Synthesis Project Report for MSc Geomatics

"Adsum, ergo sum"
I am here, therefore I am:
Indoor localisation for blind people with use of LiDAR scanning and ArcGIS Indoors

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Maren Hengelmolen
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TU Delft

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This project is made possible by:

esri

Supporters of this project: Edward Verbree
Vincent Altena
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ABSTRACT

Blind and visually impaired people currently have inconveniences locating themselves in the indoor environment. No standardized system exists for them yet. After an inventory of the requirements of blind people, different representations do qualify for providing specific information blind people need. The main research question is: "How can blind people localise themselves (near) real-time in indoor environments with the combination of three representations of reality, namely (1) LiDAR point cloud matching, (2) ArcGIS Indoors and (3) Audio dynamic tactile map as the user interface?". Room detection and positioning of the user within the room are obtained by LiDAR scanning and point cloud matching. The processed point cloud height raster grids are acquired and imported into the Esri ArcGIS platform. The rooms are geo-referenced, and data is enriched by contextual awareness. As a user interface for blind people this report proposes two deliverables: a dynamic tactile map and an added or stand-alone audible supported user interface. Preliminary results of the qualitative validation show positive outcomes.

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PREFACE

The Geomatics Synthesis Project is a 10-week group project for the students in the fifth quarter of the Master of Science in Geomatics for the Built Environment at the Delft University of Technology. This project gives students the opportunity to apply the knowledge obtained in the first year of their master's studies. This project is also an opportunity to work with real stakeholders and client involvement. This is also a group project which involves project management. The final report has the goal to showcase all the processes from problem formulation, research question, data acquisition, data analysis, data modelling and data publishing. This report has the objective of providing a general overview for the reader of this report.

The title is derived from the quote from Descartes: ”Cogito, ergo sum”. The “I think” element in the Cogito implies the direct, immediate, certain knowledge of one's own existence.
The report “Adsum, ergo sum” extrapolates the idea of Descartes. Blind people do have a complicated relationship between mind and body. While moving through environments they do experience a lot of disorientation. This report aims to address the importance of the conviction of blind people that they should be able to localise themselves independently within indoor environments. Since they do exist in a place and therefore they are.

CONTENTS

Abstract v

1 Introduction 1
1.1 Problem definition . . . 1
1.2 Objective . . . 2
1.3 Reading guide . . . 2

2 Literature Review and Related Works 5
2.1 Orientation requirements for people in indoor environments . . . 6
2.1.1 Orientation & Localisation . . . 6
2.1.2 Orientation & Navigation . . . 7
2.2 Indoor data model . . . 8
2.2.1 IndoorGML and ArcGIS . . . 8
2.2.2 LiDAR scanning . . . 10
2.3 Existing application models for blind people . . . 10
2.3.1 Tactile map . . . 10
2.3.2 Existing applications as user interfaces for blind users . . . 12
2.4 Preffered requirements for an indoor localisation system for blind people 14

3 Research methodology 15
"How can blind people localise themselves (near)real-time in indoor environments with the use of these three representations of reality, namely (1) LiDAR point cloud matching, (2) ArcGIS Indoors and (3) Audio tactile map?"

4 Results 19
4.1 LiDAR (near-)real-time point cloud scanning and matching to a reference point cloud . . . 19
4.1.1 Data acquisition and post processing . . . 19

4.1.2 Point cloud analysis raster grid reference scan 21
4.1.3 Position of the user within the reference point cloud scan 21
4.2 ArcGIS information 22
4.2.1 Position of doors of a room 22
4.2.2 Directional relationship of the user to doors 22
4.2.3 List of Esri ArcGIS database Information 24
4.3 User Interface 25
4.3.1 Audio supported tactile map as the user interface for the user (blind cartography) 25
4.3.2 Audio Supported Device and User Interface 27

5 Validation **31**

6 Conclusion **35**

7 Future Study **37**

A SWOT analysis on existing applications **47**

B Project Organisation **59**
B.0.1 Contributions and Responsibilities 59
B.0.2 Contributions and Responsibilities 60
B.0.3 Time management 61
B.0.4 Related courses 63

C Boundary Extraction Using alpha-shape Algorithm **65**

D Audio Instructions **67**

E Questionnaire validation **69**

F Python Code **71**

G Arduino **81**

LIST OF FIGURES

1.1 Test case area: Architecture and the Built environment faculty building at the TU Delft; East Wing; First floor . . . 3

2.2 POI in IndoorGML (Left); Indoor POI within IndoorGML (Right) (Both retrieved from (Claridades *et al.*, 2019) page 362 CC Claridades et al. . . 9
2.3 Responsive and scalable tactile map retrieved from page 725 CC (Kepczyńska-Walczak, 2018) . . . 11
2.4 Metec dynamic tactile display retrieved from CC (Metec AG, n.d.) . . . 12
2.5 Web GIS translated tactile maps for visually impaired people with audible features (page 2/3 of abstract paper CC (Touya *et al.*, 2022) . . . 12

3.1 Flowchart from a user perspective . . . 16

4.1 Scanning environment with SiteScape app on Apple mobile device (own image) . . . 19
4.2 Post-processed scans with aligned bounding boxes of rooms and hallways of 1st floor of the East wing of the Architecture faculty (a) Hallway with coffee corner (b) Room C (c) Room U (own images) . . . 20
4.3 User scan of room U (yellow) matches with reference scan room U (blue) (own image) . . . 20
4.7 Route to describe the orientation of yourself in relation to the door . . . 24
4.9 Crisp boundaries extracted from rasters. Example of Room U . . . 26
4.10 3D model in Rhino . . . 26
4.11 The three tactile maps, with different scales . . . 27
4.13 Python script of ArcGIS query . . . 28
4.14 User Interface . . . 29

5.1 User Validation (own images) . . . 33

7.1 New user selfie scan proposal (also considering the ceiling (green) as static point cloud data) 39

G.1 Test setup Arduino 81
G.2 Arduino code from https://bc-robotics.com/tutorials/controlling-a-solenoid-valve-with-arduino/ 82

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Synthesis project
Msc Geomatics, Technische Universiteit Delft

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Abstract
Blind and visually impaired people currently have inconveniences locating themselves in the indoor environment. No standardized system exists for them yet. After an inventory of the requirements of blind people, different representations do qualify for providing specific information blind people need. The main research question is: "How can blind people localise themselves (near) real-time in indoor environments with the combination of 3 representations of reality, namely (1) LiDAR point cloud matching, (2) ArcGIS Indoors and (3) Audio dynamic tactile map as the user interface?". Room detection and positioning of the user within the room are obtained by LiDAR scanning and point cloud matching. The processed point cloud height raster grids are acquired and imported into the Esri ArcGIS platform. The rooms are geo-referenced, and data is enriched by contextual awareness. As a user interface for blind people this report proposes two deliverables: a dynamic tactile map and an added or stand-alone audible supported user interface. Preliminary results of the qualitative validation show positive outcomes. This report is a stepping stone for the possibility of integrating multiple into one device.

Key words
Indoor localisation for blind, digital twins, point cloud matching, adaptive tactile map

1. Introduction and objective

Descartes: "Cogito, ergo sum". The "I think" element in the Cogito implies the direct, immediate, certain knowledge of one's own existence. Blind people do experience difficulty moving through environments they do experience a lot of disorientation and uncertainty which can cause harm in the long-term (Koester, 2008). Right now no such standardised system exist for blind people to guide them in indoor environments. In addition a technological gap exists for retrieving indoor positioning and localisation methods. Wi-Fi Fingerprinting and BLE are commonly named as additional installed devices within buildings to retrieve indoor positions of people. Wi-Fi fingerprinting is not that accurate and BLE is accurate (Montilla et al., 2022). Those additional devices do imply extra maintenance from employees within that building. In order to come up with a system that can be extended to every building this report extends the idea of data retrieval by other means. The objective of this report is to address the conviction of blind people that they should be able to orient and localise themselves in indoor environments independently. This research is performed with a literature review, adopted qualitative research and explorative research. This research is carried out at a part of the first floor of the West Wing of the faculty of Architecture at the TU

Delft. First an inventory of related work is necessary. The inventory is split into 3 parts (1) the requirements of blind people whilst localising themselves in indoor environments and (2) existing Indoor data models will be explored and the fit of these models to blind people. Finally (3) an inventory of existing wayfinding apps on mobile phones are explored. The approach of this research will be based on the previously named inventories. Synthesis of of data acquired of the Architecture Faculty Building will be processed accordingly to the research approach. The second chapter entails the related work. The third chapter will take into account the research methodology conducted from the related work. The fourth chapter will explain the results. The fifth chapter addresses the preliminary validation of the qualitative research. Lastly some conclusions are proposed as well as proposals for future work.

2. Related work

2.1 Requirements of blind people for indoor navigation

For indoor navigation models the terms: positioning, localisation, orientation and navigation are evident. Positioning is important for mapping to determine your position in the world coordinate system. Localisation is the semantic way of telling your position. However, for blind people it is important to have proper orientation to localise themselves independently in indoor environments. Orientation gives them the ability to orient themselves and wander around through the indoor environment in order to explore the possibilities within indoor environments (Righthear, nd). Orientation requires the interlinked idea of localisation and navigation to procede further. Orientation requires the understanding of spatial relationships between you and the environment the person is in (Sithole & Zlatanova, 2016). This can be diversified by topological relationship and directional relationship. In this case the topological relationship refers to, if the person is included, or close to an object. Directional relationship requires the frame of reference of the person within the room towards an object. Blind people operate merely from a user-centric frame (Egenhofer, 1989). The Euclidean reference frame expresses the metric distance between points or places. In order to incorporate these metric distances the expression of navigation will be used. This can be split into wayfinding and locomotion. Wayfinding gives the approximate turn by turn directions from the user to certain objects or room entrances. Locomotion gives the real-time component reaffirmation to the user if it reaches the preferred location without being obstructed by objects. In this case it is important to have an updated overview of the available walkable navigable spaces. Other natural language descriptions next to localisation are the benefit of contextual awareness describing the functions and activities mentioned in the room.

