Coarse Registration of Airborne Point Clouds Across Island with Overlaps, Using Road Markings as Key Feature

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1 Introduction

Point cloud data plays a crucial role in the development of the built environment due to its ability to provide precise, high-resolution 3D digital representations of real-world objects. Several techniques have been developed to acquire point cloud data, with airborne laser scanning being one of the most effective methods for capturing large-scale areas. For example, airborne laser scanning was used to acquire point cloud data in the Netherlands' AHN project (AHN). In practice, the acquisition of airborne laser scanning point-cloud data often requires dividing the survey into multiple flight plans due to various circumstances, such as when the survey area is very large to prevent loss of data in case of a system failure Saylam (2009) or the need for multi-temporal surveys to monitor environmental changes Riofrío et al. (2022) or to update the old dataset. These flight plans may be conducted at different times, using different sensors, and different calibration in each flight plans which might result in slight positional mismatches which might detected in the overlapping areas Sun et al. (2023), Schenk (2001) illustrated in Figure 1.

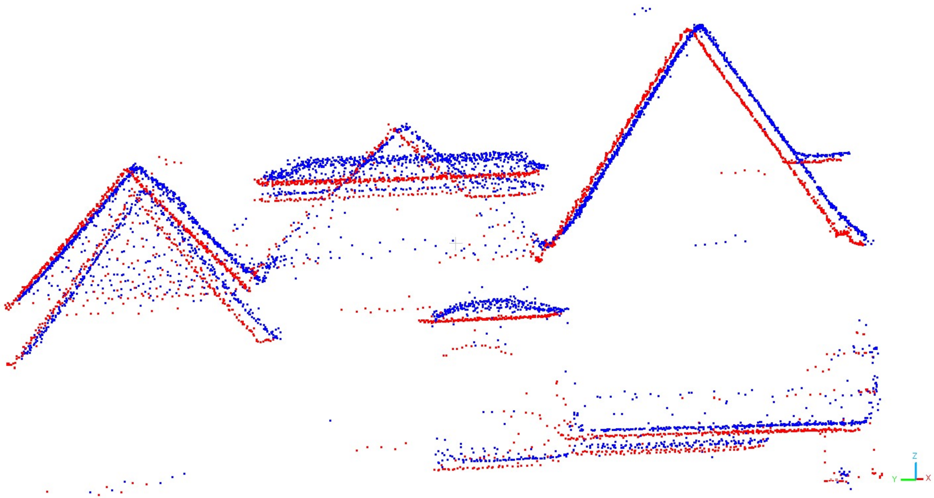

Figure 1: Slight positional mismatch in overlapping point cloud data. Blue points represent Point Cloud Data 1, and red points represent Point Cloud Data 2

A slight mismatch in overlapping point cloud datasets might be problematic, especially for datasets integrated from multiple flight plans to support infrastructure projects where high accuracy and precision are required. For example, point cloud datasets to support designing cross-island infrastructure such as bridges, tunnels, or energy grids. Such mismatches can lead to confusion due to a lack of clarity in the representation of objects in overlapping areas and raise doubts about the accuracy of the datasets. In such cases, point cloud registration of two overlapping point cloud datasets might be useful in reducing gaps between the misaligned data.

Registration is a well-researched procedure performed either manually or semi-automatically by detecting corresponding key features in the overlapping areas of the two point cloud datasets. The positional difference between these key features are measured to estimate the roto-translational matrix needed to align one point cloud dataset to the other, which is considered the reference Pirotti et al. (2023).

There are several methods for point cloud registration to integrate two overlapping point cloud datasets. One such method is feature-based point cloud registration, which is classified as global point cloud registration, as studied in Fontana et al. (2021) and Cheng et al. (2018). This method relies on the extraction of key geometric features that represent salient points on the surfaces of real-world objects. The extraction of key features for point cloud registration is a well-researched area. For instance, the combination of tree canopies and their corresponding ground points was introduced in Shao et al. (2022) to register airborne and ground laser scanner point clouds in forest environments. In another approach, linear polygon features of building roof facets were investigated in Wu and Fan (2016) to register airborne laser scanner point clouds in urban areas. Furthermore, line features of road markings also extracted from airborne laser scanners were recently studied by Daan van der Heide for registering point clouds in large-scale point cloud projects.

