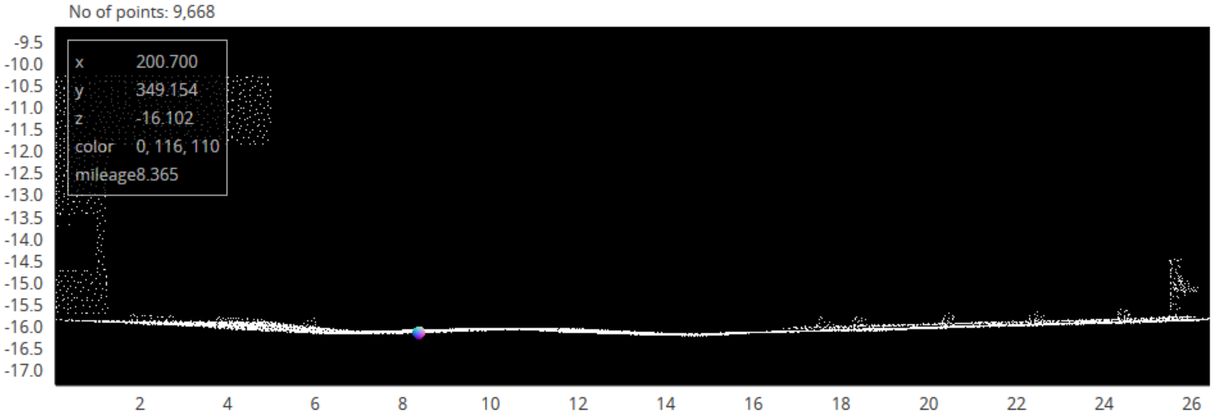


Figure 7.1: Waalhaven road design example: point cloud



No of points: 9,668

x 200.700
y 349.154
z -16.102
color 0, 116, 110
mileage8.365

Figure 7.2: Waalhaven road design example: height profile

The 3D modellers were content with this specific approach. The project manager who was responsible for the redesign of the roads was also very content with using 3D data. He put it rather bluntly:

> “2D should just get out, this must be done with 3D!”

The project manager was also happy with the cost savings that could be realised with the use of 3D laser scans:

> “We saved the developer a lot of money, because the engineering costs went down from 8-9% to 2% of the total project costs”

An active combination could be used here, to also integrate areas that are outside the roads in the redevelopment. A high absolute accuracy, especially for the z value (height) and a high point density are both required for this kind of application. In the project that was discussed, the vertical absolute accuracy was about 0.5 cm. This kind of application is only done by advanced users.

7.2.5 REDEVELOPMENT PROJECTS

Laser scan data is also used in redevelopment projects. An example that was mentioned by a 3D modellers working for the engineering office (*“Ingenieursbureau”)* of the municipality, is the redevelopment of the Brienenoord island. The public space of the island, that is owned by the municipality, will be restructured. Since the island is not accessible by road, only ALS data was used.

The respondent added however that better results could have been achieved, had the island been accessible for MLS vehicles. However, it is possible to use a combination of ALS and MLS data in redevelopment projects of locations that are accessible by road vehicles.

The ALS data was used in both an active and passive way. The active use involved automatic detection of trees on a large scale. The redevelopment involved cutting old trees and planting new ones, for which it was important to know where to cut the trees. The available data on trees on the island was outdated:

> "We maintain a lot of trees as municipality, but there are far more trees than the ones we know of. I'm currently busy with the Brienenoord island, which is full of trees. However if you look at our data, you'll only see a handful of trees"

This is also shown Figure 7.3, where the available data is visualised in 3D and in Figure 7.4, where the trees were detected in the ALS dataset. As seen, the number of trees in reality (on the right) does not correspond with the number of trees known to the municipality (on the left).

Figure 7.3: Trees in Rotterdam 3D model, based on known data

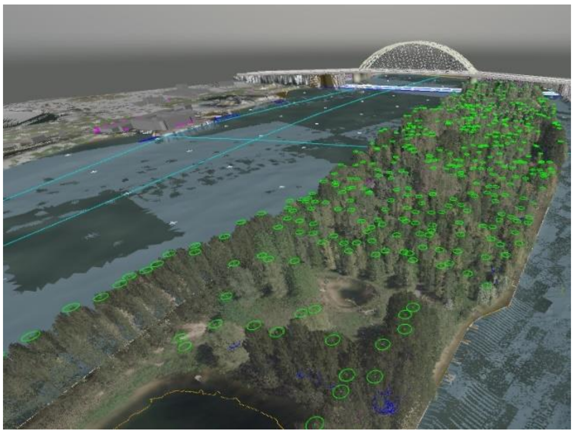


Figure 7.4: Trees on Brienenoord island highlighted in ALS data (overlaid on a 3D model)

The passive use involved using the ALS for the determination of the ground level. The ALS data was also used as underlay, to visualise the new developments:

> "What we often do is use the point cloud as underlay, to do our modelling on"

The use of point cloud data for redevelopment projects is limited to advanced users.

7.2.6 MANAGEMENT AND MAINTENANCE OF PUBLIC SPACE

Within the municipality, for the maintenance of the public space the software package "Obsurv" is used. Obsurv contains information, such as the location, of all objects that are managed by the municipality. Examples include traffic signs, lamp posts and trees, but also roads and green areas. However, it is often the case that the data does not match with the situation in reality. A GIS analyst of the Department of Basic Information, mentioned the following about this:

> "The information *inside* does not match with the information *outside*"

A 3D modeller mentioned the example of charging stations for electric cars:

> "With a laser scan you can see all the mutations, including the ones you didn't know were there. An example is the location of charging stations.

> (…) We don't always have a full picture of where those are in our own databases. During the project I discovered that the laser scan was the only way to identify all of them. Especially when you're redesigning the space it's convenient to know where they are, otherwise it's a surprise with extra costs."

There are two reasons for this. The first reason is that the data is often based on construction plan drawings. However, it often occurs that something is not realised according to the plans. This causes the real situation to differ from the situation in the system. The second reason is that objects change under influence by natural conditions or human interference. Examples include lamp posts that tilt, trees that grow or people who illegally expand their gardens on public green spaces. These sorts of things are manually inspected by municipality workers.

An additional challenge is that the information in Obsurv is often limited. It is interesting to know what the direction of a lamp post is (road-facing or pavement-facing):

> "Currently we only have a point object for each lamp post in our database, and we don't know the direction of the light fitting. So you know where the lamp post is, but not where the light is"

In the case of trees, the exact diameter or height are interesting to know. This information can be used for the maintenance of such objects, but this information is not yet present in the system.

If airborne and mobile laser data were periodically collected, the management and maintenance of public space could be executed more cost-efficient. This would involve active use of point cloud data. There are four main reasons for this:

1. The existing data on objects (often from construction plans) can be checked and can be updated based on the laser scan data
2. Deterioration of lamp posts or growth of trees can be checked
3. Changes under human influence can be checked
4. Extra information on objects can be collected (such as tree diameter and height)

An additional advantage of periodical collection, is that over time changes can be observed. Based on the observations, predictions can be done, which in turn can be used to determine future maintenance needs.

Especially combination of ALS and MLS data is interesting for two reasons:

1. Some places are only visible in ALS data and some places are only visible in MLS data
2. The top of trees (the exact height) is in MLS not clearly visible and in ALS clearly visible, while the bottom of trees (the diameter of the trunk of the trees) is clearly visible in MLS data and not clearly visible in ALS data

The use of point cloud data for the maintenance of public space would require the use by advanced users. However, the derivative products are mainly used by basic users. A high point density and positional accuracy would be required.

7.2.7 MAINTENANCE OF MONUMENTAL BUILDINGS

The municipality manages and maintains many monumental buildings. It is often important to preserve historical details. Examples include cast iron fences or inscriptions in stone. It is interesting to know whether these details show deterioration. Apart from that, it is also worthwhile to record the situation before a renovation. The next section (7.2.8) will be dedicated to this.

