Using sensor-data collected by a *meet rollator* for deriving outdoor accessibility information concerning mobility impaired people

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USING SENSOR-DATA COLLECTED BY A *MEET ROLLATOR* FOR DERIVING OUTDOOR ACCESSIBILITY INFORMATION CONCERNING MOBILITY IMPAIRED PEOPLE

By

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PREFACE

The outdoor accessibility, an important subject which should receive more attention, because not all pedestrian paths are accessible for mobility impaired people who need assistance or mechanical aid in terms of a wheelchair, rollator or mobility scooter. Without insight into the accessibility of the outdoor environment, it is hard for road managers to decide which pavements need to be refurbished to make them accessible for everybody. This thesis forms the research performed during the past 8 months and is written as part of the Master of Science program Geomatics. The knowledge and skills of the 1st and 2nd year were combined. This graduation project is part of the theme 'GIS and Spatial analysis' and accounts for 45 ECTS (European Credit Transfer System; 1260 hours study).

In this section I would like to thank everybody who has helped and supported me during this time. First I would like to thank my supervisor Edward Verbee for his support, guidance and making time for meetings. In addition, I would like to thank my professor Sisi Zlatanova for her time and valuable comments to keep improve my work. From the *meet rollator* project I want to thank my supervisor Ron van Lammeren and his colleague Philip Wenting for their interest, valuable input and providing me with the opportunity to do my thesis as part of the *meet rollator* project of the Amsterdam Institute for Advanced Metropolitan Solutions (AMS). And last but not least I would like to thank my family for their support.

SUMMARY

Nowadays, not all pedestrian paths are accessible for mobility impaired people. Especially paths which consist of complex public spaces and old streets constitute problems. However, no reliable information is (quickly) available about problems that cause hindrance. The sensing rollator called ***meet rollator*** is equipped with several sensors that provide detailed data about a range of factors which affect the accessibility of the outdoors environment. A *meet rollator* gathers data that is supplementary, new and different.

The goal of this thesis is to use sensor-data collected by a *meet rollator* to develop a geo-database that provides insight into the accessibility of pedestrian routes for mobility impaired people who need a wheelchair, rollator or mobility scooter. In order to achieve this goal, the following research question is defined: Does the current setting of the *meet rollator* provide insight into the accessibility of pedestrian routes for mobility impaired people? If not, how can the current setting be improved? This research has evaluated the available sensor (handheld Global Positioning System (GPS), Real-Time Kinematic (RTK) GPS and camera) data collected by a *meet rollator*.

Literature study showed that in order to determine walking restrictions in the outdoor activity space of people with mobility impairments, the geometrical demands for movement can be taken into account. According to the Manual-book of Accessibility and an expert Job Haug, a good pedestrian path for people with a wheelchair, rollator and scoot mobile has to meet three geometrical demands for movement. This means that a pedestrian path forms an obstacle if it is narrower than 0.9 meter, steeper than 9.46° or if the height difference on the path is higher than 0.05 meter.

The outcome, according to the assessment of the three available sensors (handheld Global Positioning System (GPS), Real-Time Kinematic (RTK) GPS and camera) of the *meet rollator* by using the knowledge of the Master of Science program Geomatics, is that with a handheld GPS no precise positioning can be reached. Therefore handheld GPS data is not useful for generating accessibility information. According to the knowledge the two sensors RTK GPS and camera are useful for generating accessibility information. The outcome, according to the implementation of the developed workflow for deriving outdoor accessibility information for a selected research area, is that some paths in the outdoor environment of Amsterdam require improvements to make them accessible for mobility impaired people. Furthermore through data processing, more insight is gained into the usefulness of RTK GPS and camera data. The results showed that the used sensors did not provide the needed precision.

For the validation of the derived outdoor accessibility information a division is made between the validation of RTK GPS observations and camera observations. The BGT+ is proved suitable for providing more insight in and put semantics to the total observations obtained by implementing the workflows. The ground truth is proved suitable for validating the obtained accessibility information derived from RTK GPS and camera data. Finally, the results of an algorithm made by the Urban Modelling Group (UMG) of the University College Dublin are proved suitable for validating the obtained accessibility information derived from camera data.

A geo-database that structures the validated accessibility information is created in order to give an overview of the accessible and non-accessible paths for the research area. The derived accessibility information obtained via camera data can best be stored by using polygons, to represent complex areas. The derived accessibility information obtained via RTK GPS data can best be stored by using line strings.

In conclusion, this MSc thesis has demonstrated that the current setting of the *meet rollator* provides insight into the accessibility of pedestrian routes for mobility impaired people. However, the used sensors did not provide the needed precision. In order to improve the current setting of the *meet rollator* the usefulness of other sensors should be further investigated.

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LIST OF ACRONYMS

2D	Two-dimensional
3D	Three-dimensional
AHN-2	Height model of the Netherlands (Dutch: Actueel Hoogtebestand Nederland), second version
BGT	Dutch key registry for large scale topography (Dutch: Basisregistratie Grootschalige Topografie)
DEM	Digital Elevation Model
DGPS	Differential global positioning system
GIS	Geographic information system
GNSS	Global navigation satellite systems, any of the existing satellite-based positioning systems, such as GPS, GLONAS, Galileo and Beidou
GPS	Global positioning system
LiDAR	Light detection and ranging
TIN	Triangulated irregular network
RTK	Real Time Kinematic

1. INTRODUCTION

This introduction will start with a motivation and background. Subsequently, the problem description will be discussed. Hereafter, the defined research objectives and questions, and research limitations will be described. The methodology describes how this research is executed. Subsequently, the research area, which is used for achieving the objectives, will be defined. Finally, a reading guide is provided, to guide the reader through this thesis.

1.1 MOTIVATION AND BACKGROUND

Rollators, wheelchairs and mobility scooters are a godsend to many people, allowing them to move without fear of falling and providing them with more independence and mobility, especially in urban environments like Amsterdam (located in North-Holland, province of The Netherlands). Unfortunately, many pedestrian paths are not always that friendly for mobility impaired people who need assistance or mechanical aid in terms of a wheelchair, rollator or mobility scooter. There are bikes blocking pavements, curbs without ramps, streets dug up for repair and road construction works. Several previous studies (i.e. (Matthews & Vujakovic, 1995) and (Sanford, Arch, Story, & Jones, 1997)) have demonstrated how the imperfect design of the built environment tends to restrict mobility and creates insecurity for those with mobility impairments. The sensing rollator called ***meet rollator*** gathers data about popular routes and their accessibility. It is equipped with several sensors that provide detailed data about a range of factors which affect the accessibility of the outdoors environment. To help map and eventually prevent problems like these, in this thesis sensor-data collected by a *meet rollator* will be used.

Knowing the range of factors which affect the accessibility is also important because of the relatively large aging population. The number of mobility impaired people is expected to increase. Approximately 17% of the population in the Netherlands is over the age of sixty-five. Society is highly motivated to insurance that this growing aging population stays independent. And perhaps more importantly, most people themselves want to be independent for as long as possible (AMS, 2015).

In the Netherlands people with disabilities are still in a disadvantaged position, which causes that they are not able to (fully) participate in society. There are laws and regulations with the aim to increase the participation of people with disabilities and to strengthen their rights. On 13 December 2006 the United Nations adopted the "Convention on the Rights of Persons with Disabilities (CRPD). This convention aims to promote, protect and guarantee human rights of people with disabilities, and describes what the government should do to ensure that the position of people with disabilities will improve. The Netherlands has signed the CRPD on the 30th of March 2007, but it is not yet ratified. Soon the Netherlands will ratify this convention the focus on accessibility for people with disabilities will become more relevant (Rijksoverheid, 2014).

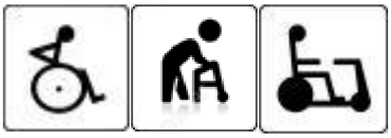
1.2 PROBLEM DESCRIPTION

Nowadays, not all pedestrian paths are accessible for every pedestrian. Especially paths which consist of complex public spaces and old streets constitute problems. Road managers have the responsibility that everyone should be able to move over an accessible pedestrian path, but unfortunately they do not apply the criteria which make pedestrian paths accessible for every pedestrian. Furthermore there is no reliable information (quickly) available about problems that hinder pedestrians. A geo-database (i.e. a collection of data stored with the help of a DataBase Management System (DBMS)) that provides insight into the accessibility of pavements does not exist in the Netherlands.

Each municipality employee who is working on issues, for which information is needed about the problems on a street or intersection, will recognize the lack of information. Therefor different problems (that hinder, cause interruptions or force people to detour in the pedestrian network) have to be investigated. The data gathered by a *meet rollator* provide reliable information about the possible problems that hinder pedestrians in the urban environment. A *meet rollator* gathers data that is supplementary, new and different.

1.3 RESEARCH OBJECTIVES AND QUESTIONS

<u>The goal of this research is to use sensor-data collected by a *meet rollator* to develop a geo-database that provides insight into the accessibility of pedestrian routes for mobility impaired people who need a wheelchair, rollator or mobility scooter.</u>



In order to achieve this goal, the following research question is defined: Does the current setting of the *meet rollator* provide insight into the accessibility of pedestrian routes for mobility impaired people? If not, how can the current setting be improved?

The research goal and the research question are devised to develop a new methodology that can support managers of the municipality in the design, refurbishment and management of the environment (like upgrading of the pavement) so that well informed decisions can be made to make pedestrian paths accessible for mobility impaired people. Road managers must know the potential problems and therefore the accessibility information should be structured. With the results the existing infrastructure can be optimized. For many paths improvements are required to make them accessible for every pedestrian (young, old, good walkers or rollator-users). To efficiently improve these paths, knowledge about the location of problems that hinder pedestrians in the urban environment is necessary and how these affect the accessibility. In order to achieve the research goal and research question, four objectives and corresponding sub question are determined.

Objective 1: Define the problems and primary requirements for people with mobility impairments.
Sub question 1: What are potential problems presented by the public space and primary requirements for people with mobility impairments regarding the accessibility?

This objective and corresponding sub question will give an overview of potential obstacles for movement in a wheelchair, rollator and scoot mobile, with the primary conditions.

Objective 2: Identify which data, programs and packages can be used to develop a methodology that generates accessibility information, and determine the accessibility by this proper set of software and data.
Sub question 2: Which measure-method could be developed to generate accessibility information, by making use of the sensor (handheld Global Positioning System (GPS), Real-Time Kinematic (RTK) GPS and camera) data collected by a *meet rollator*, software package PhotoScan, Geographic Information System (GIS) analysis tools and the core-registration Large-scale Topography of the Netherlands (BGT)?

This objective and corresponding sub question will deal with identifying methods and techniques for detecting and extracting outdoor accessibility information. For this purpose GIS Software, specifically developed to support the study of geographic phenomena, will be used. The choice to use the software Agisoft Photoscan Professional (version 1.1.0) is affected by the required accuracy, the available budget and the desired end result.

Objective 3: Design a workflow for validating, providing more insight in and put semantics to the generated accessibility information, by using: the ground truth, results of an algorithm made by the Urban Modelling Group (UMG) of the University College Dublin, airborne laser scanning data (AHN-2) and the BGT+.
Sub question 3: How can the ground truth and results of the UMG algorithm be used to validate the generated accessibility information? And do the AHN-2 and BGT+ provide more insight in and put semantics to the generated accessibility information?

The BGT+ and the AHN-2 are less accurate and detailed than the generated accessibility information and therefor they cannot be used for the validation. The BGT+ and the AHN-2 are both core registrations and national datasets. The ground truth is the most real value. The results of an algorithm made by the UMG are selected for the validation, because their approach can be compared with the measure-method developed for this thesis.

Objective 4: Design a database that structures the (validated) outdoor accessibility information.
Sub question 4: In what way can the results best be stored in a geo-database in PostgreSQL?

After developing a workflow for deriving outdoor accessibility information, the validated information has to be stored and maintained. The structure of a database is very important. Afterwards a map can be made which can be used to communicate and give advice. A manager will not read a whole document, but wants to see where problems occur. This will be communicated via a map. If someone needs to know the inaccessibility of a street for certain management activities, the derived outdoor accessibility information can be added as an 'additional' layer to other data, like the BGT+ in a GIS environment.

1.4 RESEARCH LIMITATIONS

Although the research scope is indicated by the research objectives and the research questions, this paragraph tries to further delimit the research by discussing some research limitations. Below several research limitations are shown:

- The dataset is limited in time

The *meet rollator* can be seen a platform with sensors which supplies raw data. The dataset, delivered by the *meet rollator*, consist of two observations at two moments in time. The database needs to be fed. So every time new data is available, it has to be analyzed (there is a time-span). The timeliness of the data will not be included in this thesis.

- The dataset is limited in area

It is not feasible to look at all the streets in the world. Therefor the focus will be on one street in Amsterdam.

- Fully automated point cloud processing is out of scope

This research will not deal with fully automated point cloud processing. Point clouds are processed stepwise, with human intervention.

- Some important criteria for mobility impaired people are out of scope

It will not be achievable to discover all important criteria for people with a wheelchair, rollator and scoot mobile. Therefor bus, tram and metro stations; exit structures; guide lines, leading lines and contrast markings; connecting of pedestrian paths to buildings; disabled parking spaces; etc. will not be discussed in this thesis.

- Three-dimensional space is out of scope

My procedure is constrained to two-dimensional space, by taking into account differences in the height coordinates of cells and the restrictions to movement in a wheelchair, rollator and scoot mobile. This is also referred to 2.5D: (x, y) + z.

1.5 METHODOLOGY

The methodology used in order to answer the research questions can be seen in Figure 1 on page 18. This paragraph will discuss how this research is executed. Each sub research question, defined in the paragraph above, will be discussed.

Sub question 1: What are potential problems presented by the public space and primary requirements for people with mobility impairments regarding the accessibility?

This sub question will be tackled by preforming a literature review on relevant scientific books and papers concerning potential problems and primary requirements regarding accessibility.

Sub question 2: Which measure-method could be developed to generate accessibility information, by making use of the sensor (handheld Global Positioning System (GPS), Real-Time Kinematic (RTK) GPS and camera) data collected by a *meet rollator*, software package PhotoScan, Geographic Information System (GIS) analysis tools and the core-registration Large-scale Topography of the Netherlands (BGT)?

This sub question consists of a mixture of measurements, software and existing data. It will be tackled by preforming a literature review, to gain knowledge about the different sensors. Furthermore this sub question will be tackled by developing a workflow for generating accessibility information. This workflow will discuss a method which can be used. The workflow will consist of two parts (see Figure 1 on page 18):

(1) Generating accessibility information via camera data;
(2) Generating accessibility information via handheld GPS and RTK GPS data.

During the processing of camera data, the BGT will be used for making a georeferenced point cloud in the program PhotoScan.

Finally this sub question will be tackled by implementing the developed workflow. The workflow will be tested for the research area, which is defined in paragraph 1.6. The research area is within the Netherlands and is chosen because of data availability.

Sub question 3: How can the ground truth and results of the UMG algorithm be used to validate the generated accessibility information? And do the AHN-2 and BGT+ provide more insight in and put semantics to the generated accessibility information?

This sub question will be tackled in four different parts:

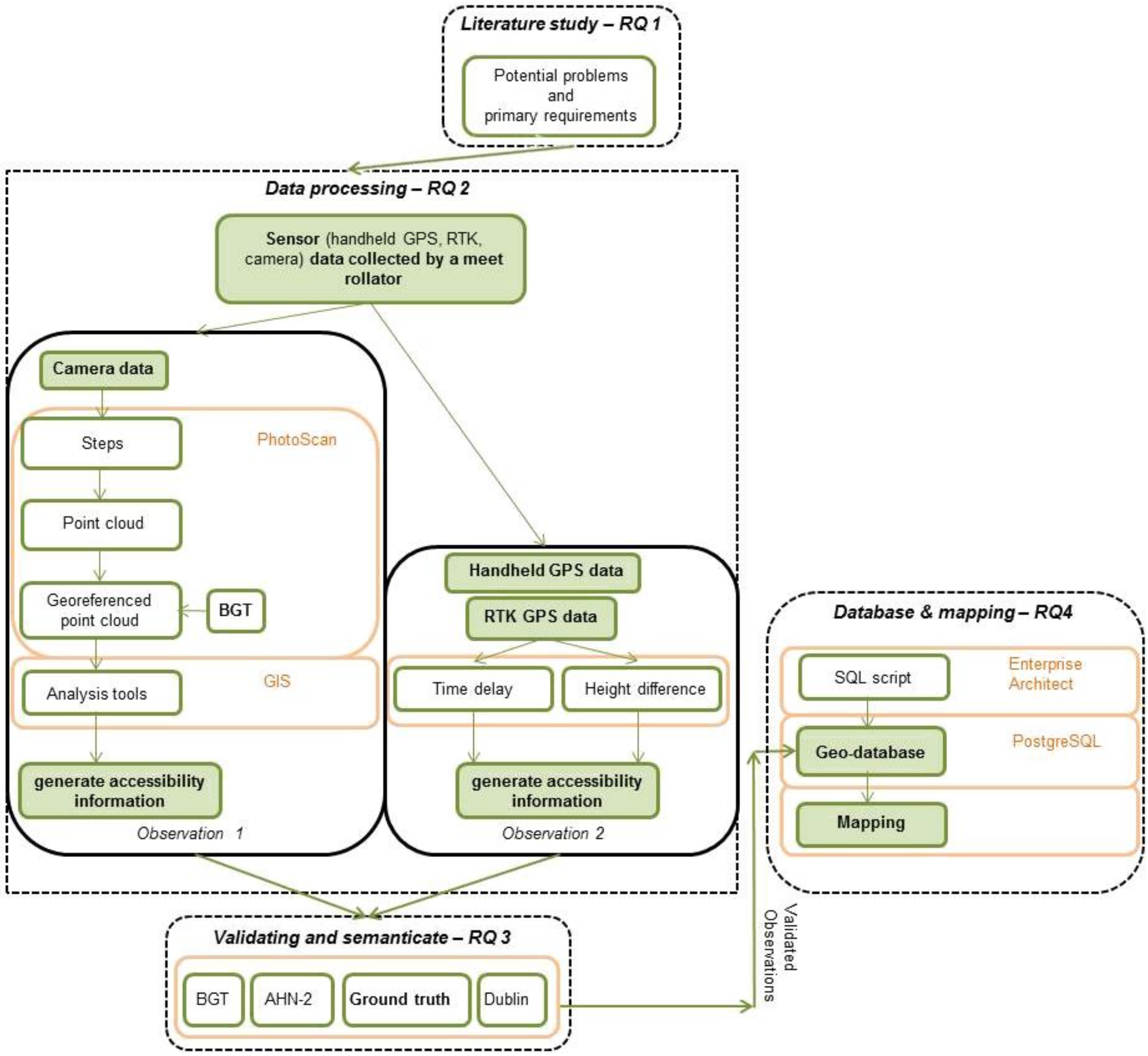
(1) Validating with the ground truth;
(2) Comparing with the BGT+;
(3) Comparing with the AHN-2;
(4) Validating with results of an algorithm made by the UMG

The BGT+ is obtained through the municipality of Amsterdam, which is the system-manager. The AHN-2 is downloaded via the website: http://3dsm.bk.tudelft.nl/matahn which is made by the group members of 3D geo-information at Delft University of Technology. The results of an algorithm made by the UMG are obtained via Anh Vu Vo, one of the members of the UMG.

Sub question 4: In what way can the results best be stored in a geo-database in PostgreSQL?

This sub question will be tackled by developing a geo-database that provides insight into the accessibility of pavements. For designing a database the interdependencies of each database-class need to be determined. Afterwards the verified outdoor accessibility information will be placed in the database. Furthermore a map will be constructed to communicate to managers by showing the positions with restrictions for mobility impaired people.

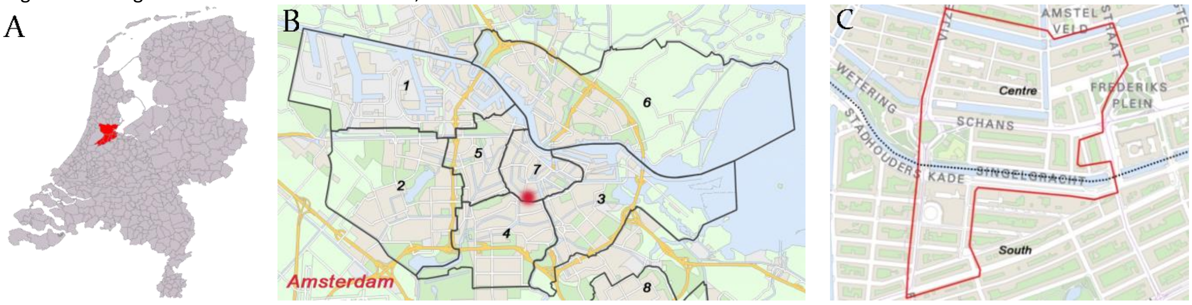
Figure 1: Work Breakdown Structure



1.6 RESEARCH AREA

Figure 2 A shows the location of the research area (red plane) with respect to the Netherlands. Figure 2 B and C show the research area in the municipality of Amsterdam. The municipality of Amsterdam is located in the province North-Holland and is broken up in eight city districts. The defined research area is located in the districts Amsterdam-South and -Centre, and is visualized by numbers 4 and 7 in Figure 2.

Figure 2: Image A and B show Amsterdam, and C shows the research area



Source: (Wikipedia, 2009) (de Haan, 2015)

The focus will be on these two districts (South and Centre) since this area offers a complex public space for people with mobility impairments due to the amount of old streets. District South covers an area of 17 square kilometers and has 132.000 residents. District Centre covers an area of 8 square kilometers and has 81.000 residents. Furthermore the *meet rollator* was used in this area on:

- 16-12-2014 (December);
- 22-01-2015 (January).

1.7 READING GUIDE

After the introduction, chapter 2 will discuss the materials and sensing rollator called *meet rollator.* The focus of this research is on deriving outdoor accessibility information concerning mobility impaired people with sensor-data collected by a *meet rollator.* Therefore, chapter 3 provides an in-depth literature review on related work concerning high-precision surface models, the basics of photogrammetry, a couple of theories and definitions that are often used, and a variety of geometrical demands and obstacles. Chapter 4 will discuss how accessibility information can be generated with the use of the available sensor (handheld GPS, RTK GPS, camera) data collected by a *meet rollator*, software package PhotoScan, GIS analysis tools and the BGT. This chapter will deal with the development of a workflow. Afterwards the developed workflow will be implemented for the research area, which will be discussed in chapter 5. Chapter 6 will discuss a workflow for validating, providing more insight in and put semantics to the generated accessibility information, by using: the ground truth, results of an algorithm made by the UMG, the AHN-2 and BGT+. Chapter 7 will deal with examining how to store the validated accessibility information. Subsequently, the conclusions and recommendations for future research will be provided.

2 MEET ROLLATOR

Because developing a geo-database that provides insight into the accessibility of pedestrian routes with the use of sensor-data collected by a *meet rollator* is the main focus of this thesis, it is necessary to know what the *meet rollator* project means. First of all, paragraph 2.1 will discuss the *meet rollator* project. Paragraph 2.2 will discuss the manner in which the data is collected. Subsequently, paragraph 2.3 will explain how the sensor-data looks like.

2.1 MEET ROLLATOR PROJECT

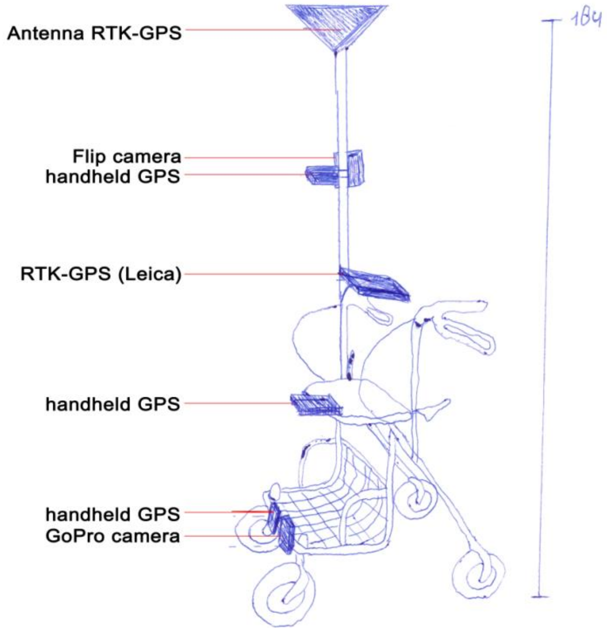
This thesis is part of the *meet rollator* project – a project which was started in 2013 and developed during a brainstorm session between Ron van Lammeren and his colleague Joske Houtkamp. According to van Lammeren, the municipality of Amsterdam selected the idea of this project within the context of four data added-value research projects (Beautiful Noise, Meet Rollator, Social Sensing on Demand, Social Glass). This project has been prepared for teaching, research, governments (mainly municipalities) and elderly (organizations). The findings of this project will also be available via the Amsterdam Institute for Advanced Metropolitan Solutions (AMS), in the context of the *meet rollator* project.

AMS aims to become an internationally leading institute where talent is educated and engineers, designers, digital engineers and natural/social scientist jointly develop and valorize interdisciplinary metropolitan solutions. Metropolitan solutions require cooperation between knowledge institutes, companies, cities and citizens. The city of Amsterdam is in full support of AMS. AMS consists of three academic partners, namely: Delft University of Technology, Wageningen University & Research center, and Massachusetts Institute of Technology in the USA. AMS collaborates also with the knowledge institute TNO, which is an independent research organization (AMS, 2015).

2.2 HOW IS THE DATA COLLECTED

In Figure 3 a sketch is shown of the current setting of the *meet rollator*.

Figure 3: Setting of the *meet rollator*



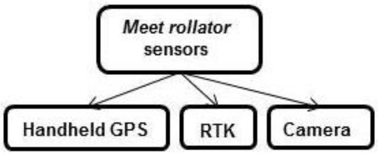
Two measurements were already performed with a *meet rollator* for which the purpose was: to discover whether a handheld GPS receiver is as useful as RTK GPS for position determination. These measurements were performed on: 16-12-2014 (December) and 22-01-2015 (January).

During these measurements the *meet rollator* was equipped with different sensors:

- 2 Video-cameras (GoPro and Flip camera) → Videos
- 3 Handhelds GPS (Garmin Etrex-30) devices on 3 heights → GPX-files
- 1 RTK GPS (Leica) → CSV-file

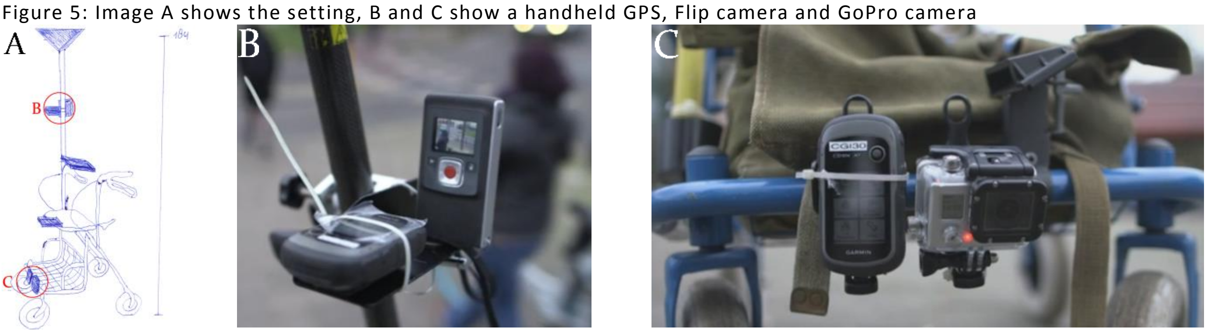
Three Garmin Etrex-30 handhelds were positioned on different heights, to check which handheld receive the best satellite signals to determine the most accurate position. The available sensors (handheld Global Positioning System (GPS), Real-Time Kinematic (RTK) GPS and camera) are shown in Figure 4.

Figure 4: The available sensors



In Figure 5 B the handhelds GPS and Flip camera are visualized. They were installed on a stick (2 meter high). In Figure 5 C the handhelds GPS and Go-Pro camera are visualized. They were installed nearby ground (street-level).

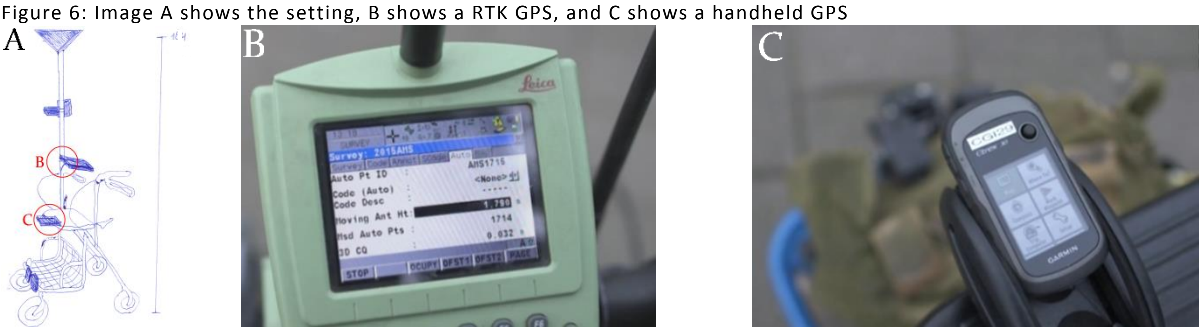
Figure 5: Image A shows the setting, B and C show a handheld GPS, Flip camera and GoPro camera



Source: (AMS, 2015)

Figure 6 B visualizes the RTK GPS which was installed on a height of 1.5 meter above the ground. The antenna of the RTK GPS was installed on a height of 1.84 meter (eye-level). In Figure 6 C the third handhelds GPS is shown which was installed on the sit-platform.

Figure 6: Image A shows the setting, B shows a RTK GPS, and C shows a handheld GPS



Source: (AMS, 2015)

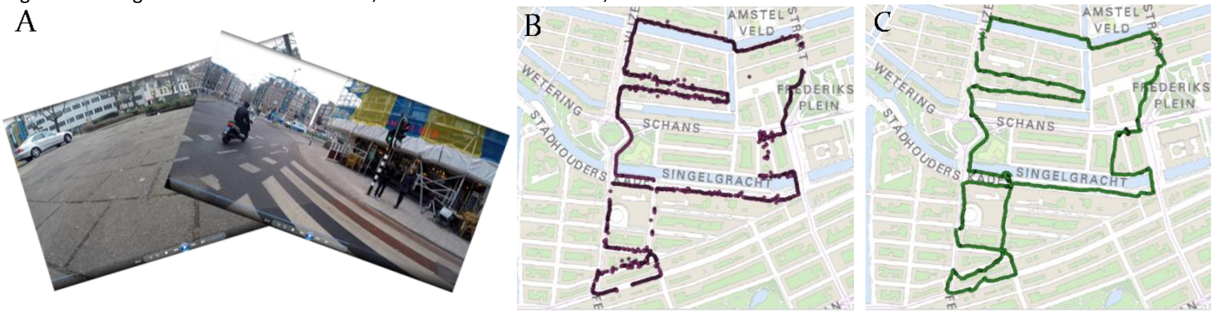
The measurement on 16-12-2014 was performed with six handheld devices and a RTK GPS. Four handhelds were installed on the *meet rollator* (CGI33 (top), CGI34 (sit-platform), CGI36 (street-level), E42 (street level)) and two were carried by hand (CGI32, CIG37). One of the four installed devices was an old handheld GPS device (E42). Also the GoPro and Flip camera were installed on the *meet rollator*.

The measurement on 22-01-2015 was performed with three handheld devices which were all installed on the *meet rollator* (CGI28 (top), CGI29 (sit-platform), CGI30 (street-level)) and a RTK GPS. Also a Flip camera and GoPro cameras were installed on the *meet rollator* performed by the company Synergique (located in Haarlem).

2.3 HOW DOES THE DATA LOOK LIKE

The data provided by the *meet rollator* are: videos, *.GPX files (also KLM files and Text documents) of the handhelds GPS devices and CSV-files of the RTK GPS with the x, y, z-coordinates (see Figure 7).

Figure 7: Image A shows camera data, B shows RTK GPS data, and C shows handheld GPS data



Source: (AMS, 2015) (de Haan, 2015)

In 2015 seven videos were made with the *meet rollator.* One video was made with the Flip camera and the other six videos with the GoPro camera. In 2014 the Flip camera made two videos and the GoPro four. The *.GPX files of the handhelds GPS devices and the CSV-files of the RTK GPS of 2015 contain data over a distance of 2.0 km.

The *.GPX files of the handhelds GPS devices and the CSV-files of the RTK GPS of 2014 contain data over a distance of 6.3 km (see Table 1). The important technical specifications of the cameras used in the study are described in Table 2.

Table 1: Overview of the available camera data

	GoPro video(s)	Flip camera video(s)	Distance
2014	4	2	6.3 km
2015	6	1	2.0 km

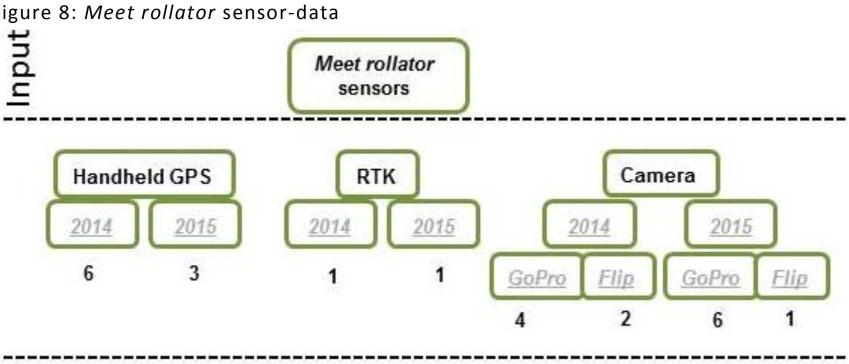
Table 2: Important technical specifications of the cameras used during the performed measurements

	Type	Frames/ second	Frame width	Frame height	Video resolution	Field of View (FOV)	Lens focal length
Flip camera	Video Camcorder Model F260B-UK	30	640	480	30 frames per second frame rate	Narrow: 28mm	80.01 cm (31.5 in)
GoPro camera	GoPro 3	59 or 25	1920	1080	48 frames per second frame rate	Wide: 14mm Medium: 21mm Narrow: 28mm	6.86 cm (2.7 in)

Source: (GoPro, 2015)

For this study the meet rollator sensor-data is used of the measurements which were already performed in December 2014 and January 2015!