Despite the variety of features explored in point cloud registration, road markings offer unique advantages for large-scale point cloud registration applications. As linear geometric features commonly found on roads, they provide consistent and easily identifiable patterns across extensive spatial areas. These characteristics make road markings a promising choice as key features for registering point clouds, particularly in large-scale regions where road networks are established and widely distributed.

As discussed in D et al. (2023), a sufficient quantity and proper distribution of control points are crucial for achieving valid positional accuracy in data validation. However, since road markings are considered natural objects in this context, their quantity and distribution cannot be controlled during the pre-data acquisition process. This raises the issue of identifying which scenarios make the distribution of road markings suitable for use as a key feature in the registration process. Beyond their quantity and distribution, road markings undergo several steps to be modelled as line-type key features for registration. Meanwhile, the extraction of building ridge lines, also as line-type key features, has also been studied and presented at the Netherlands' AHN Congress in 2024 by Peters (2024) and Elberink and Vosselman (2024) to do registration of airborne point cloud, using a different modelling approach. This raises the question of whether a different approach to extracting key features affects the registration quality. Cheng et al. (2018) highlights that proper feature identification is critical for registration accuracy. Daan van der Heide explained that two key attributes for identifying road markings in point cloud data are intensity and density. This highlights the need to evaluate the robustness of road markings as key features under varying point cloud densities.

This study builds on the work of Daan van der Heide, who demonstrated the potential of road markings as features for point cloud registration in large-scale projects. Expanding on this, the current research focuses on testing the implementation of road markings as key features in the context of coarse registration of airborne point clouds from spatially separated islands. The registration of livable island point clouds presents an excellent study case due to its large-scale nature, the presence of established road networks and buildings, and the varying geographic conditions of the islands, which may be surrounded by other islands or have only one adjacent neighbour. However, these scenarios are particularly challenging due to the presence of water bodies in overlapping areas, which limits the availability of road markings as control features. The findings of this research are expected to provide insights into the applicability and robustness of road markings as features in large-scale point cloud data integration, especially in spatially separated island areas.

2 Related work

Several studies were reviewed to support this research, starting with exploring the underlying reasons for airborne point cloud registration and the errors that necessitate this process. The review also examines the potential limitation of registration, specifically focusing on methods that relate to the use of road markings as key features. Furthermore, the methods of key feature extraction for registration are reviewed. Finally, methods for validating the result of the registration process are evaluated to ensure reliable outcomes.

2.1 Study on the Source of Misalignment in Airborne Laser Scanners

Airborne laser scanner systems are classified as active remote sensing technology. They conceptually record point cloud data by transferring the carrier's coordinates, obtained via GPS, to points on the Earth's surface. This is achieved by measuring the laser pulse travel time and the laser transmission angle, which is corrected using the carrier's flight attitude data Killinger (2014). This technology integrates three systems that work systematically during the data acquisition process: global navigation satellite systems (GNSS), inertial navigation systems (INS), and laser ranging technologies. According to Schenk (2001), each subsystem has its own reference frame and formulation for recording the real-world coordinates of points on the Earth's surface. However, each sensor may introduce systematic errors, which could potentially affect the accuracy of the measurements.

According to Schenk (2001), the gap between potential accuracy and actual accuracy achieved with airborne laser scanner highlighted by several reasons; errors are not well-explained, calibration methods are insufficient and lack proper quality controls, correcting systematic errors is time-consuming and lacks validations due to absence of an error model. These challenges underscore the need for better error modelling, transparent calibration methods and more automated error correction processes.