A laser scan can be used to record historical details periodically, especially in places that are hard to reach. These places could be scanned with an Unmanned Aerial Vehicle (UAV). As part of a pilot, a lighthouse has been scanned with a laser scanner-equipped UAV. UAV laser scanning is actually a special case of Airborne Laser Scanning. The pilot turned out to be unsuccessful, because eventually the historical details were not clearly visible. The UAV was not stable enough as scanning platform, which caused the fact that in certain locations, points were missing. In some places the point density was too low. This led to the details not being visible enough. Someone who was involved in the project said the following:

> "You can see all sorts of roughness. You can see bulges that don't exist, you can see little dents that don't exist, while from a maintenance perspective, this is the kind of information that you want to have right. Because based on that information, you decide if something has to be done."

It was concluded that the reliability of UAV scanning is not good enough.

A combination of ALS and MLS could be used here instead of a UAV. Until a certain height, the buildings will be visible in a mobile scan, scanned from street level. Above that height, buildings will only visible in a point cloud scanned with an airplane or UAV. However, this applies only to buildings that are high enough. A disadvantage of a (high flying) airplane is that the accuracy and resolution are generally lower, while a disadvantage of the UAV is its lower reliability. Eventually, a trade-off will have to be made here. A third option is using a lower-flying airplane or a helicopter, in order to achieve a higher point density. This would result in a higher detail level, without having to use an unreliable UAV.

Since this application mainly involves visual inspection, this application can be categorised as passive use of point cloud data by basic users.

7.2.8 RENOVATION OF MONUMENTAL BUILDINGS

The municipality is responsible for the maintenance of a large number of monumental buildings. A major challenge is that these buildings often have an important function, but that historic details cannot be changed.

Many pumping stations, which are in use for Rotterdam's sewer system and are maintained by the municipality, are very old. However, because of increased rainfall over the last years, the pumping station's capacity needs to be expanded. Because of the pumping station's house's monumental status, the housing cannot be enlarged, and therefore the capacity expansion should be realised within the existing house. This is often a challenge, and therefore 3D laser scanning is used to record the existing situation. A terrestrial laser scanning (TLS) station on the inside of the pumping station is used. The resulting point cloud is used to build a 3D model, which is used to design the new installations. The 3D model is also enriched with asset information to create a BIM model for asset management. This is shown in Figure 7.5.

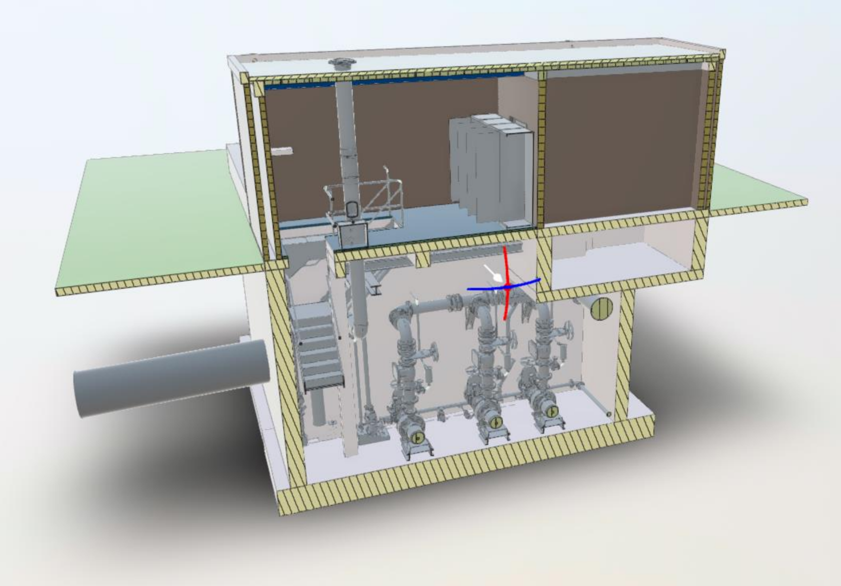


Figure 7.5: BIM model of a pumping station

Another aspect is that the current situation is often not documented in a proper way. The building plans often do not reflect the current situation because they are outdated. Sometimes the drawings have been of poor quality from the beginning and sometimes the buildings have been altered from the original design. A project leader, responsible for the renovation mentioned the following:

> "We would like to use a 3D laser scan because the measurements that we saw on the drawings do not match the situation in reality. This is especially important because there is asbestos in the building."

Often the point clouds are transformed to a BIM model. This was the case for the Binnenhof parliamentary complex in The Hague, that was scanned in order to create a BIM model. The BIM model is being used for the renovation. The point cloud is shown in Figure 7.6.

A last aspect is that monumental buildings often have a lot details that should be preserved. A renovation can be a risky process in which historical details could be damaged. It is important to have an accurate 3D representation of the current situation, to restore that situation as accurate as possible after the renovation. A related example is a laser scan of the Shipping Gallery. The gallery was eventually demolished, but the 3D laser scan was made in order to preserve a digital version of the gallery. This is shown in Figure 7.7.

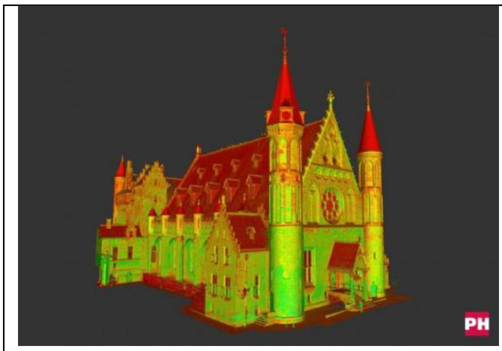


Figure 7.6: Binnenhof laser scan

Figure 7.7: Shipping Galleries laser scan

Thus, laser scans could be used for renovations of monumental buildings for two reasons:

- The current situation is often poorly documented
- The laser scan can be used to restore the old situation

For these kinds of applications, a very high level of detail is necessary, and therefore a very high point density is required. The indoor areas of buildings are almost exclusively scanned by TLS scanners. The combination of ALS and MLS could be interesting because of the large scale of the buildings: not every location is accessible by either ALS scanners or MLS scanners. However, usually a terrestrial scanning solution is chosen, because of the desired high point density and accuracy. This is required by the need to create a BIM model and to see historic details. The complete datasets are usually a combination of multiple TLS point clouds. To also use a combination of MLS and ALS point clouds, including UAVs, technological developments will have to be awaited.

7.2.9 DETECTION OF MUTATIONS IN THE BGT

The key registry of large scale topography (or *Basisregistratie Grootschalige Topografie, BGT*, in Dutch) is a digital 2D representation of the real world that is maintained by the Dutch municipalities and some other organisations. It is important to keep this key registry updated, because a lot of processes are dependent upon it.

Currently, the BGT is updated manually and with the use of aerial photographs. However, periodic laser scans could also be utilised to automatically detect mutations. This could save a lot of time. The combination of MLS and ALS data could especially be interesting for two reasons:

- ALS can be used for large scale topography and off the public roads, while MLS can be used for smaller objects on public roads

- If the collection of MLS and ALS data is properly timed, mutations can be detected more frequently

This would be an active combination. The detection of objects would require a high point density and a high positional accuracy.

7.2.10 REASONS FOR NOT USING LASER SCAN DATA

While a lot of respondents mention the wide range of applications of point cloud data, there are also respondents who mention practical objections to the use of point cloud data.

One respondent is responsible for the maintenance of quay walls. Currently, quay walls are visually inspected by someone who looks for things such as cracks in the walls. In theory these cracks could be detected in a laser scan. The combination of ALS and MLS data could also prove very interesting because quays have a part that is visible from land and a part (the wall) that is visible from the water, for which a mobile laser scanner attached to a boat could be used. However, the quays are often occupied by ships who block the view from the water. Therefore it is more efficient to let someone peek over the quay from the land. Besides this, the costs of visual inspection are not sufficient enough to achieve cost savings with laser scanning.