Figure 8: *Meet rollator* sensor-data

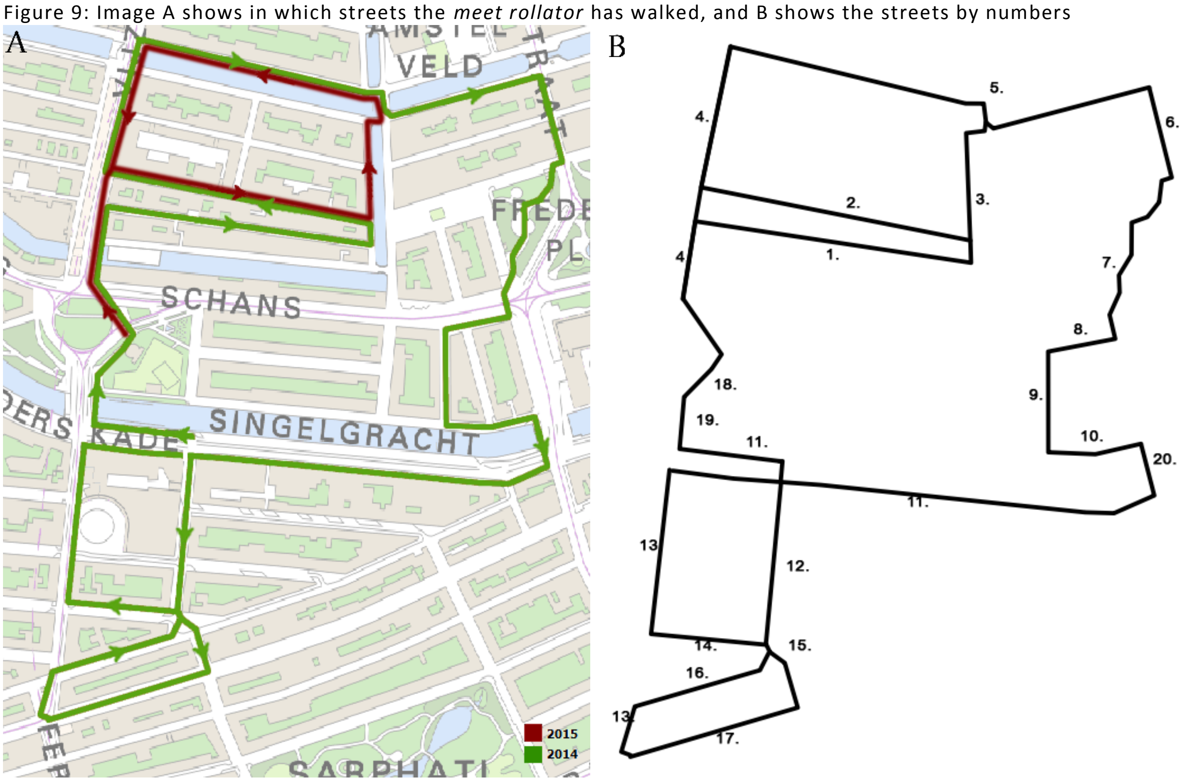


The streets where the *meet rollator* was used are:

1. Fokke Simonszstraat
2. Nieuwe Looiersstraat
3. Reguliersgracht
4. Vijzelgracht
5. Prinsengracht
6. Utrechtsestraat
7. Frederiksplein
8. Weteringschans
9. Pieter Pauwstraat
10. Nicolaas Witsenkade
11. Stadhouderskade
12. Eerste van der Helststraat
13. Ferdinand Bolstraat
14. Daniël Stalpertstraat
15. Gerard Douplein
16. Gerard Doustraat
17. Albert Cuypstraat
18. H.M.V. Randwijkplantsoen
19. Weteringlaan
20. Westeinde

These numbers correspond with the numbers visualized in Figure 9.

Figure 9: Image A shows in which streets the *meet rollator* has walked, and B shows the streets by numbers



Source: (de Haan, 2015)

3 REVIEW

It is necessary to know which related work is already available with respect to the creation of detailed surface models, basics of photogrammetry and accessibility information. First of all, paragraph 3.1 will discuss the related work concerning detailed models. Paragraph 3.2 will discuss the basics of photogrammetry. Subsequently, paragraph 3.3 will explain related work concerning accessibility information. Paragraph 3.4 will explain the use of GPS for positioning. Afterwards a couple of theories and definitions that are often used will be discussed. Finally the potential problems and requirements regarding accessibility will be discussed in paragraph 3.6. Thereby, objective 1 (define the problems and primary requirements for people with mobility impairments) will be achieved.

3.1 RELATED WORK CONCERNING DETAILED MODELS

The request for detailed three-dimensional (3D) models for various applications has risen over recent decades. Detailed digital surface and elevation models can be used for different purposes, in order to extract information from it, within various industries such as surveying, civil engineering and archaeology. In the Netherlands, dike safety is very important and depends on tiny details. The requirements of water management and dike management lead to a massive dataset, for example suitable hydrologic modelling. About 20% of the 17.600 km of dikes in The Netherlands has a height of less than 1 meter and can be almost invisible in the landscape. Therefor an up-to-date high-precision high-density surface model is needed.

Another relevant research in which a detailed digital surface model was created is Hydrocity. Hydrocity introduces an approach for generating a detailed surface model (1:1.000) by combining high-density laser data (AHN-2) with a detailed topographic base map (BGT). This detailed surface model was used for applying water run-off modelling within urban areas.

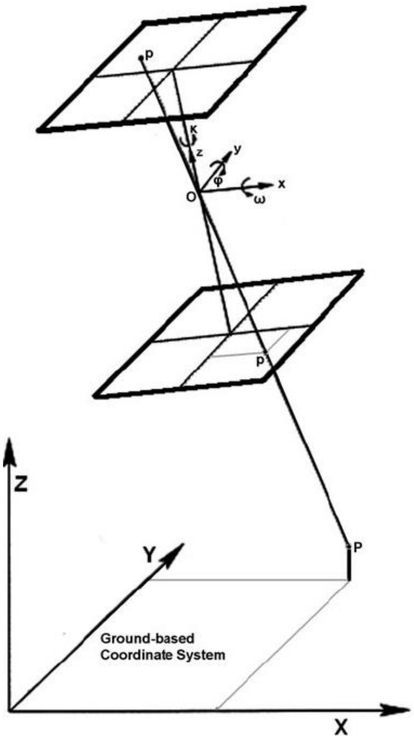
Niels van Beek (2015) discovered for his GIMA Master thesis how airborne laser scanning can be used for deriving topographic features for the purpose of general boundary based cadastral mapping. Topographic features, which are visible due to height differences, can be detected in point clouds produced by airborne laser scanning, by considering them as highly detailed digital elevation models (DEMs).

3.2 BASICS OF PHOTOGRAMMETRY

The professional field dealing with information extraction from images is photogrammetry. Photogrammetry was already in existence more than 150 years ago. The basic task of photogrammetry is to transfer the coordinates of points as measured in images to 3D coordinates in an object-space related reference system. The fundamental assumption is that each and every point in the image uniquely correspondents to one point in the terrain, or more generally, object space. The geometry of a camera is modelled as a central projection. That means the rays of sunlight reflected by each point in the scene pass the camera exactly through one point, the projection center. The basic notion in which all the mathematics in photogrammetry is founded is that object point, projection center and image point constitute one straight line; they are collinear. Mathematically this notion is expressed by a collinearity equation (see Figure 10 on page 26). The collinearity equation is called the central mathematical relationship in photogrammetry. This notion is explained in Figure 10, which shows the linking between the coordinate system of the camera with the ground-based coordinate system, through the six parameters of exterior orientation. The collinearity equation consists out of two equations, in order to retrieve coordinates from an image plan in 2D, to object coordinates in 3D (Lemmens, 2011).

This equation is dealing with the coordinates from object space of a point P (X, Y, Z) and the transformation to those onto image plane coordinates of p (x, y). Three parameter describe the geometry of a camera, those are (x_0,y_0,c), which cover the interior orientation. In order to apply the collinearity equation for obtaining the x, y, z of a point in space, also the exterior orientation are needed, containing the position of the projection center during exposure in (X_o, Y_0, Z_0), plus the attitude of the image plane in (ω, ϕ, κ) relative to the reference system. The X, Y, Z coordinates describe the position of the projection center of the camera in the object-space related reference system at the instantaneous moment of taking the image. The angular parameters describe the direction of the optical axis and the image plane of the camera with respect to the three axis of the coordinate system of the object-space.

Figure 10: The central mathematical relationship in photogrammetry



$$x - x_0 = -c\,\frac{r_{11}(X - X_0) + r_{21}(Y - Y_0) + r_{31}(Z - Z_0)}{r_{13}(X - X_0) + r_{23}(Y - Y_0) + r_{33}(Z - Z_0)}$$

$$y - y_0 = -c\,\frac{r_{12}(X - X_0) + r_{22}(Y - Y_0) + r_{32}(Z - Z_0)}{r_{13}(X - X_0) + r_{23}(Y - Y_0) + r_{33}(Z - Z_0)}$$

Source: (Lemmens, 2011)

These six parameters of the exterior orientation can be determined along direct or indirect methods. The indirect determination consists of using a set of well-distributed Ground Control Points (GCP). The direct method uses on board GNSS receivers for determination of the three coordinates. When the three parameters of the interior orientation and the six parameters of the exterior orientation are known, the image coordinates of an object point of which the X, Y, Z coordinates are known can be computed by using the collinearity equation. At least three observations are necessary to compute three unknown parameters. Therefore, one actually needs two images with overlap that cover the same point in space (Lemmens, 2011).

APPLICATIONS

This rise of the request for detailed 3D models has brought with it the necessary technological advancements in photogrammetry and computer vision to be able to rapidly build detailed 3D reconstructions from two-dimensional (2D) digital photographs. One example of a computer vision method for advanced 3D scene reconstruction is multi-view 3D reconstruction. It is a technology that uses complex algorithms from computer vision to create 3D models of a given target scene from overlapping 2D images obtained via a digital camera. There is already a lot of discussion in the literature on applications of photogrammetry. Yilmaz et al. (2007) adjust photogrammetry for reconstructive purposes, to document a burned building very accurate. Gelli et al. (2003) make use of photogrammetry and digital photo-models to detect damage on materials of historic buildings, with the purpose of restoration work and an evaluation of the required costs. Guidi et al. (2004) use photogrammetric techniques for the digital three-dimensional modeling of a wooden statue, the Maddalena by Donatello.

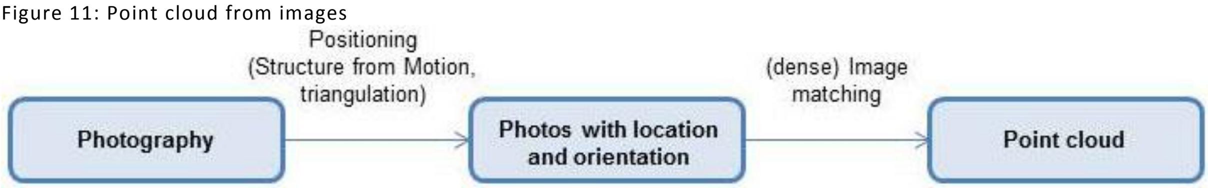
PHOTO MODELLING SYSTEMS

Modeling systems have emerged the last decade, thanks to new techniques. There are different photo modelling systems for producing three dimensions (3D) models starting from a series of photos. One photo modelling system is *Pix4D* https://pix4d.com/ which is a Swiss program. The disadvantage of this program is that it is quite expensive and there are no free versions available on the internet. Another program is *Bundler* http://www.cs.cornell.edu/~snavely/bundler/. Bundler is a Structure from Motion (SfM) system for unordered image collections written in C and C++. Bundler produces sparse point clouds. For denser points the software package called *PMVS2* is needed (for running dense multi-view stereo). The usefulness of a recent photo modelling system, called PhotoScan Professional (Agisoft LLC) http://www.agisoft.com/, has already been shown in several studies. PhotoScan creates point clouds (a group of 3D vertices) from images by using overlapping images which cover the same area.

POINT CLOUDS FROM IMAGES

Matching is a very general notion to select corresponding phenomena in two or more observation sets. Corresponding phenomena are different mappings of the same object phenomena. Matching refers to identifying corresponding visual phenomena in image sequences, caused by the same phenomena in object space. To acquire a 3D point field ((x, y, z)-coordinates) the exterior orientation of image pairs has to be known. The recording of an object space from slightly different viewpoints causes disparities and from triangulation, using the exterior orientation, 3D object coordinates can be computed (Lemmens, 1988). During the alignment of images the Structure from Motion algorithm operates. This is described in more detail in chapter 4.3 on page 41. When a lot of points are grouped together, they will form a three dimensional model (see Figure 11). Most traditional photogrammetric methods require the 3D location and position of the cameras, or the 3D location of ground control points to be known to facilitate scene triangulation and reconstruction.

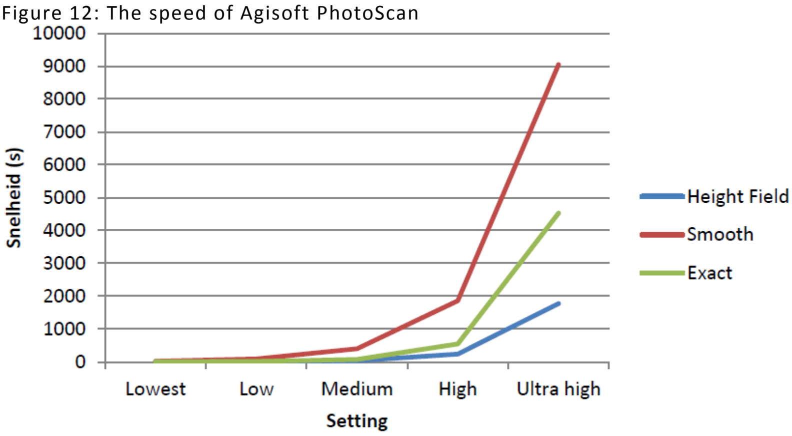
Figure 11: Point cloud from images



PHOTOSCAN

Doneus *et al*. (2011) have demonstrated that the software PhotoScan Professional provides accurate results. In another study Doneus et al. (2012) processed ten photos of each MP 10 in Agisoft PhotoScan using different methods (Height Field, Smooth and Exact) and with different quality, to check the processing speed. The speed largely depends on the selected settings (as illustrated in Figure 12) the available hardware, the number of pictures and their size. More photographs mean more point matching therefore more processing time. With a high number of overlapping photographs, the processing time will increase.

Figure 12: The speed of Agisoft PhotoScan



Source: (Doneus et al., 2011)

The reconstruction of a 3D model from multiple images is a fundamental problem in the field of computer vision. One of the general reconstruction problems is: the modelling of occlusions. An example of occlusion is when an object cannot be seen because it is hidden (occluded) by another object. Occlusion can be understood as areas without information.

3.3 RELATED WORK CONCERNING ACCESSIBILITY

Kostic and Scheider (2015) developed a navigation system for people with disability. They used the theory of affordances coupled with computer-based simulation to automatically extract accessibility information on indoor environments for use in assistive navigation systems, focusing on the case of wheelchair users. They start with a widespread and readily available information source on indoor spaces - architectural floor plans in CAD formats. By using simulation of movement in a wheelchair they compute the accessible space of an indoor environment by comparing the degree of match between geometrical demands of navigation and the relevant physical properties of the environment. The authors proposed a computer-based “translation of selected environmental attributes into a scaled suitability value for individual mobility”.

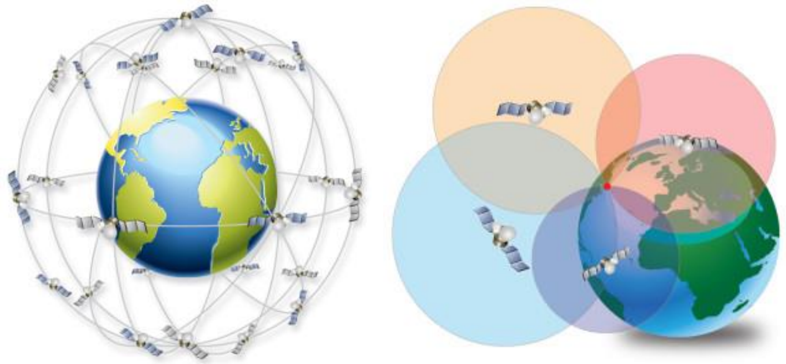
Accessibility information can also be extracted by using geographic information systems (GISs). GISs can be thought of as a toolbox with many different techniques available for a wide range of simple and complex tasks (DeMers, 2002).

3.4 THE USE OF GPS FOR POSITIONING

Global Positioning System (GPS) is originally developed by the army of the United States, but has grown to be a positioning system. Using GPS for positioning has become prevalent due to the advantages of the device, such as accuracy, speed, multi-purpose use and efficiency. The determination of a position is based on Time of Arrival (TOA) measurements. By making TOA measurements to multiple satellites, three-dimensional positioning is achieved. A minimum of four orbital satellites is necessary for positioning via GPS. Four unknowns consisting of 3 parameters of position (latitude, longitude and height) and the time should be solved. To compute these 4 unknowns, at least 4 satellites should be monitored. When the travel time of the satellite ranging signals is known the distance can be calculated, because electromagnetic waves travel with the speed of light (3 x 10^8 meter/second), and then the distance is defined by: speed of light * travel time (Penrose, 2004). An error source of electromagnetic signals is multipath. The position is calculated by using trilateration.

Trilateration is a method used to determine the intersection of sphere surfaces given the centers and radii of the spheres. In Figure 13 the satellite constellation and method of trilateration are visualized. The single red point shows the intersections of the spheres, and thus the position of a GPS receiver. Trilateration requires at least three distances to be known.

Figure 13: Satellite constellation and trilateration



Source: (Ayrapetian, 2013)

GPS has 31 satellites in orbit around the earth, of which at least 24 are transmitting signals at 95 percent of the time. This means that GPS has quite a good availability. The result of positioning is a precise pinpointed position on a map with a certain accuracy and precision. The accuracy of GPS depends on whether we are talking about standalone (single receiver) or differential positioning, single- or dual-frequency receivers, real-time or postprocessed operation, and so on. It depends greatly on the method that is used to determine the position. The accuracy can be determined based on the principle called Position Dilution of Precision (DPOD) (Langley, 1999). DPOD has to do with the configuration of the satellites. If the satellites occupy a large volume in the sky, the accuracy is higher and when the satellites are closer together, the accuracy is lower. An ideal geometry is when four satellites or more are distributed evenly in the sky. This is described in more detail in chapter 4.2.

The benefits of GPS tracking are that detailed and accurate information in space, time and duration can be obtained. Like the actually used routes (including direction), speed of transportation, destination (s) and (type of) activities. The results are measurable: duration, length of trip, stops, speed, etc. There are also other navigation systems like INS (Inertial Navigation System) and GLONASS (Global Navigation Satellite System). Integration of these systems with GPS, which is thought to increase the quality of positioning, is being proposed.

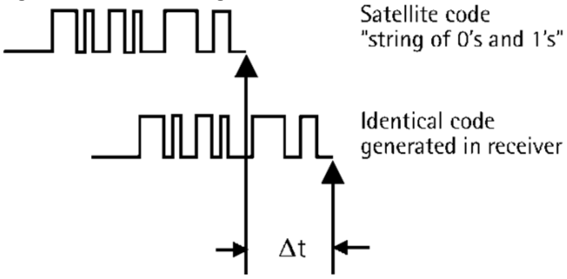
GPS is based on, as mentioned, on TOA measurements. There are two ways to extract the instant of transmission from the signal, and these two ways result in the following principles for GPS positioning.

- Pseudo range GPS
- Carrier phase GPS

PSEUDO RANGE GPS

The pseudo range is a measure of the range, or distance, between the GPS receiver and the GPS satellite (more precisely, it is the distance between the GPS receiver's antenna and the GPS satellite's antenna). This method compares the pseudo-random-signal that it receives from the satellite with an identical signal it generates itself and measures the difference between the signals, as can be seen in Figure 14. The satellite sends out this signal every millisecond, and once the receiver recognizes the signal, it starts generating the same signal (Warner & Johnston, 2003). The receiver matches the signal and looks for delays caused by the travel time. This method is less accurate, because the signals can be quite a lot out of phase, but still match. This is because the values of the signals can be the same, even though the signals are not completely in sync (Unknown, 2001).

Figure 14: Pseudo range measurement

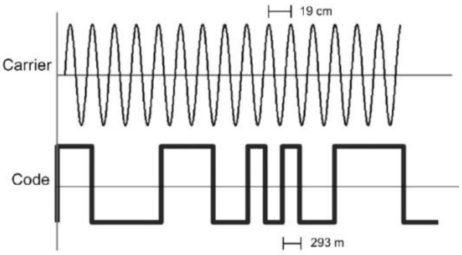


Source: (Unknown, 2001)

CARRIER PHASE GPS

This method also looks at the carrier frequency of the code, but in this method the carrier frequency is much higher than the signal frequency, as consequence that a much higher accuracy can be achieved. The accuracy that can be achieved lies in the millimeter level. The problem with this method is that all waves are really uniform which makes it difficult to determine which ones are the same. Figure 15 is showing the carrier phase measurement.

Figure 15: Carrier phase measurement



Source: (Rife et al., 2008)

3.5 DEFINITION OF TERMS

In this section, a couple of theories and definitions that are often used will be discussed.

POSITIONING AND LOCALISATION

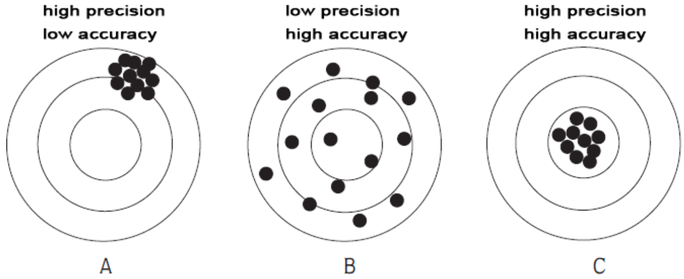
Positioning and localisation are often used interchangeable, but the definitions differ. Positioning is a synonym for position finding. It is the pinpointing (I.e. determination of a position) of a device, an object or a person. The result of positioning is a precise pinpointed location on a map with a certain accuracy and precision. This position will be given with coordinates in a particular coordinate reference system. It is particularly used to emphasize that the target object has been moved to a new location.
Localisation is a location without actual coordinates, like room 1.1. The location can be given in everyday text, instead of in coordinates. Localization is mainly associated with rough estimation of location for low-accuracy systems such as for locating mobile phones. (Mautz, 2012)

ACCURACY AND PRECISION

The term accuracy has been defined in the Joint Committee for Guides in Metrology (JCGM) as the closeness of agreement between a measured quantity value and a true quantity value of a measure. 'Positioning accuracy' should be understood as the degree of conformance of an estimated or measured position at a given time, to the true value, expressed for the vertical and horizontal components (Mautz, 2012). This means that two values must be known in order to say something about the positioning accuracy, namely: a real value and an (average) measured value.

Precision refers to the closeness of repeated measurements to the sample mean. According to Yoshimura and Hasegawa (2003) precision can be calculated and compared using the root mean square (RMS), which is calculated by the following equation: $\sigma_{precision} = \sqrt{\sigma_r^2 + \sigma_u^2}$ where 'σ precision' indicates RMS, and 'σr' and 'σu' indicate the standard deviation of the positional error, respectively. Precision and accuracy are briefly explained in Figure 16.

Figure 16: Precision and accuracy



Source: (Yoshimura & Hasegawa, 2003)

GEO-DATA AND INFORMATION

What is geo-data? There is a difference between data and information. Most of the time, we use the two terms almost interchangeably, and without the risk of confusing their meanings. By data, we mean representations that can be operated upon by a computer. Data are raw, unorganized facts or details from which information is derived. It needs to be processed to become information. More specifically, by spatial data we mean data that contains positional values relative to the Earth's surface. Spatial data refers to *where things* are, or perhaps, where they were or will be. Human perception and mental processing leads to information. So when data is processed, organized, structured or presented in a given context to make it useful, it is called information. Geo-information is a specific type of information resulting from the interpretation of spatial data (Huisman & de By, 2009).

Geo-information, or geographical information, is the term applied to any information which can be linked to a specific point on the Earth's surface. This can be related to the position of a road or bridge, altitude, type of vegetation at a given point, etc. Geo-information is often invisible. For example, it provides the necessary information for safe navigation and the offshore industry, it enables dike deformation monitoring through satellites, 3D modelling for urban space management and building tunnels, and location based services such as TomTom and Google maps. It is also used for traffic monitoring, risk assessment of areas that are vulnerable to flooding, and for much more.

WHEELCHAIR, ROLLATOR, MOBILITY SCOOTER

A wheelchair is a chair equipped with wheels and is used by people for whom walking is difficult or impossible due to illness, injury, or disability. Wheels and chairs were known in prehistoric times, possibly 4000 before Christ. The vehicle for those who could not walk was the litter. Since the dawn of history it has hardly changed. In China chairs were used before modern times, and is dated about 525 after Christ (DINBelg 2005 Toegankelijkheidsbureau, 2006). The European used this technology during the German Renaissance. The first lightweight, steel, collapsible wheelchair was invented in 1933 by Harry Jennings and Herbert Everest. There are several variants of wheelchairs. Below a distinction is made between five types, namely:

1. Manual wheelchair (hands and arms can be used to move the wheelchair)
2. Handbike
3. Push stroller (someone else should help to move)
4. Electric wheelchair (moves via an electric motor)
5. Children wheelchair

There are several other variants of wheelchairs and they have been manufactured in various sizes, like a standing wheelchair, a knee scooter, etc. People use a wheelchair when they have problems with standing and walking.

A rollator is used by people who need support while walking. Because of the small wheels, a threshold of 20 mm can be a major obstacle. A rollator is 600 to 700 mm wide and has a turning radius of about 1100 mm. Mobility scooters are increasingly being used, and are suitable for passing distances of 10 to 30 km. Nowadays there are also folding models that can be taken in a car. A mobility scooter is about 700 to 900 mm wide; 1.200 to 1.600 mm long and has a turning radius of about 2500 mm.

A mobility scooter is suitable for passing distances of 10 to 30 km. A mobility scooter is about 700 to 900 mm wide; 1.200 to 1.600 mm long and has a turning radius of about 2500 mm.

3.6 POTENTIAL PROBLEMS AND REQUIREMENTS REGARDING ACCESSIBILITY

Accessibility is a measure of how friendly an area is to walk (Vine, Buys, & Aird, 2012). Accessibility is the extent to which the built environment supports and encourages walking. There can be little literature found that investigate the problems of people with mobility impairments in their outdoor activity space. Most literature focuses on accessibility indoors (like public buildings or residences) by looking at interior conditions (Verschuur, 2014). For half a century, accessibility is an issue. Therefor, 17 years ago the first version of the Manual-book of Accessibility was introduced, which contains guidelines for outdoor spaces, buildings and homes, developed by experts (Wijk, 2012).

Walking restrictions in the outdoor activity space for people with mobility impairments can be determined by taking into account the geometrical demands for movement. To make the outdoor space suitable for each user, it must comply with criteria. Concerning these criteria wishes and primary requirements need to be distinguished. There are permissible sizes which can be used, but every size has its own story. At the same time designers are mostly not aware that these sizes are indicated with maximum or minimum, and that there is also a desirable level. Furthermore the outdoor space is dynamic. If someone opens the door of a car it will become a walking restriction. Also a problem occurs when two people come by and want to pass each other. That is why one has to be critical with norms, because this tends to be the maximum or minimum but for the improvement of the outdoor space we would have to go for proper quality and not achieving a maximum or minimum. For this thesis is focused on the three most important parameters for mobility impaired people, because it is not achievable to discover all important quality values and criteria. Therefor bus, tram and metro stations; exit structures; guide lines, leading lines and contrast markings; connecting of pedestrian paths to buildings; disabled parking spaces; etc. will not be discussed.

According to the Manual-book of Accessibility (Wijk, 2012) and an expert Job Haug (Advisor of Construction Consulting Services for Accessibility), a good pedestrian path for people with a wheelchair, rollator and scoot mobile has to meet three geometrical demands for movement. A pedestrian path should be recognized as a safe route, especially next to busy roads and cycle paths. For people with mobility impairments a minimum free passage must be guaranteed. Furthermore, not everyone can climb stairs and a ramp is not suitable for everyone. Height difference can only be bridged when it is provided by an elevator, stair, or ramp, which must satisfy many limits in order to be practical and safe. Additionally, the use of an angle of inclination requires an effort which is dependent on the steepness in relation to the length of the slope. The higher the altitude, the less steep a slope must be to remain accessible for many people. In short, the three geometrical demands for movement used in this thesis are:

1. **Suitable free passage**

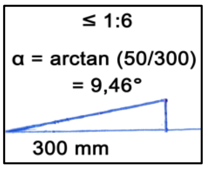
   The free passage is at least 0.9 meter wide (without passing at local constrictions).

2. **Minimum angle of inclination**

   The angle of inclination is not steeper than the ratio 1:6 (height:length). This means that a length until 0.3 meter must not have a rise higher than 9.46°. So the maximum height for this length is 0.05 meter (see Table 3).

Table 3: Angle of inclination

	Angle of inclination
Ratio (height : length)	≤ 1:6
Max. length until (grid size)	0.3m
Max. angle of inclination (rise)	9.46°
Max. height until (rise)	0.05m



Source: (Wijk, 2012)

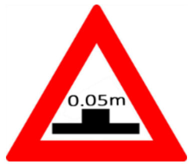
3. **Minimum threshold**

If a threshold is necessary, then a maximum height of 0.05 meter is permitted, which may be caused by paving stones that lie slanting or different pavement materials.

"This means that a pedestrian path forms an obstacle if it is narrower than 0.9 meter, steeper than 9.46° or/and if the height difference on the path is higher than 0.05 meter."

Suitable free passage

Minimum angle of inclination



Minimum threshold

An obstacle in the middle of the pavement will cause more trouble than one on the side. Also an obstacle on a small pavement will cause more trouble than on a wider pavement. Potential obstacles for movement in a wheelchair, rollator and scoot mobile are listed below.

Permanent obstacles:

1. lampposts
2. fire hydrants
3. trees
4. waste containers/disposal locations
5. advertising pillars (permanent)
6. bollards (in this case in Dutch: Amsterdammertjes)
7. traffic bollards/lights/signs
8. banks/stools
9. expansion of houses/cafés & stairs
10. post office boxes
11. pavement height differences, like tram grooves and high curbs
12. slopes of curbs (ramps) or bridges (> 10 %)
13. lack of a slope by crosswalks or bridges
14. long inclines without a resting place

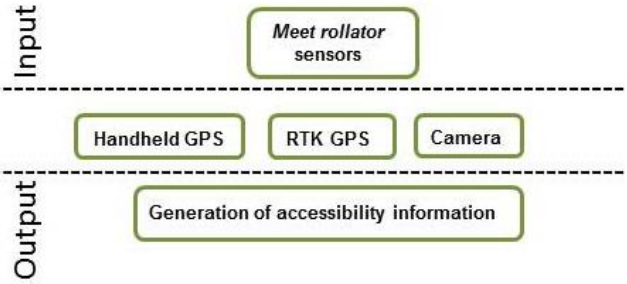
Temporal obstacles:

1. garbage bags
2. street furniture
3. incorrect parked cars/bikes/scooters
4. advertising pillars (temporal)
5. flowerpots
6. seats/tables (of a restaurant/café)
7. waste containers (temporal)
8. guided fences (for example for events)
9. road construction work
10. busy shopping-streets

4 A WORKFLOW FOR GENERATING ACCESSIBILITY INFORMATION

This chapter will discuss a measure-method for deriving outdoor accessibility information from sensor-data. A division is made in two workflows according to the available sensors which provide different data. Figure 17 is showing the available sensors: handheld Global Positioning System (GPS), Real-Time Kinematic (RTK) GPS and camera. Paragraph 4.2 will discuss a workflow developed to generate accessibility information by making use of RTK GPS data. Paragraph 4.3 will discuss a workflow by making use of camera data. Subsequently, the conclusions will be provided.

Figure 17: The available sensors



4.1 AVAILABLE SENSORS

This chapter will discuss the three available sensors: handheld GPS, RTK GPS, and camera.

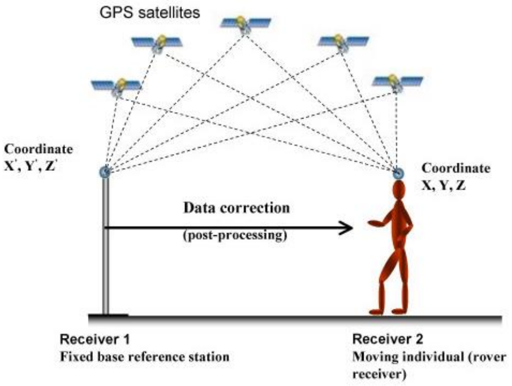
HANDHELD GPS

A handheld GPS is a device that uses the Global Positioning System, combining modern geographic technology with a portable, user-friendly device. The device is often used outdoors to pinpoint the coordinates of an certain location for future reference (Morgan, 2015). The accuracy of single point or stand-alone GPS positioning lies at the few meter to decameter level.