2.2 Evaluating the Limitations of Coarse Registration

Many point cloud registration processes employ a coarse-to-fine strategy to achieve better registration results. Cheng et al. (2018) defines line-based registration as part of the coarse registration method due to its reliance on the geometric shape of real-world objects as key features. The study also highlights the importance of proper feature identification to achieve accurate coarse registration results. Additionally, the study mentions that line-based feature registration may offer higher accuracy and precision than other shapes, as line features are easier to detect and extract.

Fontana et al. (2021) mentioned two primary drawbacks of coarse point cloud registration. Firstly, the detection of key features and the computation of their descriptors are computationally expensive. Secondly, the accuracy of the registration results is often limited, making coarse registration suitable primarily for providing an initial estimate, which is then refined using other techniques, such as fine registration. However, there is no direct, quantitative comparison between the two types of techniques in the study.

Xu et al. (2022) employs a coarse-to-fine registration strategy to align airborne LiDAR bathymetry point clouds. The coarse registration is performed using the RANSAC method, with curved lines as key features generated from extracted isoline points. The outcome is then refined using the ICP method. The study highlights the registration accuracy achieved through both the coarse and fine registration processes. The results demonstrate that better point cloud transformation parameters are obtained after the ICP fine registration step. This indicates that coarse registration alone may not achieve the same level of accuracy as fine registration. However, fine registration performs more effectively when the initial position of the point cloud to be registered is first estimated through the coarse registration process.

2.3 Methods of Key Feature Extraction for Coarse Registration

Many key features for registration have been developed over the past decade. This progress has been driven by the challenge of misalignment in overlapping point cloud data collected using various point cloud acquisition techniques across different survey locations. Moreover, developing key feature extraction methods in some studies has been accompanied by novel research on automated corresponding feature identification.

In Xu et al. (2022), the study focuses on underwater point clouds, where the density is sparse (approximately 1 to 1.5 points per square meter), making it difficult to identify distinct objects. To address this, the researchers introduced the use of curve lines as key features for coarse registration. These curve lines are generated by interpolating isoline points within the overlap area of underwater point clouds collected by airborne LiDAR bathymetry. To perform the matching, the study employs the Longest Common Subsequence (LCSS) algorithm and the curve deformation energy function to identify corresponding curves in the data. The results of the coarse registration show a significant improvement in the alignment of the two point clouds, proved by the reduced distance between them after the coarse registration process. This indicates that the approach effectively estimates the initial positions of the the point clouds.

In Shao et al. (2022), the study focuses on registering ground laser scanner and airborne laser scanner data in forested areas to support forestry inventories, as tree height is one of its attributes. While the ground laser scanner effectively captures tree height in dense forests, it struggles to collect information above the tree canopy. This limitation necessitates integration with airborne laser scanner data. The study determines the rotational parameters by fitting the normal vectors of ground points from both ground and airborne point clouds. Further refinement of the rotational relationship along the z-axis is achieved by matching the top-view projections of both datasets' canopy shapes, converted into 2D images. To do that, corners with significant geometric gradient changes on canopy contours are extracted as key features by determining the connectivity between each point on the curve and its four neighbouring points. A matching strategy based on the distance between two points is proposed to identify corresponding key features and further enhanced by analyzing the differences in image grids at the same positions. However, the approach relies on the consistency of both datasets in the horizontal direction, making it more suitable for refinement rather than providing an initial estimation.

The road marking extraction method proposed by Daan van der Heide is developed to register large-scale airborne point cloud datasets. Along with the building ridge lines, which were presented by Peters (2024) and Elberink and Vosselman (2024) in the AHN Congress of The Netherlands, road markings might have the potential to improve the quality of registration of AHN dataset within different types or other large-scale point cloud registration. As researched by Daan van der Heide, the characteristics of road markings make it noticeable through intensity values with a sufficient amount of density. Further in the research, Daan introduced the use of six geometric features as parameters to automatically detect road markings in point cloud data as presented in Table 1.