2.2 Indoor data model specified for blind people

Indoor data models that are explored within the research are (1) IndoorGML (2) ArcGIS integratio (3) LiDAR scanning by iPhone 12 or 13. IndoorGML is a model standardised by the OGC (OGC,nd.). This indoor model does express the topological relationship between primitive nodes representing the cellular spaces of rooms (Claridades et al., 2019). This indoor model is extended by Points of Interest (POI): doors and turns in hallways. Further developments look for more data enrichment through Indoor POI (Claridades et al., 2019). Those Indoor POI can serve as landmarks for the blind people and therefore help the user be sure of their location and their proximity to other objects. Due to the changeable walkable spaces, these indoor data models aren’t enriched enough to completely satisfy the needs of blind people. ArcGIS is another platform that can be used to create an indoor informational model (Esri, nd B). Following the hierarchical structure provided by Esri, it is possible to create a 3D / Multi-Level map of a building. Lastly LiDAR scanning by iPhone is quite accurate and user friendly constructing of Indoor data models. Dardavesis (2022) explores the point-cloud matching algorithm by scanning ceilings in indoor environments. The matching helps understanding the localisation of the user. LiDAR scanning can be extended to perform also the position of the user within the room as well as information of the available navigable walkable spaces. All the methods do have their own scale specific benefits related to the topological understanding of the person within the indoor environment.

2.3 Existing apps for blind people

Various indoor apps are on the market. Also the conventional user interfaces are explored for carto graphing the world for the blind such as tactile map. Recent developments are the adaptive tactile map of Metec (nd) by pinart to represent text in braille or geometries or shapes of objects. Next to this the research, Touya et al. (2022) create semi-real time tactile map through OSM. Metec and Touya et al. developments could be integrated. In addition a

SWOT analysis is carried out of nine existing navigation apps for blind people. The most prominent apps were eZwayZ (nd), Navilens (nd), Envision (nd)and Lazarillo (nd). eZwayZ is qualified as an indoor navigation tool and uses pre-scanned point clouds with an overlay of contextual information necessary for the blind people. This app is still in the latest developments. While the project was running their approach is not taken into account in this report.

2.4 Preferred requirement for a system for blind people for indoor localisation

In conclusion, blind people benefit from independency if they are able to orient themselves freely. Information that is required is localisation and navigation methods to express the spatial relationships. For the indoor data models is stated that each indoor model has certain qualities for integration system for the blind. Digital twins (Esri, nd A) are named as a solution to have a combination of existing representations next to each other. As a preferred user interface tactile maps are explored as well as existing applications. Those interfaces strengthen the idea to have real-time and scale dynamic display of the indoor environment. The tactile map and the user interface stress other senses available for the blind to be reaffirmed of their correct location.

3. Research methodology

The research methodology is established to combine various digital representation of the localisation and orientation of blind people. This research explains the main research question:

"How can blind people localise themselves (near)real-time in indoor environments with the combination of three representations of reality, namely (1) LiDAR point cloud matching, (2) ArcGIS Indoors and (3) Audio dynamic tactile map?"

The 3 representations are used:

1. LiDAR point cloud scanning acquisition and matching for direct topological relationship and directional relationship
2. ArcGIS intertwines the topological relationship of the raster grids established by the LiDAR scanning. It maps the LiDAR averaged height raster's on room level and adds the specific contextual awareness
3. A dynamic supported tactile map and an added or stand-alone audio supported user interface applicable to the phone

4. Results

4.1 LiDAR scanning and point cloud matching

The first digital twin is obtained by LiDAR scanning this is done by using an iPhone device with LiDAR camera (Apple Inc, 2020). First the reference point cloud scan will be made, including the configuration of objects and activity points of that given day (Figure 1). Those scans will be simplified to height raster grids. This average height grid is obtained by Cloud compare (Cloud compare, nd). The grid size was set to 0.40 since it was close to the average step size of a blind person, which is 0.48m and it was able to capture 2 gridcells of the width of the table (See figure 2).

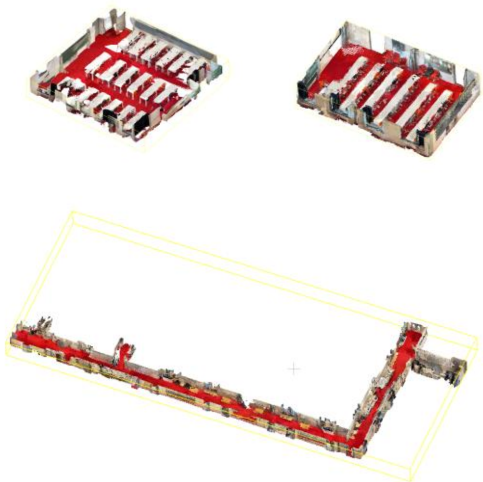

Fig. 1. Indoor scans First floor West Wing of TUDelft faculty of Architecture (Room C, Room U and the attached hallway)

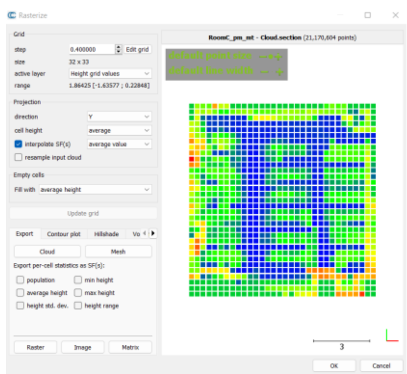

Fig. 2. Indoor height map of Room C

After establishing this database of point clouds of the certain rooms it is possible for the user to scan their environment. This is done by making a user-selfie 360 degrees scan. The scan will be matched to the database of point clouds and has an fitness and RMSE indicator to in what extent this point cloud match. Next to the localisation of in which room the user is the height of the person is scanned and therefore the position of the person within the room is estimated on top of the walkable surfaces grid. With the user selfie scan it is possible to determine also the directional user centric relationship as well (see figure 3).

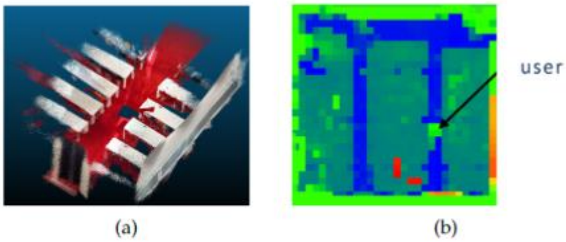

Fig. 3. Matching of person within Room C

Eventually the outlines of the LiDAR scans can be imported through concave hull and can be georeferenced to the ArcGIS Indoors platform containing the topological relations of rooms within the building. Georeferencing is done by the position of the middle point of the room and the points of interest: doors (See figure 4). The ArcGIS platform gives topological contextual awareness of the table through UNIT_ID, LEVEL_ID and USE_TYPE.

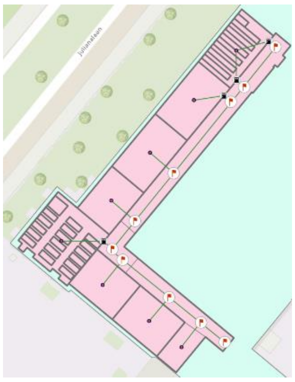

Fig. 4. ArcGIS Indoors topological relationship between rooms of the West Wing of TU Delft faculty of Architecture

The adaptive tactile map will be based on the technology of the Metec (nd) devices to be able to represent the topological relationship of the immediate topological relationships and the topological relationship of rooms. Blind people will become aware of the available navigable walkable space. During this project, there was not enough time to develop a real dynamic tactile map with audio supported user interface. That is why these user interfaces are separated in a semi adaptive tactile map with an Arduino localisation display using the methods of Touya et al. (2022). Secondly a workable audio supported user interface. By scanning and matching of LiDAR scanning the topological and directional relationship are retrieved. The information from the ArcGIS adds the contextual information to the user. The adaptiveness of the user interface adds the value of the locomotion real time component for orientation.
The audio supported user interface intertwines the idea of the user-centric frame and Euclidean frame reference. In this report the Euclidean frame reference with respect to the user centric frame is expressed by distance related descriptions in forms of the A* algorithm is used to describe in distance related terms the relationship between user and the encountered objects and static elements.

With the user interface the user will be able to obtain with the LiDAR Scan information in which room the user is located. It will retrieve topological and contextual information from ArcGIS for the connection of the other rooms next to the room. The user interface gives an overview of the possible destinations to go to. This enriches the blind user for determining their options within indoor environments.

4.1 Validation

For preliminary results of the qualitative research the procedure is carried out by test persons. The persons were asked to wonder freely through one of the rooms and find their way to another activity object within the room or towards another room. Afterwards the test persons were asked to fill in a questionnaire relating to the experience of the usability of the tools for them. The test persons needed to emphasize with the blind people, therefore they needed to be disoriented and not knowing the environment beforehand. The tactile map was beneficial to the users for determining their location in relation other rooms. The user interface with A* algorithm integrated added the real-time locomotion element from the user centric frame towards the locations the user wanted to go to. The validation process showcases preliminary satisfied user results. For future research a larger validation group is required as well as a real representation of the target group. The validation process emphasises on a good integration between both user-interfaces. Also the locomotion element was very evident and not always that satisfactory to the user preferences.

4.2 Future research

At the moment this research components do exist separately next to each other. The integration of all these techniques through one overarching application making use of these different separate techniques will strengthen the product development of this tool for the blind people. As an addition the point cloud matching algorithm does not work at all times for the determination of the position of the person within the room. Also if another configuration of tables are used. This is due to the 360 degrees scanning method. This scanning method does not take into account as much static environmental factors within the room. For further research it is beneficial to take into account an orbital scan and taking into account the ceilings as well.

A better adoption of IndoorGML could be intertwined in this report.

The validation part should have a larger amount of testers to have an academic attitude for research. This research explores the urgency of addressing the need of blind people to orient themselves in indoor environments.

This research is a stepping stone for further research.