RTK GPS

A Real Time Kinematic (RTK) rover with radio modem (or GSM phone) is used for high-accuracy GPS surveying. It contains of a dual frequency GPS receiver of the highest accuracy and with on-board RTK. RTK is a special form of the Differential Global Positioning System (DGPS) which is based on two receivers simultaneously (a fixed base reference station and a moving individual), see Figure 18. In DGPS only encrypted information from the satellite signals will be used and in RTK the phase of the satellite signals will also be used on which these codes are modulated. RTK is based on measuring distances to the satellites with carrier phase. Carrier phase GPS is described in more detail in chapter 3.4 on page 28. With RTK-GPS positioning, sub-centimeter precision could be reached.

Figure 18: The principle of DGPS

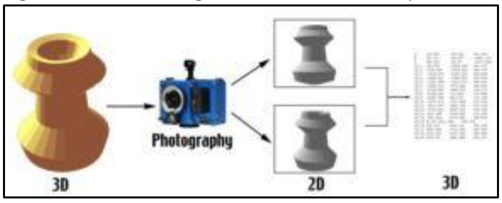


Source: (Terrier & Schutz, 2005)

CAMERA

A camera is the device that makes the transformation from the real 3D world into flat 2D images (see Figure 19 on page 34). This process is called photography. Videos come in many different formats (AVI, MOV, MPEG, FLV, MKV, and MP4), so it is hard to decide which of the many (free) video conversion tools the best video converter is. To extract 3D information from imagery, one has to use overlapping images, as explained in chapter 3.2 on page 25. From two overlapping images the three-dimensional coordinates of any point in object space can be accurately computed, provided that the interior orientation parameters and the six parameters of exterior orientation are known. From the two coordinates of a point in the one image and the two coordinates of the corresponding point in the other image, the three coordinates of the object point can be computed.

Figure 19: Producing 3D models from 2D photos



Source: (Marlow, 2015)

HYPOTHESIS

The outcome, according to the assessment of the three sensors (handheld Global Positioning System (GPS), Real-Time Kinematic (RTK) GPS and camera) by using the knowledge of the MSc Geomatics, is that a handheld GPS is not as useful as a RTK GPS for position determination, because with RTK GPS more precise positioning could be reached. Therefore handheld GPS data is not useful for generating accessibility information. According to the knowledge the two sensors RTK GPS and camera are useful for generating accessibility information.

	According knowledge:
Handheld GPS	✗
RTK GPS	✓
Camera	✓

Each of the available sensor data will be evaluated on the fit for purpose to derive accessibility information (in chapter 5.4).

4.2 WORKFLOW RTK GPS DATA

This chapter will discuss a workflow for generating accessibility information by making use of Real-Time Kinematic (RTK) GPS data. But first a hypothesis will be explained and how this hypothesis will be proved. Finally the workflow will be explained.

HYPOTHESIS

The hypothesis is that RTK GPS data (collected by a *meet rollator*) and GIS analysis tools can be used to develop a methodology that generates accessibility information, and determines the accessibility. For this methodology two of the three geometrical demands for movement (explained in chapter 3.6) will be used, namely:

Minimum angle of inclination   Minimum threshold

This means that a pedestrian path forms an obstacle if it is steeper than 9.46° or/and if the height difference on the path is higher than 0.05 meter.

HOW TO PROVE IT

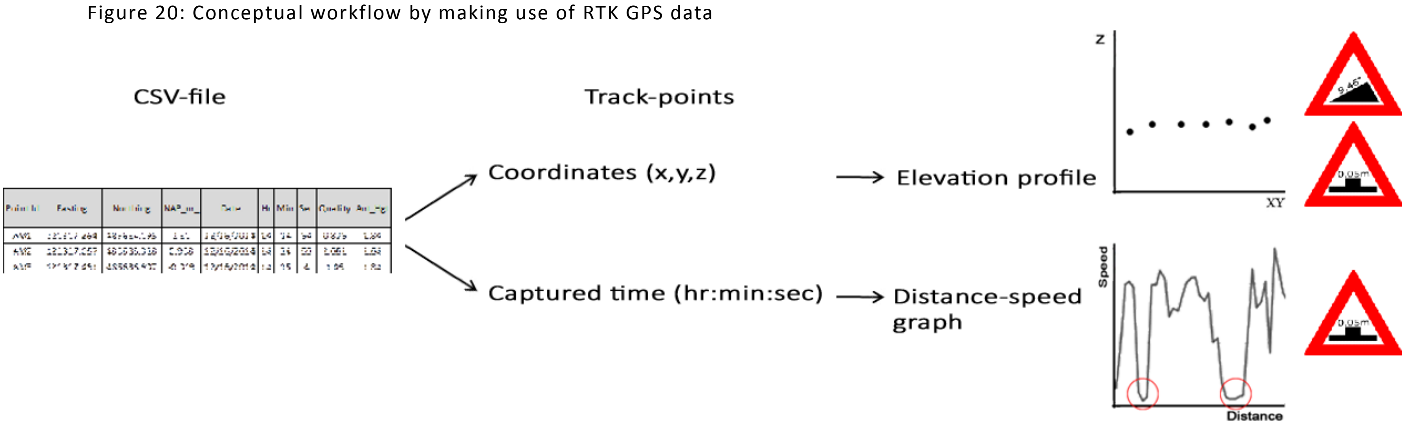
As explained in chapter 2.2, a RTK GPS (Leica) provides a CVS-file in which inter alia the track-point IDs, coordinates and date/time stamp are included. Track-points have three dimensional coordinates (latitude longitude/easting northing; and elevation). Figure 7 B on page 23 is showing RTK GPS track-points. A RTK GPS receiver records track-points which define a track formed by connecting points with lines. The "track" represents the path that is followed.

Multiple RTK GPS measurements are required for the generation of accessibility information. If you walk around with a RTK GPS device, you have a displacement in time, distance and elevation from which the angle of inclination and threshold information can be derived. The elevation is recorded per track-point so it is possible to get an elevation profile for the track. From this elevation profile the angles of inclination and thresholds can be determined.

The same is true for a displacement in time. If there is a transition from a street to a sidewalk (most of the time) a threshold is present which can be detected as a moment of standing still or stopping. This moment can be found by analyzing the differences in time stamp between track-points. The delay between consecutive track-points, which will be caused by the difference between their time stamps, is called time delay. It is needed to make a graph of the travelled distance (which can be calculated from the coordinates) and speed between consecutive track-points (which can be calculated by using the date/time stamp) to see where time delays occur. When the distance-speed-graph drops down to zero, this will indicate that there is a threshold causing the speed is reduced (see Figure 20).

In this way RTK GPS data can be used for generating and determining accessibility information, by making use of two geometrical demands for movement.

Figure 20: Conceptual workflow by making use of RTK GPS data

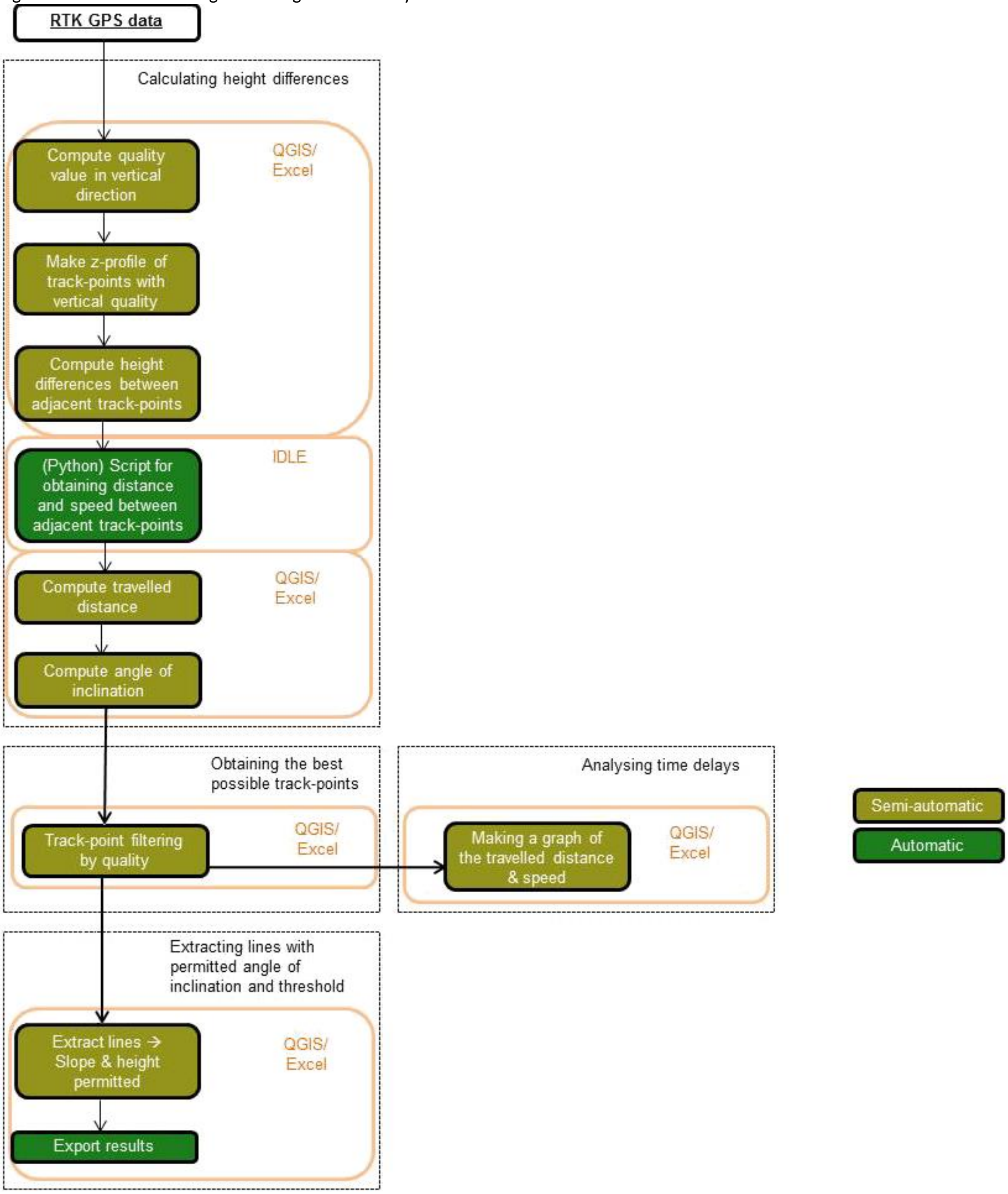


WORKFLOW

The conceptual workflow shown in Figure 20 can be translated into a measure-method to generate accessibility information by making use of GIS analysis tools. Figure 21 is showing the workflow for deriving outdoor accessibility information from RTK GPS data. This workflow can be divided into the following parts:

(1) Calculating height differences
(2) Obtaining the best possible track-points
(3) Extracting lines with permitted angle of inclination and threshold
(4) Analysing time delays

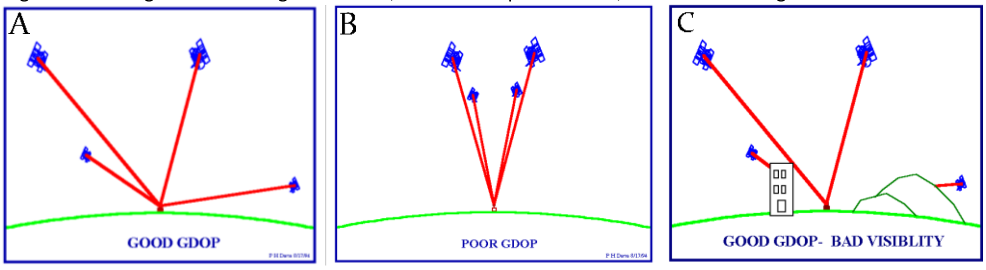
Figure 21: Workflow for generating accessibility information from RTK GPS data



(1) CALCULATING HEIGHT DIFFERENCES

The first step towards the generation of accessibility information is to obtain the quality value in vertical direction from RTK GPS data. The error in the vertical direction is twice as large/worse as the horizontal direction. This can be explained by the term Dilution of precision (DOP). DOP comes in various flavors, including geometrical (GDOP), positional (PDOP), horizontal (HDOP), vertical (VDOP) and time (TDOP). HDOP values are typically between 1 and 2. VDOP values are larger than the HDOP values indicating that vertical position errors are larger that horizontal errors. VDOP values are almost always above 3 and sometimes as large as 7. Good satellite geometry is essential to ensuring accurate readings of position and date collection. An ideal DOP value will be low, like PDOP <= 6 or HDOP <= 4 (Langley, 1999). Figure 22 is showing both good and bad DOP values.

Figure 22: Image A shows a good GDOP, B shows a poor GDOP, and C shows a good GDOP but bad visibility

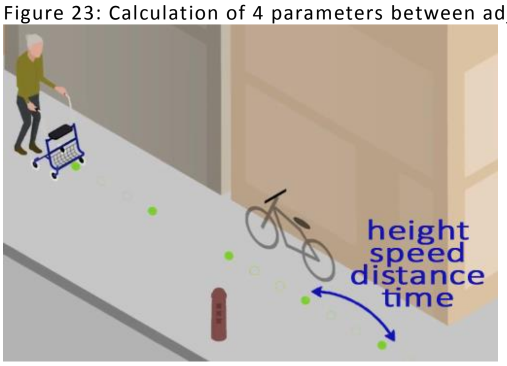


Source: (Langley, 1999)

The greater the number of satellite, generally the lower the PDOP value, but this is not always the case. There are also cases where half a dozen satellites may be clustered in one area of the sky, giving good satellite coverage but poor PDOP. This will often occur at very high latitudes (ex. Greenland or Antarctica (north and south latitudes)) or in equatorial regions, because there are fewer satellites high in the sky.
In urban canyons, a GPS receiver's antenna may not have a clear view of the whole sky because of obstructions. If it can only receive GPS signals from a small region of the sky, the DOPs will be large, and positions accuracy will suffer. Being able to track more satellites can help in this environment (Langley, 1999).

With the use of the obtained (horizontal) quality values of RTK GPS data it is possible to calculate the quality value in vertical direction by multiplying the obtained quality by a value of 2. As explained before, the error in the vertical direction is twice as large/worse as the horizontal direction that is why it has to be multiplied with a value of 2.
Afterwards it is necessary to make an elevation profile of all track-points with their vertical quality and computed height differences between adjacent track-points. In addition, the speed and distance between track-points need to be determined (see Figure 23).

Figure 23: Calculation of 4 parameters between adjacent track-points



There is no easy way to compute the speed and distance between track-points by using QGIS. The easiest way to compute this is by creating a program that can read RTK GPS data. Therefore a script can be made which uses the CSV file obtained by a RTK GPS device. For this thesis a Python script is made which is used during the implementation of the workflow (see chapter 5.2). Python is a widely used high-level programming language (Downey, 2014). The output of this script should contains the distance, time and speed between adjacent track-points (i.e. between point 1 and 2, point 2 and 3, point 3 and 4, etc.) by following the track-line. The output CSV file of the script can be opened in Excel or a GIS environment, like QGIS. Finally, it is necessary to compute the travelled distance and height difference between adjacent track-points for compute the angle of inclination.

(2) OBTAINING THE BEST POSSIBLE TRACK-POINTS

RTK GPS data need to be filtered based on quality. Track-points need to be extracted with a quality of several centimeters. In short, a RTK GPS quality value of 0.021 indicates a horizontal precision of 21 millimeter, which is a very good measurement. It indicates that the values for x and y may vary up to 21 millimeter.

(3) EXTRACTING LINES WITH PERMITTED ANGLE OF INCLINATION AND THRESHOLD

The third step towards the generation of accessibility information is to filter track-points out with a threshold bigger than permitted, by using the height difference between adjacent track-points. In addition, the slope-value can be used to filter track-points out with an angle of inclination bigger than permitted. The height difference and angle of inclination between adjacent track-points can also be seen as an (imaginary) line, so a part of the track-line. The lines between adjacent points obtained after filtering do meet the permitted threshold and angle of inclination. These lines (with points) can be saved to a new CSV file and exported.

(4) ANALYSIS TIME DELAYS

This step will use information about time delays between adjacent track-points. It is needed to make a graph of the travelled distance and speed to see where time delays occur. When the speed-graph drops down to zero and the speed will stay for a while around zero km/h, this will indicate that there is an obstacle causing the speed is reduced. If this is the case, the consecutive points need to be filtered out with a small speed value.

4.3 WORKFLOW CAMERA DATA

This chapter will discuss a hypothesis, how this hypothesis will be proved, and a workflow for generating accessibility information by making use of video camera data.

HYPOTHESIS

The hypothesis is that video camera data collected by a *meet rollator*, the software Agisoft Photoscan Professional, GIS analysis tools and the BGT can be used to develop a methodology that generates accessibility information, and determines the accessibility. As stated before, the three geometrical demands for movement used for this methodology are:

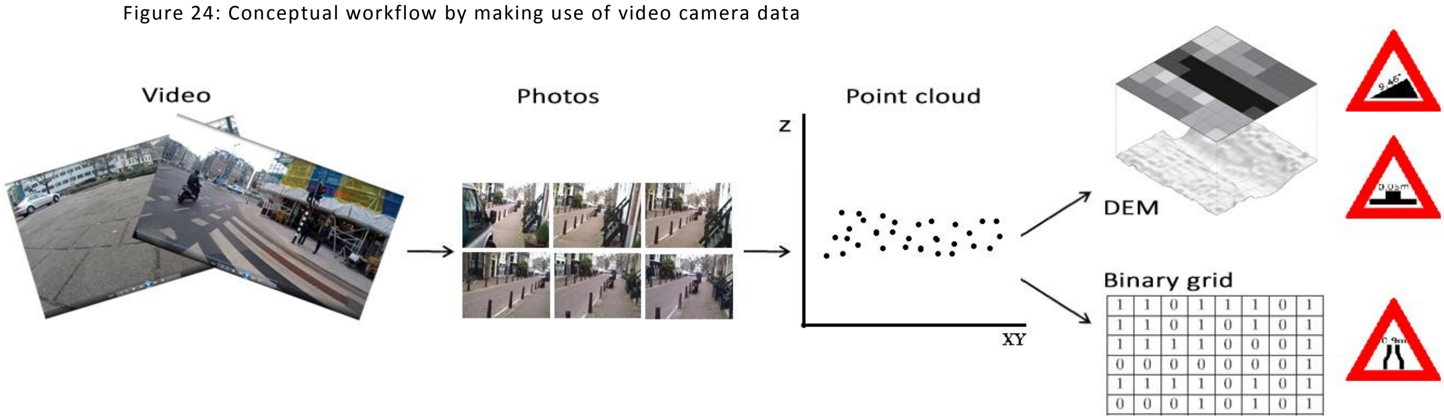
Suitable free passage | Minimum angle of inclination | Minimum threshold

This means that a pedestrian path forms an obstacle if it is narrower than 0.9 meter, steeper than 9.46° or/and if the height difference on the path is higher than 0.05 meter.

HOW TO PROVE IT

A video camera provides videos which can be converted to photos (see Figure 24). By using these photos a point cloud (i.e. a group of 3D points) can be created. Multiple photos are required for the generation of a point cloud. In a point cloud the free passage, angle of inclination and threshold can be determined. Therefor the point cloud needs to be transformed into a digital model of height (DEM) to obtain the permitted angle of inclination and threshold for people with mobility impairments. These are places where mobility impaired people can pass. Furthermore the point cloud needs to be transformed into a binary grid (each cell can either have the value 0 or 1) for checking whether the points satisfy the permitted free passage for mobility impaired people (by using a script). In this way video camera data can be used for generating and determining accessibility information, by making use of the three geometrical demands for movement.

Figure 24: Conceptual workflow by making use of video camera data



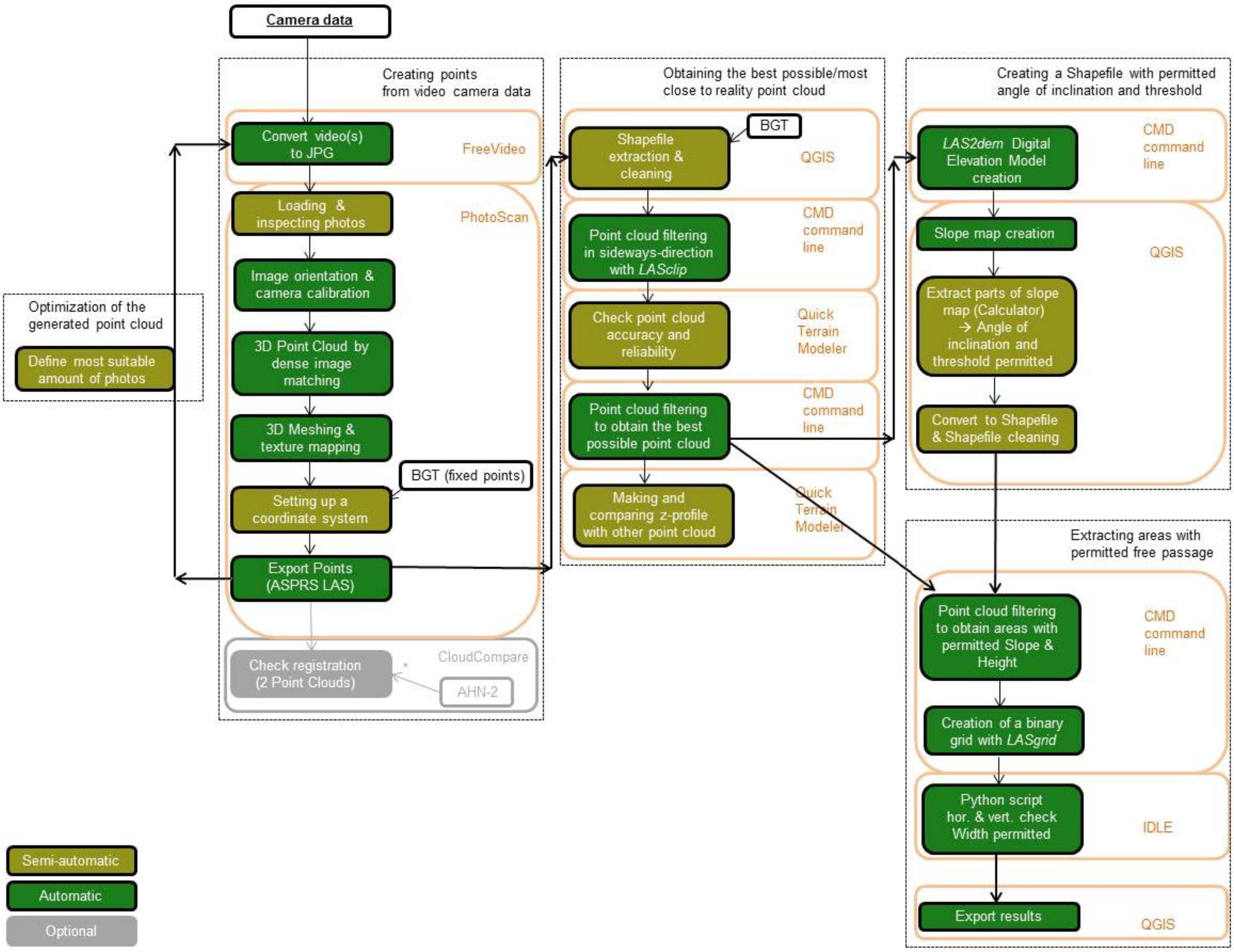
Source: (SCR, 2015)

WORKFLOW

This conceptual workflow can be translated into a measure-method to generate accessibility information, by making use of the software package PhotoScan, GIS analysis tools and the BGT. Figure 25 on page 40 is showing the workflow which consists of several steps:

(1) Creating points from video camera data
(2) Obtaining the best possible/most close to reality point cloud
(3) Creating a Shapefile with permitted angle of inclination and threshold
(4) Extracting areas with permitted free passage
(5) Optimization of the generated point cloud

Figure 25: Workflow for generating accessibility information from video camera data



(1) CREATING POINTS FROM VIDEO CAMERA DATA

The first step towards the generation of accessibility information is to create points (LAS file) from videos. With the use of images (constructed from video camera data) it is possible to create points by using the programs FreeVideo and PhotoScan. The FreeVideo software is free, easy to use and has advanced options, to select frames from videos and record them as separate images (JPG formats). The PhotoScan software is released in 2010 by the Russian producer Agisoft LLC. PhotoScan is a software package for producing professional 3D models starting from a series of photos. It relies on the latest 3D design technologies. PhotoScan could be used to generate 3D models, point clouds (a collection of individual points) and Digital Surface Models (DSMs) via photogrammetric processing of digital images. PhotoScan offers all kinds of tools and features that promote ease of use (Belien, 2012).

Camera data needs to be converted into a series of photos with the program FreeVideo. It is necessary to use contiguous photos with overlap. Afterwards these photos need to be loaded into PhotoScan via:

Workflow → Add photos

It is necessary to inspect the loaded photos and remove unnecessary photos which are not calibrated or not aligned. Loaded photos are displayed in PhotoScan with flags reflecting their status. The following flags can appear (next to the photo name): not calibrated (NC) and not aligned (NA). Incorrect photo alignment is usually a result of poor overlap or insufficient amount of texture details on the object surface.

The next step is to match photos to generate a sparse 3D point cloud. This can be done in PhotoScan via:

Workflow → Align photos

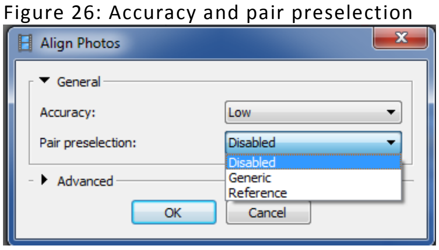
PhotoScan searches for common points on photographs and matches them, as well as it finds the position of the camera for each picture and refines camera calibration parameters. The estimation of the geometric characteristics, i.e., the focal length (f) of the lens, the coordinates of the center of projection of the image (x_p, y_p), the radial lens distortion coefficients (k_1, k_2, k_3), is performed through the camera calibration process. PhotoScan detects points in the photos which are stable under viewpoint and lighting variations and generates a descriptor for each point based on its local neighbourhood. These descriptors are used later to detect correspondences across the photos. PhotoScan uses a greedy algorithm (i.e. a set of rules written in a computer language) to find approximate camera locations, and refines them later using a bundle-adjustment algorithm to solve for camera intrinsic and extrinsic orientation parameters. As a result a sparse point cloud and set of camera positions are formed (Semyonov, 2011).

Greedy algorithm wants to use the fewest points as possible. The algorithm makes a sequence of decisions. Dijkstra's shortest path algorithm is a greedy algorithm, because it only gets one shot to detect the shortest path to a given destination. It processed each destination once and the decision is irrevocable.

Bundle-adjustment algorithm minimizes the re-projection error between the image locations of observed and predicted image points. The determination of the 6 exterior orientation parameters (3 position coordinates (X_0, Y_0, Z_0) and 3 rotation coordinates (ω, ϕ, κ), as discussed in chapter 3.2 on page 25) is done in one single simultaneous solution using least squares adjustment. Given the redundant observations the most optimal solution is found, while blunders may be detected and removed and not only the values of the orientation parameters determined but also their precision.
During this step, some parameters can be set. The accuracy can be set on *low, medium* or *high*. The higher the accuracy setting, the more accurate the estimation of the camera positions will be. *High* is best for smaller photosets, and *medium* is best for larger photosets. The alignment process can be accelerated by selecting a pair preselection method: *disabled, generic* or *reference* (see Figure 26).

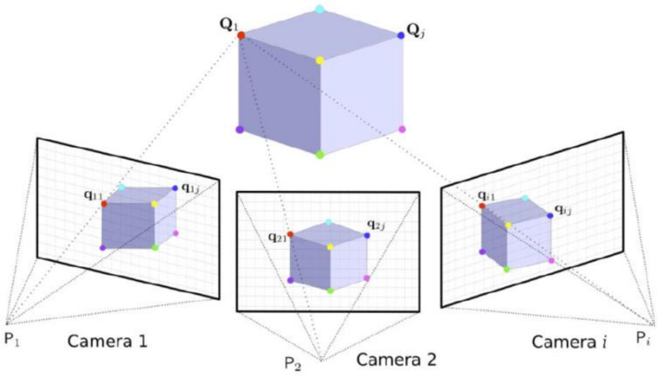
- Disabled**,** default, works for most datasets.
- Generic, means that overlapping photo-pairs will be selected by matching the photos based on lower accuracy institutions.
- Reference, means that overlapping photo-pairs will be selected on the basis of measured camera locations (if these are available for example by using Ground Control Points (GCPs)).

Figure 26: Accuracy and pair preselection



During the alignment of the pictures the Structure from Motion (SfM) algorithm determines for each picture the camera position during the time of recording (see Figure 27).

Figure 27: Structure from Motion algorithm



Source: (Agarwal et al.)

The fifth step of the workflow is to generate a dense 3D point cloud. This can be done in PhotoScan via:

Workflow → Build dense point cloud

Based on the sparse point cloud the model geometry is generated. During this step, the quality parameter can be set. *Quality* can be set on: *High*: great for smaller photosets (up to +/- 150 photos), or *medium*: good for larger datasets (over 150 photos). The quality parameter controls the density and accuracy of the raw photogrammetric point cloud. Higher density of a point cloud helps to maintain more fine level details. With each higher quality level the density of points increases 4 times.

The fifth step of the workflow is to generate a 3D polygon (i.e. area entity) mesh, which can be done in PhotoScan via:

Workflow → Build mesh

Based on the estimated camera positions and pictures themselves a 3D polygon mesh is build representing the object surface. A polygon is a planar surface, defined by 1 exterior boundary and 0 or more interior boundaries (Ledoux, Arroyo Ohori, & Meijers, 2014). Two surface types can be applied: *Arbitrary*: is used inter alia for closed objects such as buildings, or *height field:* is optimal for modeling flat surfaces and aerial photography. Height field shows the result from a top view. Finally, four face count settings can be applied, which determine the number of faces or surfaces that are used for the construction of the mesh: high (90.000), medium (30.000), low (10.000) and custom. Firstly, PhotoScan calculates the mesh with the maximum number of faces, and afterwards performs a generalization down to the 'face count settings'.

Afterwards texture can be given to the mesh via:

Workflow → Build texture

PhotoScan parametrizes a surface cutting it in smaller pieces and then blends source photos to form a texture atlas. The texture is given based on one or a combination of different selected photos. The main setting for this step is the *mapping mode*. The correct mapping method provides an optimal visual quality of the final model. The mapping modes which can be applied:

- Generic, creates the most uniform texture.
- Orthophoto, makes use of the orthographic projection, which gives worse results for vertical surfaces such as walls.
- Adaptive orthophoto, divides the area in horizontal and vertical parts.

Furthermore the blending mode can be chosen:

- Mosaic (default), gives more quality for an orthophoto than the Average mode, according to the Agisoft PhotoScan User Manual of 2011.
- Average, specifies the average value of the pixels of all the individual pictures which are used.

Finally, the texture size/count can be applied. These parameters determine the number of pixels that the final texture will contain, in the length and in the width. Mostly the quality of texture depends on the texture atlas size and the quality of the original images.

Step eight of the developed workflow is to place markers with the correct Global Positioning System (GPS) coordinates for setting up a coordinate system. PhotoScan does not handle the CRS transformation correctly. Therefor the correct GPS-coordinates have to be matched by placing markers.

Finally, the points need to be exported in the desired format. PhotoScan supports various formats, like the formats for exporting points: Wavefront OBJ, Stanford PLY, XYZ text file format, ASPRS LAS. This latter format contains binary data, and is little-endian which means that multi-byte data fields are stored in an order in which the least significant value in the sequence is stored first. An example, in a little-endian system the two bytes required for the hexadecimal number 4F52 would be stored as 524F (52 at address 1000, 4F at 1001) (ASPRS, 2013).

Optionally, in the program CloudCompare can be checked whether the created points are correctly georeferenced. By using airborne laser scanning data (AHN-2) and the created points in CloudCompare an overlay between the data can be analyzed to check whether they correspond. As earlier discussed a piece of the AHN-2 can easily be downloaded via internet. Three versions can be downloaded: surface level (ground or filtered), non-surface level (man-made or filtered), and both. For this purpose the AHN-2 version 'both' with surface level and non-surface level can be used. The tool which can be used in CloudCompare to analyze overlapping data is:

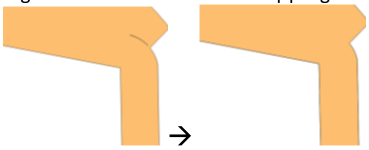
Tools → Registration → Fine registration (ICP)

When in both point clouds a distinctive feature is present, it can be used for more precise matching.