Another respondent mentioned that he looked into the applications of laser scanning, but did not find the time to learn more about it. It is true that working with point cloud data has a steep learning curve. He also mentioned that the available analysis tools did not always yield the desired results. More attention for the training of employees could make employees better equipped to work with point cloud data.

8. COMBINATION METHODS FOR THE MUNICIPALITY OF ROTTERDAM

In this chapter, combination methods of ALS and MLS point clouds that suit the applications within the municipality of Rotterdam will be discussed. This chapter will therefore answer the third sub question:

> *"What is the best way to combine MLS and ALS data for the municipality of Rotterdam?"*

In Chapter 6, the different aspects of the combination of ALS and MLS have been discussed. These categories are: co-registration, data integration and making the data available. In Chapter 7, the different applications of point clouds that have been found at the municipality of Rotterdam have been discussed. Two different user groups were discussed: advanced users and basic users. This chapter will discuss what choices should be made within the categories, in order to make the combined point clouds suit for the two user groups. The combined point clouds should have the end result that the municipality has in mind. Section 8.1 will discuss co-registration, Section 8.2 will discuss data integration and Section 8.3 will discuss making the data available. In each section, a distinction will be made between advanced and basic users.

8.1 CO-REGISTRATION

Users do not have an opinion on registration of point cloud data, as long as the data is georeferenced. However, they do have requirements regarding the absolute accuracy of the combined data. Generally speaking, there are two strategies for the co-registration of MLS and ALS data: 1) the ALS data is the ground truth or 2) the MLS data is the ground truth.

Section 8.1.1 will discuss co-registration for basic users and Section 8.1.2 will discuss co-registration for advanced use.

8.1.1 CO-REGISTRATION FOR BASIC USERS

Basic users have rather low requirements regarding absolute accuracy. It is evident that the accuracy requirements should follow the application. Therefore, for basic users it would be sufficient when the registration of the MLS data would be done based on the ALS data.

8.1.2 CO-REGISTRATION FOR ADVANCED USERS

Advanced users have high requirements regarding absolute accuracy. The advanced users have thus far mainly used the Waalhaven MLS dataset. The absolute accuracy of the x and y values is around 1 centimetres, while the absolute accuracy of the z value is around 0.5 centimetres. This is necessary for the applications of the advanced users, such as road design. The absolute accuracy of the ALS dataset however, is lower, namely around 4 centimetres. When combining these two sources, the MLS dataset should be used as ground truth, otherwise the combined dataset would be unsuitable for the original MLS applications.

Currently, the registration of the MLS data is performed by using ground control points. Manually matching ground control points is a lot of manual work. On the small current scale this is the best option. However, when MLS data will be collected on a large scale in the future, another solution should be found. The registration could be done based on ALS data, but this would mean a decrease of accuracy. A third option is to take the MLS as ground truth in some locations and take the ALS as ground truth in other locations, but this can be very complicated:

> “You could say: in open areas the GPS position of the mobile scan is better, and in urban canyons the GPS position of the airborne scanner is better. And then use the position that is the most accurate. But this is computationally very complex. You will have to find a scale that says something about the reliability. And you will find situations where differences in positional shifts between scanning sessions. When you would want to do this, you will open a pandora’s box of complexity.”

8.2 DATA INTEGRATION

Data integration consists of removing overlap and down sampling of the point density.

Most users mention that noise should be filtered as well. Noise, such as cars, is already being filtered after data collection. A 3D modeller mentioned that there is also extra noise that is not filtered out, namely points within buildings:

> “If you scan from the street, the scanner also looks inside through the windows, and then you can also see the ceilings. I would like to filter these out. Automatic filtering of such things could be of added value.”

Some users mention that the overlap of points is not really a problem, since the point density of ALS data is only 30 points per meter, and the point density of MLS data could be a 1000 points per meter. The extra 25 points would not be a problem because it is only a small portion of the total amount points.

There are differences in the way data should be integrated between advanced users and basic users. Section 8.2.1 will discuss data integration for basic users and Section 8.2.2 will discuss data integration for advanced users.

8.2.1 DATA INTEGRATION FOR BASIC USERS

Basic users have rather low requirements regarding point density. Therefore, the point density could be down sampled substantially, before it is made available to the basic users. Basic users often benefit from passive combination, which means that data integration is not necessary. The way the data is integrated strongly interrelates with the way the data is made available. This will be discussed in the following section.

8.2.2 DATA INTEGRATION FOR ADVANCED USERS

Advanced users have high requirements regarding point density: they want the point cloud to be as detailed as possible. They want to have as much influence on the data their selves as possible. They prefer however to omit points if they do not add anything:

> “Combination is good, but leaving out is even better. If it’s not relevant: then get out.”

Therefore, they will benefit from algorithms that could filter irrelevant points.

8.3 MAKING THE DATA AVAILABLE

Currently the municipality makes the point cloud data available in various ways. On the municipality’s network drives, the data is available as file for each area and as derivative products. Apart from that, the data is available in Pointer, an online platform that was developed by the company GeoSignum. Pointer is a web viewer for the complete ALS and MLS point cloud, but it also allows users to export data or use analysis tools based on pre-defined areas. Its advanced analysis tools are the most important features.

A geo-information advisor mentioned the advantages of storing the point cloud data on an external platform. There are two major advantages. The first is that the municipality does not need to worry about the issues that come with such an enormous amount of data:

> “A major advantage is that we do not have the host the data ourselves. Especially in large organisations such as the municipality of Rotterdam, this is an issue the ICT department struggles with.

The second advantage is that the municipality can benefit from the newest developments:

> “But a more important advantage is that we do not have to develop the tools ourselves. The field is developing quickly, and you want to offer new possibilities quickly. The needs of the users will also increase.”

Using an external platform is a good solution for the municipality and for its users. One the one hand, the municipality does not need to attract and maintain the knowledge about the software, but can use external knowledge and services in exchange for a reasonable fee. On the other hand, the users can benefit from the newest developments. A third advantage is that the external web platform is not limited by the constraints of the municipality’s infrastructure, which is not suited to handle large quantities of data and heavy graphical processing.

This solution is beneficial to both basic and advanced users. Basic users can view the data in an accessible way, and advanced users can use the advanced analysis. When advanced users want to use the point cloud data in their own software, they can export the area they are interested in:

> “That is the most accessible way in any case. The specialist could also download parts of the data. They can look around in a 3D environment, but the moment the actually want to do something, they can define a project area, download it and load it into their GIS or CAD software.”

Section 8.3.1 will discuss making the data available for basic users and Section 8.3.2 will discuss making the data available for advanced users.

8.3.1 MAKING THE DATA AVAILABLE FOR BASIC USERS

Most basic users will not directly use a point cloud, says a respondent:

> “Most users at the municipality will not use the point cloud itself, if we can make enough serious derivative products”

They would like the point cloud as simple as possible. Therefore, derivative products are very important. At the moment, there are already a lot of derivative products. For basic users, the combined point cloud should also be available as different derivative products. One could think of the following examples:

- Objects, such as lamp posts or trees, as points
- 3D polygon mesh
- Raster

Basic users benefit from RGB colours and EDL. A respondent who designs pumping stations also discovered this:

> “I once made the mistake of asking for a black-and-white 3D scan, because I thought that would be cheaper. Sometimes you have to make concessions, because it was thought that 3D scans were too expensive. However, we discovered that the difference in grey scale was insufficient to distinguish certain features. Then we decided to only do

> coloured scans from then on. It may cost a little bit more, but then you know that you can work with what you're going to get"

8.3.2 MAKING THE DATA AVAILABLE FOR ADVANCED USERS

Similarly to basic users, advanced users also benefit from web viewers to export the point cloud data they need. Their next step is often to load the point cloud data in highly specialized 3D software packages. The data should be suitable to work with in a wide range of different 3D software packages, which is supported by a quote by a 3D modeller:

> "It should load in Revit, it should load in Inventor, it should load in ProEngineer, it should load AutoPlant. I could name all of them, those 3D softwares."