5. Conclusion

This report proposes the importance of being able to orient yourself as a blind persons. This is only possible with the integration of localisation and navigation information. With an inventory of indoor models and existing apps this report proposes the combination of 3 representations namely: (1) LiDAR scanning and matching (2) ArcGIS Indoors topological and contextual information (3) Audio supported dynamic tactile map. The LiDAR scanning and point matching technique helps to detect the localization and position of the person within the room. Also with the LiDAR scanning it is prominent that the topological relationships are prominent. The ArcGIS Indoor helps to give topological and contextual information to the user. The user interface helps to translate the information in a comprehensible manner to the user by touch and sound. The proposed validation method shows good preliminary results. For further research the integration of IndoorGML could be better intertwined within the project. For the validation it is important to dive deeper into the usability of the integration of both the tactile map and the user interface.

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ACRONYMS

AI Artificial Intelligence 13

CAD Computer Aided Design 16

LiDAR Light Detection And Ranging 15

ICP Iterative Closest Point 20

IPS Indoor Positioning System 38

LBS Location Based Services 1

OGC Open Geospatial Consortium 8

OSM OpenStreetMap 12

POI Points of Interest 9

SWOT Strengths, Weaknesses, Opportunities and Threats 13

TTS Text-To-Speech 27

CHAPTER 1

INTRODUCTION

1.1 Problem definition

Through the technological development of the provision of location-based systems Location Based Services (LBS) on mobile devices, most people are nowadays able to be aware of their location. Additionally, they can position themselves with respect to other locations. The visual interpretation of maps, signs and displays plays significant role of 75% for the determination of people find their way in indoor environments (Stone, 2010). Challenges do occur for people with visual disabilities. Visually impaired or blind people cannot make use of location-based services on mobile devices because of the visual support for transferring the information where they are (Park *et al.*, 2020; Gorgonio & Javier, 2015). The guidance devices that blind people use are white canes to detect and avoid obstacles. In the outdoor environment, blind people are guided by special detectable pavement or crossing walkways. In indoor environments, such aids are not provided and blind people do experience difficulties finding their way in indoor environments. Unfortunately, they are not equipped enough to locate themselves within outdoor and indoor environments. This causes a lack of independence for moving around (Alghamdi *et al.*, 2012; Hegarty, 2002). Therefore, blind people experience respect to sighted people more often a poor sense of direction and experience disorientation on a regular basis when additional tools are not provided. Geographic disorientation may be long-lasting uncertainty (Koester, 2008). Next to the shortages of the independence of the target group, it is possible to address technical limitations of LBS systems applicable to the indoor environment. GNSS radio waves, which are commonly used for outdoor LBS are inefficient in indoor environments due to signal attenuation losses. For indoor environments, a higher level of accuracy is needed in comparison to outdoor environments (Pérez-Navarro *et al.*, 2019; Simões *et al.*, 2020). In order to avoid attenuation losses, other indoor localisation systems need to be explored. Worth mentioning is that not every building is mapped out for Indoor Localisation systems, this causes a lack for indoor localisation if no such Indoor model already exists. Literature mentions other technical possibilities such as are WiFi fingerprinting and Bluetooth Low Energy (BLE) beacons (de Jong *et al.*, 2021). WiFi fingerprinting causes still some distance errors. BLE gives high accuracy but requires additional installment of devices within buildings and is also in need of extra maintenance (Esri, n.d.a; Montilla *et al.*, 2022). In order to extend this research to other buildings this report focuses on a localisation method of without the extra installment and maintenance. On the other hand blind people are most of the time equipped equipped of an iPhone device since it supports most of the audible supported apps (Morris & Mueller, 2014).

1.2 Objective

The objective of this paper is to seek a system to provide localisation requirements for blind people without extra installation of positioning devices within rooms. In this way, this project is scalable to other buildings as well.

How can blind people localise themselves without the extra installations of additional devices within indoor environments?

This research will be performed on a part of the TU Delft faculty building of Architecture and the Built environment (fig. 1.1).

1.3 Reading guide

In order to satisfy the need of where blind people are within an indoor environment, first an inventory is required of the requirements of blind people in case of locating themselves in indoor environments. Secondly, an inventory is required on how the localisation information is required for communicating this information to the user. This is done by literature and a SWOT analysis of existing localisation apps for blind people. Based on this inventory a research methodology will be established. The synthesis of how blind people can locate themselves in indoor environments will be described as a following up step. Validation is required to test if blind people are able to know where they are and where they could go to. Lastly, some conclusions and future work will point out the coverage of the report.

This report is structured in the following manner. Chapter 2 will showcase the related work on location awareness for blind people and preferred user interfaces for blind people. Chapter 3 explains the research methodology. Chapter 4 shows the synthesis of these requirements and presents the steps to achieve our goals. Chapter 5 discusses

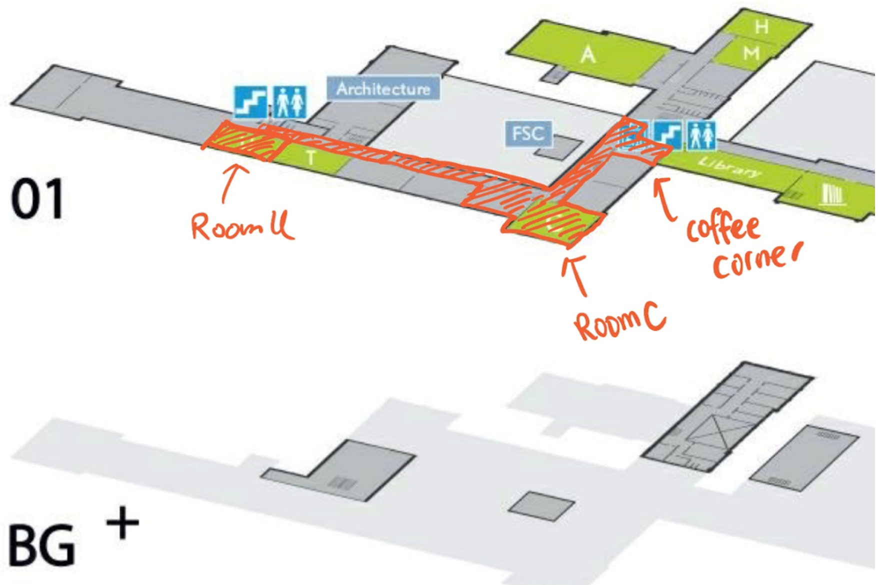


Figure 1.1: Test case area: Architecture and the Built environment faculty building at the TU Delft; East Wing; First floor

the validation of the products conceived by our test users. Chapter 6, will draw a conclusion and discuss our findings for this project. And the final chapter, Chapter 7, will discuss possible future steps.

CHAPTER 2

LITERATURE REVIEW AND RELATED WORKS

In order to construct a system for blind people to localise themselves independently within a building, several concepts need to be explained: positioning, localisation, orientation, and navigation. For mapping, it is important to what the position of a person or object is in relation to the world coordinate system (Afyouni *et al.*, 2012). This is called positioning. Most LBS use this as an input to relate the position of the user with relation to the world. Localisation helps to describe in a natural language the position of the user in the environment; namely being within a city, building or room (Sithole & Zlatanova, 2016). In order to let someone walk independently within the indoor environment two concepts are important: orientation and navigation (Right Hear, 2022). Orientation is having an understanding of what is around you. Navigation is knowing your way from the origin to a destination point. Orientation gives information about all the things surrounding a person, not just the ones relevant to getting to a specific destination. This navigation is a supported aid to let people find their way with turn-to-turn descriptions, but orientation gives a greater overview of the placement of the person within the building. To cite (Right Hear, 2022):

"Being well-oriented allows you to wander and explore the venue without having to have a specific place in mind [...] Because you have an idea of how certain hallways connect or where different points of interest are, you can independently choose where to go and when to go there with complete independence".

Orientation is for this purpose the main aim of this report. But since the terms localisation, orientation and navigation are interlinked, localisation and navigation will support the orientation part. This chapter addresses the requirements for localisation explained in terms of orientation and navigation. It is important to address the additional requirements for blind people. Besides the requirements, the available manners of data models to represent the indoor environment. These data models will be checked if they fit the needs of blind people. Lastly, the existing apps and user interfaces will be addressed to qualify the method technologies. In the end, a summary will be given of what requirements our system should have.

2.1 Orientation requirements for people in indoor environments

2.1.1 Orientation & Localisation

People can orient themselves through clues in their environment observed by their sensory system of visual, audible, tactile elements (CRC for Construction Innovation, n.d.). Several studies show how people orient by the use of their sensors in their indoor environment. Montello & Sas (2006) distinguish three major environmental factors that have been identified that affect the ease of orientation and wayfinding in buildings, namely: (1) differentiation in rooms within the floor map, (2) visual access of rooms, and (3) layout complexity. Differentiation of rooms with respect to size, shape and colour helps people memorise the different rooms. Visual access to how rooms are connected helps to orient persons as well. Thirdly is the complexity of the layout of the rooms. If there is a well-connected hallway without too many turns, this layout is comprehensible for the Wayfinder (Weisman, 1981). Contextual awareness is an introduced term which showcases the dynamic aspect of localisation. Contextual awareness is a way people practise within their environments, such as user activities, user preferences and needs.

Orientation is expressing what is around you in manners of spatial relationships: topological and directional relationships (Sithole & Zlatanova, 2016). The topological relationship represents the neighbourhood between two objects or rooms, which allows the inclusion (being within a certain location) and proximity (meet, or next to). Lastly, directional relationships are more complex and require a specific frame of reference and/or context. The context interpretation of these three spatial relationships by people can be based on the interpretation of topological and geometric distance between points - the Euclidean frame reference explained by Egenhofer (1989). However, it can be a user-centric frame referenced as provided by Clementini (2013) as well. For the topological relationship "landmarks" are mentioned for orientation (Weisman, 1981; Grifoni *et al.*, 2018; Lynch, 2008). Landmarks could be distinct rooms or vertical traversal points in an indoor environment. People construct in their minds a simplified map of their environment by relating themselves in the proximity of those landmarks or landmarks in relationship to each other.