(2) OBTAINING THE BEST POSSIBLE/MOST CLOSE TO REALITY POINT CLOUD

In order to obtain the best possible points it is necessary to filter out points which are less precise. LAStools is able to filter out points. Therefore, an overlay of a Shapefile with the points needs to be performed by using LAStools. Therefore it is necessary to make a Shapefile. A Shapefile can be made by using BGT data in a GIS environment, like Quantum GIS (QGIS). A part of BGT data can be extracted. It is important that the Shapefile contains clean polygons or lines that are free of self-intersections, duplicate points, and/or overlaps, and that they all form closed loops (Isenburg, 2014b). A Shapefile can automatically be cleaned in QGIS by using the plug-in '*prepare'* Hugo Ledoux (assistant-professor in the 3D geo-information research group at Delft University of Technology) made. This plug-in repairs broken GIS polygons according to the international standard ISO19107 (ISO: International Organization for Standardization). When points are not repeated but just very close, the QGIS tool '*snapping'* can be used. Figure 28 is showing the result of the QGIS tool '*snapping'.*

Figure 28: Result of the snapping tool



The cleaned Shapefile can be used to filter points out by using LASclip. LASclip takes as input a polygon and clips away all the points that fall out of the (input) polygon, and stores the surviving points to a new LAS file. LASclip can be run in the CMD command line in Windows.

When the points are filtered, it is necessary to check the precision and reliability of the points in order to determine accessibility information as well as possible. This starts with the best possible points in which as much as possible confidence can be achieved. The determination factor to have more confidence in a specific area of points than in another area is (partly) defined by the amount of frames which determine a certain area. When an area of points is constructed with more overlapping frames, it is more confident. A profile across a point cloud can be made with the program Quick Terrain Modeler to check and compare height differences between points. In this profile the most precise and reliable part of the point cloud can be visually detected. This part needs to be obtained by (again) filtering the points with LASclip. Therefor a new Shapefile needs to be made. As a result the most precise and reliable part of a point cloud can be obtained.

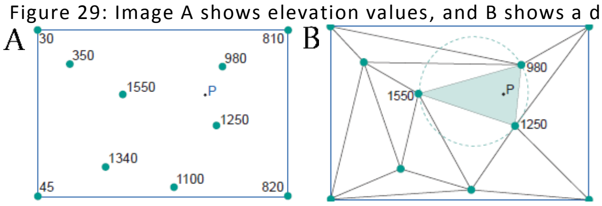
Finally the precision of points needs to be checked. This can be done by using other point clouds of the same area. These point clouds can be made with more or less frames of the same measurements or by using other camera measurements for making a comparison. Therefor step 1 'Creating points from video camera data' must be followed again for the creation of these other point clouds of the same area. In this way points can be compared based on their z-profiles. By comparing point clouds conclusions can be drawn about the quality of points. When the profiles of different point clouds (that contain the same area) look similar, it can be concluded that the quality is sufficient.

(3) CREATING A SHAPEFILE WITH PERMITTED ANGLE OF INCLINATION AND THRESHOLD

After obtaining the most precise and reliable part of a point cloud, points need to be obtained with the permitted angle of inclination and threshold for people with mobility impairments. Therefore a DEM needs to be constructed. A DEM is a digital model of height, which closely matches the earth's surface. Las2DEM is able to store the actual values of the points of a point cloud into a DEM image, by triangulating points into a temporary triangulated irregular network (TIN) and then rasterizes this TIN (Isenburg, 2014a).
Triangulation is a complete partition of the study space into mutually non-overlapping triangles, usually on the basis of georeferenced measurements. A *TIN* is built from a set of locations for which a measurement is known, for instance an elevation. The locations can be arbitrarily scattered in space, and are usually not on a nice regular grid. Any location together with its elevation value can be viewed as a point in 3D space. From these 3D points, an irregular tessellation made of triangles can be constructed. A TIN (i.e. irregular tessellation) is a vector representation: each point has a stored georeference.

LAS2dem uses standard linear interpolation within each of the Delaunay TIN triangles. A Delaunay triangulation is an optimal triangulation. This means that the triangles are as equilateral as they can be (given the set of anchor points) and for each triangle the circumcircle through its three anchor points does not contain any other anchor point. One such circumcircle is depicted in Figure 29 B. Each pixel in a DEM has a value assigned, which is the height for that grid.

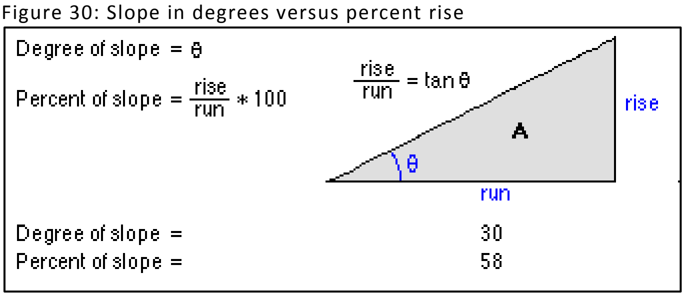
Figure 29: Image A shows elevation values, and B shows a delaunay triangulation



Source: (Huisman & de By, 2009)

It is important to use the right DEM raster size (f.e. 0.5 by 0.5 meter) and to check the created DEM in a GIS environment, like QGIS. When the DEM is created a slope map can be generated. This can be done both with LAStools as in QGIS. The z-factor can be set when generating a slope map in QGIS, which is needed when the x, y coordinates are different from the z-unit. If the x, y and z coordinates are displayed in meters a z-factor of 1 is needed which avoids the need to reproject.
According to Burrough & McDonell (1998), the maximum rate of change in value from a cell to its neighbours is calculated in a slope map. Basically, the maximum change in elevation over the distance between a cell and its eight neighbours identifies the steepest downhill descent from the cell. Conceptually, the tool fits a plane to the z-values of a 3 x 3 cell neighbourhood around the processing or center cell. The slope value of this plane is calculated using the average maximum technique. Figure 30 is showing the slope which can be calculated in degrees (0-90°) or percent rise.

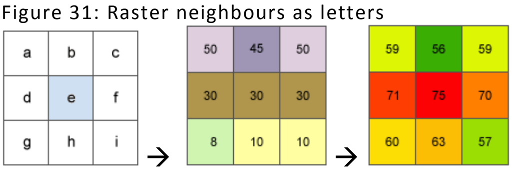
Figure 30: Slope in degrees versus percent rise



Source: (Esri, 2015)

The rates of change of a surface in the horizontal and vertical directions from a center cell determine the slope. The values of a center cell and its eight neighbours determine the horizontal and vertical deltas. Figure 31 is showing the neighbours identified as letters from *'a'* to *'i'*, with *'e'* representing the cell for which the slope is being calculated.

Figure 31: Raster neighbours as letters



Source: (Esri, 2015)

The rate of change in the x direction for cell *'e'* is calculated with the following algorithm:

[dz/dx] = ((*c* + 2*f* + *i*) - (*a* + 2*d* + *g*) / (8 * *x_cellsize*)

The rate of change in the y direction for cell *'e'* is calculated with the following algorithm:

[dz/dy] = ((*g* + 2*h* + *i*) - (*a* + 2*b* + *c*)) / (8 * *y_cellsize*)

After the creation of a slope map the permitted parts of this map need to be extracted. This can be done by using an expression in the Raster Calculator in QGIS, like "filename" <= 9.46°. This expression will set the value of the pixel to 1 if matches the expression and 0 if it does not. When the permitted parts are extracted they have to be converted to a new Shapefile. In QGIS this can be done by using the mask of the Raster Calculator via:

Raster → Conversion → Polygonize (Raster -> Vector)

A vector data structure produces a smaller file size than a raster image, because a raster image needs space for all pixels while only point coordinates are stored in vector representation. Also vector data is easier to handle on a computer than raster data, because it has fewer data items and it is more flexible to be adjusted for different scale.

The result is a Shapefile with the angle of inclination values that are accessible for mobility impaired people. This shapefile contains immediately the permitted height.

(4) EXTRACTING AREAS WITH PERMITTED FREE PASSAGE

Afterwards the points (obtained during step 2) need to be filtered by using the created Shapefile with the permitted angle of inclination and threshold (obtained during step 3). Points can be clipped out by using LASclip. In this way points will remain which do have the permitted threshold and angle of inclination.

The next step is the creation of a binary grid for checking whether the (filtered) points satisfy the permitted free passage for mobility impaired people. A binary grid can be made by using LASgrid with the '-occupancy' option. LASgrid is a tool that reads points and grids them onto a raster. LASgrid can result into multiple formats, like ASC. With a binary grid the width of points can be determined. This can be done by making a (Python) script that checks in horizontal and vertical direction whether grid cells meet the permitted width for mobility impaired people. The output file of LASgrid can be used as input for this script. The script should result into (two) new files which contain all grid cells that satisfy. When using a grid (as input) with a small step size, no width check has to be performed in diagonal direction, because the check applied in horizontal and vertical direction will already assess the width in a proper way. Afterwards the resulting grid cells can be converted to a new Shapefile.

The Shapefile with permitted free passage and the Shapefile with permitted threshold and angle of inclination (obtained during step 3) have to be overlaid in a GIS environment. The result will be a new Shapefile with the permitted angle of inclination, threshold and free passage for people with mobility impairments. So these areas do meet the three geometrical demands for movement and are accessible for mobility impaired people.

(5) OPTIMIZATION OF THE GENERATED POINT CLOUD

The last step is to define the most suitable amount of photos to get a proper point cloud. It is necessary to know on forehand, which scene or object needs to be reconstructed in a particular area of country. For defining a suitable point cloud density the Nyquist-Shannon sampling theorem can be used. The Nyquist-Shannon sampling theorem originates from the information theory and defines the process of sampling an analogue signal into a discrete signal, without losing important information during this transaction. The equation of the Nyquist-Shannon sampling theorem shown below can be used to calculate the smallest (i.e. the most suitable) point cloud density per square meter (D), for generating outdoor accessibility information, by determining the smallest dimension of a point cloud (Kraus, 2007).

$$D \text{ (point per } m^2) = (1 / (\text{Smallest dimension of a pedestrian path} / 2)^2)$$

An object within a point cloud has three dimensions: width, length and height. The smallest dimension of an object in a point cloud should be used to determine the most suitable point cloud density. Suppose a path has a width of 0.5 meter, a length of 10 meter and a height of 0.7 meter. In this example, the width is the smallest dimension of the path. Therefore, the width of this path should be used to determine the most suitable point cloud density for detecting the path in a point cloud. Thus the smallest point cloud density for detecting the path is:

$$D = (1 / (0.5m / 2)^2) \qquad D = 16 \text{ points per } m^2$$

Afterwards, the right point cloud has to be obtained. Therefore it is necessary to define how many images are needed to derive this suitable point cloud density. Based on related work concerning 3D reconstruction with the program PhotoScan the following conclusions can be drawn:

- There is <u>not</u> a rule of thumb how many images are needed for 3D models (Agisoft Community Forum, 2012) ;
- The amount of images needed for good quality 3D models really depends on what scene or object needs to be reconstructed, like capturing a full human head or a face of a head. There is no manual for this (Agisoft Community Forum, 2013a) ;

- A highly redundant network of overlapping images is required (Thoeni, Giacomini, Murtagh, & Kniest, 2014) ;
- The amount of overlapping images needed depends on the field of view of the camera (Thoeni et al., 2014).

Not only will the amount of images determine the quality of a point cloud, also the:

- Camera used. The density of a point clouds varies depending on the camera used (Thoeni et al., 2014). Cameras which could not supply high resolution images and videos are less suitable for photogrammetry use (Balletti, Guerra, Tsioukas, & Vernier, 2014). However nowhere is stated what the minimum pixel requirement per camera is for a successful 3D model (Agisoft Community Forum, 2013b).
- Image resolution. With a higher image resolution, more details can be incorporated (Agisoft Community Forum, 2013b). In general, images with a lower resolution are more affected by noise and will result in lower resolution point clouds. Comparable results with low-resolution images can be achieved by using more images to provide sufficient overlap (Agisoft Community Forum, 2013b) ;
- Direction of images taken with respect to the object. The precision of a point cloud will be optimized when the images are taken parallel to the object with high overlap (Balletti et al., 2014) ;

4.4 CONCLUSIONS

A division is made in two different workflows according to the different sensors.

For the RTK GPS data it is necessary to compute height differences between adjacent track-points. Afterwards the speed and distance between track-points need to be obtained. The travelled distance together with the height differences could be used for computing the angle of inclination between adjacent track-points. The best possible points should be obtained by filtering the RTK GPS data based on quality. A quality of several centimeters is sufficient. Finally the lines between adjacent track-points can be extracted by filtering out the observations which do not meet the permitted angle of inclination and/or threshold. The lines which do meet the permitted threshold and angle of inclination can be saved to a new (CSV) file.

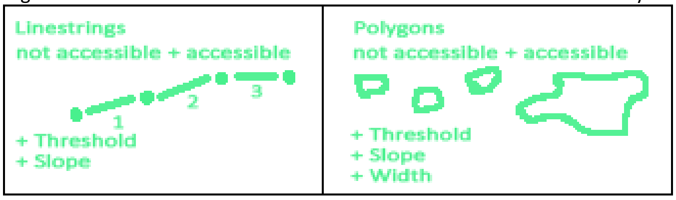
For the camera data it is necessary to convert the data into a series of photos wherefore the program FreeVideo can be used. A point cloud needs to be generated by using these photos. For this purpose the program PhotoScan can be used. It is necessary to filter a point cloud to obtain the most precise points. For checking the point cloud precision and reliability a profile can be made to compare height differences between points. A point cloud produced by camera data can be converted to a highly detailed DEM image, which matches the earth's surface. In addition a slope map can be created from this DEM image. After the creation of a slope map the permitted parts of this map need to be extracted. When the permitted parts are extracted they have to be converted to a new (Shape) file. Afterwards the points need to be filtered by using the created Shapefile with the permitted angle of inclination and threshold. The next step is the creation of a binary grid for checking whether the points satisfy the permitted free passage for mobility impaired people. Afterwards the resulting grid cells can be converted to a new (Shape) file. This file (which contains regions that do have a proper free passage) and the (Shape) file with the permitted threshold and angle of inclination can be overlaid in a GIS environment. The result is a new (Shape) file with the permitted angle of inclination, threshold and free passage for people with mobility impairments.

Which of the proposed workflows is the best for a municipality?
Both workflows are useful, but they did not work very well. The municipality will not be happy with workflows that consist of different types of software to derive outdoor accessibility information. For the proposed workflow by making use of RTK GPS data two programs are needed, namely: QGIS and IDLE. For the proposed workflow by making use of camera data five programs are needed, namely: Freevideo, Agisoft Photoscan Professional (version 1.1.0), QGIS, Quick Terrain Modeler and IDLE (the Command Line is a default program). However, there are operations that are done (during the implementation of the workflow) with software that can also be performed with other software.

For this thesis QGIS was used because it is an open source and free GIS software enabling to visualize, manage, edit and analyze data. IDLE (Python's Integrated Development and Learning Environment) can also be downloaded for free and is used during the MSc program Geomatics. As stated before, the FreeVideo software is free, easy to use and has advanced options to select frames from videos and record them as separate images, and therefor selected as program for the workflow. The PhotoScan software has been very suitable for this research. It was chosen because it produces professional point clouds starting from a series of photos and relies on the latest 3D design technologies. Quick Terrain Modeler was selected for this thesis because a free trial license can be downloaded, and with this program a bite can be taken out of the profile of a point cloud in x-direction and y-direction so that other points (for example a wall) will not been shown. This is very useful for analyzing the data. This operation can also be performed with other software, like LP360 (http://www.qcoherent.com/index.html) which is an extension to ArcMap.

Both workflows differ in the representation. The RTK GPS data processing is a kind of point-measurements. In a certain street mobility impaired people can or cannot pass. However, the camera data is modelled following a raster-based approach. This was done to limit complexity of the methodology, but when in future more information will be linked to pavements (like route attractiveness) a raster-based method might not be sufficient. Additionally, for the methodology of RTK GPS data two geometrical demands for movement will be used, and for the methodology of camera data three geometrical demands. Furthermore the workflows produce different results. The generated accessibility information of RTK GPS data will consist of linestrings between adjacent track-points with the maximum threshold (in meters) and slope (in degrees) (see Figure 32). The derived accessibility information of camera data will consist of polygons with the maximum threshold (in meters) and slope (in degrees), and the minimum width (in meters) that appears in the geometry.

Figure 32: Differences between the derived outdoor accessibility information



The workflow for generating accessibility information by making use of RTK GPS data is recommended to a municipality. It takes less time to process RTK GPS data and fewer programs are needed. Furthermore, for the position determination RTK GPS should be able to work fine, especially by waiting a bit longer before the device achieves a good quality.

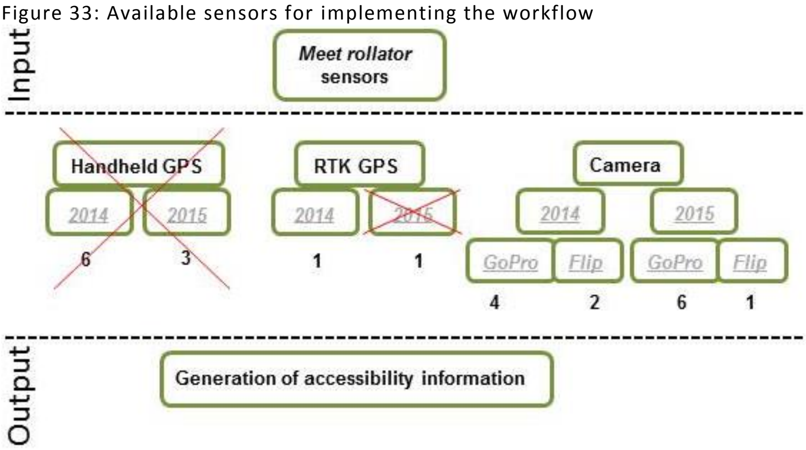
5 IMPLEMENTING THE WORKFLOW

This chapter will implement the workflow for generating accessibility information, by using sensor-data collected by a *meet rollator* for the research area, which is defined in paragraph 1.6. Paragraph 5.1 will discuss the data, which is used for implementing the workflow. Paragraph 5.2 will generate accessibility information from RTK GPS data of the research area. Paragraph 5.3 will generate accessibility information from camera data of the research area. Thereby, objective 2 (identify which data, programs and packages can be used to develop a methodology that generates accessibility information, and determine the accessibility by this proper set of software and data) will be achieved. Finally each sensor will be evaluated on their fit for purpose.

5.1 USED DATA

In chapter 4.1 the available sensors (handheld GPS, RTK GPS, and camera) on the *meet rollator* were assessed by using the knowledge of the MSc program Geomatics. In this chapter the RTK GPS and camera sensors will be evaluated on the fit for purpose to derive accessibility information. Figure 33 is showing the input sensor-data collected by a *meet rollator* in December 2014 and January 2015.

Figure 33: Available sensors for implementing the workflow



HANDHELD GPS

For this thesis the measures of handheld GPS devices obtained with the *meet rollator* in December 2014 and January 2015 will not be used for generating accessibility information. As stated before, a RTK GPS device is more precise than a handheld GPS (see Table 4).

RTK GPS

The measures of the RTK GPS Leica device will be used, which can achieve an accuracy of 2-3 cm in XY-direction and 5 cm in Z-direction. The RTK GPS data collected in December 2014 will be used as test data for implementing the workflow. This data consist of 2118 track-points which cover a distance of 6.28km.
The RTK GPS data collected in January 2015 will not be used. This RTK GPS data is not reliable because the device stopped working during the measurement (it was broke). Therefor no accurate elevation data and quality value in horizontal direction are available.

Table 4: Comparison of a RTK GPS and handheld GPS

	RTK GPS Leica 	Handheld GPS Garmin eTrex-30 
Dimensions	22.5 x 10.5 cm	10.7 x 5.6 x 3.0 cm
Accuracy	1 cm	< 10 m
Altimeter accuracy	-	+/- 3 m, 30 cm resolution

Source: (Hall, Cooper, & Lawton, 2008)

CAMERA

The camera data collected with a Flip camera, equipped on a *meet rollator* in January 2015, will be used as test data for implementing the workflow. It is not feasible to look at all the streets in this part of Amsterdam. Therefor the focus will be on a pedestrian path in a street which is expected to show the most locations that do meet the three requirements. Of the camera data only a part will be used, namely which cover a part of the focus street (see Figure 34).

Furthermore, a part of the data collected in December 2014 will be used that cover the same part of the focus street. The GoPro videos will be used to check, in the 'Optimization' part (see chapter 5.3) whether the Flip camera and GoPro camera will provide the same point cloud quality.

Figure 34 shows the research area (a part of the municipality of Amsterdam) and focus street. The workflow for generating accessibility information by making use of camera data will be performed on the street called: 'Nieuwe Looiersstraat'.

Figure 34: Image A shows the research area, B shows a focus street, and C shows a photo of this street

Source: (de Haan, 2015) (AMS, 2015)

5.2 IMPLEMENTING WORKFLOW RTK GPS DATA

This paragraph will implement the workflow for generating accessibility information from RTK GPS data, which is discussed in chapter 4.2, by using RTK GPS data for the research area which is defined in paragraph 0.

Table 5 is showing a small part of the CSV file obtained by the RTK GPS device in December 2014. NAP is an abbreviation for Normal Amsterdam Level (Dutch: Normaal Amsterdams Peil). This shows how high the land is located with respect to the sea level.

Table 5: CSV file of RTK GPS data obtained in 2014

Point Id	Easting	Northing	NAP_m_	Date	Hr	Min	Sec	Quality	Ant_Hgt
AM1	121317.264	485684.195	2.81	12/16/2014	14	14	54	0.825	1.84
AM2	121317.657	485685.318	0.958	12/16/2014	14	14	59	1.081	1.84
AM3	121317.451	485685.907	-0.019	12/16/2014	14	15	4	1.05	1.84

(1) CALCULATING HEIGHT DIFFERENCES

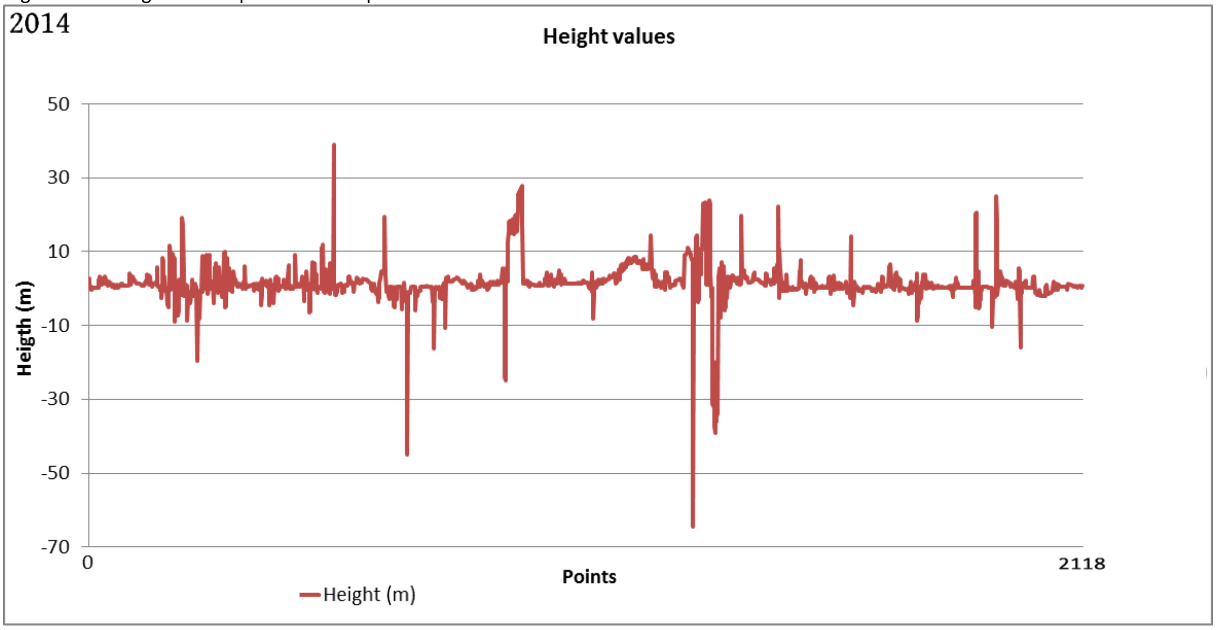
According to the workflow, the first step in the "Calculating height differences" part of the workflow is to obtain the quality value in vertical direction from RTK GPS data. Table 6 is showing a small part of the RTK GPS data for which the quality value is determined in vertical direction.

Table 6: RTK GPS data with quality

Point Id	Easting	Northing	Quality hor. [m]	Quality vert. [m]
AM1	121317.264	485684.195	0.825	1.650
AM2	121317.657	485685.318	1.081	2.162
AM3	121317.451	485685.907	1.05	2.100

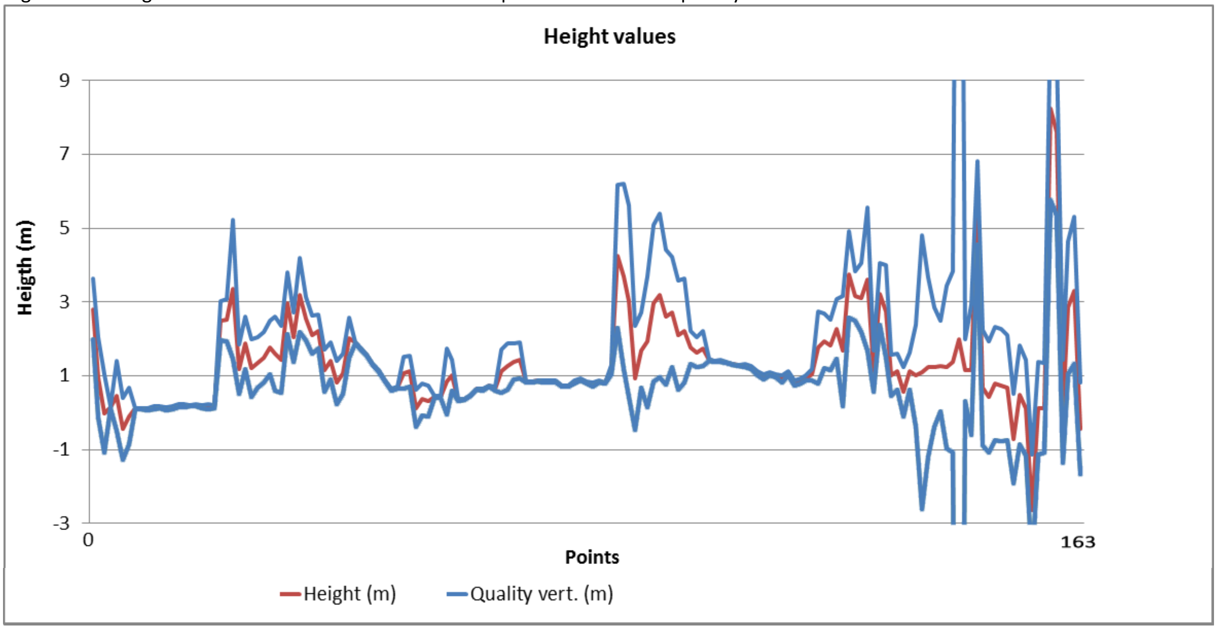
Afterwards a z-profile of the data is obtained and height differences between adjacent RTK GPS points are computed. As stated before, the distance covered by the RTK GPS data from 2014 is 6.28km. Figure 35 is showing all height data. It is hard to draw conclusions by using this figure.

Figure 35: Height value per RTK GPS point



That is why more graphs are obtained which shows the height between consecutive points. Figure 36 on page 52 is showing one of these graphs in which the height and quality in vertical direction of the RTK GPS data per 163 points is visualized. The quality is shown by blue lines. For some points the quality in vertical direction is very bad (several blue lines fall outside the graph).

Figure 36: Height values for the first 163 RTK GPS points with their quality



For this thesis a Python script is made which obtains the speed and distance between all track-points of the RTK GPS measure. The CSV file of the RTK GPS is used as input for this script.
Table 7 is showing the output (a new CSV) file of the script that contains the distance, time and the speed between track-points.

Table 7: CSV file with distance, time and speed

Line Id	Point Id 1	Point Id 2	Distance difference [km]	Time difference [s]	Speed [km/h]
1	AM1	AM2	0.0012	0:00:05	0.857
2	AM2	AM3	0.0006	0:00:05	0.449
3	AM3	AM4	0.0025	0:00:05	1.832

The next step is to compute the travelled distance between adjacent points. In this way also the total travelled distance can be derived. Table 8 is showing the calculated distance, height and slope between adjacent RTK GPS points.

Table 8: Computed slopes between adjacent track-points

Line Id	Point Id 1	Point Id 2	Height difference [m]	Distance difference [km]	Slope [°]
1	AM1	AM2	1.85	0.0012	57.3
2	AM2	AM3	0.98	0.0006	57.4
3	AM3	AM4	-0.17	0.0025	3.8

(2) OBTAINING THE BEST POSSIBLE POINTS

Afterwards the RTK GPS points are filtered to obtain the best possible points. It is important that points are well positioned, otherwise the distance between points will not be sufficient: it will be too large or too small which will affect the calculated speed value. Therefor it is necessary to filter the RTK GPS data based on their quality value. Table 9 is showing the quality values indicated by meters. ‘No’ means that a point needs to be filtered out. For this thesis the points with a horizontal precision bigger than 10 centimeter are filtered out.

Table 9: Quality check

Line Id	Point Id 1	Point Id 2	Point 1 Quality hor. [m]	Point 2 Quality hor. [m]	**Complies** to Quality hor. < 0.1m
1	AM1	AM2	0.825	1.081	No
2	AM2	AM3	1.081	1.050	No
3	AM3	AM4	1.050	0.032	No

With reference to the used RTK GPS data for this thesis, only 367 points of a total of 2118 points do have a horizontal precision better than 10cm.

(3) EXTRACTING LINES WITH PERMITTED ANGLE OF INCLINATION AND THRESHOLD

The next step is to filter the data based on the height difference and slope between adjacent points. For this thesis the permitted height is 0.05 meter and slope is 9.46°. These values are used for filtering the points (see Table 10).

Table 10: Quality and slope check

Line Id	Point Id 1	Point Id 2	Point 1 Quality hor. [m]	Point 2 Quality hor. [m]	**Complies** to Quality hor. < 0.1m	Height difference [m]	**Complies** to Height diff. < 0.05m	Slope [°]	**Complies** to Slope < 9.46°
8	AM8	AM9	0.019	0.024	YES	0.00	YES	2.5	YES
9	AM9	AM10	0.024	0.019	YES	0.01	YES	3.0	YES
10	AM10	AM11	0.019	0.031	YES	-0.04	YES	0.4	YES

As stated before, adjacent points can also be seen as a line, a part of a track-line. The lines between adjacent points obtained after filtering the points can be saved to a new CSV file and exported.
For this thesis this results in a file that contains 330 lines that do meet the permitted height difference and slope in the research area. Of these lines in total 124 lines are <u>not</u> accessible and the other 206 lines are accessible according to the three demands used for this thesis. Table 11 is showing the resulting CSV-file.

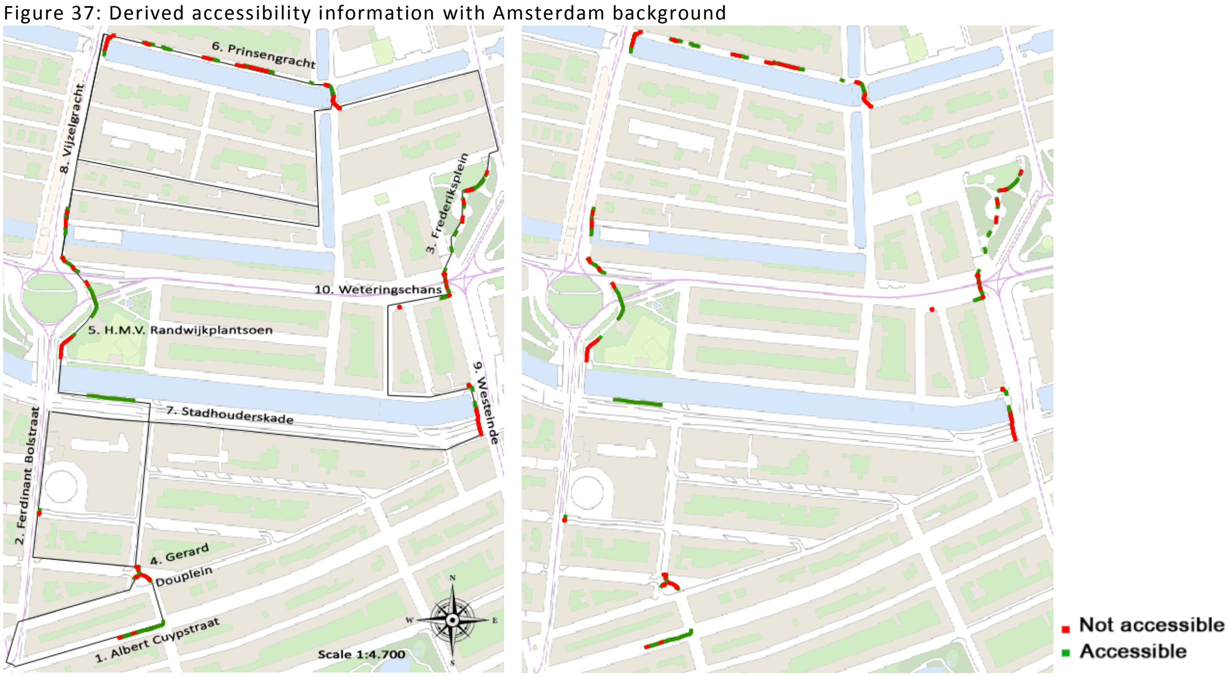
Table 11: Resulting CSV-file with LINESTRINGS

province	municip_name	district	neighbourhood	accessible	line_id	good_quality
North-Holland	Amsterdam	Zuid	Oude Pijp	YES	8	YES
North-Holland	Amsterdam	Zuid	Oude Pijp	YES	9	YES
North-Holland	Amsterdam	Zuid	Oude Pijp	YES	10	YES

geom	point_id_one	point_id_two	data_year	obtained_year
LINESTRING (121300.098 485691.008,121300.076 485691.002)	AM8	AM9	2014	2015
LINESTRING (121300.076 485691.002,121299.903 485691.021)	AM9	AM10	2014	2015
LINESTRING (121299.903 485691.021,121294.435 485691.591)	AM10	AM11	2014	2015

This CSV file can be opened in a GIS environment, like QGIS. Figure 37 on page 54 is showing the derived accessibility information within the research area. The left image shows the (ten) streets by numbers with correspond to the numbers in Table 12 on page 54.