Table 1: Geometric Features and Their Formulas As Parameters of Road Marking Extraction from Airborn Point Cloud Data

Name	Formula
Linearity	$\frac{\lambda_1-\lambda_2}{\lambda_1}$
Planarity	$\frac{\lambda_2-\lambda_3}{\lambda_1}$
Sphericity	$\frac{\lambda_3}{\lambda_1}$
Anisotropy	$\frac{\lambda_1-\lambda_3}{\lambda_1}$
Sum of the Eigenvalues	$\sum_{i=1}^{3} \lambda_i = \lambda_1 + \lambda_2 + \lambda_3$
Change in Curvature	$\frac{\lambda_3}{\sum_{i=1}^{3} \lambda_i}$

2.4 Quality validation

The term accuracy in point cloud registration typically refers to the remaining mismatch distance between the registered and the reference point cloud. Various methods have been developed to measure this mismatch distance between two overlapping point cloud datasets. It is often calculated as the average distance of checkpoints. However, some studies use additional methods for mismatch calculation to further support their findings.

Wu and Fan (2016) proposes an evaluation of registration accuracy by manually selecting a number of point pairs on the surfaces of salient objects as checkpoints and computing the distance between each pair. The average of these computed distances is then calculated and presented as the registration accuracy. To further assess the registration accuracy, several building roofs in the overlapping area are selected to measure the vertical differences between points representing the building roofs in each point cloud dataset. Furthermore, an error sensitivity analysis was performed to evaluate the robustness of the proposed registration method by defining the true transformation parameters and introducing varying levels of random error to the test data. However, the validation did not include the angular rotation and translation deviation measurement between the proposed method and the ground truth.

Xu et al. (2022) proposes an evaluation method to measure angular rotation and translation deviations. This is done by manually registering the test datasets and using the resulting rotation and translation parameter values as ground truth. These ground truth values are then compared with those generated by the proposed registration method. This approach allows for analysing the spatial distribution of the key features. For instance, if a high deviation is observed in the angular rotation along the x-axis, it could indicate issues with the key features located in the northern or southern parts of the overlap area. Such issues might caused by poor key feature extraction or the absence of usable key features in those regions. However, this method heavily depends on the operator's role in manual registration, where the visualization of the point cloud may influence the key feature selection process.

Donkers (2024) proposes a method to validate the quality of overlapping point cloud datasets by comparing surfaces generated from samples of points on both datasets to samples of points in the corresponding area. With this approach, the distance between the sample points and the ground truth surface can be modelled as another surface, allowing the normal vectors of both surfaces to be compared. This enables the modelling of angular rotation deviation with reduced operator involvement. However, the distribution of the test areas must be carefully considered to ensure accurate results.

3 Research questions

3.1 Objective

The main research question of this research is:

"How effective are road markings as key features for coarse registration of airborne point cloud datasets from spatially separated islands with overlap?"

With that research question, the effectiveness of road markings as key features in the registration procedure will be tested and evaluated based on their implementation. To achieve this goal, the following sub-research questions are formulated:

- How does the availability of surrounding ground with road markings influence the coarse registration accuracy of point cloud datasets across islands?
- How does the modelling approach of road marking extraction compare to building ridge lines extraction in influencing the accuracy of point cloud registration?
- How robust are road markings as control features for coarse registration under varying point cloud densities?

With these sub-research questions, spatially separated islands provide a suitable test case for road markings in point cloud registration. The islands have varying geographic conditions and extensive road networks. However, the presence of water bodies in overlapping areas poses challenges, making them an effective context to evaluate how well road markings perform.

3.2 Scope of research

The study will focus on testing the effectiveness of road markings as key features for registration. The use of geometric features in registration is classified as coarse registration (see Section 2.2), which is intended for initial estimation. Further refinement of accuracy through fine registration may provide additional parameters for the registration process. However, this will not be discussed at this stage. Although there are various methods for feature extraction, road markings as line-type key features will only be compared with other line-type key features, such as building ridge lines, to ensure a fair comparison. Comparisons between different types of key features will not be explored at this time. While both density and intensity attributes influence the detectability of road markings, the robustness test for road markings in this study will focus solely on density.