2.1.2 Orientation & Navigation

Blind people do use their white cane to have an immediate topological relationship if they are obstructed by objects. They depend more on sounds from their environments and on the sense of touch with their white cane. They need to be informed by external artefacts expressed in these sensible manners, in order to be informed of the environment as a manner to orient themselves. For the purpose of orientation, it is relevant to know the placement of the user within the building and also the topological relationships of being in a room related to other rooms. For orientation, it is relevant to be informed of the layout of the room based on being familiar with the available walk-able space (Simões *et al.*, 2020; Miao *et al.*, 2011a; Nakajima & Haruyama, 2013). For the confidence of the user, reaffirmation is urgent of knowing being obstructed by the type of obstruction. Next to this, directional relationships are required because blind people do not know what they are facing. Since blind people have the ability to be informed by their senses what the euclidean directional relationship is in front of, the user has to be explained from a user-centric perspective. For orientation, the definition of landmarks does change. The landmarks can be based on functions which are related to sound, such as a room occupied by persons or objects provoking noise such as coffee machines or printers. Vertical movement places could be marked as landmarks as well, such as staircases or elevators. And on the scale of a room, the door can be a landmark (Makri, 2015).

For a tool for blind people the context-aware location-based service is therefore preferred which includes the whole context awareness process, that is the context acquisition, the context representation, and the context reasoning and adaptation (Grifoni *et al.*, 2018). Blind people do need to know the size of the room and the location of critical spaces such as doors, stairs and elevators (Montilla *et al.*, 2022). According to the definition of being well-oriented by Righthear, it is important that the user is set in the centre of what they want to perform. Alonso *et al.* (2006) proposes the presentation of the preferred information appropriate to the task that a blind person wants to perform. Blind people will otherwise have a cognitive overload without proper referencing where all the objects are placed for example.

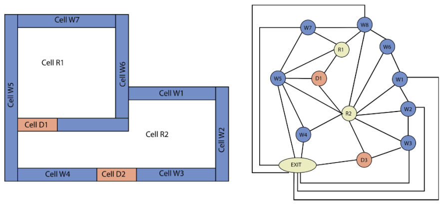
For orientation, it is relevant to have a directional and topological relationship between the user and the environment. However, in order to orient the person the directional relationship of the user to critical spaces such as doors, elevators and stairs needs to be expressed. Navigation can be used to express the directional relationship of the origin of the user to the location of the door for example. Montello & Sas (2006) distinguish two things in navigation namely way-finding and locomotion.

Way-finding refers to knowing the placement of the origin of the user towards a destination. Way-finding requires a sequence of topological connectedness of rooms. This method of the spatial relationship of the user with their indoor environment is translated through a chain of associated locations (Dalton *et al.*, 2015). For orientation and expressing this for way-finding in the building, Richter & Klippel (2002) suggest two essential components: critical locations along the route such as the origin and landmarks, next to that the turning (direction) information to capture the spatial relationship between the user and their environment. Allen (n.d.) distinguishes route instructions into directives and descriptors for describing the spatial objects encountered along the way. Richter & Klippel (2002) and Allen (n.d.) explain on different scales the topological relationship of the user to its environment. Locomotion refers to the information whenever a person successfully goes in the direction they intended without injuring themselves to their environment. It requires orientation to the immediate surroundings directly accessible to our sensory and motor systems at a moment in time. Locomotion requires us to solve problems such as identifying surfaces of support, avoiding obstacles and barriers, and directing our movement toward perceptible landmarks (Montilla *et al.*, 2022). Locomotion emphasises the real-time reassurance of a good directional relationship of the user to reach a certain destination. For navigation through the environment for blind people, way-finding and locomotion are important. Way-finding can happen by orienting the user with respect to passable landmarks. For the orientation, the position of doors within the boundaries of rooms are important since they are decision points to pass through to enter another location. Locomotion is of high importance for blind people since they have to move in real-time in the right direction without injuring themselves or moving into obstructions. Blind people require a higher refinement of spatial relationship information related to their spatial environment. Additional semantic information such as direction and travel distance from the origin to the destination should be provided (Nakajima & Haruyama, 2013).

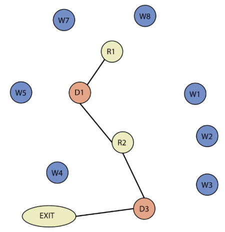
2.2 Indoor data model

2.2.1 IndoorGML and ArcGIS

Ways to represent such a data model could be demonstrated by a graph or by a raster grid for example. The Open Geospatial Consortium (OGC), developer of **citygml!** (**citygml!**), developer of CityGML, has created a more indoors-focused data model format known as **indoorgml!** (**indoorgml!**). IndoorGML is a relatively new standard for indoor navigation. IndoorGML is expressed by point primitives representing cellular spaces or rooms (see Figures 2.1a & 2.1b). The main objective of IndoorGML is that it models spaces and not objects in space. Cellular spaces are spaces defined as a set of non-overlapping cells. Each cell in this case a room has a cell ID, geometry, topology and semantics. IndoorGML points can be retrieved from CityGML or from a geographical infrastructure system such as ArcGIS provided by Esri. As an indoor model, the representation of maps by Esri can be used (2022).



(a) Topological and geometric relationships in forms of adjacency graph (Retrieved from (Ki-Joune Li, n.d.) CC Ki Joune li)



(b) Adjacency graph (Retrieved from (Ki-Joune Li, n.d.) CC Ki Joune li)

Claridades *et al.* (2019) do emphasises the notion of the addition of other Points of Interest (POI). POI critical spaces such as doors, elevators and stairs. POI's are placed in the IndoorGML with (x,y,z)-coordinates, in relation to the world coordinate system. As an additional layer, Indoor POI are stated as important locations. Those are not walkable spaces but do represent a place, service or facility or event in an indoor space. Indoor POI's are "objects of interest", "landmarks" or "places of interest" such as coffee machines (see Figure 2.2.

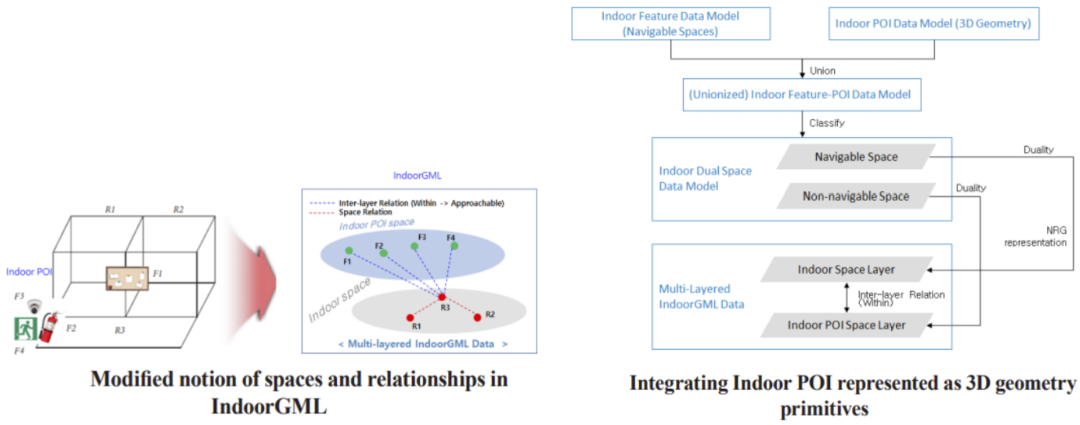


Figure 2.2: POI in IndoorGML (Left); Indoor POI within IndoorGML (Right) (Both retrieved from (Claridades *et al.*, 2019) page 362 CC Claridades et al.

As previously mentioned in the last paragraph, blind people need to know the topological relationship between rooms but the direct topological relationship between them and objects placed in the room. For blind people, it is important to know the amount of available walkable spaces. Li *et al.* (2018) describe barrier-free way-finding based on the relationship between the geometry layer, topological layer, and semantic layer. Although Indoor POI are placed as an added layer to IndoorGML they are projected as a referenced (x,y,z) point. Next to the normal navigation requirements the users need, updated contextual information is required, which allows them to be aware of their changing environment. Obstacles could obstruct the pass-through of rooms for example (Simões *et al.*, 2020; Nakajima & Haruyama, 2013). For blind people it is useful to include in the orientation the whole context awareness process, that is the context acquisition, the context representation, and the context reasoning and adaptation (Dalton *et al.*, 2015). Due to the requirements of available walkable spaces, blind people are not satisfied enough with the implementation of IndoorGML with the extension of Indoor POI or POI. Objects are projected to point primitives and don't give the refinement of walkable spaces required for blind people. Other methods are required.

But the ArcGIS platform does offer the opportunity to offer store real-time contextual information, topological relationships and geometric representation within the world coordinate system. It offers the opportunity to store newly made indoor floor plans if they are not available yet. In this case, every building could be stored in this way.

2.2.2 LiDAR scanning

LiDAR scanning is used to obtain a good refinement spatial layout of the indoor environment. Dardavesis (2022) makes use of LiDAR camera by the iPhone 12 or 13 devices. His report explains the method of point-cloud matching method. The user makes a scan of the static environmental factors like the ceiling. This scan will be matched to an already available database of all the room point clouds. By the scanning of these rooms, the localisation is clear. The position of the user within the room with respect to objects or available navigatable walkable spaces is unclear. However, his research does not take into account the contextual awareness of the room. Those scans need to be georeferenced to be placed within the world coordinate system as well as to have an understanding of the topological relationships between the rooms.

2.3 Existing application models for blind people

Since visually impaired people are not equipped with visual access to familiar cues or landmarks this information should be sensed by other external artefacts. A distinction is made by several applications: physical tactile map and existing applications.

2.3.1 Tactile map

Several studies have shown the user interfaces of blind people to locate themselves in their environments. The most known physical tool is the tactile map. The tactile map stands for the localisation of blind people mostly for the use of memorisation of their environment as well as preparation before entering an environment (Brock, 2017; Ducasse *et al.*, 2015). This physical tool helps the user as a cognitive preparation before entering a building. The tactile map showcases the topological relationship of the user to its environment. The tactile map is a stylisation of the real environment, displaying walls. It does lack a responsive display of the environment with a set use of information. Also with the display of braille aside from the tactile map, confusion is expected as and delay in understanding the description on the side (Alonso *et al.*, 2006). Therefore Ducasse *et al.* (2015) refer to the concept of interactive audio-tactile maps. Brock *et al.* (2014) explains the gestural interaction techniques that enable a blind person to choose between different types of information, retrieving names or detailed information about points of interest or measuring the distance between them.