Figure 37: Derived accessibility information with Amsterdam background



Source: (de Haan, 2015)

Table 12: The derived accessibility information per street

		Results after implementing workflow		
		Total lines	*Accessible*	*Not accessible*
1.	Albert Cuypstraat	31	29	2
2.	Ferdinant Bolstraat	13	6	7
3.	Frederiksplein	57	31	26
4.	Gerard Douplein	33	20	13
5.	H.M.V. Randwijkplantsoen	14	7	7
6.	Prinsengracht	78	51	27
7.	Stadhouderskade	13	13	0
8.	Vijzelgracht	42	24	18
9.	Westeinde	28	12	16
10.	Weteringschans	21	13	8
		330	***206***	***124***

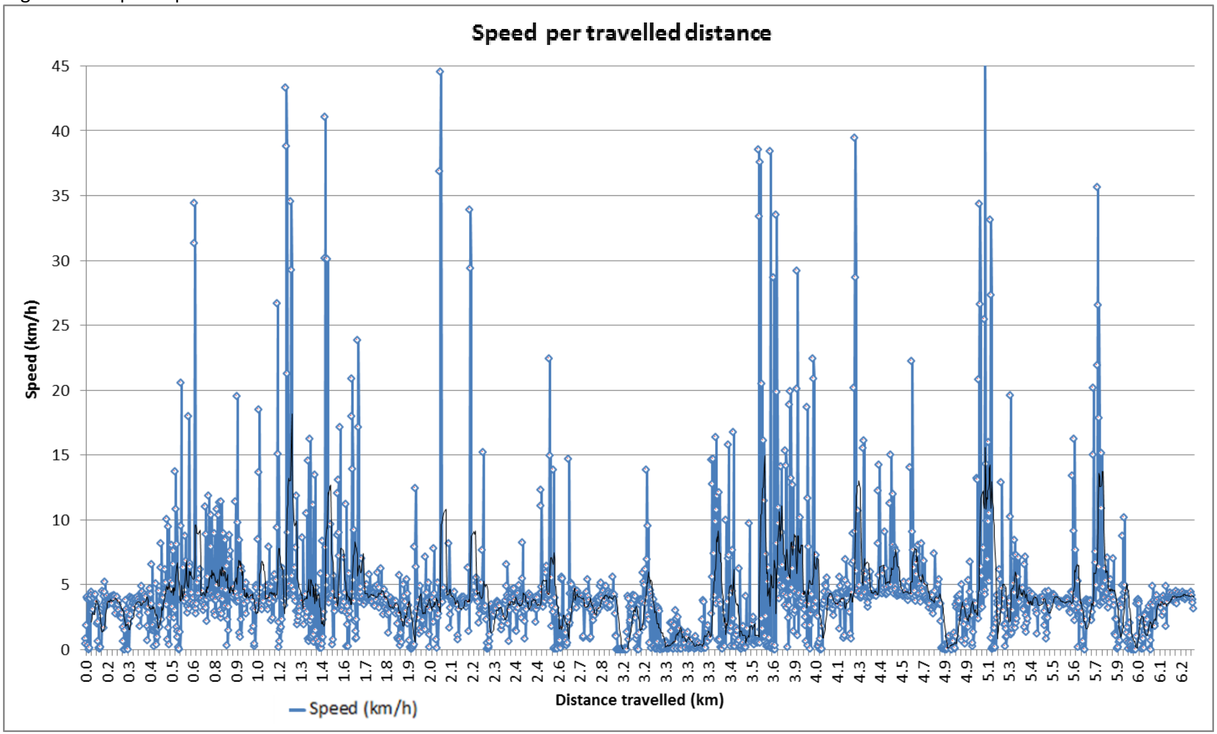
For this thesis most lines which are not accessible are situated in the ‘Prinsengracht’ and ‘Fredriksplein’.

When someone with a wheelchair, rollator or mobility scooter is entering a street and wants to continue walking through this street, sometimes it does not matter when one can or cannot pass a certain part in a street, because when a part of a street is blocked, the whole street is inaccessible. In this case, if for one position in a street an obstacle is present, the whole street is inaccessible. For this thesis this was not the case, so there are no complete streets marked as inaccessible, because for every street in the research area a detour is possible.

(4) ANALYSING TIME DELAYS

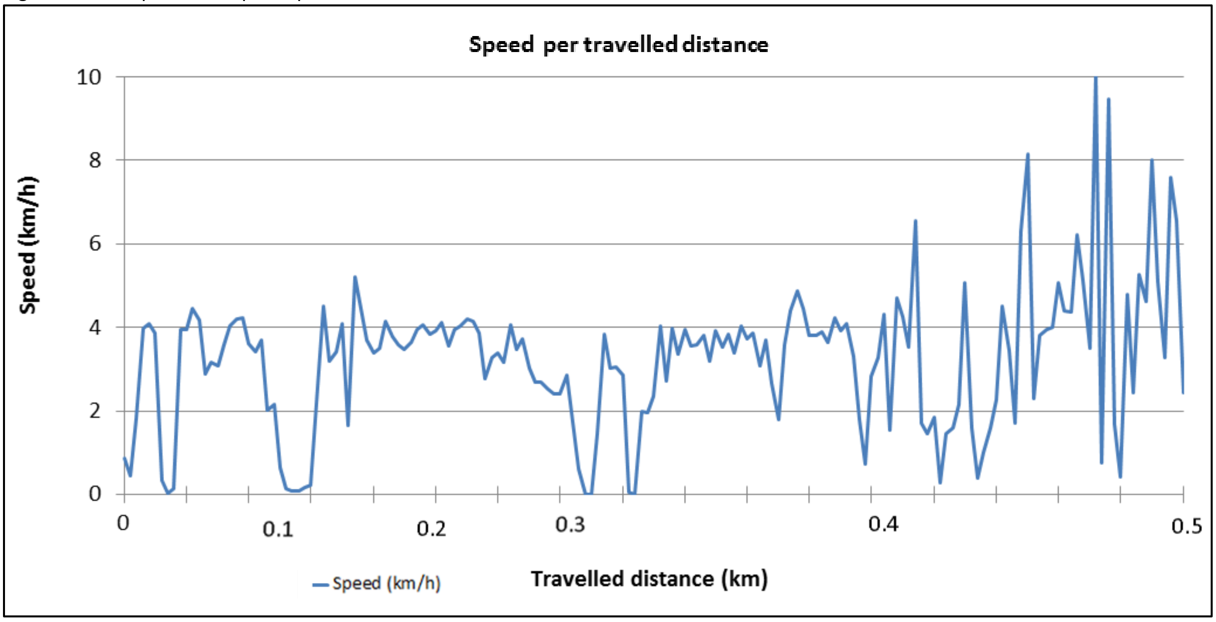
By making a graph of the travelled distance and speed, time delays can be determined. Figure 38 is showing the travelled distance and speed values of the RTK GPS data. By using this figure it is hard to draw conclusions.

Figure 38: Speed per travelled distance



That is why more graphs were made which show the speed between consecutive points per traveled distance of 0.5 kilometer. Figure 39 is showing one of these graphs.

Figure 39: Graphs with speed per travelled distance of 0.5 kilometers



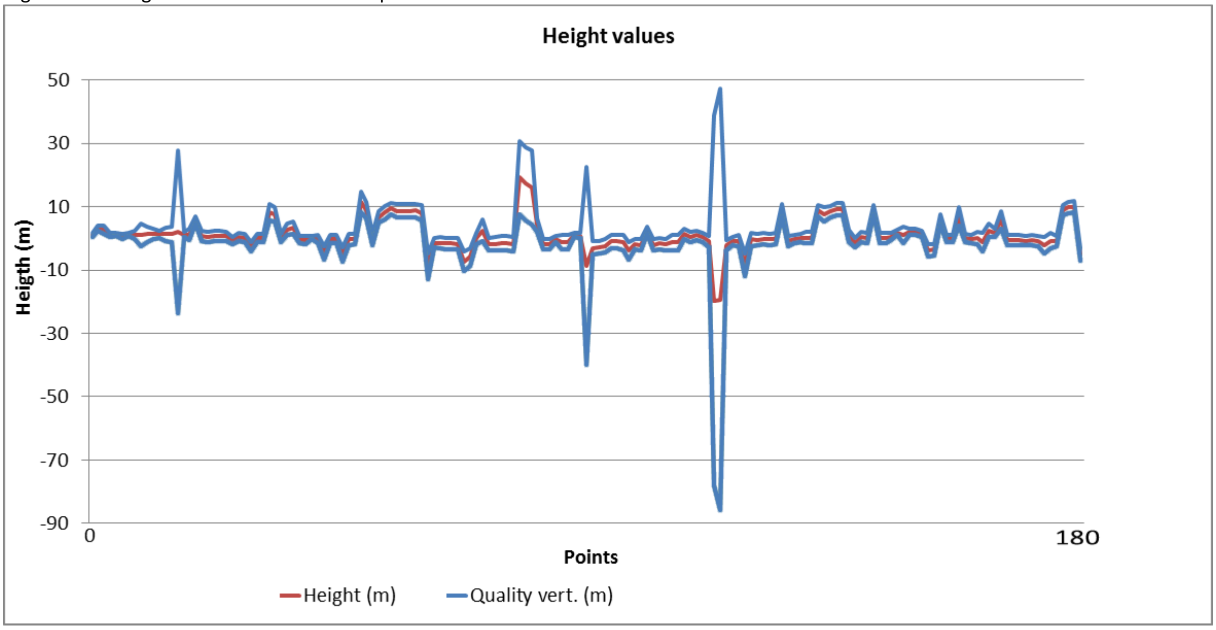
The graph is showing that the rate varies. For the RTK GPS data used for this thesis the speed varies between 0 -45 km/h. A speed of 45 km/h cannot be correct, since the average walking speed of a human 5 km/h. The speed varieties and wrong speed values can be explained with reference to the horizontal precision. The insufficient horizontal precision of the used RTK GPS data has the effect that the (calculated) distance between consecutive points is <u>not</u> correct, and therefore the (calculated) speed is not correct. Therefore the observations of the time delay cannot be used for this thesis.

It should be noticed that when the horizontal precision of RTK GPS data is sufficient, it is still hard to transform the obtained results into accessibility information.

CONCLUSIONS

With reference to the focus street in the research area, the RTK GPS measurement conditions were harsh. For the RTK GPS track-points in the focus street, all quality values are a very bad measure. Figure 40 is showing the z-profile of the points with their vertical precision, which is not precise.

Figure 40: Height values with vertical precision in the Nieuwe Looiersstraat



In the neighbourhood of (high) buildings GPS is not reliable. This was the case in the Nieuwe Looiersstraat in Amsterdam, according to Ron van Lammeren (developer of the *meet rollator* project; performer of the *meet rollato*r measurements in 2014 and 2015). More outliers occur when there are not enough intersections between satellites to get a good dilution of precision (DOP) value. The large buildings along the Nieuwe Looiersstraat have blocked the view to the satellites. In this way no position can be determined with a high precision (low quality).

Furthermore the RTK GPS present gaps at certain places. At these places not enough satellites were visible to determine its position. GPS failed due to buildings obstructing the path between the receiver and the satellites and the Leica-program stopped with the position-registration. The Leica-program continued when there were again enough satellites visible. Because a Leica-measurement can be aborted by poor conditions, it can take a long time before the position-determination starts again.

5.3 IMPLEMENTING WORKFLOW CAMERA DATA

This paragraph will implement the workflow for generating accessibility information from camera data, which is discussed in chapter 4.3, by using camera data for the research area which is defined in paragraph 0.

(1) BUILD POINT CLOUD

According to the workflow, the first step is to build a dense georeferenced point cloud from camera data. The camera data needs to be converted into a series of photos with the program FreeVideo. Figure 41 is showing the result of this conversion. In total 17 photos (of the Flip camera obtained in 2015) are shown which can be used for implementing the workflow. As stated before, the workflow for generating accessibility information will be performed on the street called: 'Nieuwe Looiersstraat'. The 17 photos cover a part of this focus street.

There is also tried to implement the workflow by using more photos which can be seen in Figure 65 on page 67. The 17 photos have resulted in a sufficient point cloud for deriving outdoor accessibility information (for this focus street). However by using more photos, fewer points are located underneath the road surface (noise) and this result in a point cloud which is more close to the reality.

Figure 41: Photos used for processing

Afterwards these photos were loaded into the program PhotoScan and inspected. For the alignment of photos it is necessary to set the accuracy at the highest level to get a more accurate estimation of the camera positions. The setting 'generic' for the pair preselection method means that that overlapping photon pairs will be selected by firstly matching the photos based on lower accuracy settings. Figure 42 A is showing a top view of the 17 photos (blue rectangles) with the result of alignment.

For generating a dense point cloud it is important to use 'high' quality settings, because a higher density of points helps to maintain more fine details. Figure 42 B is showing the result of building a dense point cloud. These points cover an area of 33 x 13 meters (429 m^2).

Figure 42: Image A shows the result of alignment, and B shows the result of building a dense point cloud

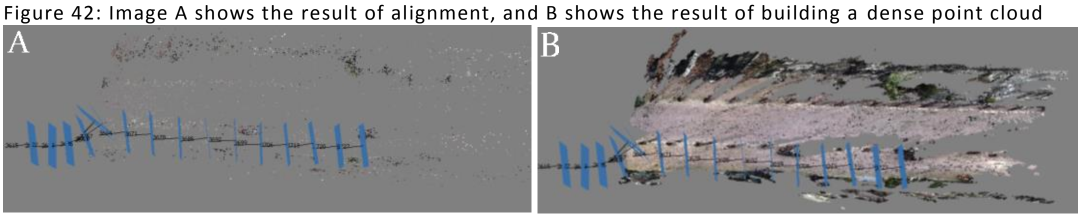


Figure 43: Image A shows the result of building a mesh, and B shows the result of the creation of texture

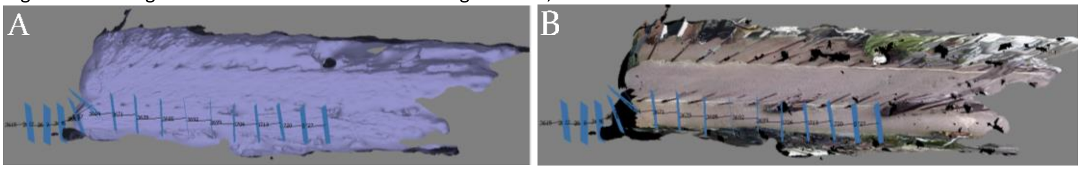


Figure 43 A is showing the created mesh. The final step for processing is the creation of texture. The main setting for this step is the mapping mode. The setting ‘generic’ creates the most uniform texture and is best suited for upright objects, like bollards (Dutch: Amsterdammertjes). Figure 43 B is showing the created texture.

In each of these steps, the program exists of the possibility to select certain settings. These settings have, inter alia, an influence on the eventual precision and the processing time. Table 13 provides an overview of the choices made in this thesis.

Table 13: Settings for Agisoft PhotoScan

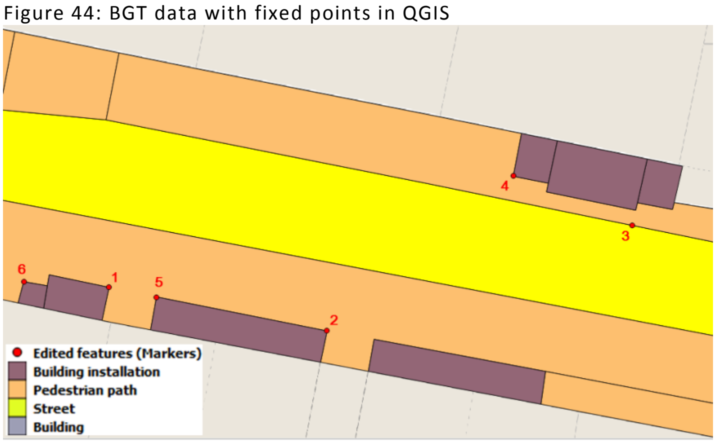
	Alignment of photos
Accuracy	High
Pair preselection method	Generic
	Building a dense point cloud
Quality	High
	Building a mesh
Surface type	Arbitrary
Source data	Dense cloud
Polygon count	High
	Build texture
Mapping mode	Generic
Blending mode	Mosaic

Step eight of the developed workflow is to place markers with the correct Global Positioning System (GPS) coordinates for setting up a coordinate system. For this thesis BGT data is used to get coordinates from the real world. In the created point cloud a number of fixed points were also included in the BGT data, like stairs, used for georeferencing. The extracted coordinates of the BGT data are put as markers into PhotoScan. The applied coordinate system for the BGT is the Rijksdriehoekmeting (RD system). For the extraction of the coordinates by using BGT data a new Shapefile layer (with type: point) in QGIS is made via:

Layer → Create Layer → New Shapefile layer (type: Point)

For this thesis six features, located on fixed points, were edited to the new Shapefile layer. These features occur in both the created point cloud as the BGT data. Figure 44 is showing the BGT data with these six (manually) edited features in QGIS.

Figure 44: BGT data with fixed points in QGIS



ID	X	Y
1	121508.655	485944.393
2	121515.866	485942.951
3	121525.9544	485946.4432
4	121522.0286	485948.0696
5	121510.221	485944.0731
6	121505.832	485944.5782

To fulfil georeferencing task, an even spread of markers is required to achieve results with the highest quality, both in terms of the geometrical precision and georeferencing accuracy. It is also true that the more markers are used for georeferencing, the more accurate the x and y-measurements in a point cloud. In this way a point cloud is better georeferenced.

The x and y-values of the six features (visualized in Figure 44) will be used for imported the (easting and northing) coordinates in PhotoScan by making markers with the exact same location. In this way the point cloud is closer to/on the real points with reference to reality. To extract the id, x and y-values of features in a Shapefile, it needs to be saved to a new CSV file by using 'GEOMETRY=AS_XY'.

In PhotoScan the total georeferenced-error is estimated based on the east, north and altitude (i.e. the elevation of an object above a reference surface) error. This means that the average total error (XYZ) of the markers in PhotoScan is estimated. In other words, the error shows the difference between where each photo is located according to 'the extracted coordinates' (in this thesis from the BGT) versus 'the coordinates predicted by the model of PhotoScan' (see Figure 45).

Figure 45: Print screen of the total error in PhotoScan

Markers	Easting	Northing	Altitude	Error (m)
point 1	121508.474824	485944.518789	0.002071	0.000000
point 2	121525.793197	485946.777613	-0.104459	0.000001
point 3	121516.079956	485942.933467	-0.001322	0.056691
point 4	121522.028565	485948.069633	0.000000	0.552485
point 5	121510.221034	485944.073085	0.000000	0.382507
point 6	121505.832031	485944.578213	0.000000	0.561088
Total Error				**0.358140**

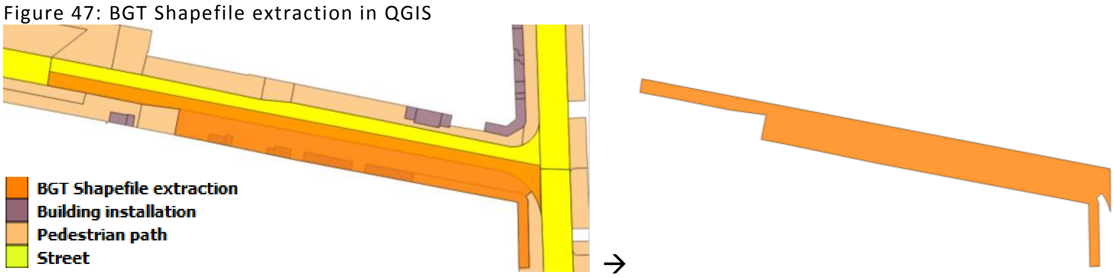
It is examined that the determination factor to have more confidence in a point cloud is defined by the amount of markers used for setting up a coordinate system. Figure 46 is showing a side view of the created points for this thesis. It consists of 237.250 points and covers an area of 33 x 13 meters (429 m^2). These points were exported in PhotoScan in LAS format.

Figure 46: Point cloud exported from PhotoScan (side view)

(2) OBTAINING THE BEST POSSIBLE/MOST CLOSE TO REALITY POINT CLOUD

When the construction of a point cloud is finished, the next step is to filter points in order to obtain a point cloud with the highest precision. For this thesis a Shapefile is extracted in QGIS from the BGT data used to filter the points in sideways-direction. The Shapefile contains a boundary of a pedestrian path and a small part of the street (Nieuwe Looiersstraat). Half of the street is used, because the *meet rollator* has walked on the sidewalk (not on the street) and in forward-direction the highest precision can be achieved. In this Shapefile the *Building Installations* from the BGT data are considered to be passable passages (see the purple fields in Figure 47). Figure 47 is showing the orange part which is the extracted Shapefile used for filtering the point cloud in sideways-direction.

Figure 47: BGT Shapefile extraction in QGIS



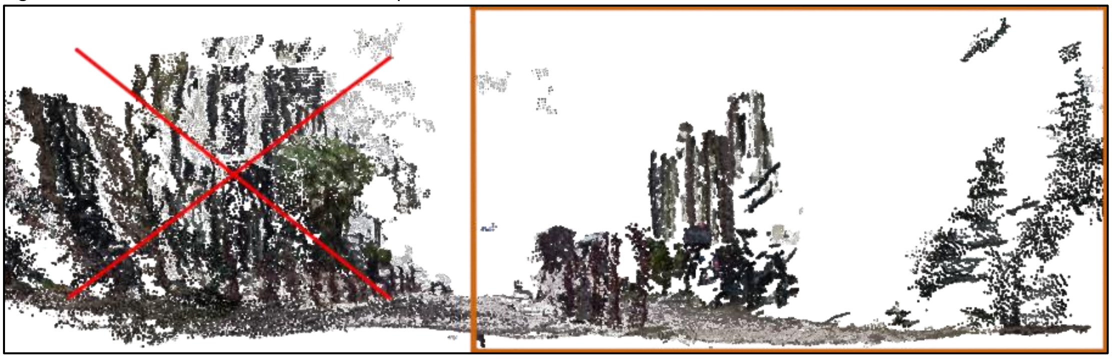
For the Shapefile creations of the BGT the post-processing function '*dissolve'* is used which merges adjacent features with the same category into one bigger feature (Huisman & de By, 2009). Dissolve can be found in QGIS via:

Vector → Geoprocessing Tools → dissolve

The 'snapping' tool in QGIS is used to clean the Shapefile.

The Shapefile extracted from the BGT and the LAS file created with PhotoScan (during step 1) were used as input files for the tool LASclip, which clips away all the points that fall outside the polygon, and stores the surviving points to the output LAS file. After LASclip the output LAS file consisted of 135.440 points (instead of 237.250 points). So in total -101.810 were removed. Figure 48 is showing the deleted points.

Figure 48: Point cloud with the deleted points



To know the point density and spacing of a LAS file, the tool LASinfo can be used with the command '-compute_density'. The numbers reported by LASinfo are computed by using a simple occupancy grid of 2x2 m cells and estimating the area that are covered by points as the total area of all cells that are receiving points. The area is then simply divided by the total number of points. This gives an 'average point density'. For this thesis the filtered point cloud has a density of: 664 points/m^2.

More about point cloud density can be found in step 5 'Optimization of the generated point cloud' on page 66. A point cloud density of 664 points/m^2 is a good number but, as stated before, a higher density of points helps to maintain more fine details. By using the Nyquist-Shannon sampling theorem (explained in chapter 4.2) there can be checked what kind of threshold can still be detected by using a point cloud with a density of 664 points/m^2.

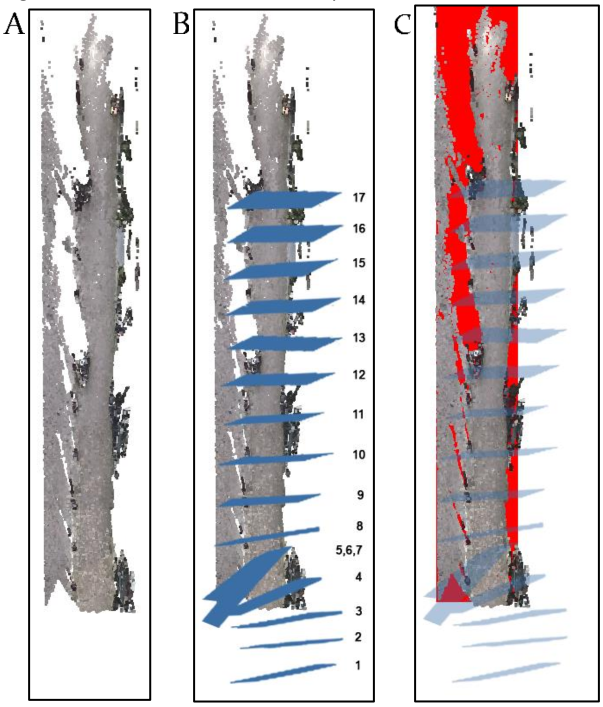
$$664 \text{ points per meter}^2 = 1 / (x / 2)^2$$
$$x = 0.08m$$

So with this density a threshold can be detected of approximately 0.08m. For this thesis a threshold of 0.05m needs to be detected (according to the geometrical demands for movement explained in chapter 3.6) so it is better to use a slightly higher density than 664 points/m^2. If the point cloud density is half, so 332 points/m^2, a threshold of approximately 0.11m can be detected by using this point cloud.

Afterwards the precision and reliability of points need to be checked. It is examined that the determination factor to have more confidence in a specific area than in another area is defined by the amount of frames which determine a certain point cloud area. The use of more photos (as input for PhotoScan) will provide greater overlap and so a more proper point cloud. Figure 49 is showing different top views of the filtered point cloud (visualized in Figure 48). Figure 49 A shows the points with camera view direction (orange arrow). Figure 49 B consists of the 17 photos used in this thesis for the creation of points. Figure 49 C shows the locations (in red) for which no points are indicated. That is due to several obstacles (like bollards and parked scooters) on the pedestrian path that have blocked the view of the camera. The beginning and center of the point cloud are constructed with more overlapping frames than the end of the point cloud. Therefor the beginning and center of the point cloud are more confident to be used for processing.

It should be noticed that the amount of frames are selected during step 1 and loaded into the program PhotoScan for generating a point cloud. So during this step the density of a point cloud will be controlled.

Figure 49: Precision and reliability check



The precision of points can also be checked by making a profile with the program Quick Terrain Modeler. By using this profile height differences can be compared. Figure 50 is showing the profile made for this study, which covers a length of 25m.

Figure 50: Profile across the points

Figure 51: Resulting profile AA'

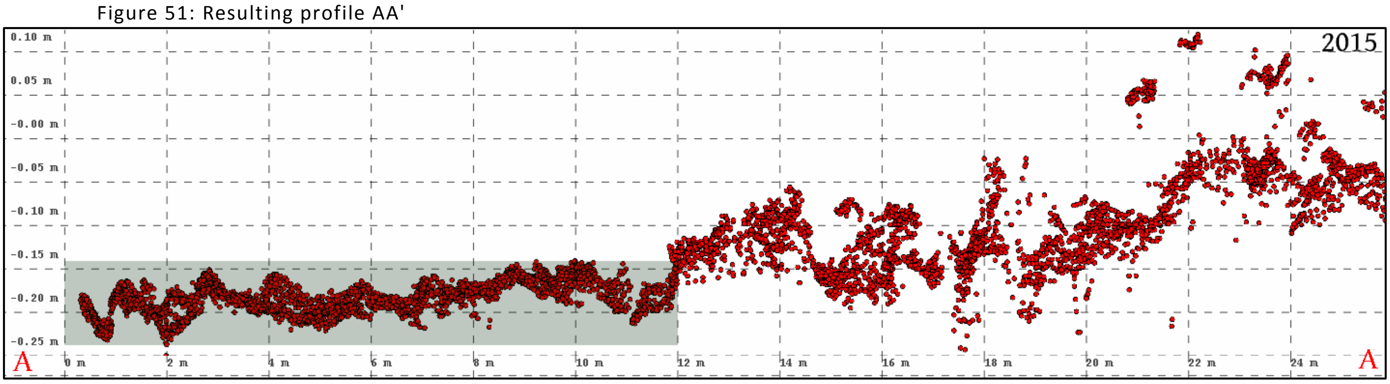
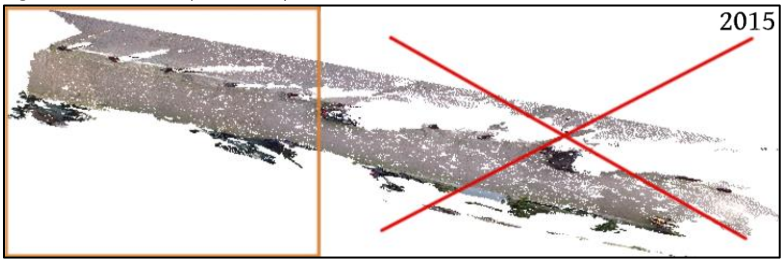


Figure 51 is showing profile AA'. The y-axis shows a height difference of -0.25 until 0.1 meter. The left part of the profile (in gray, until the (x-as) distance of 12m) is showing a height difference of 0.1m. The height differences become bigger in the right part of the profile (after the distance of 12m). This could be explained by the point cloud reliability which varies per area. The left side of the profile, so the beginning and center of the point cloud, is defined by more frames than the right side. More confidence can be achieved in the height differences of the left part (until the (x-as) distance of 12m), because this is defined by 12 frames and the right part is defined by less frames.

It is necessary to filter the points out in which less confidence can be achieved. For this thesis the points where filtered out after the distance of 12m, to have the best possible point cloud (see Figure 52 on page 62). The resulting LAS file consists of 70.235 (instead of 135.440 points).

Figure 52: Filtered points in point cloud made with camera data of 2015



Finally the precision of points is checked by using another point cloud of the same area. Another point cloud of the same area was generated. In this way the points were compared based on their z-profiles. The corresponding part, obtained by using a Flip camera video of 2014, is visualized in Figure 53 (orange rectangle).

Figure 53: Filtered points in point cloud made with camera data of 2014

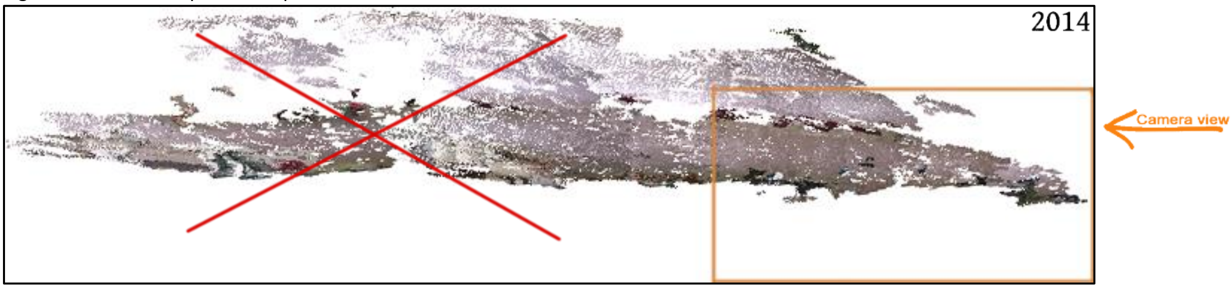
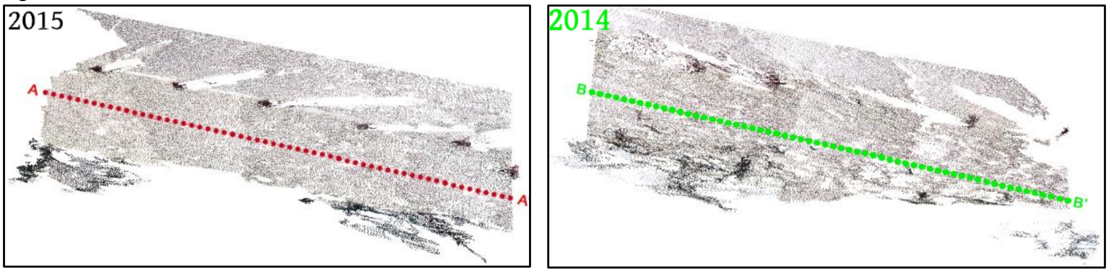


Figure 54: Cross-section AA' and BB'



Point cloud 1 of Flip camera data of **2015**: **70.235** points (visualized in **red**)
Point cloud 2 of Flip camera data of **2014**: **65.035** points (visualized in **green**)

Figure 54 is showing the cross-sections AA’ (in point cloud 1) and BB’ (in point cloud 2). By comparing both point clouds conclusions can be drawn about the quality of points. When the profiles of the point clouds (that contain the same area) look similar, it can be concluded that the quality is sufficient. The profiles are shown in Figure 55 and Figure 56. From these figures can be derived that point cloud 1 (created with Flip camera data of 2015) is more precise than point cloud 2 (created with Flip camera data of 2014), because the height differences vary less. Both look similar to each other in terms of height differences.