4 Methodology

There are two main methodologies conducted in this research

1. Methodology to evaluate the effectiveness of road markings as key features for coarse registration of airborne point clouds across islands with overlap.

2. Methodology of the coarse registration processes.

4.1 Evaluation of Road Markings as Key Features Effectivity

This section provide methods to evaluates the effectiveness of road markings as key features for coarse registration of airborne point clouds across islands with overlaps, focusing on three key aspects:

4.1.1 Evaluating the Suitability of Road Markings in Different Island Geographic Distributions

There are two variations of island geographic conditions that will be tested in this study. The first involves an island located in the middle of a landmass, surrounded by other islands. This condition means the island is likely to have overlapping areas in almost all directions. The second variation is an island neighbouring another island on only one side, while the other side is bordered by water bodies. In this case, the island only have limited area of overlap which is in the direction of its neighbouring island as illustrated in Figure 2.

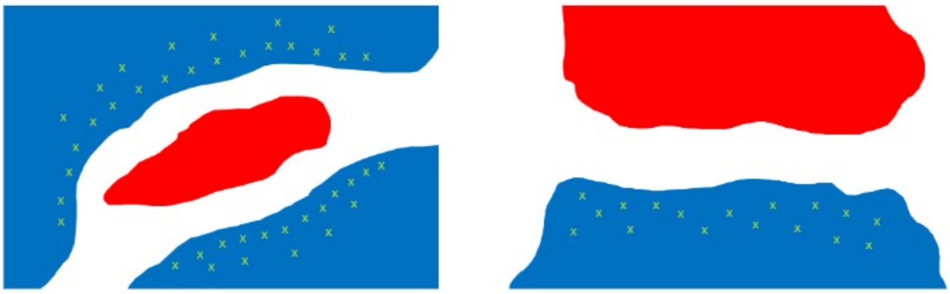

Figure 2: Illustration of Two Cases of Island Geographic Location. Left: Island Surrounded by Other Island, Right: Island with Neighboring Island Only on One Side, Red Colour: To Be Harmonised, Blue Colour: Reference, Green Colour Potential Key Features

A random sample of checkpoint pairs in the overlapping area will be selected to validate the registration results, and the distances between them will be measured and averaged. In addition, a comparison of surfaces within the overlapping area, as proposed by Donkers (2024), will be conducted by selecting random flat grounds distributed in the overlapping area. The validation results of the two conditions will then be compared and analysed, focusing on the distribution of the key features.

4.1.2 Assessing the Impact of Different Modeling Approaches: Road Markings vs. Building Ridge Lines

In conducting this assessment, three tests will be performed: the first test will use only road markings, the second will use only building ridge lines, and the third will use both features. The distribution and number of key features must be the same in these tests to ensure a more reliable comparison. To achieve this, the overlapping area will be divided into six grids using imaginary lines, and in each grid, one key feature will be randomly selected, one for road markings and one for building ridge lines, as shown in Figure 3. This approach ensures that the distribution and number of each key feature used are assumed to be the same.

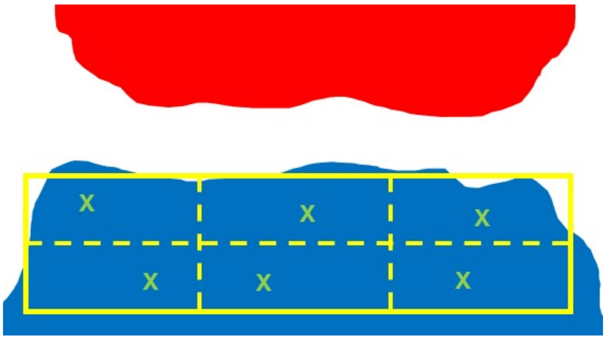

Figure 3: Illustration of Key Feature Selection in Assessing the Impact of Different Modeling Approaches. Red Colour: To Be Harmonised Data, Blue Colour: Reference Data, Green Colour Potential Key Features, Yellow Colour: Overlap Area Divided into Grids