New tactile maps are dynamically responsive. In the project of Kepczyńska-Walczak (2018), responsive tactile maps could be created by human interface design. The tactile map is able to represent multiple scales of the same building (fig. 2.3).

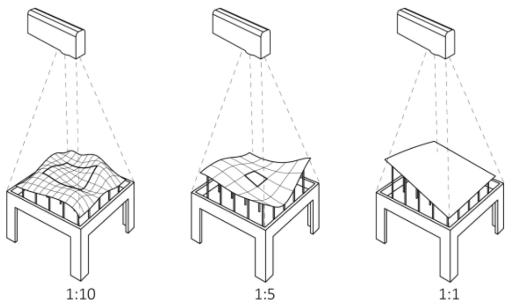


Figure 2.3: Responsive and scalable tactile map retrieved from page 725 CC (Kepczyńska-Walczak, 2018)

Company Metec AG with their "Laptop for the blind" has the same concept of a portable device containing 6240 tactile dots which can pop up for braille display, spatial structures and graphic symbols (fig. 2.4). This tactile map has the potential to be a dynamic and adaptive localisation tactile map which is resizable to the size of the indoor environment. However, there is no distinction made between obstructing geometries, since they are equally lifted (See figure 2.4).

Figure 2.4: Metec dynamic tactile display retrieved from CC (Metec AG, n.d.)

Touya *et al.* (2022) proposes the retrieval of maps for tactile representation via a semi-dynamic way. The tactile maps are conducted by OpenStreetMap (OSM) Location-based service and with steps of scene extraction, data enrichment and map design a 3D model is created. This is a near real-time representation of the indoor environment with an added context awareness (See figure 2.5).

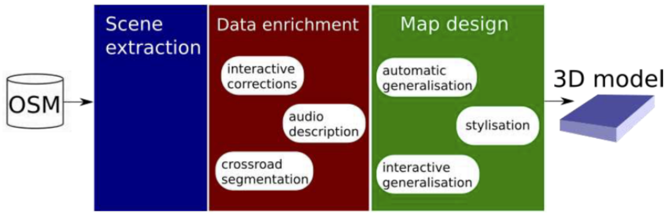


Figure 2.5: Web GIS translated tactile maps for visually impaired people with audible features (page 2/3 of abstract paper CC (Touya *et al.*, 2022)

From the literature, the application for the blind should be handy in use (Alonso *et al.*, 2006). This application needs to be connected to a geographical infrastructure system that is available for sighted people to check the system provider to blind people (Miao *et al.*, 2011b). For the localisation and orientation, it should provide a balance between location accuracy and speed of response since it takes into account the real-time topological and directional relationship of persons with objects (Montilla *et al.*, 2022).

For an application for the blind user, it is beneficial to integrate the qualities of these methods.

2.3.2 Existing applications as user interfaces for blind users

Research on related applications is done to get an overview of the available interfaces, technologies and methods and to learn from them. Another reason is to determine the current state of indoor localisation applications (what is already existing and what is missing).

For each application, a Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis is made to help identify the most suitable methods, technologies, and interfaces for this project (by listing the strengths and weaknesses), and determine if and how the already existing application can be (partially) integrated into this project (by listing the opportunities and threats). More details can be referred to the Appendix A.

In this section, only a few applications are discussed. The complete SWOT analysis can be found the appendix, A.

- eZwayZ: This app is able to determine the user position and allows users to navigate in the indoor environment. The app uses a pre-scanned point cloud with an overlay of information made accessible to visually impaired people. A route description can be given to the user via voice-over and vibrations (eZwayZ, n.d.). This method is interesting due to the high-quality information provided to the users and the user-friendliness of the app. Indeed, users do not need extra equipment next to their mobile phones.
- NaviLens: This app uses large QR codes to describe objects (products and facilities) in the surrounding environment. Therefore, the QR codes are placed near these objects and can be scanned to hear the information about them via voice-over (Navilens, n.d.). For the project, QR codes might be used to identify objects or facilities in the surrounding environment of the users.
- Envision AI: This app recognises surrounding objects, text and faces through Artificial Intelligence (AI) (Envision, n.d.). This app is interesting for marking-points identification and occupancy determination.
- Lazarillo: This app allows users to determine their position and navigate in the out- and indoor environments. Outside, the app uses GPS, inside it uses Bluetooth Beacons. These beacons are small, accurate, and low in maintenance (Lazarillo, n.d.), which makes them interesting for the project. However, this project focuses on localisation without extra costly instalments indoors.

Using point-cloud matching and Bluetooth Beacons seem to be accurate methods for indoor positioning. Using QR codes and labels seems to be a suitable method for object recognition for the visually impaired, but probably not the best solution for the blind. Indeed, the users need to find the QR codes and labels before being able to scan. This is a challenging operation for the blind. However, AI seems to be a better solution for them. AI allows users to receive instant information about the objects they are facing. Besides, AI is not only limited to the objects on which a QR code or label is attached (e.g. face recognition is possible). Another method that is discussed in the SWOT analysis is the involvement of volunteers within the application. The blind could video call them and ask what they are facing. Yet, because one of the objectives is to increase the autonomy of the blind, this method will not be considered during this project.

2.4 Preffered requirements for an indoor localisation system for blind people

The following requirements are proposed for blind people after the literature review

- Multiple techniques to retrieve information about context awareness, localisation and orientation
- Real-time component for orientation and localisation of user in an indoor environment
- Dynamic spatial accuracy of navigable spaces in terms of the detailed topological relationship
- Dynamic review of context awareness (function, user activities)
- Cognitive topological relationships by touch
- Orientation should be user-centric
- Landmarks should be expressed as a navigable tool in the tactile map or in the real-time scan
- Semantic description of instructions related to the actions of the user

CHAPTER 3

RESEARCH METHODOLOGY

What was stated in the previous paragraph is that blind people cannot rely on one user interface as well as one method to retrieve the information required for their orientation requirements. Therefore this report introduces multiple techniques to achieve the orientation for the user. Multiple methods will be used and for this purpose, the methods represent three types of representing reality, also called "Digital twins"(Esri, n.d.b):

1. Light Detection And Ranging (LiDAR) (near-) real-time point cloud scanning and matching to a reference database (data acquisition and localisation)

2. List Esri ArcGIS database info (data storing and updating contextual information: retrieve functional information from web services, user activities)

3. Audio supported dynamic tactile map as the user interface for the user (blind cartography)

Therefore the main research question is and integration of these methods:

"How can blind people localise themselves (near)real-time in indoor environments with the combination of three representations of reality, namely (1) LiDAR point cloud matching, (2) ArcGIS Indoors and (3) Audio dynamic tactile map?"

These digital twins correspond with each other and update them according to the information they can provide.

1. LiDAR scanning has the ability to create topological scans which are context-aware. LiDAR scanning can retrieve finer representations of the change and the type of obstacles in the room. In addition, it is possible to detect the user's position within the room as well as the position of doors to that room. The method to detect the position is point cloud matching to detect the user's position as well as the inquiry where doors are placed.

2. This report has ArcGIS coordinate reference system and contextual awareness ability. Therefore the Computer Aided Design (CAD) files generated from the LiDAR scans or available AutoCAD files will be placed on the ArcGIS platform.

3. The audio-supportive tactile map is the main user interface. It integrates the LiDAR scan and ArcGIS contextual awareness list. In the optimal situation, an adaptable tactile map like Metec AG (n.d.) should be provided at the entrance of every building, in order for people to memorise their way and have a dynamic display of information when needed while being within the building.

The following flowchart shows the research methodology with the user as the centre for this research (fig. 3.1)

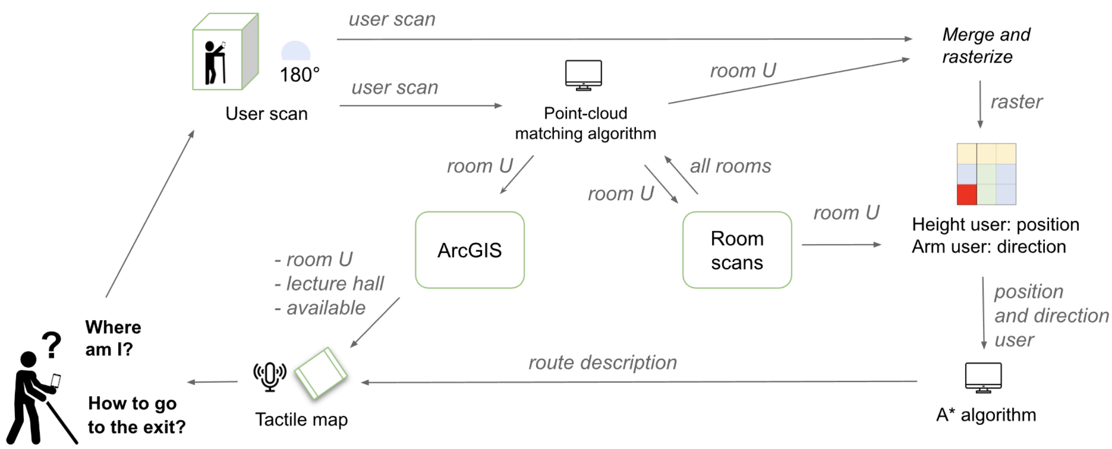


Figure 3.1: Flowchart from a user perspective

The user is able to get their position and their itinerary by making a scan of 360° of their indoor environment. They have to be on the scan as well (have to take a "selfie"). All this information is given to the user via an audio-supportive dynamic tactile map. A point-cloud matching is used to match their scan with the indoor reference scan and to define the room in which they are located. Information about the room (e.g. room function, availability) is extracted from ArcGIS and provided to the user. The output of the point-cloud matching algorithm is used to define the user's position within the room. Therefore, the reference scan of the room and the user scan are merged and rasterised. By detecting the user height on the raster, the user position can be defined.