Each software has its own specialisation, and each 3D modeller often uses a combination of different software packages. This variety highlights the importance of interoperability and using standards. A geo-information advisor said about this:

> "Most of the guys work with 10 different software packages, figuratively speaking. And if there's a new one, then they'll work with that one. So for us it's important that we make the data available in such a way, that it works in many different applications. So we should use the standards"

While advanced users are used to work with large amounts of data, more than basic users, advanced users would still like to minimise the amount of data that is needed. This idea is supported by different respondents:

> "That's the thing with a point cloud, it's so big. So cumbersome. It looks nice, but if you want to actually use it, then you have to wait very long."

The file size of point cloud data has led 3D modellers to become data specialists, instead of designers:

> "The computers that are used to make the designs are very heavy, and so is the data. The designers are becoming data specialists: what is the best software to work with these data without my computer crashing? That is the question here. What can I do so I don't have to wait 3 hours before everything has rendered? That is a real struggle here."

To the 3D modellers the file size is very important, because it has a large influence on their software's performance:

> "There's a big difference between looking at 40 GB or 4 GB. But the possibilities of the software to deal with the point clouds are very variable. The performance differs greatly between different software packages."

The advanced users think that the raw data is important, but that irrelevant points should be removed as early in the pipeline as possible. This has already been mentioned in the previous section about data integration.

> "Points should be omitted if they don't add anything new. I want have a good algorithm that detects the trees and automatically replaces them with generic tree objects."

Thus, advanced users would greatly benefit if the data was made available in such a way, that common objects could automatically be detected and replaced by generic objects. A group of points of a lamp post, for instance, would be replace by a single point containing the height of the lamp post. For visualisation purposes, this point could be visualised by a generic 3D polygon of a lamp post with the right height. The InfraWorks software package can do this:

> "You can take a single point, and then tell the software it should make a tree of that point, or a traffic sign, or whatever you'd like. This is based on rules: if a point is of type A, then take 3D object type A. That's very convenient."

Leaving out redundant data would make the processes overall faster. On the other hand, advanced users also benefit from the raw data:

> "You have to think in two directions. One way is the actual picture: the point cloud is a full 3D representation of the reality, that you can use for designing. The other way is to simplify the point cloud to the maximum, to scale back the amount of data to a minimum."

For advanced use, visualisation of the data is very important. Both RGB and EDL are very beneficial to advanced users. A 3D modeller mentioned eye dome lighting's benefits:

> "I really use EDL. We don't have algorithms to recognise everything yet, so we are still very dependent on what we actually see in the point cloud. For me that's very important, for instance here: on this image you can see the steps, and on the other image you can't."

This is also highlighted in Figure 8.1 and in Figure 8.2. In the image on the left, the steps are hardly distinguishable when EDL is turned off. In the image on the right, EDL is turned on, and the steps are distinguishable. EDL adds more perspective to the image.

 *Figure 8.1: Steps hardly distinguishable with EDL off*	 *Figure 8.2: Steps distinguishable with EDL on*

9. CONCLUSION

In this chapter, the conclusions that can be drawn from this research are provided. In Section 9.1, the research sub questions will be answered. In Section 9.2 the main research question will be answered. In Section **Fout! Verwijzingsbron niet gevonden.** the limitations and reflection will be discussed.

9.1 ANSWERING THE RESEARCH SUB QUESTIONS

The sub questions were the following:

1. Which methods to combine MLS and ALS data are known in the scientific literature?
2. What possible applications of the combination of MLS and ALS data exist within the municipality of Rotterdam?
3. What is the best way to combine MLS and ALS data for the municipality of Rotterdam?

9.1.1 METHODS TO COMBINE MOBILE LASER SCANNING DATA AND AIRBORNE LASER SCANNING DATA

The first research sub question was the following:

> "Which methods to combine Mobile Laser Scanning and Airborne Laser Scanning data are known in the scientific literature?"

The combination of Mobile Laser Scanning point clouds and Airborne Laser Scanning point clouds is subdivided into two types of combination: active combination and passive combination.

Active combination involves the full integration of point cloud datasets, which means that the end product is a single point cloud. Active combination is especially beneficial for intensive processes, such as generating a 3D polygon mesh or designing roads. For active combination three processes are essential: 1) (co-)registration, 2) data integration and 3) making the data available. The co-registration should be performed in such a way that the resulting positional accuracy of the data suits the desired application of the point cloud data. Data integration involves the removal of overlapping points and thinning of the point density. A lower point density is advantageous for the processing speed and required storage space. There are different methods of making the data available: there are different data formats, but the point cloud can also be made available in a web viewer, which is the most accessible way.

Passive combination however, involves the overlay of two point cloud datasets. Passive combination will not produce a single integrated point cloud. This means that passive combination is only suitable for simple visual interpretations or analyses.

9.1.2 APPLICATIONS OF THE COMBINATION OF MOBILE LASER SCANNING DATA AND AIRBORNE LASER SCANNING DATA IN ROTTERDAM

The second research sub question was the following:

> "What possible applications of the combination of Mobile Laser Scanning data and Airborne Laser Scanning data exist within the municipality of Rotterdam?"

There is a large number of possible applications of Airborne Laser Scan data and Mobile Laser Scan data. The number of current applications of combined point cloud is low, but this is not a surprise since the concept is quite young.

A difference is made between advanced users and basic users, thus advanced applications and basic applications. The most important advanced applications are road design, increasing the level of detail of the 3D model and renovations of monumental buildings. The most important basic applications are BAG-WOZ inspection and maintenance of public area.

9.1.3 THE BEST WAY TO COMBINE MOBILE LASER SCANNING DATA AND AIRBORNE LASER SCANNING DATA FOR ROTTERDAM

The third research question was the following:

> “What is the best way to combine Mobile Laser Scanning data and Airborne Laser Scanning data for the municipality of Rotterdam?”

The combination of Mobile Laser Scanning data and Airborne Laser Scanning data should be differentiated for two groups: the advanced users and the basic users. The advanced users would like the point cloud data as raw as possible, in order to have full control of the data. The basic users benefit more from derivative products and from passive combination. Advanced users benefit the most from active combination. Regarding co-registration, the best option is to perform registration of MLS data based on manually selected ground control points. The co-registration of the ALS data will then be based on the MLS data. This will suit the current applications the best. Regarding data integration, for advanced users the point density should not be altered and for basic users the point density should be minimised. Regarding making the data available, a web platform would be the best solution. A web platform would allow both basic and advanced users to analyse, view and export the data. Basic users would also benefit from a wide range of simplified derivative products, such as a 3D polygon mesh.

9.2 ANSWERING THE MAIN RESEARCH QUESTION

The main research question was as follows:

> Which way to combine Airborne Laser Scanning and Mobile Laser Scanning point clouds suits the municipality of Rotterdam the best?

To conclude this research: the way the data is combined strongly depends on the eventual application of the dataset. There is a wide range of different applications within the municipality. However, the best way to combine the data is to keep the point cloud as close to reality as possible. It is evident that the combination of Airborne Laser Scanning data with Mobile Laser Scanning data has a very high added value. Advanced users would benefit the most from a combined point cloud if the high point densities and overlap were maintained, thus giving them full control of the data. However, basic users would benefit more if the data was made available to them in a more simplified form, as derivative product. The data should be made available in a very accessible web viewer, and allow users to export data to work with it in various software packages.

10. DISCUSSION

In this chapter, the interpretation of the results of the research will be discussed.