Figure 55: Point cloud made with camera data of 2015

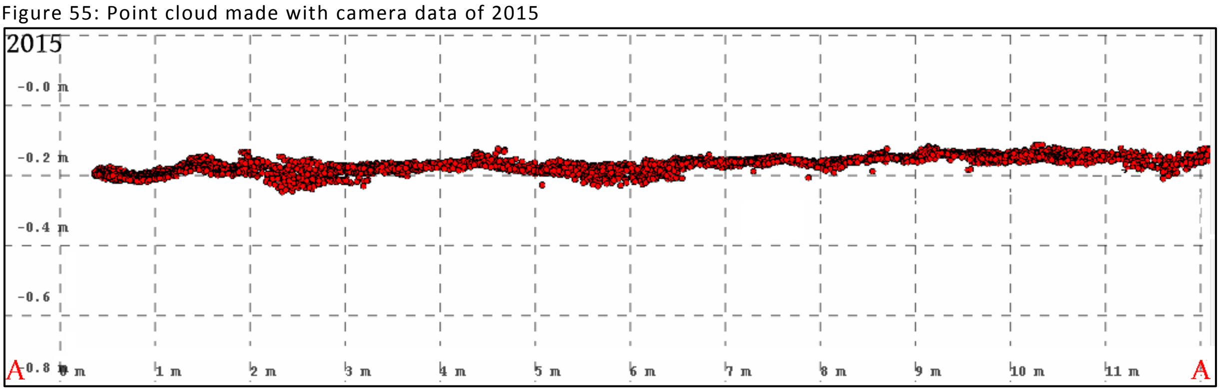


Figure 56: Point cloud made with camera data of 2014

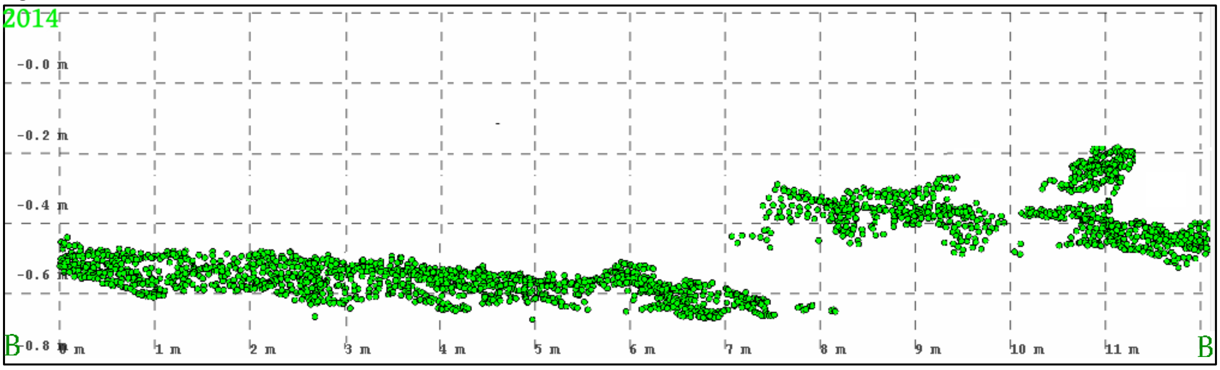


Figure 56 is showing the biggest height difference, which is in 0.4 meter, so accessible for people with mobility impairments. Furthermore point cloud 2 (created with Flip camera data of 2014) is more precise in the beginning (until 7m) than at the end. This was also the case for the point cloud of 2015 (after 12m). So to process point cloud 2, firstly the part after 7m needs to be excluded to obtain the best possible point cloud. It should be noticed that point cloud z-values are randomly chosen by PhotoScan, because no zero-reference z-value is used. That is why the profiles visualized above are not positioned at the same height level.

(3) CREATING A SHAPEFILE WITH PERMITTED ANGLE OF INCLINATION AND THRESHOLD

After the obtainment of the best possible point cloud, the points have to be used for constructing a DEM. For this thesis a DEM step size of 0.3 meter is used, because it suits with the point density and it originates from the maximum inclination value of 9.46° permitted for people with mobility impairments, which is associated with the height of 0.05m, which is discussed in chapter 3.6. This means that a height up to 0.05m must not exceed an angle of inclination to the ratios 1:6 (height:length). Figure 57 is showing the constructed DEM which covers an area of approximately 12x6m (77 m^2).

Figure 57: The constructed DEM

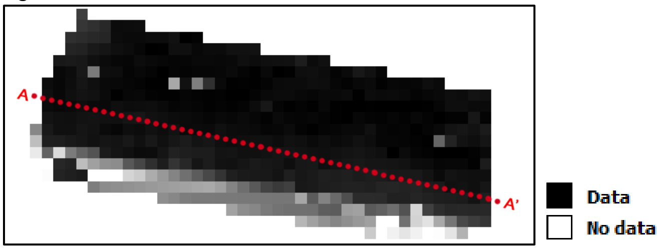


Figure 58 is showing a profile across the DEM visualized in Figure 57. This profile can be compared with the profile visualized in Figure 55. The z-values of both profiles look similar to each other which mean that the computed z-values for the DEM are correct. Figure 59 on page 64 is showing a comparison of the profiles in which can be seen that the profile of the DEM is located between the distributions of the points.

Figure 58: Profile across a DEM

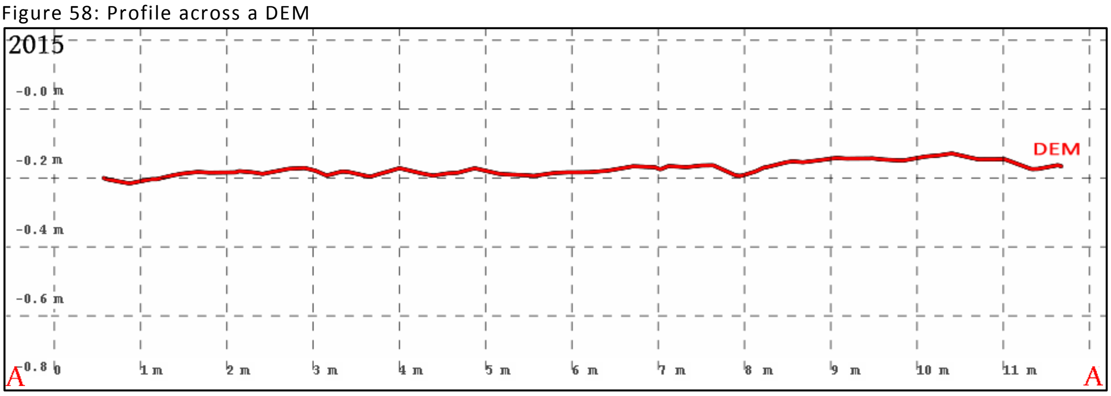
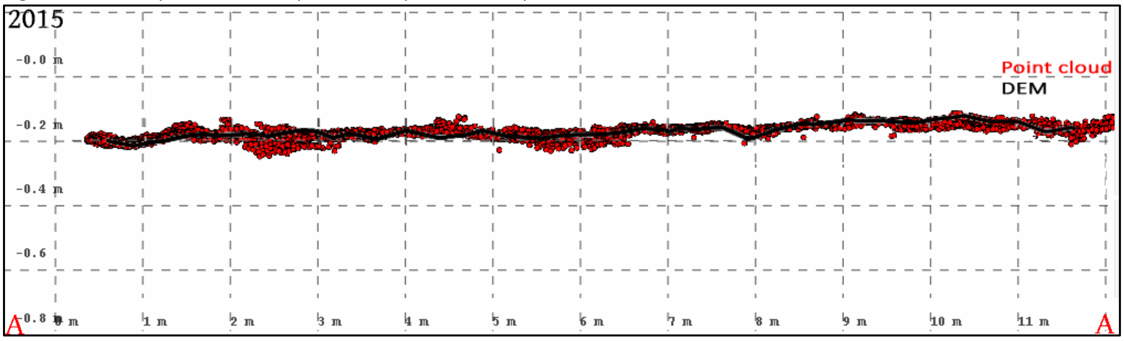


Figure 59: DEM profile in comparison to point cloud profile

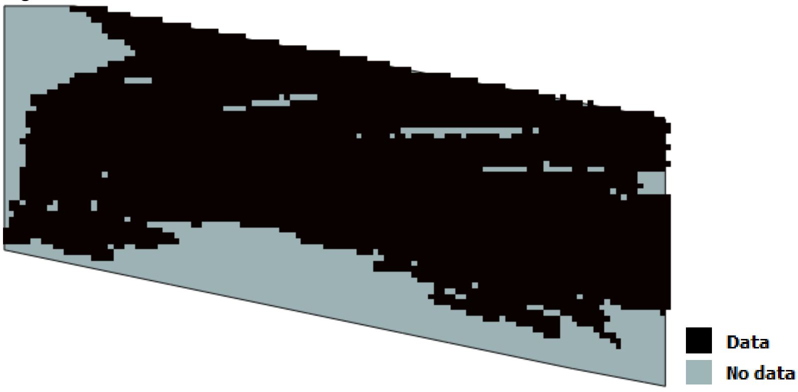


In addition, a slope map is generated by using QGIS. The next step is to extract the parts of a slope map which do have a permitted angle of inclination (9.46°) permitted for people with mobility impairments. Therefore the Raster Calculator in QGIS is used. After the extraction is done, the raster file needs to be converted to a vector format.

Figure 60 is showing the resulting raster file with the angles of inclination <= 9.46° and height until (rise) 0.05m, which are accessible for mobility impaired people. Finally the permitted parts were extracted and converted to a new Shapefile. It should also be noticed that only for a part of the processed area data is available (see Figure 61).

Figure 60: Angle of inclination and threshold

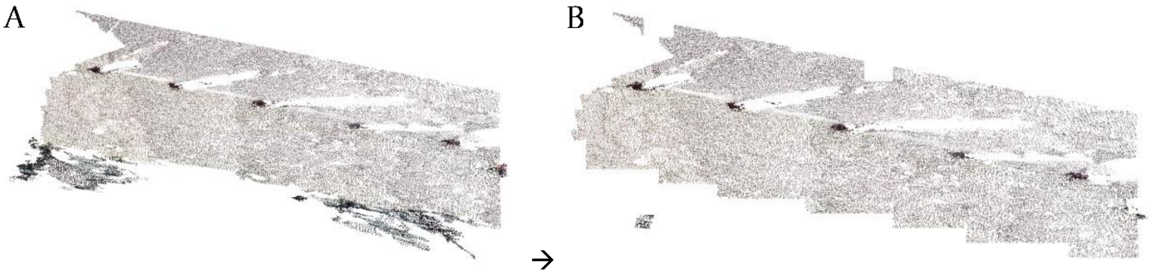
Figure 61: Available data in raster format



(4) EXTRACTING AREAS WITH PERMITTED FREE PASSAGE

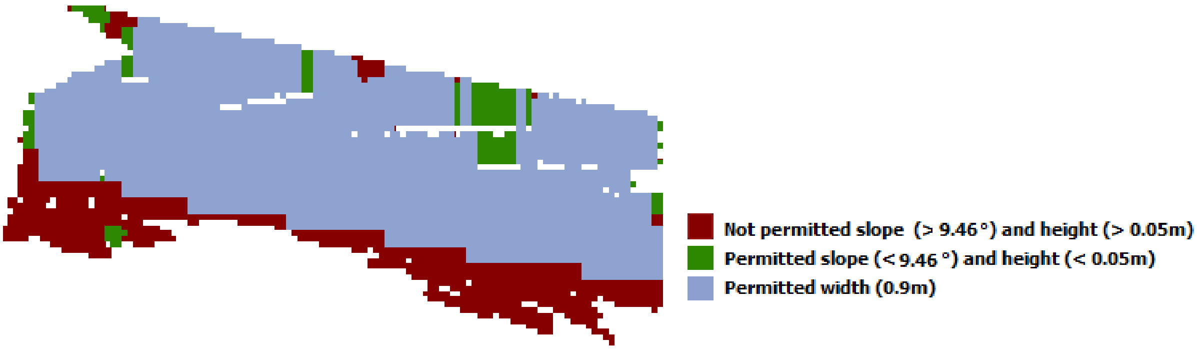
The next is to use the points (obtained during step 2) and the created Shapefile with the permitted angle of inclination and threshold (obtained during step 3) for filtering the points. The tool LASclip is used together with the Shapefile layer to clip out the parts of the points which do meet the permitted angle of inclination and threshold. Figure 62 is showing the resulting filtered point cloud. After LASclip the output LAS file consisted of 53.086 points (instead of 70.235 points). The filtered point cloud has a density of: 699 points/m2.

Figure 62: Image A shows the non-filtered point cloud, and B shows the filtered point cloud



Afterwards the width of points needs to be determined. For this thesis a binary grid of the points is used, created with the tool LASgrid, with a step size of 0.1 meter, because this gave the most precise raster file and it suited with the density of the points.
For this thesis a Python script was made which checked in horizontal and vertical direction whether the grid cells meet the permitted free passage of 0.9 meter for mobility impaired people. The created binary grid was used as input for this script. Figure 63 is showing the resulting file, containing the width check. For this thesis only the vertical check was necessary, because the pedestrian path of the chosen focus street is positioned in horizontal direction.

Figure 63: The overall derived accessibility information



Finally the raster file with the generated accessibility information was converted to a vector format and CSV file. Table 14 is showing the resulting CSV-file with the accessible and not accessible region.

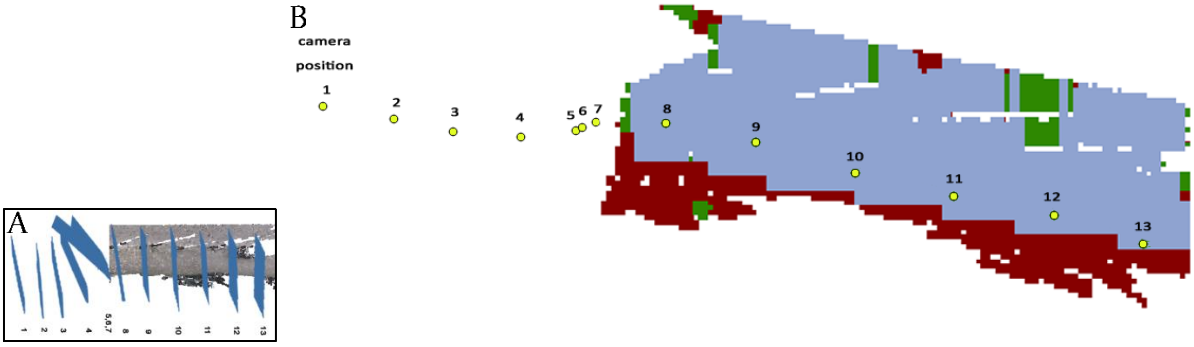
Table 14: Resulting CSV-file with POLYGONS

province	municip_name	district	neighbourhood	street	accessible
North-Holland	Amsterdam	Centre	De Weteringschans	Nieuwe Looiersstraat	Yes
North-Holland	Amsterdam	Centre	De Weteringschans	Nieuwe Looiersstraat	No

geovlak	data_year	obtained_year
POLYGON (((121501.802 485949.410475, 121501.802 …)))	2015	2015
POLYGON (((121498.416 485945.507241, 121498.416 …)))	2015	2015

As reference to the camera positions, determined by Agisoft PhotoScan, these areas are accessible for the *meet rollator*. Figure 64 on page 66 is showing the exact route where the *meet rollator* has walked based on the camera positions calculated with PhotoScan. This is the most real position that could be determined from the point cloud.

Figure 64: Image A shows the camera positions in PhotoScan, and B shows the exact route of these positions



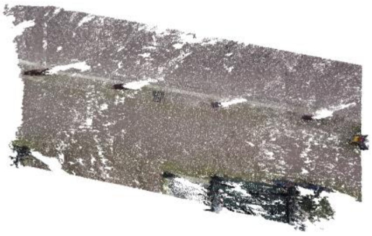
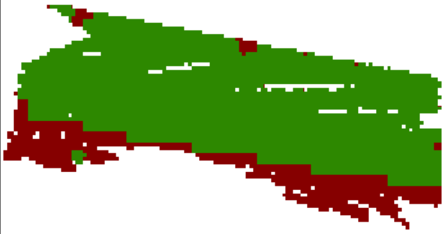
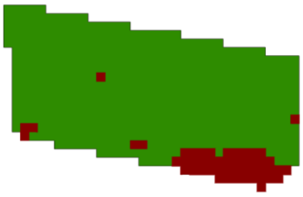
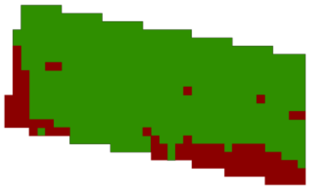
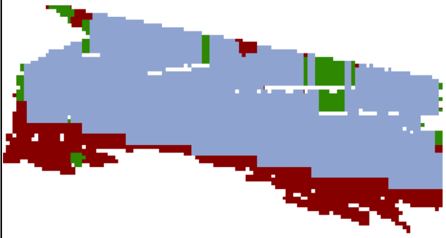
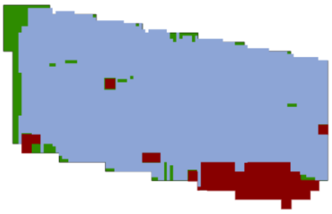
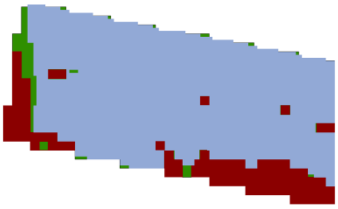
(5) OPTIMIZATION OF THE GENERATED POINT CLOUD

After explaining the Nyquist-Shannon sampling theorem in chapter 4.2, the sampling theorem has to be tested. In order to test the sampling theorem, the right point cloud datasets have to be obtained. In the research area a threshold of 0.05m needs to be detected, which may be caused by paving stones that lie slanting or different pavement materials. Therefore the smallest point cloud density is:

$$1600 \text{ points per meter}^2 = 1 / (0.05m / 2)^2$$

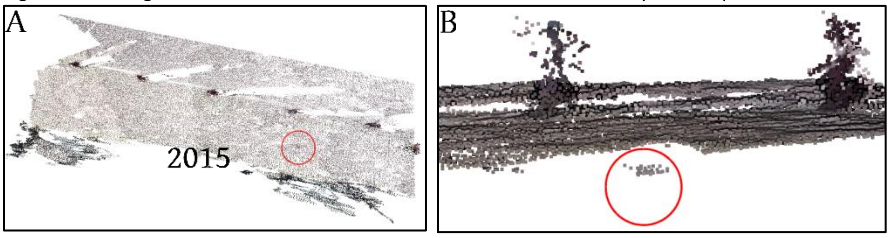
The number of pictures needed for different scenes and their effect on the point cloud density is examined for a small area in the focus street 'Nieuwe Looiersstraat' within the research area. Figure 65 is showing three created point clouds and the generated accessibility information.

Figure 65: Comparison of the point cloud quality

Input setting 1	**Input setting 2**	**Input setting 3**
 Flip camera	 GoPro	 GoPro
Data of 2015	Data of 2015	Data of 2015
photos: 17 resolution: 30 frames per second points: 53.086 density: 699 points/m^2 noise: points are located underneath the road surface	photos: 17 resolution: 48 frames per second points: 385.214 density: 4.586 points/m^2 noise: points are located underneath the road surface	photos: 37 resolution: 48 frames per second points: 925.262 density: 10.057 points/m^2 noise: no
Height and angle of inclination		
 0.05m and 10^o	 0.05m and 10^o	 0.05m and 10^o
Accessible regions		
 0.9m	 0.9m	 0.9m

In this section is examined whether the Flip camera data and GoPro camera data provide the same point cloud quality. The first point cloud visualized in Figure 65 (left) has quite a lot of missing points due to occlusion. This is causes by both the poles between the street and the path, and cars and people who moved along this way which blocked the view of the camera. This point cloud consists of noise, because some points are located underneath the road surface. Figure 66 is showing some spurious points underneath the road surface.

Figure 66: Image A shows the zoomed-in location, and B shows spurious points underneath the ground



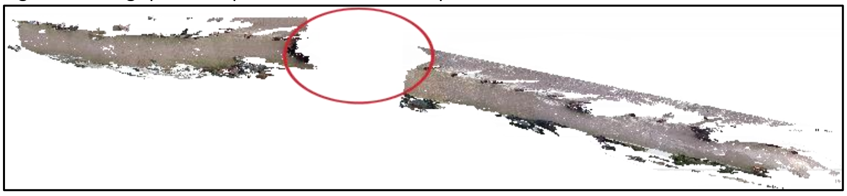
Input setting 3 gives the best results because it is most close to the reality, has the least number of missing points, consists of the least noise and has the highest density of points which helps to maintain more fine details. From these three generated point clouds can be concluded that both the amount of images, camera used and image resolution consequence the point cloud quality.

CONCLUSIONS

During this research, LAStools is used for point cloud filtering and converting point cloud into a DEM image. LAStools can be worked with by using a command line window. The program QGIS can be used for the creation of a slope map from a DEM image. QGIS can also be used for: the creation and cleaning of a Shapefile (by using BGT data) to remove points that are less precise (from a point cloud); extracting the permitted parts of a slope map by using an expression in the Raster Calculator; visualizing results; and converting raster formats into vector formats. LAStools can also be used for gridding points onto a raster, into an ASCII format (binary grid). This binary raster can be implemented into a script (f.e. a Python script) to check in horizontal and vertical direction whether the grid cells meet the permitted free passage for mobility impaired people.

PhotoScan does not explicitly impose any limits on the number of photos. But the 3D reconstruction algorithms are very resource intensive, so the maximum count of photos is usually limited by the available RAM size and available computation time. For this thesis a larger area (than approximately 15 meters) was processed by using more photos to see whether this will result in a proper point cloud. Unfortunately this went wrong. The problem of processing a larger area is the presence of obstacles (like cars). As a consequence most of the photos are not aligned and gaps are present in the generated point cloud. Figure 67 is showing a result of processed a larger area by using more photos in PhotoScan.

Figure 67: A gap in the point cloud due to a parked car



5.4 EVALUATE FIR FOR PURPOSE

The final step is to assess the sensors on the *meet rollator* using the results obtained by implementing the workflow for generating accessibility information, by using sensor-data collected by a *meet rollator* for the research area.

RTK GPS

With reference to the focus street (Nieuwe Looiersstraat) in the research area, the RTK GPS measurement conditions were harsh. In this street the RTK GPS data is not reliable, because large buildings have blocked the view to the satellites. The precision of the RTK GPS data was for several places not good enough.

CAMERA

The generated accessibility information by using camera data is a relative measurement, because the created point clouds were integrated into a coordinate system by adding markers (manually) in PhotoScan. Furthermore, the generated accessibility information is binary: it is either accessible or non-accessible. It cannot be checked whether the obtained results are correct (for example a height of 0.05m can be a threshold, but it can also be noise in the data).

CONCLUSION

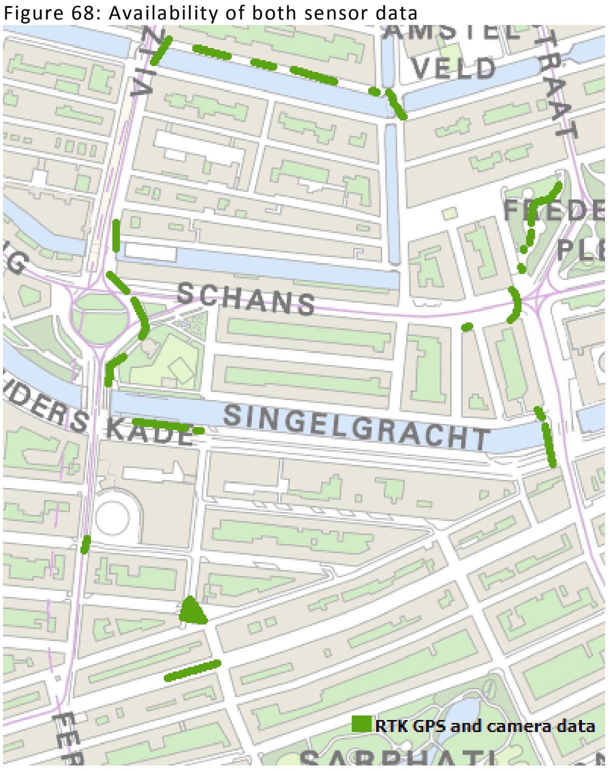
Through data processing, more insight is gained into sensor data and about the usefulness of the different sensors. This research has shown that the used sensors did not provide the needed precision for deriving outdoor accessibility information concerning mobility impaired people.

	According knowledge:	According implementing workflow:
Handheld GPS	✗	✗
RTK GPS	✓	✗
Camera	✓	✗

5.5 COMPARISON OF RTK GPS AND CAMERA DATA

There are areas where both data is available, which can be seen in Figure 68. For this purpose all RTK GPS data was obtained with a quality value/horizontal accuracy better than 10 cm, which resulted into areas in ten different streets. For these areas also camera data (obtained by the *meet rollator*) is available.

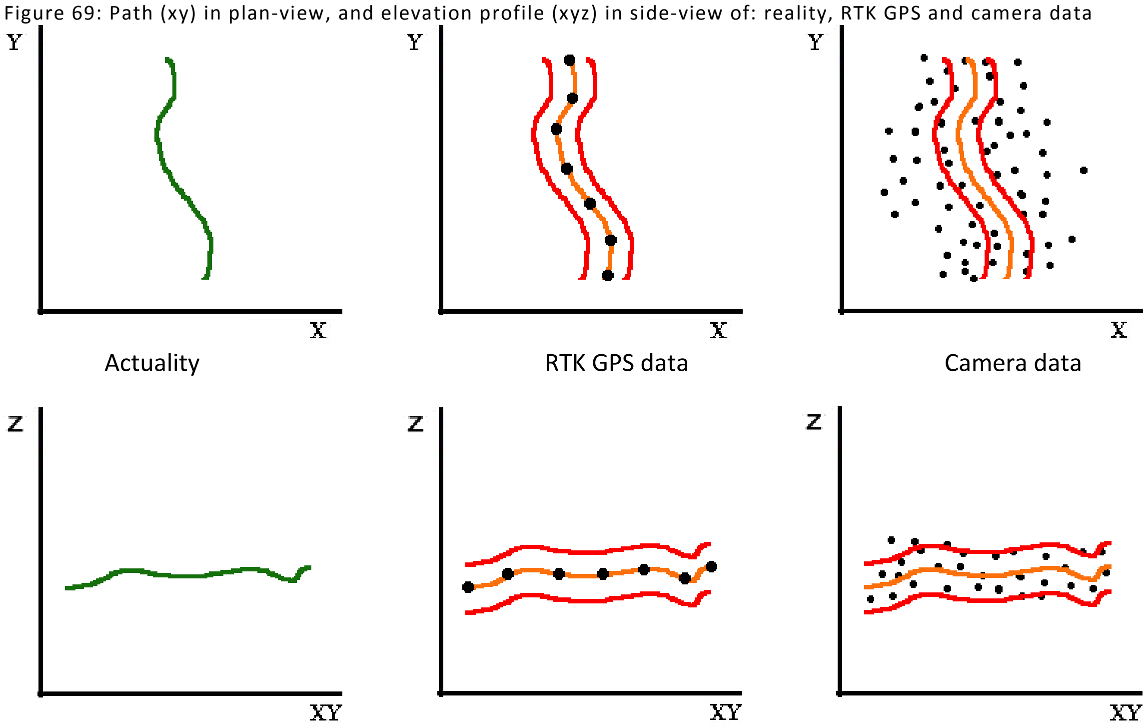
Figure 68: Availability of both sensor data



Source: (de Haan, 2015)

However, no comparison is made between camera and RTK GPS data for the same area. Figure 69 is showing the problem. In black the available (RTK GPS and camera) data, in orange the defined path and elevation profile, and in red the uncertainty is shown.

Figure 69: Path (xy) in plan-view, and elevation profile (xyz) in side-view of: reality, RTK GPS and camera data



RTK GPS data provides a path in the xy-surface and an elevation profile in the xyz-surface. Processed camera data provides a cloud of points in the xy-surface. By defining a path within this point cloud, an elevation profile in the xyz-surface can be derived. The problem is if one extracts a path from the available data, this path is not exact because there is an inaccuracy in the data. So an assumption has to be made where the path is situated, but this path could also be situated (a bit) next to it. This is also true for the defined path by using the processed camera data. The available sensor data cannot be compared, because there is no real truth. The uncertainty in the path caused that when the exact path is situated next to the defined path, a different elevation profile will be derived, and in this way a different angle of inclination and threshold will be calculated.

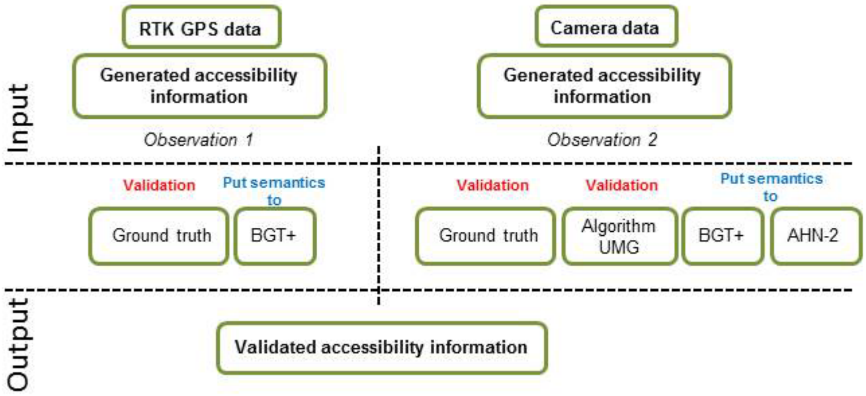
As beforehand was thought that it would be good to obtain the real truth, so the real route and the real elevation profile, then the real truth could be compared with the RTK GPS data, and with the camera data. The real truth could be obtained with a surveyor's level (Dutch: Waterpasinstrument) that can measure for a given test-path an accurate altitude profile. This is the most accurate method. A surveyor's level is an optical device that can realize a horizontal plane and measures height differences with high precision. This will result in point measurements. With this instrument heights and distances between points can be measured. In this way the accurate altitude profile can be used for making a comparison with the RTK GPS data, and with the camera data. However for the *meet rollator* project this was not the case.

6 VALIDATING AND PUT SEMANTICS TO THE GENERATED ACCESSIBILITY INFORMATION

This chapter consists of validating, providing more insight in and put semantics to the total observations obtained by implementing the workflows for generating accessibility information, by using sensor-data collected by a *meet rollator* for the research area which is defined in paragraph 1.6. Thereby, objective 3 (design a workflow for validating, providing more insight in and put semantics to the derived outdoor accessibility information by using: the ground truth, an algorithm made by the Urban Modelling Group, the AHN-2 and BGT+) will be achieved.

It is important to say that not the measurements, but the derived observations (angle of inclination, threshold and width) will be compared in this chapter. So the result of this chapter will be whether the additional data will or will not provide more insight in and put semantics to the derived outdoor accessibility information. It should be noticed that the AHN-2 (in the form of a 3D point could) is only suitable for proving more insight in and put semantics to the observations obtained by using camera data (see Figure 70). Also the algorithm made by the UMG (which can be applied on point cloud data) is only suitable for validating the observations obtained by using camera data. It is not possible to compare the AHN-2 and the results of the algorithm with the RTK GPS observations. This is visualized in Figure 70.

Figure 70: Data used for the validation



Paragraph 6.1 will discuss the used data. Paragraph 6.2 will validate and put semantics to the generated accessibility information obtained by RTK GPS data by using: the ground truth and BGT+. Paragraph 6.3 will validate and put semantics to the generated accessibility information obtained by camera data by using: the ground truth, results of the UMG algorithm, BGT+ and AHN-2.

6.1 USED DATA

The used datasets and results will be discussed in more detail below.

AHN-2

AHN-2 is the second part of the Height model of the Netherlands (Dutch: Actueel Hoogtebestand Nederland), which contains detailed and precise elevation data of the entire Netherlands using airborne laser scanning. The Netherlands is the first country that was entirely covered by airborne laser altimetry measurements through the AHN project. During the first phase of the AHN project between 1997 and 2003 the entire Netherlands was laser scanned to make a height model with a point density varying from 1 point per 16 m^2 to 1 point per 32 m^2. The second part is being carried out since 2007 by several companies. Figure 71 is showing an AHN viewer.

Figure 71: Image A shows Amsterdam in an AHN viewer

Source: (AHN, 2015)

The new height model has an unprecedented spatial resolution: it has an average density of 10 points per m^2 (high-resolution). The Netherlands has an area of 41.543 km², when scanned with a density of at least 10 points per m^2 the result will be a dataset of at least 415 billion points. The AHN-2 is delivered in subunits of 125 hectare of 1 km × 1.25 km (Wijga-Hoefsloot, 2012). The AHN-2 is owned by the national government (Rijkswaterstaat) and 26 water boards. Water boards are the oldest legislative bodies in the Netherlands responsible for monitoring dykes and managing water quantity and quality.
The hypothesis is that the AHN-2 data is rich and dense enough to determine profile information, which makes it useful for providing more insight in and put semantics to the generated accessibility information.