In this assessment, the accuracy of key feature modelling will be tested by measuring the distances between points representing the line and the line key feature represented by those points as illustrated in Figure 4. The average distances from points to the lines will be analysed and compared with the accuracy of the registration results. A control point pair and a surface comparison area will be placed in each grid to evaluate the registration accuracy.

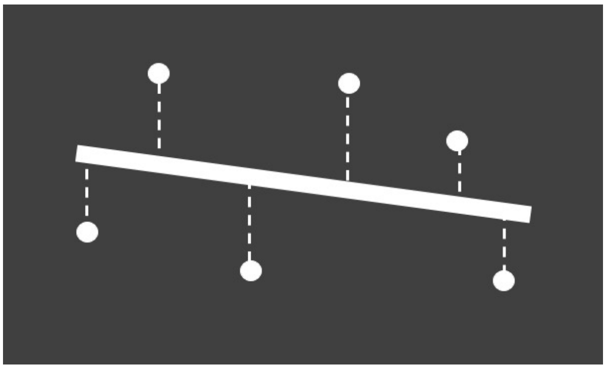

Figure 4: Illustration of Distance Measurement Between Points to Line

4.1.3 Testing the Robustness of Road Markings Under Varying Dataset Densities

To conduct this assessment, datasets with varying densities are required. These datasets will be sourced from open-access airborne point cloud platforms provided by countries other than the Netherlands' AHN project, as each country has its own specifications for airborne point cloud datasets. The accuracy validation of the coarse registration process will be conducted by picking a number of control point pairs distributed over the overlapping area. Then the averaged value of the distance between corresponding control points will be compared with the other registration validation results conducted in different datasets.

The accuracy validation results will be plotted on a line graph, with the x-axis representing the names of the countries and the y-axis representing the accuracy, example shown in Figure 5. This will facilitate the robustness analysis. The trend of the line displayed in the graph will

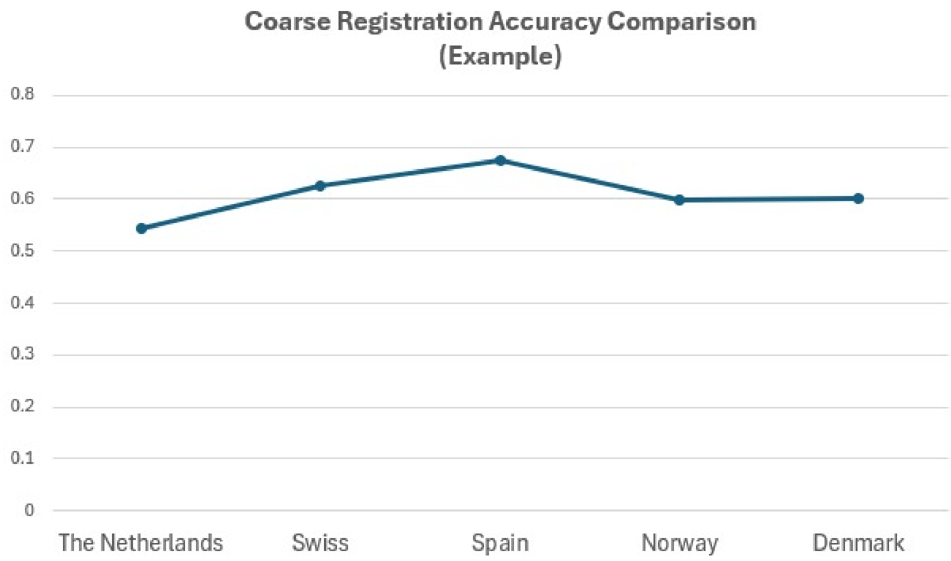

Figure 5: Example of Density Comparison Result

form the basis of the analysis: the flatter the line, the more robust the method; the more the line fluctuates, the less robust the method. Additionally, datasets that produce poor registration accuracy will be highlighted for further investigation.