This research aimed to prove the added value of the combination of Airborne Laser Scanning data and Mobile Laser Scanning data in the municipality of Rotterdam. It did so with the following objectives:

- Create an overview of considerations when combining ALS and MLS data
- Find out the needs of the municipality of Rotterdam regarding the combination of ALS and MLS point clouds
- Assess which of the available methods suits the needs and the data of the municipality of Rotterdam the best

While the combination certainly has a high added value for advanced users, basic users would still prefer to use information in a simplified form. This could indicate that there is a mismatch between technological possibilities and the organisation. Basic users do not seem to be equipped to use data. Processes in the organisation are not suited to handle point cloud data. However, this research did not focus on organisational choices.

This research has certain limitations. The first limitation regards the methodology and the second limitation regards the municipality of Rotterdam.

A qualitative approach was chosen for this research, which means that interviews with people within the municipality of Rotterdam were conducted. The number of respondents was limited, due to the limited amount of time. A larger number of respondents could have provided more insights. A different composition of respondents could have provided other insights. However, the researcher has done everything in his power to include as many respondents as possible. Efforts were also taken to make the list of respondents as representative for the organisation as possible.

The research focuses on the municipality of Rotterdam. While this has been intention from the beginning onwards, it certainly limits the value of this research outside of Rotterdam. While the outcomes can be very valuable for Rotterdam, they are of lesser value outside of this organisation. Other municipalities could have different attitudes towards and experiences with point cloud data. A fact is that the municipality of Rotterdam is a very large organisation compared to other municipalities. A consequence of this is that Rotterdam has more means for technological developments such as laser scan data. This could also limit the value of the research for a smaller municipality.

11. RECOMMENDATIONS

In this chapter, recommendations drawn from the research will be provided. First, recommendations based on the conclusion of this research will be discussed. Secondly, additional recommendations will be discussed.

First and foremost, the combination of ALS and MLS data should suit two general groups of users: basic users and advanced users. Basic users benefit the most from simple derivative products, while advanced users want to be in full control of the data. Thus, the data should be made accessible in a web platform, that allows analyses, but also viewing and exporting the data.

The additional recommendations will now be discussed. The municipality of Rotterdam should investigate the possibilities of point cloud data more. There is a desire to embrace new innovations such as point cloud data, but it is unclear how these data should be used. Therefore, the gap between the technology and the processes in the organisation should be filled.

The second recommendation is related to the first recommendation. A lot of people within the organisation know the possibilities of point cloud data, but think that working with point cloud data is too hard for them.

The third recommendation also relates to people. A lot of people are still used to working with 2D data. The processes in the organisation are also 2D-based. However, the world is in 3D. There should be a shift from 2D to 3D within the organisation. However, this is a transformation that has already started.

The last recommendation concerns information technology. During the interviews, a lot of respondents complained about the IT infrastructure of the municipality. Its graphic performance is often insufficient. We would recommend to invest more in hardware.

12. FURTHER RESEARCH

In this chapter, suggestions for further research will be provided.

- More research on the practical considerations regarding the collection of mobile laser scan data. Should this be done on a large scale or project-based? And how often should the data be collected? A combination with collection of panoramic photos could be considered.
- More research on the generation of 3D polygon meshes based on laser scan data. More and more tools become available to generate 3D meshes, but there is little knowledge on the topic. It would be interesting to know what a good point density is in order to generate a 3D mesh that is detailed enough. Another question would be: “what is detailed enough?”
- More research on people using point cloud data: the management and technical people have high expectations, but people are not used to working with point cloud data. More research on this could prove valuable insights

REFERENCES

Alho, P., Vaaja, M., Kukko, A., Kasvi, E., Kurkela, M., Hyyppä, J., … Kaartinen, H. (2011). Mobile laser scanning in fluvial geomorphology: mapping and change detection of point bars. *Zeitschrift Für Geomorphologie, Supplementary Issues*, *55*(2), 31–50. https://doi.org/10.1127/0372-8854/2011/0055S2-0044

ASPRS. (2011). *LAS Specification Version 1.4*.

Besl, P. J., & McKay, N. D. (1992). A Method for Registration of 3-D shapes. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *14*(2), 239–256.

Böhm, J. (2005). Terrestrial Laser Scanning - A Supplementary Approach for 3D Documentation and Animation. *Photogrammetric Week*, 263–271.

Böhm, J., & Haala, N. (2005). Efficient integration of aerial and terrestrial laser data for virtual city modeling using lasermaps. *ISPRS Workshop Laser Scanning*, 192–197. Retrieved from http://elib.uni-stuttgart.de/opus/volltexte/2007/3254/

Cheng, L., Tong, L., Li, M., & Liu, Y. (2013). Semi-automatic registration of airborne and terrestrial laser scanning data using building corner matching with boundaries as reliability check. *Remote Sensing*, *5*(12), 6260–6283. https://doi.org/10.3390/rs5126260

Cheng, L., Tong, L., Wu, Y., Chen, Y., & Li, M. (2015). Shiftable leading point method for high accuracy registration of airborne and terrestrial LiDAR data. *Remote Sensing*, *7*(2), 1915–1936. https://doi.org/10.3390/rs70201915

Cheng, L., Wu, Y., Tong, L., Chen, Y., & Li, M. (2015). Hierarchical registration method for airborne and vehicle LiDAR point cloud. *Remote Sensing*, *7*(10), 13921–13944. https://doi.org/10.3390/rs71013921

Christodoulou, A. (2018). *An image-based method for the pairwise registration of mobile laser scanning point clouds Antria Christodoulou October 2018*.

Christodoulou, A., & Oosterom, P. Van. (2018). Image-based method for the pairwise registration of Mobile Laser Scanning Point Clouds, *XLII*(October), 1–5.

Clode, S., Rottensteiner, F., Kootsookos, P., & Zelniker, E. (2007). Detection and Vectorization of Roads from Lidar Data. *Photogrammetric Engineering & Remote Sensing*, *73*(5), 517–535. https://doi.org/10.14358/PERS.73.5.517

CloudCompare. (2018). CloudCompare - Open Source project. Retrieved November 23, 2018, from http://cloudcompare.org/

de Haan, G. (2009). Scalable visualization of massive point clouds. *Management of Massive Point Cloud Data: Wet and Dry*, *49*, 59.

Eo, Y. D., Pyeon, M. W., Kim, S. W., Kim, J. R., & Han, D. Y. (2012). Coregistration of terrestrial lidar points by adaptive scale-invariant feature transformation with constrained geometry. *Automation in Construction*, *25*, 49–58. https://doi.org/10.1016/j.autcon.2012.04.011

GeoSignum. (2018). Pointer Cloud Software. Retrieved November 16, 2018, from https://www.geosignum.nl/index.php/product-services/pointer-cloud-software

GIM International. (2018). Point Clouds: Laser Scanning versus UAS Photogrammetry. *GIM International*.

Gruen, A., & Akca, D. (2005). Least squares 3D surface and curve matching. *ISPRS Journal of Photogrammetry and Remote Sensing*, *59*(3), 151–174. https://doi.org/10.1016/j.isprsjprs.2005.02.006

Heritage, G., & Large, A. (2009). *Laser Scanning for the Environmental Sciences*. John Wiley & Sons.

Hyyppä, J., Yu, X., Hyyppä, H., Vastaranta, M., Holopainen, M., Kukko, A., … Alho, P. (2012). Advances in Forest Inventory Using Airborne Laser Scanning. *Remote Sensing*, *4*(5), 1190–1207. https://doi.org/10.3390/rs4051190

Iavarone, A., & Vagners, D. (2003). Sensor Fusion: Generating 3D by combining Airborne and Tripod-mounted LiDaR data. In *Proceedings of the International Workshop on Visualization and Animation of Reality-Based 3D Models* (Vol. XXXIV).