BGT

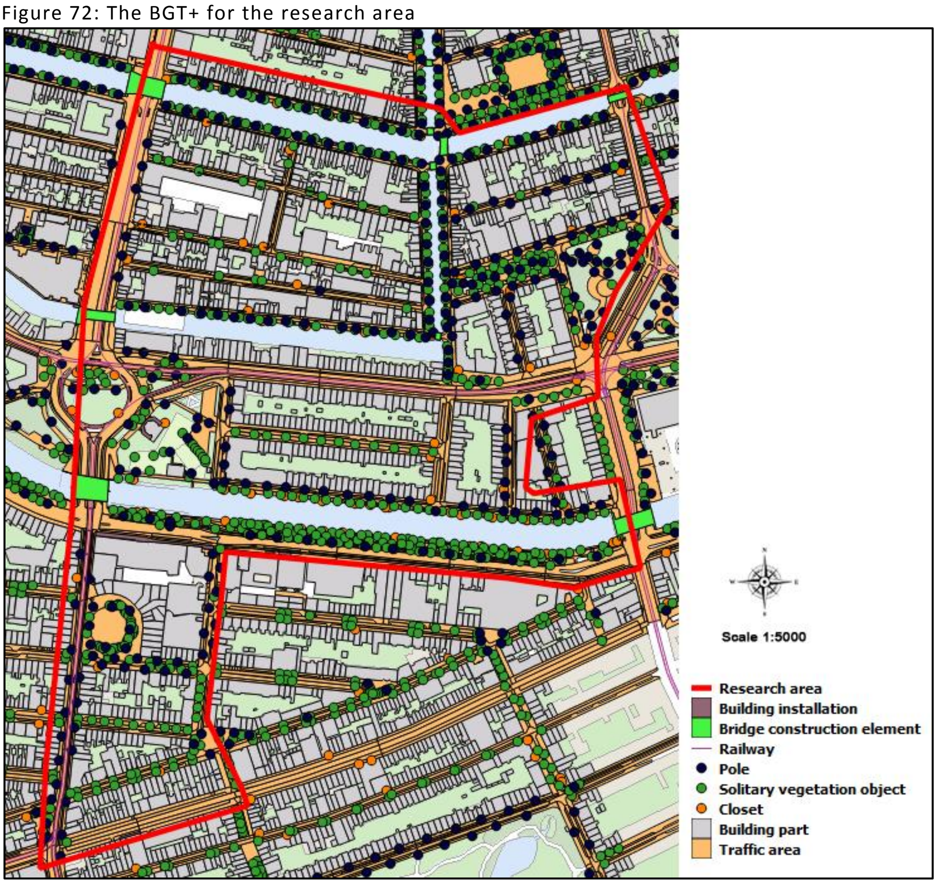
The Dutch key registry for large scale topography (BGT – Dutch: Basisregistratie Grootschalige Topografie) includes all legally established topographic objects (per 1 January 2016). Nowadays the GBKA (Dutch: Grootschalige BasisKaart Amsterdam) is used, which will be replaced in 2016 by the BGT. The BGT is not yet present, because it is under-construction until the 1th of January 2016. In the BGT a house is represented by a 2D surface, for example, with coordinates that correspond to the real world.
The BGT replaces different base maps by a uniform base map, which is standardized and will become available as Open Data. The BGT will become the detailed large-scale base map (digital map) of the Netherlands, where physical objects such as buildings, roads, parks, waterways and railways are unambiguously on recorded. The BGT consists of abstractions of objects in reality and describes the geometry of objects for an image in the scale-range 1:500 to 1:5.000 (Gemeente Amsterdam, 2015).

The BGT does <u>not</u> include height information, but the BGT+ includes the locations of:

1. lampposts
2. fire hydrants
3. trees
4. waste containers/disposal locations
5. advertising pillars (permanent)

Unfortunately the BGT+ of Amsterdam does not include the bollards (Dutch: Amsterdammertjes). Figure 72 is showing the BGT+ for the research area.

Figure 72: The BGT+ for the research area



GROUND TRUTH

A validation survey needs to be done to see whether the generated accessibility information correspond with the situation present on a certain location. Ground truth is the best way to certify that the obtained data is complete, accurate and precise.

ALGORITHM OF URBAN MODELLING GROUP

Anh-Vu Vo, Linh Truong-Hong and Debra F. Laefer (2015) of the University College Dublin, have presented a workflow including a novel algorithm for road detection. The algorithm exploits the high variance of slope and height of point data. Figure 73 and Figure 74 are showing the results of the approach for a small part of a street in Amsterdam.

Figure 73: Input, maximum directional slope and maximum directional height

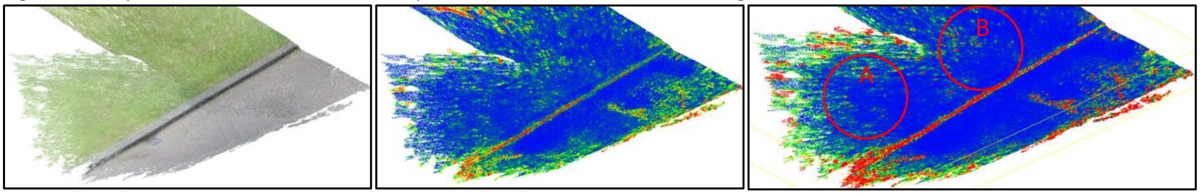
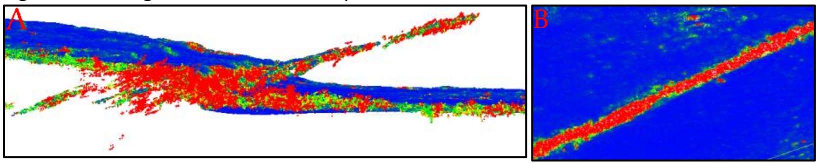


Figure 74: Image A shows a raised part, and B shows a road curb



The proposed approach is more widely applicable. With the result of the algorithm, the safe-for-mobility-impaired regions can be extracted by performing region growing considering the clearance, slope variation and height variation.

6.2 OBSERVATIONS OF RTK GPS DATA

This chapter will validate and put semantics to the generated accessibility information obtained by RTK GPS data by using: the ground truth and BGT+.

GROUND TRUTH

The validation of the generated accessibility information is performed with a direct visit to the research area. The two geometrical demands were measured using a measuring tape and by making use of the standard size of a paving stone (0.3x0.3m) and curb (0.1m). The angle of inclination was measured by using the standard height of a curb. Since the angle of inclination must not be steeper than 1:6, the slope must have a length of 0.6m. This length was checked by using/counting the number of paving stones and their standard size. The minimum threshold was checked visually and by using a measuring tape.
For this thesis the generated accessibility information consists of 330 locations that cover an area of approximately 594m2. In order to perform the validation, the generated accessibility information and the ground truth need to be compared. The result is shown in Table 15. The locations are visualized by street names and an overview is made between the obtained information (by implementing the workflow with RTK GPS data) and the validated results.

Table 15: The derived accessibility information per street

		Results after implementing workflow				**After Survey**	
		Total lines	*Accessible*	*Not accessible*		*Accessible*	*Not accessible*
1.	Albert Cuypstraat	31	29	2		31	0
2.	Ferdinant Bolstraat	13	6	7		13	0
3.	Frederiksplein	57	31	26		53	4
4.	Gerard Douplein	33	20	13		32	1
5.	H.M.V. Randwijkplantsoen	14	7	7		13	1
6.	Prinsengracht	78	51	27		62	16
7.	Stadhouderskade	13	13	0		13	0
8.	Vijzelgracht	42	24	18		35	7
9.	Westeinde	28	12	16		28	0
10.	Weteringschans	21	13	8		20	1
		330	***206***	***124***		**300**	**30**

One example of the comparison is shown in Figure 75. The generated accessibility information and the map of Amsterdam are overlaid in a GIS environment (QGIS). With the use of this overlay and the photos obtained during the visit to the research area, a comparison can be made. For the generated accessibility information is checked whether the paths with the status 'accessible' are also accessible in reality, and with the status 'not accessible' are also not accessible in reality, due to a too high altitude or too steep angle of inclination for mobility impaired people.

Most of the paths generated as 'not accessible' are often not coinciding with the ground truth. This means that the extraction of accessibility information from the RTK GPS dataset has not succeeded for these parts. A reason for this is that a lot of slope measurements between adjacent points are not correct, because the distance between these points is very small (0-0.02m). For these points the *meet rollator* did not walked for a time (but stood still) which influence the slope measurements in a bad way. However, not for all paths this is true.

Figure 75: Comparison of the generated accessibility information and the ground truth

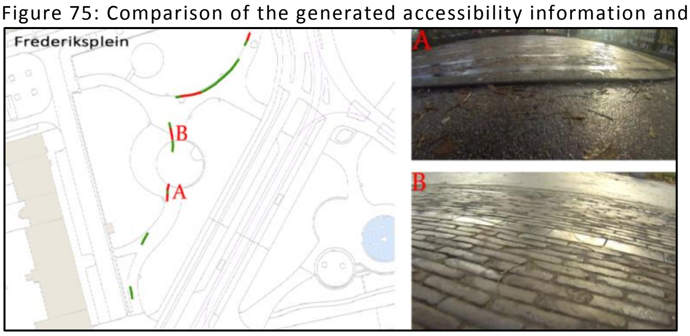


Figure 75 is showing a path on the 'Frederiksplein' which is partly accessible. At point A and B the maximum height of 0.05m is exceeded which coincide with the images taken during the visit. At these points the rollator needs to be lifted to bridge the height difference.

BGT+

With the use of a topographic map for the research area, namely the BGT+, hopefully more insight in the total observations will be gained. In order to achieve this, the generated accessibility information and the BGT+ need to be overlaid in a GIS environment (QGIS for example). The BGT+ consists of several Shapefiles representing different topographic features. To perform the overlay, the research area was divided into several smaller areas per street. In this way a good overlay could be performed. Four examples of the overlay are shown in Figure 76 and Figure 77. By using this overlay, a visual comparison could be made. The thicker green and red lines are the generated accessibility information. The legend of the BGT+ is displayed in Figure 72 and applicable for the figures below.

Figure 76: BGT+ overlaid with the accessibility information for two streets

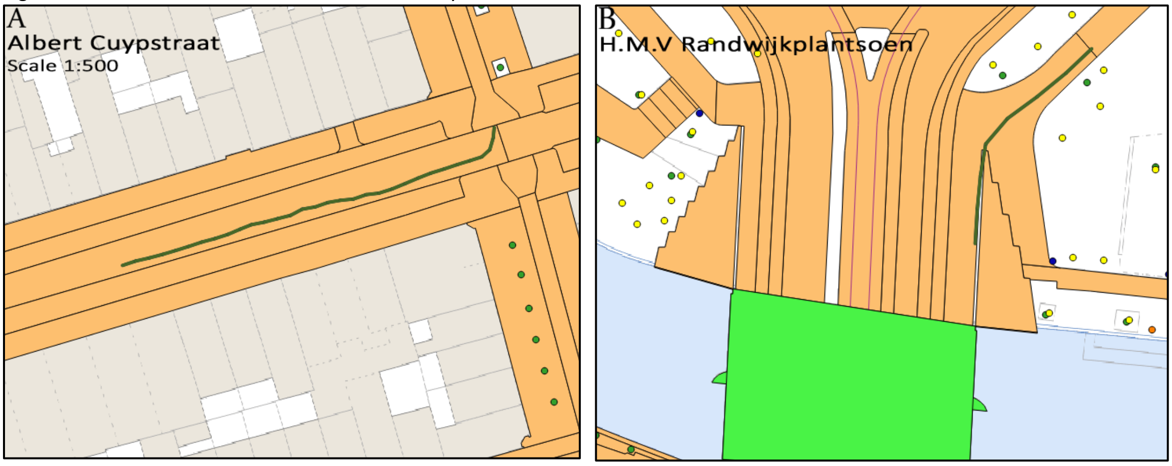
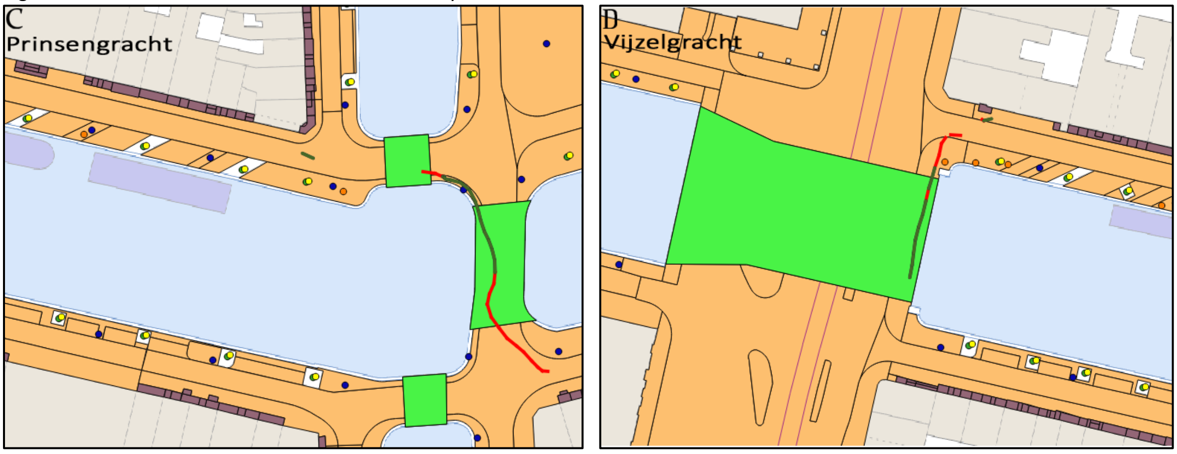


Figure 77: BGT+ overlaid with the accessibility information for two streets



After overlaying the BGT+ and the accessibility information, more significance can be given to the observations. For example, when a threshold is perceived in the observations more information can be obtained by using the BGT+, because then it becomes clear whether this threshold is caused by a railway or curbstone. The same is true for the perceived angle of inclination.

The generated accessibility information obtained with the use of RTK GPS data is often coinciding with BGT+. However, not all accessibility information is coinciding with the topographic features of the BGT. A reason for this might be that a topographic feature is not included in the BGT+ (like bollards) and therefore it cannot be seen as an obstacle for mobility impaired people. Furthermore, the polygons in the BGT+ are not really related to obstacles on the road but they indicate features, like a bridge.

Figure 76 is showing accessibility information (thick green lines) which is not hindered by topographic features included in the BGT+. This accessibility information coincides with the BGT+.

Figure 77 A on page 75 is showing not accessibility parts (thick red lines) which correspond with a bridge construction element included in the BGT+. So by using the BGT+ it became clear that these not accessible parts are caused by a bridge. So this bridge could have a too steep angle of inclination or a too high threshold which makes it inaccessible for mobility impaired people.

Figure 77 B is showing not accessibility parts which correspond with a separation line and a bridge construction element included in the BGT+. The clear separation line of the BGT+ probably indicates a height difference or transition. So this line does coincide with the inaccessible part. In this case it can be concluded that the street and pavement are located at a different height and mobility impaired people cannot cross without problems. This line of the BGT+ is an obstacle.

To conclude, most of the thicker red lines correspond with separation lines or building construction elements presented by the BGT+. In this way the BGT+ provides more insight in and put semantics to the derived observations.

6.3 OBSERVATIONS OF CAMERA DATA

This chapter will validate and put semantics to the generated accessibility information obtained by camera data by using: the ground truth, BGT+, AHN-2 and results of the UMG algorithm.

GROUND TRUTH

The validation of the generated accessibility information is performed with a direct visit to the research area. As stated before, the three geometrical demands were measured using a measuring tape, and by making use of the standard size of a paving stone and curb. The number of paving stones was counted to determine the free passage of a pedestrian path.

For this thesis the generated accessibility information consist of one location (approximately 77 m^2) in the focus street called 'Nieuwe Looiersstraat'. In order to perform the validation, the generated accessibility information and the ground truth need to be compared. The comparison is shown in Figure 78. The green and red areas show the accessibility information for the research area (also visualized in paragraph 5.3).

Figure 78: Comparison of the generated accessibility information and the ground truth

The pictures shown in Figure 78 were taken during the survey. In these pictures can be seen that the area covers a part of a street and one side of a pedestrian path (on which the *meet rollator* walked in 2015). In addition, the pedestrian path is not higher positioned in comparison to the street, but a separation between the street and path has been created by a row of poles. This area consists of 5 poles which are obstacles for movement. These obstacles need to be assigned as 'not accessible' instead of 'accessible' (as they are labeled according to the results obtained by implementing the developed workflow). Figure 79 is showing the obstacles detected during the survey. Figure 80 is showing the result of the validation.

Figure 79: Obstacles detected during survey

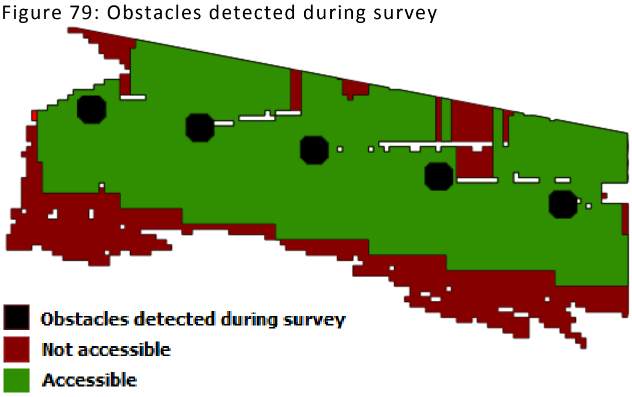
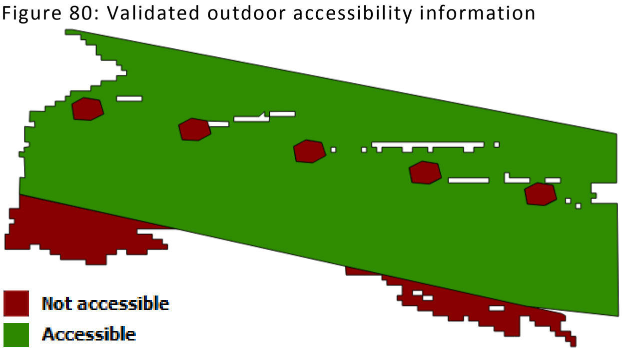


Figure 80: Validated outdoor accessibility information

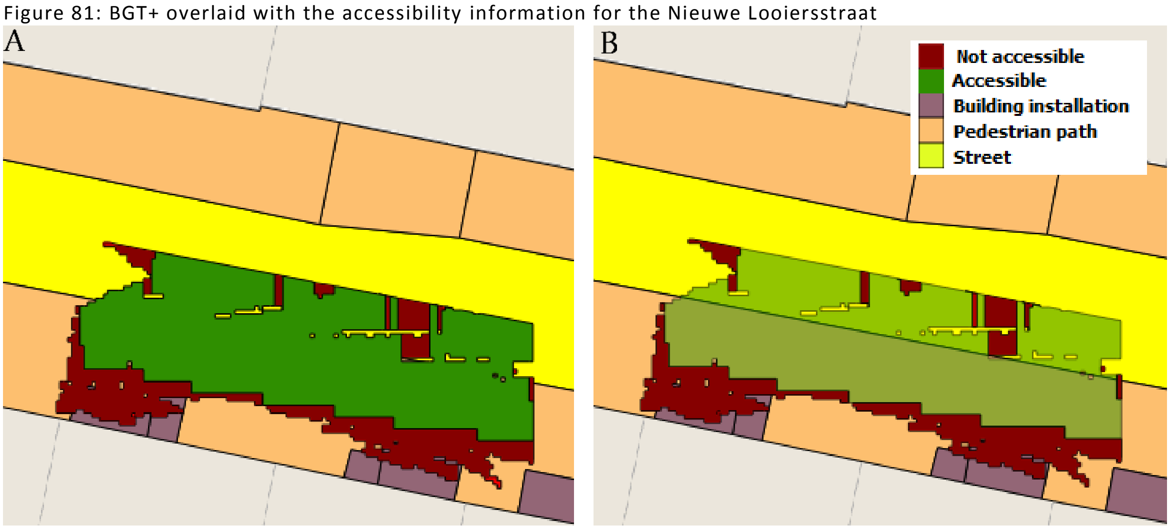


BGT+

As stated before, with the use of the BGT+ hopefully more insight in the total observations will be gained. The overlay of the generated accessibility information and the BGT+ is shown in Figure 81. The accessibility information is made transparent in order to see the topographic features of the BGT+, see Figure 81 B.

At some places the generated accessibility information is in line with the BGT+. The inaccessible areas (red) at some places match with the BGT+, especially where building installations (in the BGT+) are located. These building installations are not accessible, so this gives more insight in the inaccessible observations.
The clear separation line of the BGT+ (which probably indicates a height difference or transition) does not coincide with the accessible area. One would expect that this separation line would cause an inaccessible label in the generated information. When the street and pavement are located at a different height, this line of the BGT+ is by default an obstacle, because there will be at least a height difference of 10 cm. However for this focus street this was not the case. People can cross this street without problems. So this separation line of the BGT+ does not provide more insight into the observations.

Figure 81: BGT+ overlaid with the accessibility information for the Nieuwe Looiersstraat



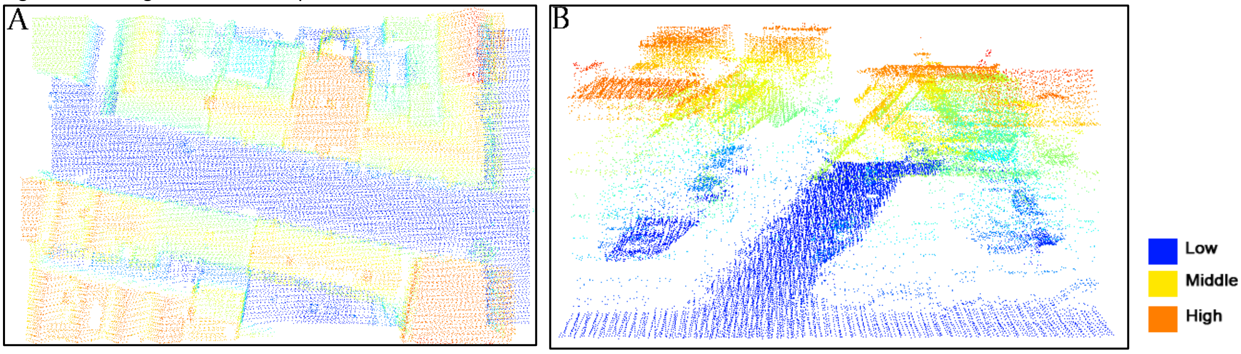
To conclude, most red areas correspond with building construction elements presented by the BGT+. In this way the BGT+ provides more insight in and put semantics to the derived observations.

AHN-2

In order to achieve more insight in and put semantics to the generated accessibility information, it needs to be overlaid with the AHN-2. With the use of this overlay, a visual comparison can be made. But first it has to be checked whether the AHN-2 is rich and dense enough for determining profile information. Figure 82 is showing two screenshots of the AHN-2 of the same area. Figure 82 A is showing a top-view of the AHN-2 data for the research area in which points are classified according to their height (low, middle, high). The points in blue represent the street and the points in red represent houses. Other profile information is difficult to derive from this data. Figure 82 B is showing a side view of the AHN-2 data in which only the roofs of houses (in yellow) and street (in blue) can be derived. The height model has an average density of 25 points per m^2.

After looking at the AHN-2 the conclusion can be drawn that this data is not completely coverage, even not close enough to be able to determine profile information. So the AHN-2 cannot be used for achieving more insight in and put semantics to the derived observations.

Figure 82: Image A shows a top-view of the AHN-2 data for the research area, and B shows a side view



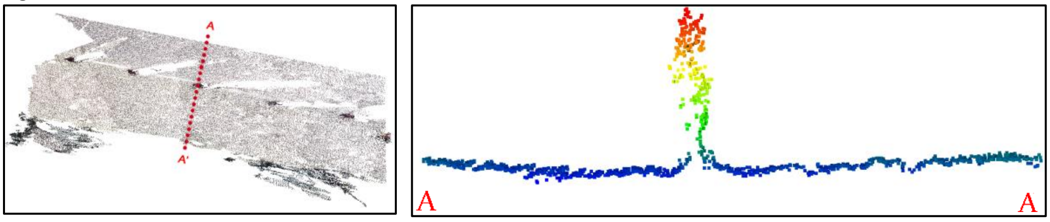
ALGORITH OF URBAN MODELLING GROUP

The Urban Modelling Group (UMG) applied their approach on the same point cloud data used for this thesis. Figure 83 is showing the data which covers a part of a street and a walking path separated by a row of poles.

Figure 83: Input point cloud data for the algorithm

To investigate the data and illustrate the data characteristics, the UMG made a cross section over the point data (see Figure 84). In this cross section no height differences are visible between the two sides of the poles.

Figure 84: Cross-section AA'



Afterwards the UMG run their code. It should be noticed that using the same input and demands (permissible threshold = 0.05m and permissible angle of inclination = 10^{o}) is not necessarily fair for making a comparison. The UMG will get more reasonable results by increasing the permissible slope and height in order to account for data noise.

Figure 87 and Figure 88 on page 80 are showing the differences between the results obtained by the UMG and the results of this thesis. For this thesis another way of computing height and slope changes is used than the UMG, which will result in different definitions. The result of the UMG is ∇_{max}slope and ∇_{max}height which are supposed to be able to pick up the surface changes better. It means the quantities the UMG compute should be always larger than the height and slope computed per pixel (for this thesis). The ∇_{max}slope and ∇_{max}height are stricter criterial than slope/height variation per pixel. In short, more bottle necks are terminating the growing in the UMG result (see letter D in Figure 88 in which the growing does not go through the bottle neck). Figure 88 is showing the result after region growing in which the accessible regions are marked in light blue overlaying. The UMG did consider the free passage using a circular disc having radius of 0.45m.

The road roughness (see letter A in Figure 87) including those caused by data imperfection (see letter B in Figure 87) showed up clearly. Regions around the street poles are excluded from the accessible path (see letter C in Figure 87). This is to a lesser extent in the result for this thesis, by computing height/slope variation per pixel (see Figure 87 right). This is also visible in Figure 85 and Figure 86 in which the regions around the poles are (for both the height and slope) assigned as not accessible by the code of the UMG. In the computed result per pixel for this thesis, these regions are assigned to be accessible.

So the UMG algorithm can pick up more obstacles (e.g. around the street poles). Even small variations on road surfaces caused by noise and data imperfection are detected as obstacles by UMG's algorithm.

Furthermore, in the results of the UMG, the red regions at the boundary are partially caused by the boundary artifacts. Their algorithm relies on an assumption that there are sufficient neighbours around a surface so that the slope and height can be computed robustly. The condition cannot be satisfied for the points near/on the edge of the cloud since half of the neighbours are missing. Because of this, you will see many boundary points were mistakenly recognized as obstacles (red color) by their algorithm. Any computation based on neighbourhood faces those problems along the boundary. The issue can be alleviated by extending the boundary of the input data.

UMG: Computing the height and slope point-based

Thesis: Computing height/slope variation per pixel

Figure 85: Height saturated at 0.05m

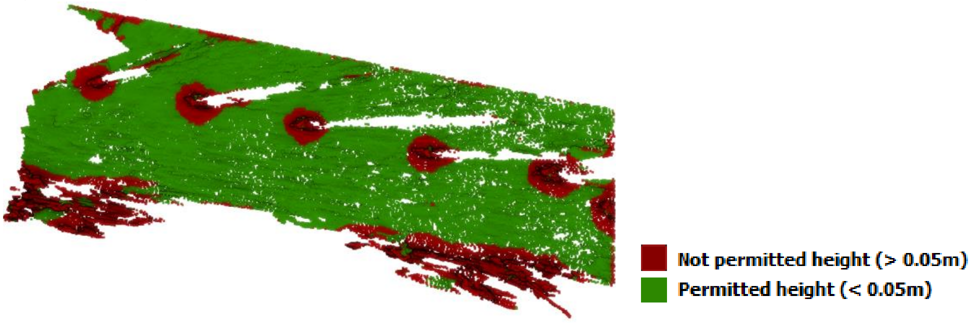


Figure 86: Slope saturated at 10°

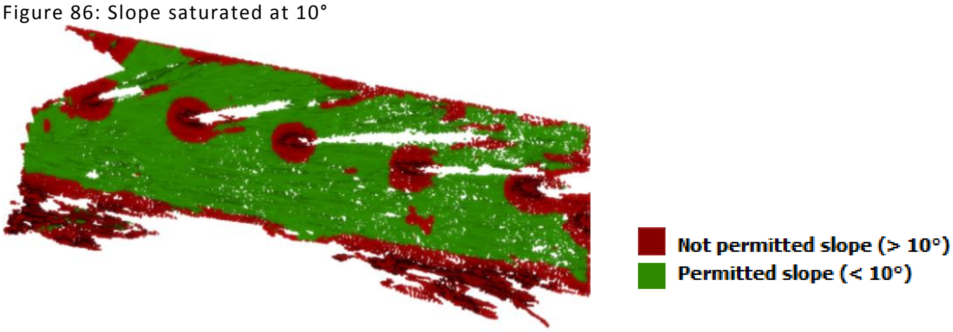
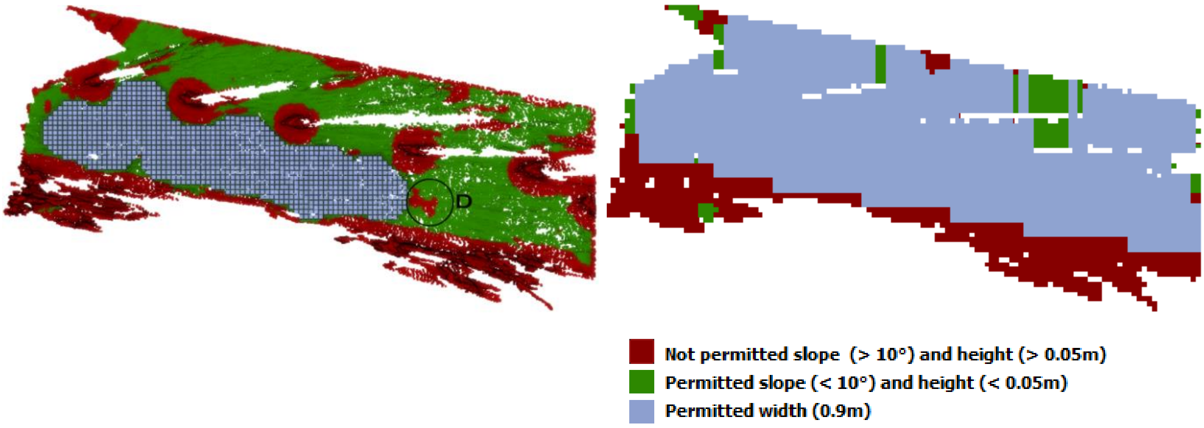


Figure 87: Slope and height

Figure 88: The overall result



To conclude, the results of the UMG are more reliable because their approach will pick up surface changes better. Also by using a smaller grid size for processing (see Figure 89), the results of the approach of this thesis are still less precise than the UMG results. However the results of this thesis are good enough for the generation of outdoor accessibility information.

Figure 89: Three different raster sizes for making a comparison with the UMG results

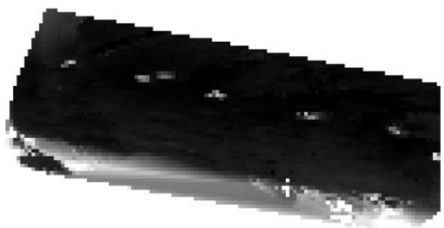
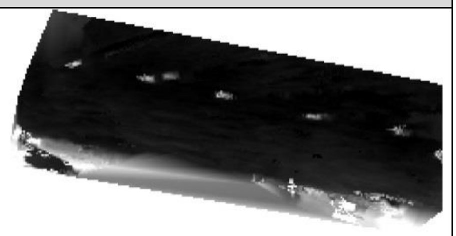
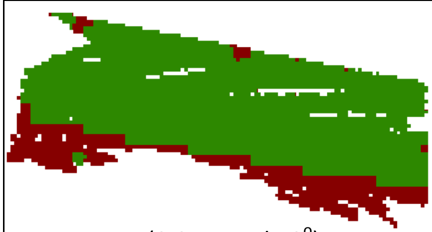
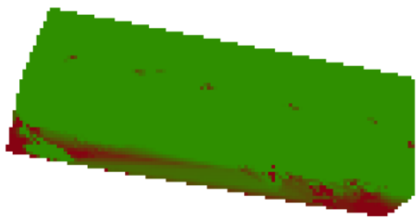
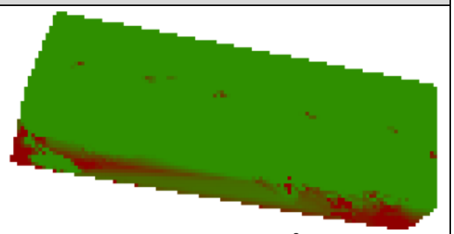
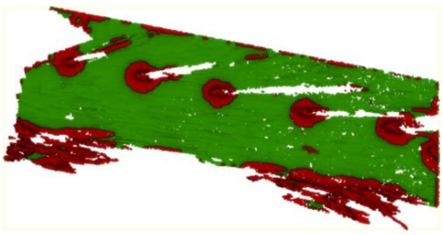
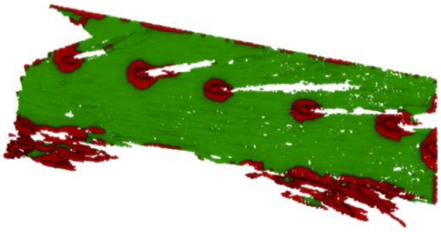
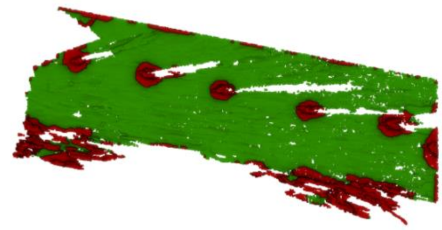
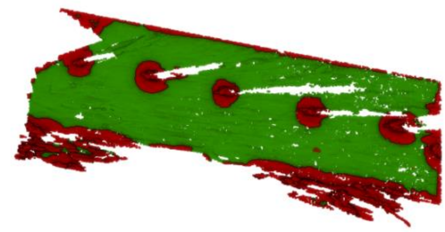
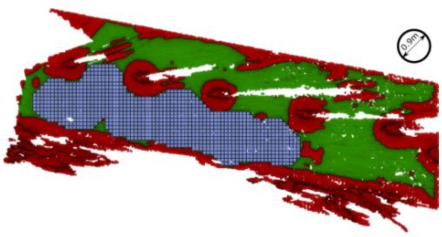
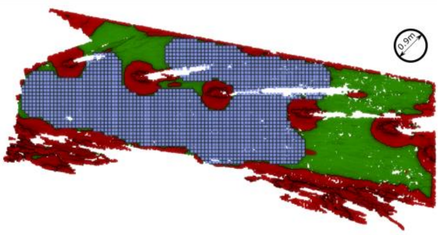
Input setting 1	**Input setting 2**	**Input setting 3**
DEM		
 (0.3 meter step size)	 (0.1 meter step size)	 (0.05 meter step size)
$_{max}$height and $_{max}$slope		
 (0.05m and 10°)	 (0.05m and 10°)	 (0.05m and 10°)

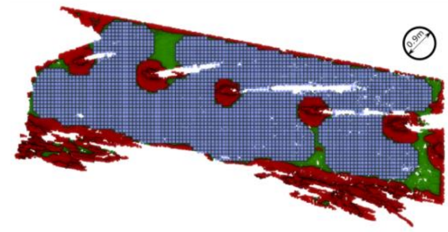
Figure 90 on page 82 is showing the results for three different settings for which the permissible slope and height increases. The three settings are made to give a better insight into how the settings influence the outcome of the UMG algorithm. The results are shown more reasonable results in order to account for data noise.