Arms are also scanned, due to the 'selfie'-mode, and help to define the direction the user is facing. Depending on the destination chosen by the user, a route description is computed by using an A* algorithm and provided to the user.

The products that will be proposed as ideal products will be the two following:

Audio supportive dynamic tactile map. This report creates a combination between the Metec device, Touya *et al.* (2022) and real-time scanning like EZwayZ (eZwayZ, n.d.). Real-time scanning will be done by LiDAR scanning with a mobile phone. This device will send the localisation and spatial information to the audio-supportive tactile map. The users will then be able to feel and retrieve the needed information for localisation and orientation.

Due to the limited amount of time for this project, the tactile map is created as one user interface to showcase the topological relationship between the user and their environment. And the real-time scanning information is obtained by making scans with a mobile phone equipped with a LiDAR camera.

The report is structured in describing the steps to do the scene extraction of the user, and how this is communicated to ArcGIS indoors for the topological relationship. This research is carried out in a test case, namely in a part of the Architecture faculty building of TU Delft. The group of de Jong *et al.* (2021) created an indoor environment constructed by CAD files provided by the TU Delft for the ArcGIS floor map.

CHAPTER 4 RESULTS

4.1 LiDAR (near-)real-time point cloud scanning and matching to a reference point cloud

4.1.1 Data acquisition and post processing

This report obtained LiDAR scanning acquisition on an Apple mobile device (Apple Inc, 2020). The app was called SiteScape to do the acquisition of point clouds of the indoor environment (SiteScape, n.d.) 4.1.

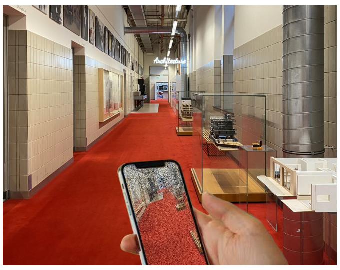
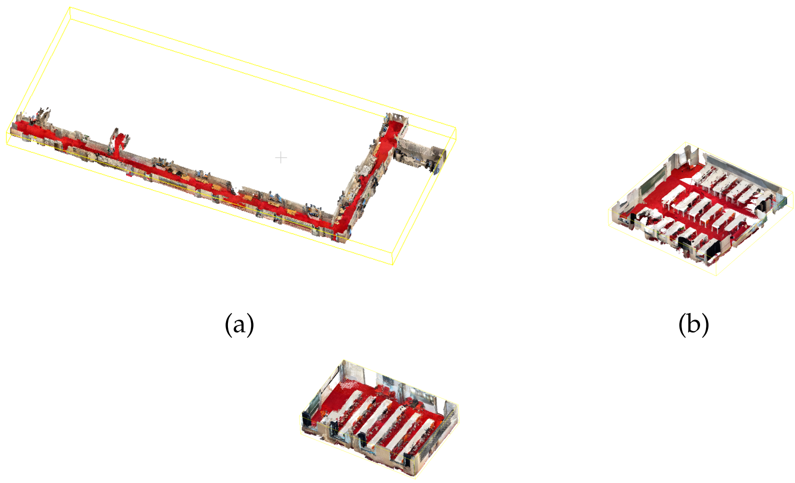


Figure 4.1: Scanning environment with SiteScape app on Apple mobile device (own image)

Multiple scans had to be made to get a complete room scan. The next step was to merge every point cloud with the software CloudCompare to reconstruct the rooms, see figures 4.2. Afterwards, some post-processing was carried out in order to clean up the point clouds (CloudCompare, n.d.). These first scans of the rooms were set up to be the reference point clouds of the rooms.



(a) (b) (c)

Figure 4.2: Post-processed scans with aligned bounding boxes of rooms and hallways of 1st floor of the East wing of the Architecture faculty (a) Hallway with coffee corner (b) Room C (c) Room U (own images)

For updating, the configuration of the room, the scan be retaken and will be matched to the reference scan. A matching algorithm is used to detect the metric relationship of the user within a room. This report makes use of the point cloud referencing algorithm of Dardavesis (2022). The python library that has been used is the Open3D library (Open3D, n.d.). The point cloud matching algorithm includes a global registration and a Coloured Iterative Closest Point (ICP) algorithm to align the two scans. As can be seen in Figure 4.3, the user scan (represented in yellow) is matched with the reference scan of the room in which the user scan was made (represented in blue)(see Fig 4.3). The point cloud matching algorithm fitness and RMSE. High fitness and low RMSE are preferred.

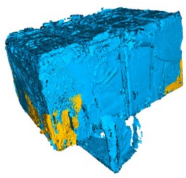
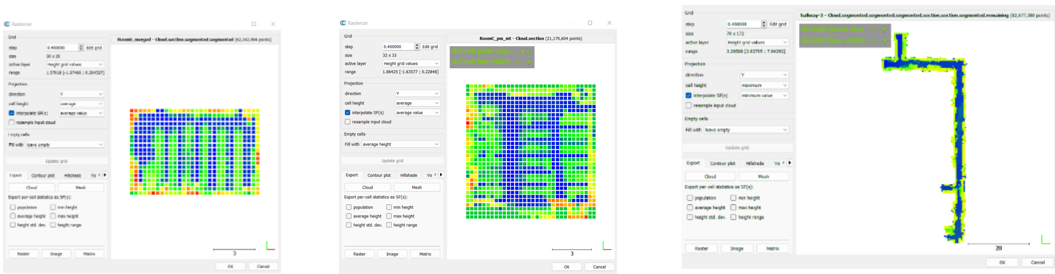


Figure 4.3: User scan of room U (yellow) matches with reference scan room U (blue) (own image)

4.1.2 Point cloud analysis raster grid reference scan

In order to have an updated room to specify a higher spatial accuracy of walkable spaces this report proposes an average height grid structure of the room. The grid values represent the boundaries of the room, objects and available walkable spaces. The average step size of a blind person is set to 0.48 m according to Kumari *et al.* (2022). The length size of the tables has an average size of 0.8 m the grid size is set to 0.40 to capture the tables more (fig. 4.4). For all the scanned rooms these CloudCompare is able to generate a text file of the matrix which is used as an input for the A* algorithm. Those files were named: `rastermatrix_roomU.txt` and `rastermatrix_roomC.txt`, `rastermatrix_hallway.txt`.



(a) (b) (c)

Figure 4.4: (a) Average height grid room U (b) Average height grid room C (c) Average height grid Hallway

4.1.3 Position of the user within the reference point cloud scan

Three methods were tested to determine the user's position within the room. Eventually, the user selfie is chosen instead of the stick scanning (see Appendix). The user scan is a scan of the user with a 360 degrees angle. Figure 4.8 is showcasing the height position of the user placed on a formally walkable space. By making the selfie scan, the arm is scanned which helps determine the direction the user is facing.

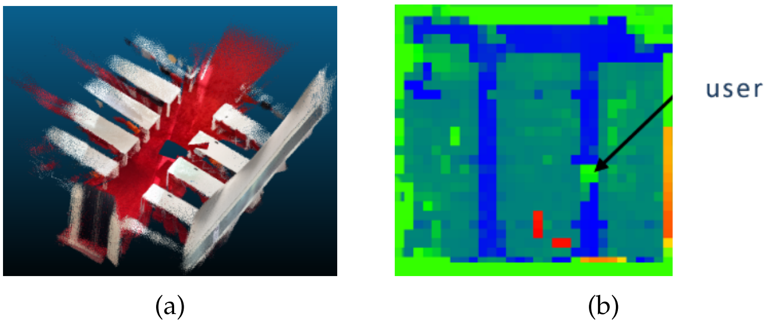


Figure 4.5: (a) User scan selfie point cloud (b) User scan position in raster grid (own images)

4.2 ArcGIS information

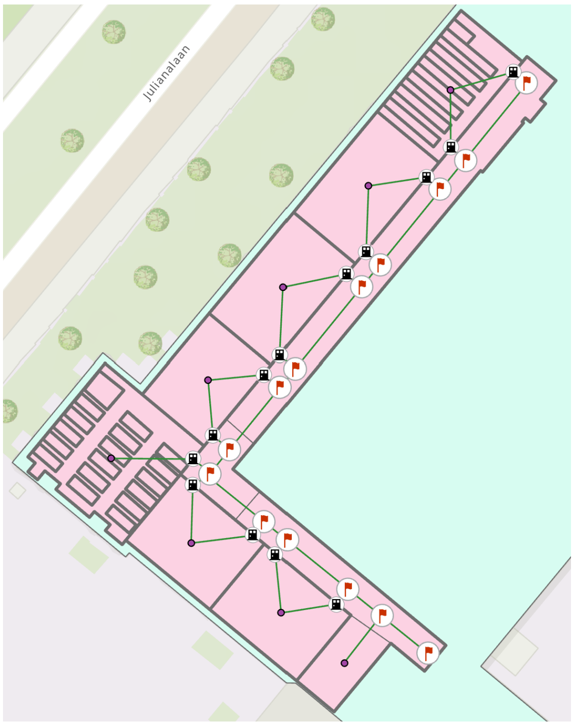
4.2.1 Position of doors of a room

The CloudCompare software generates a matrix text file with all the average height values per index. Room C has a grid of 32 by 33, with an average distance of 0.40 metres. Within the matrix file the boundaries have blue values do correspond to the doors within a room (upper right corner of 4.12. In order to place the room in the real coordinate system a link is made to the door nodes and the centre node in ArcGIS Indoors see Figure 4.6a. The matrix file is therefore enriched with the coordinates in the real world. In this case, the topological relationship between rooms is established.