Isenburg, M. (2013). LASzip: lossless compression of LiDAR data. *Photogrammetric Engineering & Remote Sensing*, *79*(2), 209–217. https://doi.org/10.14358/PERS.79.2.209

Javanmardi, M., Javanmardi, E., Gu, Y., & Kamijo, S. (2017). Towards high-definition 3D urban mapping: Road feature-based registration of mobile mapping systems and aerial imagery. *Remote Sensing*, *9*(10). https://doi.org/10.3390/rs9100975

Jaw, J. J., & Chuang, T. Y. (2008). Registration of ground-based LiDAR point clouds by means of 3D line features. *Journal of the Chinese Institute of Engineers, Transactions of the Chinese Institute of Engineers,Series A/Chung-Kuo Kung Ch'eng Hsuch K'an*, *31*(6), 1031–1045. https://doi.org/10.1080/02533839.2008.9671456

Jende, P., Hussnain, Z., Peter, M., Oude Elberink, S., Gerke, M., & Vosselman, G. (2016). Low-level tie feature extraction of Mobile Mapping data (MLS/images) and aerial imagery. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *40*(3W4), 19–26. https://doi.org/10.5194/isprsarchives-XL-3-W4-19-2016

Joosten, F. (2018). *Map supported point cloud registration*.

Kukko, A., Kaartinen, H., Hyyppä, J., & Chen, Y. (2012). Multiplatform mobile laser scanning: Usability and performance. *Sensors (Switzerland)*, *12*(9), 11712–11733. https://doi.org/10.3390/s120911712

Langley, R. B. (1999). Dilution of Precision. *GPS World*, (May).

Levi, & Judd. (1996). Dead reckoning navigational system using accelerometer to measure foot impacts.

Lewis, J. P. (1995). Fast Normalized Cross-Correlation. *Vision Interface*, *10*(1), 120–123.

Lim, E. H., & Suter, D. (2009). 3D terrestrial LIDAR classifications with super-voxels and multi-scale Conditional Random Fields. *CAD Computer Aided Design*, *41*(10), 701–710. https://doi.org/10.1016/j.cad.2009.02.010

Murali, S. (2018). Map Supported Classification of Mobile Laser Scanner data, 96.

Nebiker, S., Bleisch, S., & Christen, M. (2010). Rich point clouds in virtual globes - A new paradigm in city modeling? *Computers, Environment and Urban Systems*, *34*(6), 508–517. https://doi.org/10.1016/j.compenvurbsys.2010.05.002

Ordóñez, C., Cabo, C., & Sanz-Ablanedo, E. (2017). Automatic detection and classification of pole-like objects for urban cartography using mobile laser scanning data. *Sensors (Switzerland)*, *17*(7). https://doi.org/10.3390/s17071465

Ortner, M., Descombes, X., & Zerubia, J. (2007). Building outline extraction from digital elevation models using marked point processes. *International Journal of Computer Vision*, *72*(2), 107–132. https://doi.org/10.1007/s11263-005-5033-7

PelserHartman. (2016). *3D scannen basics*. Retrieved from http://meet-tekenwerk.nl

Peng, H., Zhi, X., Wang, R., Liu, J. Y., & Zhang, C. (2014). A new dynamic calibration method for IMU deterministic errors of the INS on the Hypersonic Cruise Vehicles. *Aerospace Science and Technology*, *32*(1), 121–130. https://doi.org/10.1016/j.ast.2013.11.005

Petrie, G. (2010). Mobile Mapping Systems: An Introduction to the Technology. *GEOInformatics*, (January), 32–43.

Plas.io. (2018). Plas.io. Retrieved January 10, 2019, from http://plas.io/

Plas.io. (2019). Plas.io Github page. Retrieved January 10, 2019, from https://github.com/verma/plasio

Potree. (2018). Potree. Retrieved November 23, 2018, from http://www.potree.org

Poux, F., Hallot, P., Neuville, R., & Billen, R. (2016). Smart point cloud: definition and remaining challenges. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *4*(2W1), 119–127. https://doi.org/10.5194/isprs-annals-IV-2-W1-119-2016

Pu, S., Rutzinger, M., Vosselman, G., & Oude Elberink, S. (2011). Recognizing basic structures from mobile laser scanning data for road inventory studies. *ISPRS Journal of Photogrammetry and Remote Sensing*, *66*(6 SUPPL.), S28–S39. https://doi.org/10.1016/j.isprsjprs.2011.08.006

Puttonen, E., Lehtomäki, M., Kaartinen, H., Zhu, L., Kukko, A., & Jaakkola, A. (2013). Improved sampling for terrestrial and mobile laser scanner point cloud data. *Remote Sensing*, *5*(4), 1754–1773. https://doi.org/10.3390/rs5041754

rapidlasso GmbH. (2018). LAStools | rapidlasso GmbH. Retrieved November 23, 2018, from https://rapidlasso.com/lastools/

Rieg, L., Wichmann, V., Rutzinger, M., Sailer, R., Geist, T., & Stötter, J. (2014). Data infrastructure for multitemporal airborne LiDAR point cloud analysis - Examples from physical geography in high mountain environments. *Computers, Environment and Urban Systems*, *45*, 137–146.

https://doi.org/10.1016/j.compenvurbsys.2013.11.004

Rönnholm, P. (2011). Registration Quality – Towards Integration of Laser Scanning and Photogrammetry by Petri Rönnholm Atlas of INSPIRE Implementation Methods. *Technology*, (59), 9--254.

Safe Software. (2018). FME | Data Integration Platform | Safe Software. Retrieved November 23, 2018, from https://www.safe.com/how-it-works/

Sanchez, J., Denis, F., Checchin, P., Dupont, F., & Trassoudaine, L. (2017). Global registration of 3D LiDAR point clouds based on scene features: Application to structured environments. *Remote Sensing*, *9*(10). https://doi.org/10.3390/rs9101014

Schuetz, M. (2016). Potree: Rendering Large Point Clouds in Web Browsers, 84.

Song, H., & Feng, H. (2009). A progressive point cloud simplification algorithm with preserved sharp edge data, 583–592. https://doi.org/10.1007/s00170-009-1980-4

Statistics Netherlands. (2018). StatLine - Bevolking; geslacht, leeftijd, nationaliteit en regio, 1 januari. Retrieved November 23, 2018, from https://opendata.cbs.nl/#/CBS/nl/dataset/70634ned/table?ts=1542981343765

Teo, T. A., & Huang, S. H. (2014). Surface-based registration of airborne and terrestrial mobile LiDAR point clouds. *Remote Sensing*, *6*(12), 12686–12707. https://doi.org/10.3390/rs61212686

Tournaire, O., Soheilian, B., Paparoditis, N., & Descartes, B. (2006). Towards a sub-decimetric georeferencing of ground-based mobile mapping systems in urban areas: matching ground-based and aerial- based imagery using roadmarks.

Vaaja, M., Hyyppä, J., Kukko, A., Kaartinen, H., Hyyppä, H., & Alho, P. (2011). Mapping topography changes and elevation accuracies using a mobile laser scanner. *Remote Sensing*, *3*(3), 587–600. https://doi.org/10.3390/rs3030587

Van Oosterom, P., Martinez-Rubi, O., Ivanova, M., Horhammer, M., Geringer, D., Ravada, S., … Gonçalves, R. (2015). Massive point cloud data management: Design, implementation and execution of a point cloud benchmark. *Computers and Graphics (Pergamon)*, *49*, 92–125. https://doi.org/10.1016/j.cag.2015.01.007

Verbree, E., & Van Oosterom, P. (2015). *Exploratieve Puntenwolken*. https://doi.org/http://dx.doi.org/10.1016/j.agrformet.2005.07.005

Virtanen, J.-P., Kukko, A., Kaartinen, H., Jaakkola, A., Turppa, T., Hyyppä, H., & Hyyppä, J. (2017). Nationwide Point Cloud—The Future Topographic Core Data. *ISPRS International Journal of Geo-Information*, *6*(8), 243. https://doi.org/10.3390/ijgi6080243

Vozikis, G., Haring, A., Vozikis, E., Kraus, K., & Greece, A. /. (2004). Laser Scanning: A New Method for Recording and Documentation in Archaeology. *Workshop – Archaeological Surveys*, 1–16. Retrieved from https://m.fig.net/resources/proceedings/fig_proceedings/athens/papers/wsa1/WSA1_4_Vozikis_et_al.pdf