Figure 90: Three different settings for the UMG code

Input setting 1	Input setting 2	Input setting 3
∇_{max}height		
 0.05m	 0.075m	 0.1m
∇_{max}slope		
 10^{o}	 15^{o}	 20^{o}
∇_{max}height and ∇_{max}slope		
 (0.05m and 10^{o})	 (0.075m and 15^{o})	 (0.1m and 20^{o})
Accessible regions		







6.4 CONCLUSIONS

To conclude, the ground truth and an algorithm made by the Urban Modelling Group can be used for the validation of the derived outdoor accessibility information. The AHN-2 and BGT+ can be used for providing more insight in and put semantics to the total observations obtained by implementing the workflows. In order to achieve this, the generated accessibility information and the BGT+, and the AHN-2 need to be overlaid in a GIS environment. The AHN-2 is not completely coverage, even not close enough to be able to determine profile information, so not suitable for providing more insight in and put semantics to the observations. The BGT+ is proved suitable for providing more insight in and put semantics to the total observations from RTK GPS and camera data. The ground truth is proved suitable for validating the obtained accessibility information derived from RTK GPS and camera data. The results of an algorithm made by the UMG are proved suitable for validating the obtained accessibility information derived from camera data.

	RTK GPS observations:	Camera observations	
AHN-2		✗	*Put semantics to*
BGT+	✓	✓	*Put semantics to*
Ground truth	✓	✓	*Validation*
Algorithm UMG		✓	*Validation*

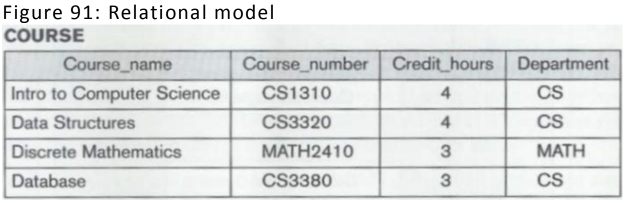
7 STORING THE VALIDATED ACCESSIBILITY INFORMATION

In this chapter will be explained how data needs to be stored. Firstly, the term database will be explained. Paragraph 7.2 will explain how to make a database in pgAdmin by loading tables. Thereby, objective 4 (design a database that structures the validated accessibility information) will be achieved. In this paragraph also some examples are given of querying in the database. Paragraph 7.3 will show a map visualization via Google Fusion Table.

7.1 GEO-DATABASE IN POSTGRESQL

A database is a digitally stored archive. A database may consist of three parts: the stored data (in one or more files), the program with which the data are maintained (database management system (DBMS)) and possibly the user-interface that allows users to handle the data. A very simple database is visualized in Figure 91. A database is meant to hold a large amount of data.

Figure 91: Relational model



COURSE

Course_name	Course_number	Credit_hours	Department
Intro to Computer Science	CS1310	4	CS
Data Structures	CS3320	4	CS
Discrete Mathematics	MATH2410	3	MATH
Database	CS3380	3	CS

Huisman & By (2009) describe various reasons why someone wants to use a DBMS for data storage and processing. Some examples are describes below:

- A DBMS supports the storage and manipulation of very large data sets;
- A DBMS supports the concurrent use of the same data set by many users;
- A DBMS provides a high-level query language.

Datasets are built up over time, which means that substantial investments are required to create and maintain them, and that probably many people are involved in the data collection, maintenance and processing. A well-designed database takes care of storing single facts only once (Huisman & de By, 2009).

A geo-database is a database that is optimized to store and query data that represents objects defined in a geometric space. Most geo-databases allow representing simple geometric objects such as points, lines and polygons. While typical databases are designed to manage various character types of data, additional functionality needs to be added for databases to process spatial data types efficiently. A geo-database stores Geographic Information System (GIS) data on one place for easily access and management. The Open Geospatial Consortium (OGC), an international industry consortium of 514 companies, government agencies and universities, has created the Simple Features specification and set standards for adding spatial functionality to database systems. Database systems use indexes to quickly look up values. Geo-databases use spatial indexes to speed up database operations.

PostgreSQL uses the spatial extension PostGIS to implement the standardized datatype geometry and corresponding functions. PostgreSQL is a powerful, open source object-relational database management system. As the software package PostgreSQL was required for the assignments of the MSc Geomatics, this research is limited primarily to *PostgreSQL* for designing a database.

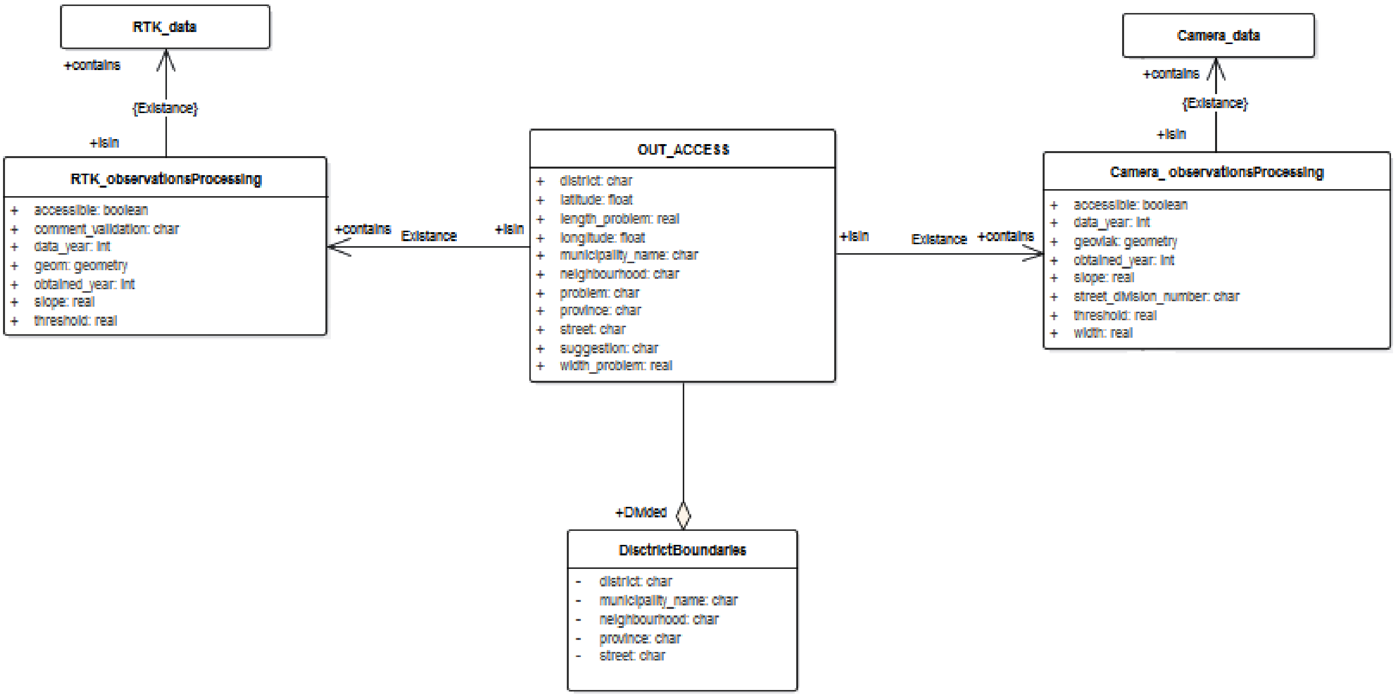
7.2 STORING THE DERIVED DATA

For the new database called 'OUT_ACCESS' different tables are linked. Before making a database (to store the data) it is necessary to create a UML diagram to see the interrelations between all the tables of the database. These tables can be represented as classes in an UML diagram.

UML DIAGRAM

Figure 92 on page 84 is showing the UML diagram made for this thesis which gives insight into how the database is composed, and visualizes the interdependencies of each class related to each other.

Figure 92: UML diagram

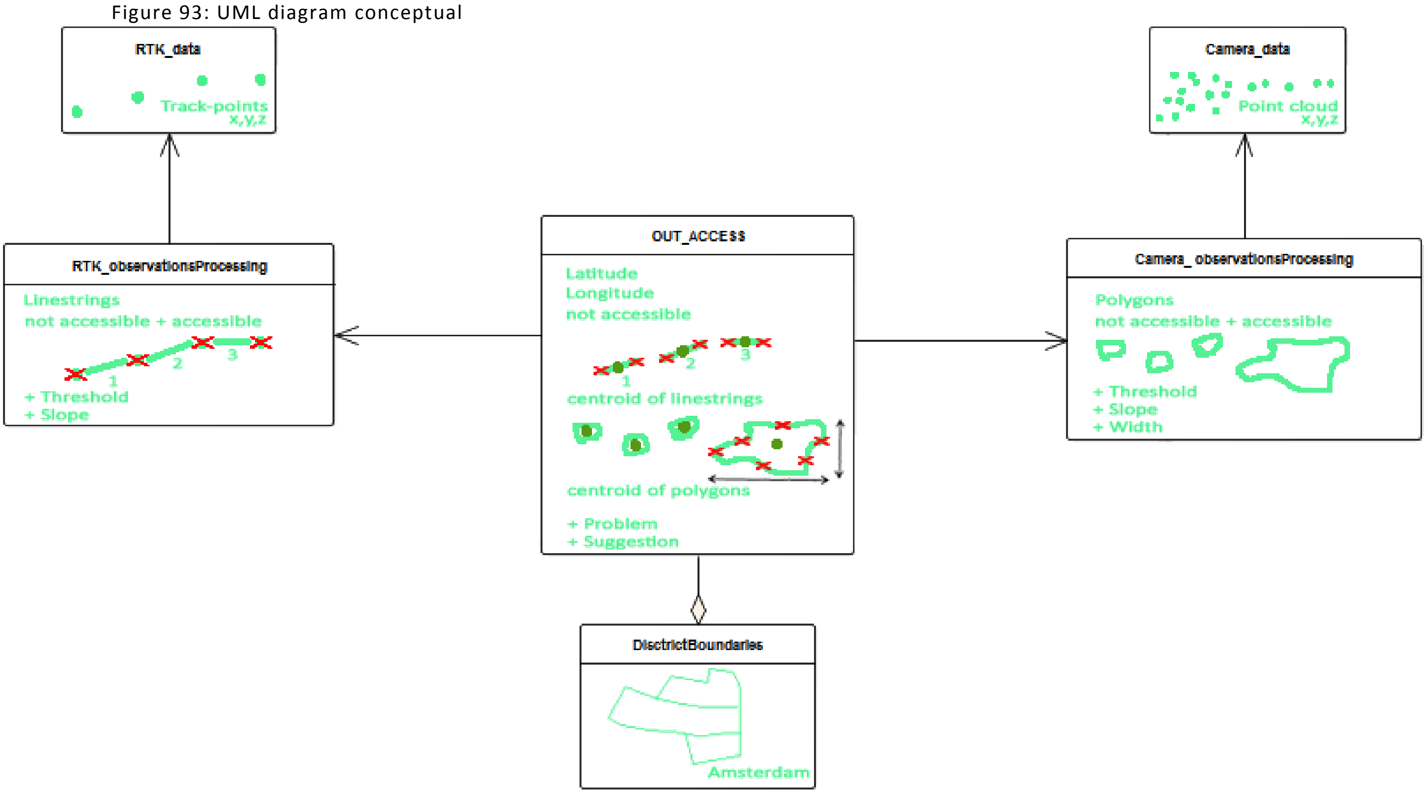


The new database called 'OUT_ACCESS' (visualized in the middle in Figure 92) consists out of three sources:

- RTK_observationsProcessing - This data is retrieved via the RTK processing method.
- Camera_ observationsProcessing - This data is retrieved via the Camera processing method.
- DistrictBoundaries - This data is retrieved via the CBS (Dutch: Centraal Bureau voor de Statistiek)

Figure 93 is showing the same UML diagram with a conceptual representation of the stored data.

Figure 93: UML diagram conceptual



When the UML diagram is finished it is possible to convert this diagram to a SQL script for creating a database. First it is necessary to create a DDL schema. This DDL schema can be converted into a SQL script. Note that this SQL script needs to be adjusted, because the generator misses some statements. This SQL script generates a database in PostGIS. With a database it will be possible to link the data to other applications in order to make it more usable.

Below the print-screens can be found of the three most important tables in the database, namely:

1. OUT_ACCESS
2. Camera_ observationsProcessing
3. RTK_observationsProcessing

TABLE 1: OUT_ACCESS

This table gives an overview of all improvements that are necessary to create a suitable route for mobility impaired people who need a wheelchair, rollator or mobility scooter. The positions where problems occur and the suggestions to improve these positions can be found in this table.

Figure 94: Table 'OUT_ACCESS' in PostgreSQL

province character(100)	municip_name character(100)	district character(100)	neighbourhood character(100)	street character(100)
North-Holland	Amsterdam	Centre	De Weteringschans	H.M.V. Randwijkplantsoen
North-Holland	Amsterdam	Centre	De Weteringschans	Vijzelgracht
North-Holland	Amsterdam	Centre	Grachtengordel-Zuid	Vijzelgracht

latitude real	longitude real	problem character(100)
121241	485842	Threshold is not accessible (crossing road)
121223	485863	Threshold is not accessible (crossing road)
121265	486150	Threshold is not accessible because paving stones lie slanting

length_problem real	width_problem real	suggestion character(100)
0.3	0.5	Apply a ramp with the right angle
0.3	0.5	Apply a ramp with the right angle
0.5	0.2	New pavement or resurfacing

Table 16 illustrates the types and definition of this table.

Table 16: Types and definitions of the 'OUT_ACCESS' table

Attribute name	Alias	Type	Notes
province	Province	Character	
municipality_name	Municipality name	Character	
district	District	Character	
neighbourhood	Neighbourhood	Character	
street	Street	Character	
latitude	Latitude	Float	The centroid of the problem is stored in WGS84
longitude	Longitude	Float	The centroid of the problem is stored in WGS84
problem	Problem for people with mobility impairments	Character	
length_problem	Length of the problem	Real	
width_problem	Width of the problem	Real	
suggestion	Suggestion to improve the problem	Character	

For the research area, which is defined in paragraph 1.6, three suggestions are made and saved in this table:

- Apply a ramp with the right angle
- New pavement or resurfacing
- Change angle of inclination (on a bridge)

This table could be of importance for a municipality. It can be used as Spatial Decision Support Systems (SDSS) by road managers since it provide them with new information about the outdoor accessibility. Paragraph 7.3 will discuss this in more detail.

TABLE 2: CAMERA_OBSERVATIONSPROCESSING

In this table the derived accessibility information via the image processing method is combined. This data gives an overview of the accessible and not accessible paths. Within this table polygons are stored (see Figure 95).

Figure 95: Table ‘Camera_observationsProcessing’ in PostgreSQL

accessible boolean	geovlak geometry(Polygon,28992)	data_year integer	obtained_year integer	threshold real	slope real	width real	street_division_number character(80)
FALSE	0103000020407100000100000029000000B29DEFA7A6A9FD4C	2015	2015	0.7	55	0.4	1a
FALSE	01030000204071000004000000350000002DEC690738AAFD4C	2015	2015	0.7	55	0.4	1b

In this table the maximum threshold (in meters) and slope (in degrees), and the minimum width (in meters) are stored which appears in a geometry (polygon). Table 17 illustrates the types and definition of this table.

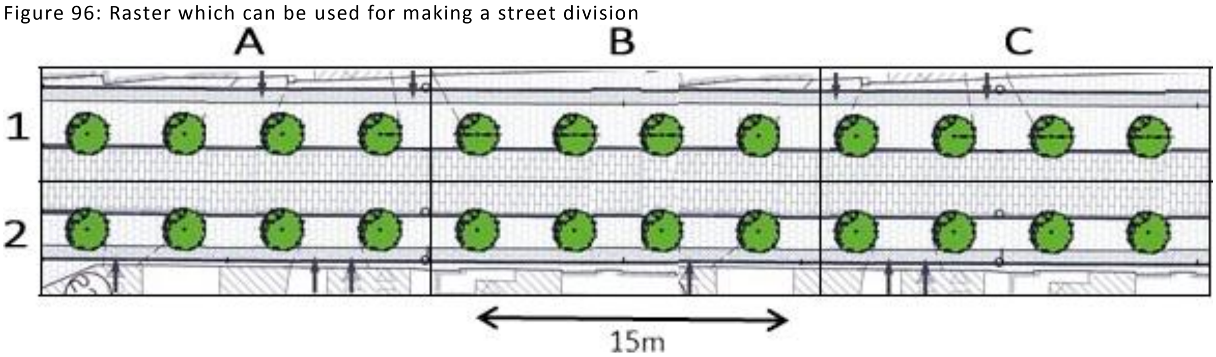
Table 17: Types and definitions of the ‘Camera_observationsProcessing’ table

Attribute name	Alias	Type	Notes
accessible	Accessible for mobility impaired people	Boolean	Do meet 3 demands: angle of inclination, threshold, free passage, or not
geovlak	Geometry surface	Geometry	EPSG:28992
data_year	Year of the data	Integer	The year in which the data was retrieved.
obtained_year	Obtained year	Integer	The year in which the data was processed and the results were obtained.
threshold	Computed threshold	Real	6 decimal digits precision
slope	Computed slope	Real	
width	Computed width	Real	
street_division_number	The raster-numbers and letters of the street division	Character	

The workflow for generating accessibility information by making use of camera data is performed on a part of the focus street called ‘Nieuwe Looiersstraat’. As explained in chapter 5.3, when processing a larger area than approximately 15 meters most of the used photos will not be aligned, gaps will be present in the generated point cloud and the precision and reliability of points will not be sufficient. To make a point cloud which is most close to reality, it is advisable to process an area up to 15 meters.

Therefore it is important to decide how to structure the information when more pieces of a street are processed. Firstly, a street needs to be divided into parts before processing. This can be done by using a raster with numbers and letters (see Figure 96).

Figure 96: Raster which can be used for making a street division



Source: (Leerne, 2014)

The database needs the attribute name ‘street_division_number’ in which these raster-numbers and letters will be saved. In short, different pieces of polygons will be stored in the database, because of the processing technique used for creating point clouds.

TABLE 3: RTK_ OBSERVATIONSPROCESSING

In this table all derived accessibility information via the RTK processing method is combined. This data gives an overview of the accessible paths where the *meet rollator* has walked in 2014 and 2015. Within this table the linestrings are stored (see Figure 97) which represent the connection between adjacent track-points.

Figure 97: Table 'RTK_ observationsProcessing' in PostgreSQL

accessible boolean	geom geometry(LineString)	data_year integer	obtained_year integer	threshold real	slope real	comment_validation character(100)
TRUE	010200000002000000B0726891419DFD40E9263108ECA41D41	2014	2015	0.04	0.36	
TRUE	010200000002000000A8C64B37419DFD40BA490C02ECA41D41	2014	2015	0.02	0.18	

In this table the maximum threshold (in meters) and slope (in degrees) are stored which appears between adjacent track-points. The types and definition of this table are illustrated in Table 18.

Table 18: Types and definitions of the 'RTK_ observationsProcessing' table

Attribute name	Alias	Type	Notes
accessible	Accessible for mobility impaired people	Boolean	Do meet 2 demands: angle of inclination, threshold, or not
geom	Geometry line	Geometry	EPSG:28992
data_year	Year of the data	Integer	The year in which the data was retrieved.
obtained_year	Obtained year	Integer	The year in which the data was processed and the results were obtained.
threshold	Computed threshold	Real	
slope	Computed slope	Real	
comment_validation	Comment according to the validation survey	Character	Which accessible-status is changed according to the survey and which status has been preserved.

7.3 APPLICATION OF THE GEO-DATABASE

The new database called 'OUT_ACCESS' could be of importance for a municipality. The exact position of problems in the outdoor environment for mobility impaired people, who need a wheelchair, rollator or mobility scooter, can help road managers to decide which pavements, crossings and bridges need to be improved to create a suitable route. In this way the database can be used as a Spatial Decision Support System (SDSS).

According to Wouwenaar, B. (Teamleader of Process Unit, department clean, at the Municipality of Amsterdam) a database with this kind of information can be very useful for the management of the public space, specifically for the management of pavements/surfacing. The purpose of management is to maintain a safe and accessible public space. If it appears that a public area is not sufficiently accessible, this information may be included in the deliberations of where a municipality commits their efforts. So this information is very useful for road managers. With this database the municipality can improve the mobility in the outdoor environment.

7.4 MAP

A map is a simplified, purpose-specific graphical representation of geographic phenomena, usually on a planar display (Huisman & de By, 2009). For making a map a GIS environments, like QGIS, can be used. However with QGIS no interactive map can be made and the map cannot be made publicly available (for embedding the map into a webpage). For this thesis the data is mapped via the Google Fusion Table application. This web application is chosen for its simple yet effective processing options, and for the fact that the data can be interactively published and easily accessed on the web. The Google Fusion Table application automatically selects the coordinates as registered in the input .csv file. With the Google Fusion Table application an interactive map can be generated by using placemarks. When clicking on a placemark an info window will appear. The way the information of a placemark is displayed can be customized. In this way a published interactive map can be made. Figure 98 on page 88 is showing an info box which appears by clicking on a placemark.

Figure 98: Map with info box displaying the derived accessibility information

8 CONCLUSIONS AND RECOMMENDATIONS

This chapter consists of the conclusions (what has become clear as a result of the investigation) and recommendations (what is advisable to other investigators).

8.1 CONCLUSIONS

The goal of this MSc thesis is to use sensor-data collected by a *meet rollator* to develop a geo-database that provides insight into the accessibility of pedestrian routes for mobility impaired people who need a wheelchair, rollator or mobility scooter. This goal has resulted in the following research question: Does the current setting of the *meet rollator* provide insight into the accessibility of pedestrian routes for mobility impaired people? If not, how can the current setting be improved? In order to answer this question, four objectives and corresponding sub question are determined.

The first objective is to define the problems and primary requirements for people with mobility impairments. This is done with the use of a literature review. To determine the walking restrictions in the outdoor activity space of people with mobility impairments the geometrical demands for movement can be taken into account. According to the Manual-book of Accessibility and an expert Job Haug, a good pedestrian path for people with a wheelchair, rollator and scoot mobile has to meet three geometrical demands for movement. The first demand is that a minimum free passage must be guaranteed of at least 900 millimeter wide (without passing at local constrictions). The second demand refers to a ramp which is not suitable for everyone. Therefore the angle of inclination must not be steeper than the ratio 1:6 (height:length). This means that a length until 0.3 meter may not have a rise higher than 9.46°. The third demand implies that a threshold may have a maximum height of 0.05 meter, which may be caused by paving stones that lie slanting or different pavement materials. This means that a pedestrian path forms an obstacle if it is narrower than 0.9 meter, steeper than 9.46° or if the height difference on the path is higher than 0.05 meter.

After examining the problems and requirements, objective two is to identify which data, programs and packages can be used to develop a methodology that generates accessibility information, and determine the accessibility by this proper set of software and data.
The outcome, according to the assessment of the three sensors (handheld Global Positioning System (GPS), Real-Time Kinematic (RTK) GPS and camera) by using the knowledge of the MSc Geomatics, is that with a handheld GPS no precise positioning can be reached. The accuracy of a handheld GPS lies at the few meter to decameter level. Therefore handheld GPS data is not useful for generating accessibility information. According to the knowledge the two sensors RTK GPS and camera are useful for generating accessibility information.

For deriving outdoor accessibility information, a measure-method has been developed. To propose generated accessibility information the developed measure-method is implemented for the selected research area. Through data processing, more insight is gained into sensor data and about the usefulness of the different sensors. The implementation of the developed measure-method has shown that some paths in the outdoor environment of Amsterdam require improvements to make them accessible for mobility impaired people. According to the results obtained by using RTK GPS data, 9% of the investigated paths need to be improved, which are 30 positions. However, the precision of the used RTK GPS data was for several places not good enough. Additionally, the generated accessibility information by using camera data is a relative measurement, because the created point clouds were integrated into a coordinate system by adding markers (manually) in PhotoScan. Furthermore, the generated accessibility information by using camera data is binary: it is either accessible or non-accessible. Additionally, it cannot be checked whether the obtained results are correct (for example a height of 0.05 meter can be a threshold, but it can also be noise in the data). This research has shown, according to the implementation of the developed measure-method by using RTK GPS and camera data collected by a *meet rollator* for the research area, that the sensors did not provide the needed precision for deriving outdoor accessibility information.

The third objective is to design a workflow for validating, providing more insight in and put semantics to the generated accessibility information, by using: the ground truth, results of an algorithm made by the Urban Modelling Group (UMG) of the University College Dublin, airborne laser scanning data (AHN-2) and the BGT+. A division is made between the validation of the RTK GPS observations and the camera observations. The BGT+ is proved suitable for providing more insight in and put semantics to the total observations obtained by implementing the workflows. The ground truth is proved suitable for validating the obtained accessibility information derived from RTK GPS and camera data. The results of an algorithm made by the UMG are proved suitable for validating the obtained accessibility information derived from camera data. However, the AHN-2 is not completely coverage, even not close enough to be able to determine profile information, so not suitable for providing more insight in and put semantics to the observations.

The next step is to design a database that structures the (validated) outdoor accessibility information. This is done by creating tables in a geo-database in PostgreSQL in which the validated outdoor accessibility information can be stored. These tables give an overview of the accessible and non-accessible paths. The derived accessibility information obtained via camera data can best be stored by using polygons, to represent complex areas. The derived accessibility information obtained via RTK GPS data can best be stored by using line strings.

In summary, the current setting of the *meet rollator* provides insight into the accessibility of pedestrian routes for mobility impaired people. However, this research has shown that the used sensors did not provide the needed precision.

8.2 RECOMMENDATIONS

It is recommended to follow the described methodology by using data of a different 'kind' of city. The research area in Amsterdam consists of a flat urban area. The derived outdoor accessibility information might be different of cities with another street pattern, compared to Amsterdam. Furthermore, the validity of the workflow will increase when it is also tested for a larger area. In this way, the amount of derived accessibility information will increase and therefore a better map can be provided.

A suggestion to improve the workflow by making use of camera data is to use more coordinates for georeferencing, like bollards in Amsterdam (Dutch: Amsterdammertjes). In this way one has a large amount of fixed points in photos which can be used as markers, for setting up a coordinate system in PhotoScan. This will result in less individual/loose points.

In the original measurement setup the validation of the results was not considered. According to this research it is advisable to other investigators to make sure that a *meet rollator* equipped with sensors works well. A measurement setup can be made by first going to the research area, chalking a line on the pavement, walking exactly on this drawn line, even knowing that there are some walking restrictions on this line, and determining the exact position of the start and end of this line. This has to be done in advance to the measurements.

The methodology did not take into account how intensively a pavement is used in certain areas, like shopping areas. In those areas it might be necessary for the pavement to be wider than the minimum geometrical demand for movement (0.9 meter), since multiple people use the pavement simultaneously and need enough space to pass each other. Therefor it is advisable to other investigators to implement this in their methodology.

In this research, the choice was made to model accessibility following a raster-based approach. This was done to limit complexity of the methodology. However, when in the future, more information will be linked to pavements (like route attractiveness), a raster-based method might not be sufficient. Therefor it is advisable to other investigators to model accessibility following a vector-based approach which might prove more suitable.

A part of the used sensors does not provide any insight into the outdoor accessibility information. Therefore the current setting of the *meet rollator* can be improved by using other sensors. It is also not only about the sensor(s) to use but also about the way they need to be used by someone. It is advisable to further investigate the usefulness of other sensors to decide which sensors produce more precise measurements and also which sensors deliver the data that is needed to be able to determine the outdoor accessibility.

For the '*meet rollator 2.0*' it is recommended to directly measure the needed information instead of calculating it. A sensor which can be used for measuring is a 3D laser scanning system. An example of a handheld laser mapping system is ZEB1, developed by CSIRO (Australia's national science agency). It is a light weight system and is designed to be hand-carried for capturing data by walking around environments. The data acquisition speed is more than 43.200 measurement points/second, the 3D measurement accuracy is 0.1% and the maximum range is 15m outdoors. Furthermore the ZEB1 allows fast data capturing. The result of a ZEB1 measurement is point cloud data which is directly available for further processing. The ZEB1 is ideally suited for building surveys; however outdoor mapping with a ZEB1 has to be further investigated. Also this system works totally independently of GPS and therefor a sensor is needed to determine its position. For the position determination RTK GPS should be able to work fine, especially by waiting a bit longer before the device achieves a good quality. It is important that the RTK device has a good precision before starting with the position determination, and that only these observations will be used for the generation of outdoor accessibility information. However, if you think of other sensors, then you may also wonder if you cannot use a sensor that derives the needed information directly without sensor data processing. Therefore it is recommended to use a little cart with (two) wheels that measures an angle of inclination and threshold directly. If you really want to know for example where a sidewalk is located, you have to use something with wheels that will run against a higher-situated pavement (by walking around) and measures at that time the presence of a curb. If a little cart is used in combination with an accelerometer (a device that measures proper acceleration) it directly measures a stop when it drives against a curb. However, it should be noticed that it is not easy to measure the needed information.

9 REFLECTION AND ACKNOWLEDGEMENT

This chapter consists of the reflection and acknowledgement.

9.1 REFLECTION OF THE RESEARCH

This thesis forms the research performed during the past 8 months, starting at March 2015 till the end of October 2015. This research focused on whether the current setting of the *meet rollator* provides insight into the accessibility of pedestrian routes for mobility impaired people. This thesis provides a methodology on how to process sensor-data in order to derive outdoor accessibility information.

The methodical line of approach in the Master of Geomatics consists of data capture, storage, analysis and visualization. The methodology used for this thesis includes these steps except the data capturing step, since for this research existing sensor-data was used. To carry out this research, knowledge from the core courses of Geomatics was needed. In particular the courses Sensing Technologies for the Built Environment, GIS and Cartography, Positioning and Location Awareness, Geo Database Management Systems and Python Programming provided information that could be applied. Part of this knowledge is described in chapters: 3.2 Basics of photogrammetry, 4.1 Available sensors, 4.3 Workflow Camera data, and 7.1 Geo-database in PostgreSQL. During the entire graduation period I have gained new knowledge, skills and insights. Among others GIS software was used for implementing sensor-data and visualization tasks. I have acquired an enormous amount of experience on how to use different analysis tools and types of software.

This research started with an in-depth literature review on related work concerning detailed models, the basics of photogrammetry, accessibility information, the use of GPS for positioning, and the potential problems and requirements regarding accessibility. Another important step was getting acquaintance with sensor-data. After the development of a workflow, the implementation could be started. RTK GPS and camera data were used for the implementation. The main focus was on the geometrical demands for movement to determine the walking restrictions in the outdoor activity space for people with mobility impairments.

The final products of this thesis are the developed workflows in order to generated accessibility information, obtained observations after implementing the workflow by using sensor-data collected by a *meet rollator* for the research area, and the developed geo-database that provides insight into the accessibility. It is important to store the observations in a database to be able to share it with others. One advantage of a database is the possibility to ask spatially related questions over the data.

The planning proved to be feasible. However, at the start of the process a majority of time was spent on the data processing. The small challenges that occurred during this research were mostly solved by using other tools and software. I have to say that after three months I realized that the current setting of the *meet rollator* did not provide the needed precision, but I prosecute with the project. Given the same kind of knowledge and skills in GPS processing and photogrammetry, and if I had known beforehand that the used sensors did not provide the needed precision, probably I would not have started this research but I would have recommended another way of working, like using other sensors.

This kind of research is important to a certain extent. The research could be of importance for a municipality, which is a place that deals with managing the outdoor environment. This research also contributes to the society as outdoor accessibility information is directly related to people and their lifestyles. Furthermore it can be used as Spatial Decision Support System by spatial planners and road managers since it provide them with supplementary, new and different information about the outdoor accessibility.

9.2 ACKNOWLEDGEMENT

The topic of this thesis is discussed with different stakeholders and experts who were contacted for exchanging information and gathering data (see Table 19 on page 94).

Table 19: Acknowledgement

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APPENDIX 1: RICH PICTURE

This rich picture has been made to explore, acknowledge and define the graduation project and express it (see Figure 99).

Figure 99: Rich picture