4.2.2 Directional relationship of the user to doors

For the directional relationship of the user towards doors, the navigation over navigable spaces should be described. The relationship is possible in euclidean distances of how many metres you are away from the door. For this purpose, it is useful to use the A* algorithm to describe distances and directions taken by blind people towards a door. Since it is a raster grid of an average stepsize of a blind person these directions can be translated in a semantic way in turn by turn directions understandable to the user. An important thing to mention is that the directional orientation of the user must be aligned to the A* algorithm. Therefore it is important to have cardinal direction information. If the doors are expressed in a cardinal direction and the user's cardinal direction is expressed the user does know to be aligned to the walkable spaces. In order to retrieve the user's cardinal direction Geo-location API[1] and the precise direction with Compass API[2] is used.

[1] https://pypi.org/project/geolocation-python/
[2] https://pypi.org/project/compass/



(a)

	OBJECTID *	Shape *	OBJECT_ID	UNIT_ID	POINT_X	POINT_Y
1	1	Point	Door	Room C	486535,553528	6801232,373474
2	2	Point	Door	Room U	486583,7677	6801290,733887
3	3	Point	Door	Room U	486574,364075	6801279,397705
4	4	Point	Door	Room T	486570,684509	6801274,826111

(b)

Figure 4.6: (a) ArcGIS door points (b) ArcGIS table with point coordinates of doors and decision points (own image)

The A* algorithm indexes the points for the user and marks the route from a different location to location. As the room is divided into a raster, the algorithm is able to find a path through the obstacles and provide a route within the walkable areas in the room. For the localisation of the user the orientation according to doors helps the user to determine the relationship of themselves within the room as well as how they are located in relation to other rooms. In the raster, the room is converted to raster cells, with walkable spaces in the room as '0', and obstacles as '1'. Due to the fact that the LiDAR scan is a snapshot of the room, only semi-fixed obstacles such as tables and chairs are perceived as obstacles. The advantage of the A* algorithm, as opposed to 'depth first search' or 'breadth first search', is that the route takes account of the direction the route is taking.

This technique maximises the traversal of routes in the most efficient way in order to find a path that leads from the origin to the preferred destination. This code is eventually expressed in how many steps should be taken and with which directives and turns from the user-centric frame. The algorithm is able to draw a route from the door to the Point of Interest within the room. The python script is written in Appendix F and works as follows:

Algorithm 1 A* algorithm

Data: raster file of the room (raster.txt) **Result:** route description in speech

1. Read the raster file
2. Convert raster cells (0 = walk-able spaces, 1 = obstacles)
3. Apply A* algorithm, output: path (fig. 4.7)
4. Convert the path in route description
   a) Determine the orientation of the room
   b) Determine the direction of the user
   c) For each step in path, determine the direction in which the user must take a step
   d) If there are more than one step that needs to be taken, add them to each other
5. Translate the route description into speech

```
Path: [(0, 0), (0, 1), (1, 1), (1, 2), (1, 3), (1, 4), (1, 5), (1, 6), (1, 7), (1, 8), (1, 9), (1, 10), (1, 11),
['1 step to the right', '1 step to the left', '1 step to the right', '20 steps forward', '1 step to the right']
```

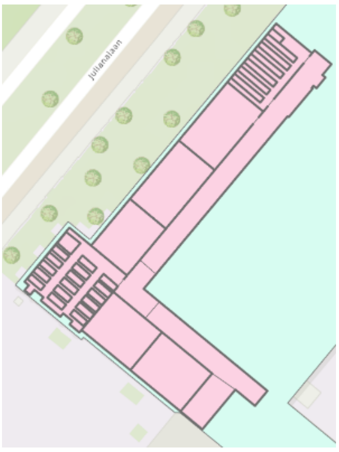
Figure 4.7: Route to describe the orientation of yourself in relation to the door

4.2.3 List of Esri ArcGIS database Information

With the (near)real-time matching of the point clouds the location is determined. In order to have the relevant geometric, topological information and contextual information of the room, a link needs to be made to the data enriched on the ArcGIS platform.

Using the CAD file from the Building Rhythms from de Jong *et al.* (2021) and ArcGIS Indoors, an information model of the first floor of the Architecture building was created. This included the Units, Details, Levels and Facilities features (de Jong *et al.*, 2021). The Units feature (fig. 4.8b) contains all data involving the rooms and halls of the building.

Semantic information could in addition added to the rooms such as the use type of the room, as well as the topological relationship connection to other rooms. And landmarks that are more relevant to blind people are stored within the table (fig. 4.8b) The 'Levels' feature stores information on the floors of the building. The 'Facilities' feature outlines the building itself and the 'Details' feature includes walls, tables, entryways and general obstructions. These features are interconnected and thus one can tell what details are in a unit, and which level the units are located on and what facility the level is a part of.



(a)

	OBJECTID *	Shape *	UNIT_ID	LEVEL_ID	USE_TYPE	Connections	DoorOrientation
1	9	Polygon	Room U	1	Lecture Hall	Hallway	S, E
2	8	Polygon	Room T	1	Lecture Hall	Hallway	S
3	12	Polygon	Room C	1	Lecture Hall	Hallway	E
4	10	Polygon	Hallway	1	Hallway	Room U, Room T, Room...	<Null>
5	13	Polygon	Coffee Corner	1	Leisure	Hallway	NE

(b)

Figure 4.8: (a)ArcGIS geometric structures (b) ArcGIS table with Unit information with semantic description

4.3 User Interface

4.3.1 Audio supported tactile map as the user interface for the user (blind cartography)

Extracting tactile map

As proposed by Touya *et al.* (2022) an enriched 3D model can be created through an online platform. This report makes use of the ArcGIS platform for the geometric and topological relationship of rooms. The Units as described in 4.8a are retrieved as the geometric representation of rooms. In addition the objects scanned with the LiDAR scan are transferred to ArcGIS. Two approaches on extracting objects from point clouds are carried out. In this way a stylisation of the boundaries and the walk-able spaces are extracted from the scene. One of our approaches is using the alpha-shape algorithm, which generalises the concave hull containing sets of points using an alpha shape (Appendix C). The other one is based on vectorizing the average height rasters using the opencv library and pillow. For this process the obtained object point clouds needed to be translated to CAD files. In the end, the vectorisation of rasters gave more crisps boundaries.

Figure 4.9: Crisp boundaries extracted from rasters. Example of Room U

The extracted CAD files of the tables are added to ArcGIS. The location of the scan is selected and mapped to the map to 'connect' them. As stated earlier though, the tables are imported as a separate feature whereas they should be part of the Details feature. Therefore, to transfer the tables to the Details feature, a polyline was drawn around the tables. In order to adapt the tables to their real representation they needed to be cleaned and made more rectangular-shaped for the 3D model.

All of this information is then uploaded to ArcGIS Online and made public in order to be accessed by anyone. In addition, the Export to CAD tool was used to generate a final CAD file for the 3D model. This report focuses on a dynamic near-real time tactile map. As stated in the research methodology in, chapter 3, this report cannot opt for the dynamic geometric representation as Metec AG (n.d.). However, this project proposes two levels of detail: the room level and the east wing representation. The CAD files are extracted from ArcGIS Indoors and translated in Rhinoceros software with Grasshoper (see fig 4.10.

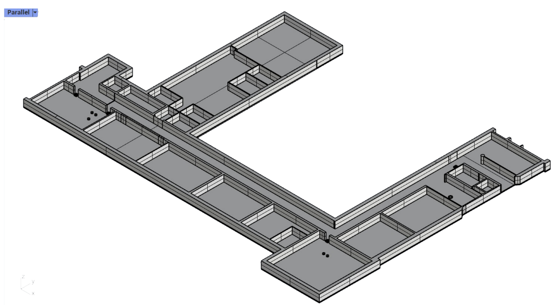


Figure 4.10: 3D model in Rhino

Actuators localisation person

A dynamic representation of the user on the tactile map helps the user to be aware of the surrounding environment. Under the map, actuators can be placed in a grid structure.

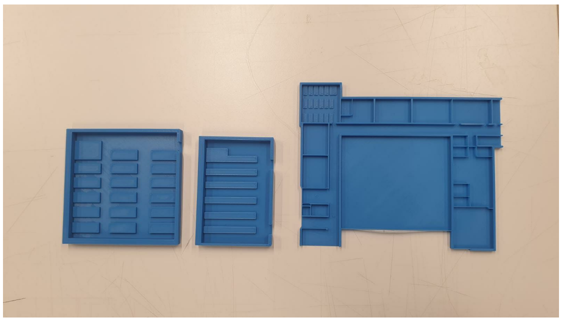
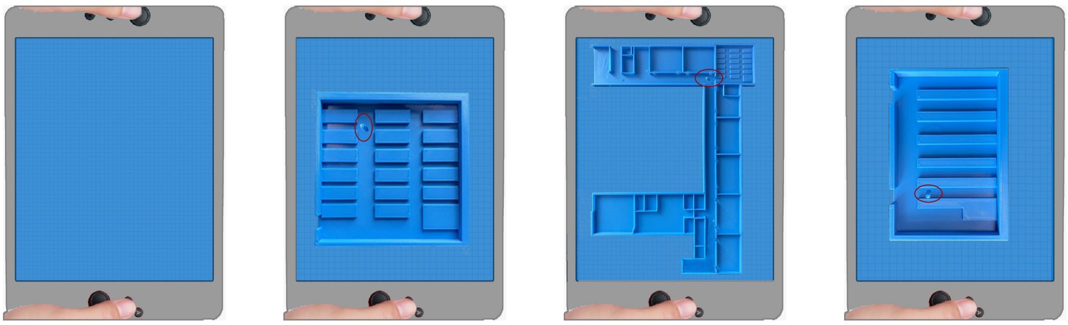


Figure 4.11: The three tactile maps, with different scales

Depending on the user's location, the actuator (with an object representing the user) pops up. This dynamic user representation was tested by using a small Arduino actuator (DC12V 5N Solenoid). The test setup and Arduino code can be shown in Appendix G.



(a) (b) (c) (d)

Figure 4.12: (a) plain interface (b) Room U (c) East wing first-floor plan (d) Room U

4.3.2 Audio Supported Device and User Interface

For contextual awareness, information can be retrieved from the ArcGIS table. The localisation of the user can be retrieved from the point cloud matching and the metric A* algorithm distances.