Weinmann, M., Weinmann, M., Hinz, S., & Jutzi, B. (2011). Fast and automatic image-based registration of TLS data. *ISPRS Journal of Photogrammetry and Remote Sensing*, *66*(6 SUPPL.), S62–S70. https://doi.org/10.1016/j.isprsjprs.2011.09.010

Wu, H., Scaioni, M., Li, H., Li, N., Lu, M., & Liu, C. (2014). Feature-constrained registration of building point clouds acquired by terrestrial and airborne laser scanners. *Journal of Applied Remote Sensing*, *8*(1), 083587. https://doi.org/10.1117/1.JRS.8.083587

Xiao, W., Xu, S., Oude Elberink, S., & Vosselman, G. (2012). Change detection of trees in urban areas using mutil-temporal airborne lidar point clouds. *Remote Sensing of the Ocean, Sea Ice, Coastal Waters, and Large Water Regions*, *8532*(0), 1–10. https://doi.org/10.1117/12.974266

Yang, B., Zang, Y., Dong, Z., & Huang, R. (2015). An automated method to register airborne and terrestrial laser scanning point clouds. *ISPRS Journal of Photogrammetry and Remote Sensing*, *109*, 62–76. https://doi.org/10.1016/j.isprsjprs.2015.08.006

Zhang, C., Du, S., Liu, J., Li, Y., Xue, J., & Liu, Y. (2016). Robust iterative closest point algorithm with bounded rotation angle for 2D registration. *Neurocomputing*, *195*, 172–180. https://doi.org/10.1016/j.neucom.2015.06.107

Zhang, S., Wang, C., Yang, Z., Chen, Y., & Li, J. (2016). Automatic Railway Power Line Extraction Using Mobile Laser Scanning Data. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLI-B5*(July), 615–619.

https://doi.org/10.5194/isprsarchives-XLI-B5-615-2016

Zhu, L., Hyyppä, J., Kukko, A., Kaartinen, H., & Chen, R. (2011). Photorealistic building reconstruction from mobile laser scanning data. *Remote Sensing*, *3*(7), 1406–1426. https://doi.org/10.3390/rs3071406

APPENDICES

12.1 TOPIC LIST (ENGLISH)

The following topic list will be used to interview respondents within the municipality of Rotterdam about the combination of Airborne Laser Scanning and Mobile Laser Scanning (LiDaR) point clouds.

1. **Introduction**

- Personal introduction
- Background information thesis
  My research focuses on the combination of Airborne Laser Scanning (ALS) and Mobile Laser Scanning (MLS) point cloud data. ALS data is captured from the air (by plane) and MLS data is captured from the ground (by car). The municipality already has ALS data every two years (Hoogtebestand). Two pilots have been done with MLS (Noordereiland & Waalhaven). For multiple reasons, the combination of ALS and MLS is interesting. The first reason is that the two sources complement each other in perspective (ground and air). The second reason is that MLS can improve the resolution (number of points) of ALS. The third reason is that ALS could be used to improve the positional accuracy of the MLS data. I intend to find out how the data should be combined and what the possible applications are within the municipality of Rotterdam.
- Interview procedure (informed consent)

2. **Role of respondent**

- What is your role within the municipality of Rotterdam?
- What are your responsibilities within that role? How is your involvement with 3D point cloud data? What are your tasks?

3. **Current applications of 3D data**

- What is your experience with 3D data in general?
- What are, in your opinion, the most promising *current* applications of 3D information within the municipality of Rotterdam?
- What are, in your opinion, the most promising *future* applications of 3D information within the municipality of Rotterdam?

4. **Experience and expertise of respondent with point cloud data**

- What is your experience with point clouds in general?
- Have you worked with Airborne Laser Scanning data or Mobile Laser Scanning data or both?
    - In what way? What did your work involve?
- Could you show or share examples of your work?

5. **Current applications of point cloud data**

At the moment, point cloud data has many applications. ALS: elevation and city modelling. MLS: building modelling, topography changes, street furniture

- For what goals do you use point cloud data? Could you be as specific as possible?
- What are the end results of these goals?
- What software solutions do you use to meet these goals?
- What are your requirements for the point cloud data, in order to support your activities?

  - Requirements regarding resolution/point density
  - Requirements regarding positioning accuracy?
- What limitations do you encounter when using point clouds?

6. Future applications of point cloud data

- Which future applications do you envision for point cloud data? Can you name some examples?
- What are, in your opinion, the requirements for the point cloud data, in order to support the future activities?

7. Applications of combined point cloud data

In my research I found out that combined point clouds can have a lot of new applications. Change detection, increasing the level of detail of building facades, road inventory, enrich the 3D model with street furniture objects and trees.

- Do you think a combination of ALS and MLS point cloud data can have many new applications?
- Which limitations of ALS or MLS can be solved by using both at the same time?
- Can you name some possible applications, and explain why?
- Do you think a combination of ALS and MLS point cloud data can improve existing applications? Can you name some examples, and explain how the combination can improve these applications.

8. Quality of point cloud data

A distinction is made between absolute and relative accuracy. Absolute accuracy concerns the shift of points relative to the real-world (absolute) position. It is determined by the quality of the positioning systems on board the scanning platform and the geometrical position of the satellites. Relative accuracy concerns the shift of points relative to each other. The targets, environment and instruments (quality, scanning distance and speed) are of influence.

- What do you think is more important, relative or absolute accuracy? Please motivate.
- To what extent is a high point density (high resolution) desirable, in your opinion? **(see screenshots 2)**
- How accurate should the position of points be, in your opinion? Please motivate.
- Which data has a better quality in general? ALS data or MLS data? Can you explain why?

9. Co-registration of point cloud data

Registration is the process of relative alignment of two point clouds. This is necessary because the location of the points in the data often does not correspond with the real-world location of the points, usually because of GNSS errors.

- Is the process of registration relevant for you, or do you assume that a good registration has taken place?
- To what extent should a registration be accurate? How much may the shift be?
- Should a registration be quick and dirty (cheap) or accurate but slow (expensive)?
- Should the municipality of Rotterdam be able to perform the registration or should they outsource this?

10. Data integration

Data integration is the process of integrating two datasets into one dataset. There are two major steps. Removing overlap and point sampling. Point sampling is the process of thinning the point cloud in order *to achieve a lower point density. This will make it harder to automatically detect small scale objects but will make recognising abstract objects easier and data processing faster.*

- Where do you think ALS and MLS data have overlap? And is this a problem, in your opinion? **(see screenshots 1)**
- When ALS and MLS data have overlap, which data source is leading? ALS or MLS data? Can you explain why?
- What is, in your opinion, a good solution to get rid of overlap?
- Is it, in your opinion, undesirable when the point density differs within the dataset? To what extent should point sampling be performed?
    - Is it better to have more points or fewer points, and why?

11. Making the data available

Making the data available concerns three things: visualisation, storage/data management, and the way that the data can be accessed and analysed. Combination can mean two things: an "active" combination, which means that the ALS and MLS point cloud are fully integrated and are offered as one "fully functional" point cloud, or a "passive" combination, which is basically just an overlay of two point clouds.