4.2 Coarse Registration Processes

This section provides an explanation of each sub-process involved in coarse registration to be undertaken in this research.

4.2.1 Data Preparation

Data preparation will be carried out using Cloud Compare software. The island point cloud will be segmented out with a random amount of overlap with its neighbouring island included. Further, a small amount of translations and rotations transformation values in all 6 axes will be applied to simulate systematic errors in the data.

4.2.2 Estimation of Road Marking Extraction Parameters Values

To estimate the values of road marking extraction parameters, approximately 1,000 road markings distributed across the Netherlands and detected in the AHN point cloud datasets will be segmented. Each road marking segment will be used to compute the six geometric features of road marking extraction as proposed by Daan van der Heide (see Table 1). The computed values for each geometric feature will then be averaged. These averaged values for each of the six geometric features will be considered the estimated road marking extraction parameter values to be used in the automatic extraction process. To carry out this task, collaboration with Daan van der Heide will be undertaken.

4.2.3 Extraction of Road Markings

The estimated parameter values obtained from the previous task will be used to automatically extract road markings from the selected datasets using a program developed by Daan van der Heide in his research. This task will be carried out in collaboration with Daan van der Heide.

4.2.4 Extraction of Building Ridge Line

Peters (2024) presented a method to extract building ridge lines at the AHN Congress 2024. This method involves several steps to extract building ridge lines from point cloud data. The process begins with plane detection using a region-growing algorithm. The detection evaluates the angular difference between the normal vector of the plane and the point's normal vector, as well as the distance between the point and the plane. Next, intersections with adjacent planes are calculated to determine the planes that cover the building. The intersection line of roof planes is then estimated as a ridge line. The extracted ridge lines undergo filtering based on several parameters, including the length of the lines, the number of points within the detected planes, the quality of plane detection, and the orientation of the plane normals. Lines that deviate significantly from a horizontal orientation are excluded.

4.2.5 Matching Processes

After the key features are extracted in the overlapping area of two point cloud datasets that want to be registered, pairs of corresponding features between the two point clouds have to be found. Further, the distance between each corresponding key feature will be calculated.

To transform the distances between key features into a transformation matrix, Wu and Fan (2016) provides a detailed mathematical derivation and a systematic workflow for calculating the rotation and translation parameters to minimise the distance between two point cloud datasets. The formulas for calculating the rotation and translation matrices will also be implemented in this research. The study uses the normal vectors of linear plane features of building roof facets as the key features to compute the rotation and translation matrices. However, in this research, the normal vectors will be replaced with direction vectors extracted from line key features.

4.2.6 Registration Accuracy Validation

There are two methods used for registration accuracy validation in this research. The first method involves manual control point pair selection, which will be conducted using Cloud Compare. The second method is a surface comparison approach, as researched in Donkers (2024), and will be implemented using a Python program.

In the first method, a number of points on salient objects within the overlapping area of both datasets will be selected as control point pairs after the registration process is completed. These objects may include building corners, roofs, or other easily identifiable features with distinct edges. The distances between the points in each pair will be calculated and then averaged. This value will be considered as the registration accuracy.

In the second method, a surface comparison will be performed by first subsetting an area of the point cloud from both datasets within the overlapping region. A plane will then be fitted to the segmented point cloud using the Principal Component Analysis (PCA) algorithm. Once a plane has been fitted to the points, the signed distance from the points to the plane will be evaluated to ensure the quality of the fitted plane. If the accuracy of the fitted plane is inadequate, the point cloud subsetting will be redone in a different or smaller area. Building upon the method proposed in Donkers (2024), adjustments have been made to better align with the requirements of this research. After creating overlapping planes from both datasets, the planes' normal vectors will be extracted and compared to evaluate the angular rotation deviation.