- Would you prefer the active or the passive combination?
- How should point cloud data be made available in general?
- How important is, in your opinion, the realism and level of detail in the visualisation of point clouds? **(see screenshots 2)**
- To what extent do you think point clouds are used for analysis, and not for visualisation?
- Are you satisfied with the current way point cloud data is available? Is it fast enough and not too difficult? **(show Pointer)**

12. Conclusion

- Summary of interview
- Thank the respondent
- Feedback
    - Involvement of respondent
    - Accountability to respondent

12.2 TOPIC LIST (DUTCH)

1. Introductie

- Persoonlijke introductie
- Achtergrondinformatie onderzoek
  Mijn onderzoek richt zich op de combinatie van Airborne Laser Scanning (ALS) en Mobile Laser Scanning (MLS) puntenwolkdata. ALS data wordt ingewonnen vanuit de lucht (met een vliegtuig) en MLS data wordt ingewonnen vanaf de grond (met een auto). De gemeente laat al elke twee jaar een ALS puntenwolk inwinnen (Hoogtebestand Rotterdam). Er zijn twee pilots uitgevoerd met MLS (Noordereiland en Waalhaven). Om meerdere redenen is de combinatie van ALS en MLS interessant. De eerste reden is dat twee bronnen elkaar complementeren in hun perspectief (grond en lucht, facades en daken). De tweede reden is dat MLS de resolutie kan verbeteren van ALS data (aantal punten). De derde reden is dat ALS gebruikt zou kunnen worden om de positionele accuraatheid van MLS te verbeteren.
- Interview procedure (informed consent)

2. Rol van de respondent

- Wat is jouw rol binnen de gemeente Rotterdam?
- Wat zijn jouw verantwoordelijkheden binnen die rol? Hoe is jouw betrokkenheid met 3D puntenwolk data? Wat zijn je taken?

3. Huidige toepassingen van 3D data

- Wat is jouw ervaring met 3D data over het algemeen?
- Wat zijn, volgens jou, de meest veelbelovende *huidige* toepassingen van 3D informatie binnen de gemeente Rotterdam?
- Wat zijn, volgens jou, de meest veelbelovende *toekomstige* toepassingen van 3D informatie binnen de gemeente Rotterdam?

4. Ervaringen en expertise van respondent met puntenwolk data

- Wat is jouw ervaring met puntenwolken over het algemeen?
- Heb je gewerkt met Airborne Laser Scanning data of Mobile Laser Scanning data, of allebei?
  - Op wat voor manier? Wat hield je werk in?
- Kan je voorbeelden van je werk laten zien of delen?

5. Huidige toepassingen van puntenwolk data

Momenteel heeft puntenwolk data veel toepassingen. ALS: hoogtemodel / gebouwenmodellen. MLS: gebouwenmodellen, topografie veranderingen, straatmeubilair

- Voor welke doelen gebruikte je puntenwolk data? Zou je zo specifiek mogelijk kunnen zijn?
- Wat zijn de eindresultaten van die doelen?
- Welke software gebruik je om die doelen te bereiken?
- Wat zijn jouw eisen aan de puntenwolk data, om jouw activiteiten uit te voeren?
  - Eisen wat betreft resolutie/puntendichtheid
  - Eisen wat betreft positionele accuraatheid
- Tegen welke limitaties loop je aan bij het gebruik van puntenwolk data?

6. Toekomstige toepassingen van puntenwolk data

- Welke toekomstige toepassingen van puntenwolk data voorzie je? Kun je een aantal voorbeelden noemen?
- Wat zijn, volgens jou, de eisen aan de puntenwolk data, om de toekomstige activiteiten te ondersteunen?

7. Toepassingen van gecombineerde puntenwolk data

In mijn onderzoek heb ik ontdekt dat gecombineerde puntenwolken veel toepassingen kunnen hebben. Change detection, het verhogen van het detailniveau van zijkanten van gebouwen (facades), inventarisatie van de wegen voor onderhoud, en het verrijken van het 3D model met straatmeubilair en bomen

- Denk je dat een combinatie van ALS en MLS puntenwolk data veel nieuwe toepassingen kan hebben?
- Welke limitaties van ALS of MLS kunnen worden opgelost door ze tegelijkertijd te gebruiken?
- Kun je een aantal mogelijke toepassingen noemen, en uitleggen waarom?
- Denk je dat een combinatie van ALS en MLS puntenwolk data bestaande toepassingen kan verbeteren? Kun je voorbeelden noemen, en uitleggen hoe de combinatie deze toepassingen kan verbeteren?

8. Kwaliteit van puntenwolk data

Er wordt een onderscheid gemaakt tussen absolute en relatieve accuraatheid. Absolute accuraatheid gaat over de verschuiving van punten, ten opzichte van de werkelijke positie. Deze wordt bepaald door de kwaliteit van de positiebepalingsinstrumenten en de stand van satellieten. Relatieve accuraatheid gaat over de verschuiving van punten ten opzichte van elkaar. De gescande objecten (oppervlak), omgeving (weer) en instrumenten (kwaliteit, afstand en snelheid platform) zijn van invloed hierop

- Wat is, volgens jou, belangrijker: relatieve of absolute accuraatheid? Kun je dit toelichten?
- In hoeverre is een hoge puntendichtheid (hoge resolutie) wenselijk? **(screenshots 2)**
- Hoe accuraat zou de positie van de punten moeten zijn volgens jou? Kan je dit toelichten?
- Welke data heeft volgens jou een hogere kwaliteit? ALS of MLS? Kun je dit toelichten?

9. Co-registratie van puntenwolk data

Co-registratie is het relatief uitlijnen van twee puntenwolken. Dit is nodig omdat de locatie (positie) van de punten in de data vaak niet correspondeert met de werkelijke locatie, vaak door GPS fouten.

- Is het proces van registreren relevant voor jou, of ga je ervanuit dat een goede registratie heeft plaatsgevonden?
- In hoeverre zou een registratie accuraat moeten zijn? Hoeveel mag de verschuiving zijn?
- Zou een registratie quick en dirty (goedkoop) of accuraat maar langzaam (duur) moeten zijn?
- Zou de gemeente Rotterdam de registratie zelf moeten uitvoeren of zouden ze dit moeten uitbesteden?

10. Data integratie

Data integratie omhelst het integreren van twee datasets tot één dataset. Er zijn twee belangrijke stappen: overlap verwijderen en point sampling. Point sampling is het proces van het uitdunnen van de puntenwolk, om een lagere puntendichtheid te bewerkstelligen. Dit maakt het moeilijker om kleine objecten te herkennen maar maakt het makkelijker om abstracte objecten te herkennen en maakt de processing speed voor veel toepassingen hoger.

- Waar hebben, volgens jou, ALS en MLS data overlap? En is dit een probleem volgens jou? **(zie screenshots 1)**
- Wanneer ALS en MLS data overlap hebben, welke databron is dan leidend? ALS of MLS data? Kun je dit toelichten?
- Wat is volgens jou een goede oplossing om van de overlap af te komen?
- Is het volgens jou onwenselijk als de puntendichtheid binnen de dataset verschilt? In hoeverre zou point sampling gedaan moeten worden?
    - Is het beter om meer of minder punten te hebben, en waarom?

11. Beschikbaar maken van de data

Het beschikbaar maken van de data omhelst drie zaken: visualisatie, databeheer/opslag en de manier waarop de data wordt ontsloten: hoe deze toegankelijk is en geanalyseerd/gebruikt kan worden. Combinatie kan twee dingen betekenen: een "actieve" combinatie, wat betekent dat de ALS en MLS puntenwolken volledig worden geïntegreerd en worden aangeboden als één "volledig functionerende" puntenwolk, of een "passieve" combinatie, wat eigenlijk gewoon een overlay is van twee puntenwolken.

- Heb je de voorkeur aan een actieve of een passieve combinatie?
- Hoe zou puntenwolk data in het algemeen beschikbaar gemaakt moeten worden?
- Hoe belangrijk is volgens jou, realisme en detailniveau in de visualisatie van puntenwolken? **(screenshots 2)**

- In hoeverre vind je dat puntenwolken moeten worden gebruikt voor analyse, en niet voor visualisatie?
- Ben je tevreden met de huidige manier waarop puntenwolk data beschikbaar is gemaakt? Is het snel genoeg en niet te moeilijk? **(laat Pointer zien)**

12. Conclusie

- Samenvatting
- Bedanken van de respondent
- Terugkoppeling
  - Betrokkenheid respondent
  - Verantwoording aan respondent