5 Time planning

5.1 Schedule

The section presents the schedule for the graduation projects, covering key activities from topic exploration to final assessment, as shown below.

Table 2: Schedule for Graduation Project

Start	**End**	**Activity**	**Weeks (roughly)**
09 Oct	11 Nov	Exploring graduation topics	2
	15 Nov	**P1 - Topic Finalisation Progress Review**	
16 Nov	10 Jan	Literature study	8
16 Nov	20 Dec	Methodology building	4
21 Dec	10 Jan	Graduation plan proposal writing	3
	20 Jan	**P2 - Formal Assessment Graduation Plan**	
03 Feb	16 Feb	Segmenting road markings	2
03 Feb	16 Feb	Making program to calculate parameters values	2
17 Feb	23 Feb	Test data preparation	1
24 Feb	9 Mar	Making program for matching processes	3
10 Mar	30 Mar	Making program for accuracy validations	3
07 Apr	13 Apr*	**P3 - Colloquium Midterm**	
14 Apr	20 Apr	Road marking effectiveness testing	1
21 Apr	07 May	Results Analysis	1
28 May	11 May	Thesis writing	2
12 May	01 Jun*	**P4 - Formal Process Assessment**	
02 Jun	08 Jun	Finalise thesis	1
09 Jun	15 Jun	Presentation Preparation	1
16 Jun	22 Jun*	**P5 - Presentation and Final Assessment**	

The exact dates for P3, P4, and P5 have not yet been determined and will be decided as the research progresses.

5.1.1 Meetings

Weekly meetings will be conducted with the responsible supervisor, Daan van der Heide, to ensure consistent progress and address any challenges. Additional guidance and feedback will be provided by the graduation professor, Jantien Stoter, at key stages of the research.

6 Tools and datasets used

6.1 Tools

To prepare the road markings segments for calculating road marking extraction parameter values, Cloud Compare will be utilised. This is due to its capability to display point clouds using intensity values, detect road markings within the point cloud datasets, and segment those point clouds by manually drawing a polygon around the desired area and saving it as a new dataset. To compute the geometric features of the segmented road markings, Python will be employed alongside specialised libraries designed for point cloud data processing. The Laspy library will be used to handle .las or .laz files. Additional Python libraries, such as NumPy for numerical calculations and SciPy for advanced geometric computations, will also be utilised to calculate the six geometric features required in this process.

In developing the programme for the matching process, implementing the building ridge extraction method, and conducting surface comparison for accuracy validation, Python will be used alongside the Laspy library to read and manipulate point cloud data. This library enables the extraction and modification of key attributes such as coordinates, intensity, and classification directly from the point cloud datasets, thereby simplifying processes such as filtering building point clouds to streamline the ridge line extraction process. Additional libraries, such as NumPy and SciPy, will be utilised to calculate the rotation and translation matrices in the matching programme, while Scikit-learn will be employed to implement the PCA algorithm in the surface comparison programme.

6.2 Datasets

The primary dataset to be used is the AHN point cloud dataset, which provides detailed elevation data across the Netherlands. However, the AHN dataset consists of very large point cloud records within each AHN grid, available at https://www.ahn.nl/dataroom, which makes it challenging to open in Cloud Compare. Therefore, the AHN point clouds that have already been simplified into smaller grids, maintained by TU Delft will be used. These are publicly available at https://geotiles.citg.tudelft.nl/.

To conduct the third test, which evaluates the robustness of road markings as key features under varying dataset densities, datasets with different densities will be utilised. Open-source point cloud data publicly available from other countries will be used for this purpose. During the methodology-building phase, several openly accessible airborne point cloud datasets from countries other than the Netherlands were identified. Examples of these datasets include those from Spain, Norway, Switzerland, and Denmark.

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