A script was written in python to speak the required information for blind people. Firstly, the ArcGIS map has to be accessed online. Using the ArcGIS library, a python script can be made to view, access, and query layers, features and attributes from the map published online. In addition to this the ArcGIS library, the `pyttsx3` library [3] was added to the script. This library takes care of performing Text-To-Speech (TTS). Using this, an automated line, that can be updated when the map is updated, can be generated

[3] Text to Speech library for Python https://pypi.org/project/pyttsx3/

for each room. This in conjunction with buttons on the 3D model could allow for a tangible and auditory positioning experience for those who are visually impaired.

```
# create feature set
synthesis_l1_fset = synthesis_l1.query(where = 'OBJECTID < 6')

# get features
synthesis_l1_features = synthesis_l1_fset.features

# display feature attributes
attributes = synthesis_l1_features[0].attributes

print(attributes["UNIT_ID"], "functions as a", attributes["USE_TYPE"])

# TTS read output
engine.say(attributes["UNIT_ID"]+" functions as a "+attributes["USE_TYPE"])
engine.runAndWait()
```

Figure 4.13: Python script of ArcGIS query

The user interface, as presented in figure 4.14 shows a test case of the user interface that will work on the blind and visually impaired person. The interface, although text-based, is proposed as an audio-based experience for our end users, and this interface is able to work with Voice Over feature on the iPhone. The text uses natural language to greet the user. It uses simple language so that the user is clear about where they stand and have a clear expectation of where they would like to travel within the indoor space. There are instructions along the way. Once they have chosen their way, the interface presents the start point and end point and displays the relevant route information. After each step, the user is able to click next for the next set of instructions. This step-by-step interface is able to take the user to their desired room. The reverse of this is also possible when the user wants to exit the room to the hallway. This process will also be an option for them to instruct to leave the building (see fig 4.14).

(a) (b) (c)

Figure 4.14: User Interface

CHAPTER 5

VALIDATION

Since the objective of this report is to develop a system that can be used by blind people to locate themselves in indoor environments, the validation of this report is of qualitative nature (Design Validation, n.d.). The aim of the validation is to test the usability of the system to the user if they are able to orient themselves within a building or room. As an additional feature, user feedback can be obtained from gathering recommendations on what is sufficient for the system and what could be improved. In order to quantify the qualitative user experience, a validation questionnaire is used to assess the user interface system by voice (fig. 4.14) and the use of the tactile maps (fig. 4.11).

The validation mainly consists of two parts. One is evaluating if the user is able to orient themselves within a room and explore the options available in the room. The other is if they feel confident enough to wander around the hallway or find their way towards another room.

First, some test users are needed for evaluating the process. Unfortunately, the preferred target group was not available to do the testing for this research. For this reason, sighted people were asked to do the testing. Due to time constraints, only two test users were able to participate in the research. The requirements for these users were:

- Are unfamiliar with the building
- Disoriented
- Blindfolded
- Could emphasize how a blind person would evaluate the space

The non-architecture students were asked to come to the building entrance and they were given some instructions to navigate as a blind person, as described in Appendix D. The recorded audio instructions are provided by one of the colleagues of the project (Ellen Zieleman), who is a blind person. The people were instructed to wear black painted glasses and make use of a white cane. In the case of this report, a red umbrella was to replace the white cane. The people were tested in sequential order and were not able to communicate with each other while the switch in people was happening. The people were taken to their start position, somewhere in Room U. They were not able to know they were placed in that room. In order to avoid Euclidean frame reference, one needed to have no sense of orientation. For this purpose, the test people were placed on top of a movable chair wearing black painted glasses and wearing noise-cancelling headphones. The people were moved on top of the chair to room U.

One task scenario was if they were able to orient themselves in the room. After the near-real-time user scan, the small-scale Room U model was given to them with an elevated section where the location of the user should be placed. This gave users an initial thought of the obstacles and size of the room. With the text-to-speech, a feature-specific description of the room was given: such as the function of the room, which floor, size, and whether it was occupied or not. This information is retrieved from ArcGIS. Eventually, several Indoor POI and POI were told to the user, for example, the position of the chalkboard to perform a presentation or the number of doors in that room to leave the room. The position of these objects was explained in a user-centric approach with semantic information like ”the chalkboard is on your right in front of you” or ”the doors are located behind you”. The options were given to them if they wanted to orient themselves where that Indoor ac poi and POI are located and step distance instructions were explained to the user. This gave them a certain direction toward those objects in a distance-related approach.

The second task scenario was similar to the first one, but on a larger scale, i.e. in the hallway. Another scale model was provided to them with the topological relationship between the hallway in relation to the room. They were offered the option to walk to the nearest coffee corner or to the further away coffee corner. One of the test users chose to have the nearest coffee corner and the second one chose the one further away. They could find their way towards points they preferred to go to. The in-between localisation points such as POI and Indoor POI helped the users arrive at their location and wander around. After the test, the users were asked to pinpoint their on the tactile map where their location was. They could pinpoint that they were in the neighbourhood of the nearest coffee corner placed in Room U because it has an apparent function that serves as a landmark.

To quantify the research, test users were asked to fill out a questionnaire. In order to quantify the user experience, scale bars were given so as to express satisfaction with the system (“1” for low satisfaction, “5” for high satisfaction). Overall the premature results showcase a good intertwined relationship between user experience and feeling comfortable wandering around with this information provision system with sound and touch. However, the number of test users does not qualify this research enough. For this reason, more tests need to be performed to qualify this as scientifically tested research. Montello & Sas (2006) mentioned the differences among individual travellers are important. One of the students was very confident with moving around, whereas the other was very cautious. For this reason, the small test group does not qualify as real research. Preferably in the future with the real target group.

One remarkable point was the error of orientation on a larger-scale map. It was easier to get lost since the space was larger. The in-between information of Indoor POI did help them to be on the right track. A prominent thing for the users was the importance of real-time information about being in the proximity of certain objects. The locomotion concept was very prominent in test situations. It was very easy for the testers to head in the wrong direction. Lastly for further research, the real-time component must be more intertwined, with an immediate connection between the user scan and the model.

This test research can be considered a stepping stone for future research.

(a) (b)

Figure 5.1: User Validation (own images)

CHAPTER 6

CONCLUSION

This report proposes the importance of being able to orient yourself as a blind person. The objective of this paper is to seek a system to provide orientation, localisation, and navigation without extra instalments of positioning devices within rooms. In this way, this project is scalable to other buildings as well. The test case for this research was a part of the first-floor wing of the faculty of Architecture of the TU Delft. This is only possible with the integration of localisation and navigation information. With an inventory of indoor models and existing apps, this report proposes the combination of three representations of reality. Each of them contributes to a different aspect of orientation for the blind person. The combination of represenations are: (1) LiDAR scanning and matching (2) ArcGIS Indoors topological and contextual information (3) Audio-supported dynamic tactile map. The LiDAR scanning and point matching technique help to detect the localisation and position of the person within the room. With the LiDAR scanning, the topological relationships are important. The ArcGIS Indoor helps to give topological and contextual information to the user. The user interface helps to translate the information in a comprehensible manner to the user by touch and sound. The validation of our test users illustrated a good outcome albeit at the preliminary stage. The POI was clearly located and the travelling test user was able to move around the POIs. Future test users that are blind and visually impaired should be invited in the future as an extension of this project, and more importantly, we are able to make the user experience improvement based on the feedback from these users, such that the user experience, technology implementation, and user interface can be better combined for a comprehensive experience. This research is a stepping stone for the further development of indoor wayfinding systems adopted for the blind.

CHAPTER 7 FUTURE STUDY

Adopting IndoorGML

Currently, as other options are outside of the scope of this project, the majority of the data ended up being stored in ArcGIS Online. Although this has done the job that was required for the project, there are standardised methods (important for the interoperability of geospatial data) of storing the 3D data that could possibly even be used in conjunction with ArcGIS Indoors to create a proper data model for indoor navigation.

The (digital) modelling and mapping of indoor spaces is a relatively young industry, however, it is one that is growing rapidly. The rise in popularity of concepts involving the digitisation of the physical world, and the subsequent technologies are probably what has given rise to this trend. To create any navigation system, an environmental model is required. For example, there is CityGML, which is an open standardised data model and exchange format to store digital 3D models of urban areas. In addition, there is a more indoors-focused format known as IndoorGML that is created. '(IndoorGML) is a promising standard for indoor navigation, since it has the potential to include both information about high-level building structure and individual object localisation. [...] However, such a data model often lacks the information essential for the navigation, eg. path traversability or room entrance permissions.' (Trybała & Gattner, 2021).

In order to create an Indoor Positioning/Navigation System model, data involving the floor plans is required to proceed further. Additionally, the creation of such models is not currently an automated process (if they do not already exist). This in itself could be another area of research. However, it is possible to create a topological model of a building based on simple floor plans stored in CAD files. This topological model will be the foundation of an Indoor Positioning System (IPS). The ArcGIS Indoors Information Model will help in managing the data surrounding interior spaces and, as explored within the project, it can convert data from the CAD file to ArcGIS Indoors geo-database layers.

As seen in this project, it is evident that by using ArcGIS Indoors, one is able to create an indoor information model, following the hierarchy and structure provided by Esri. Given that the project was only focusing on one level, the group was unable to display the topological connectedness between floors, however, it is displayed between rooms. Potential future studies/projects could maybe focus on creating this sort of 3D / Multi-Level topological connectedness of rooms. A second possible area of future study could be focused on finding a way to implement the IndoorGML data model through the attributes of features within the ArcGIS Indoors Model, this may not be directly oriented towards blind or visually impaired people initially, but is an advancement that will enable better systems to be created in order to aid people with disabilities.

Mobile device limitations

This research does make use of LiDAR scanning available on the newest iPhone devices. (Morris & Mueller, 2014) suggests that most blind people equip an iPhone device since it has the best audio support for blind people. Still, other mobile phones are excluded from this research. It is worth mentioning that older iPhones are not yet equipped with LiDAR feature. Therefore it does exclude the target group in usability. However, this report showcases the potential for the future.

Scale of the project

The scale of the project is kept small and manageable. A corridor within the Faculty of Building and Architecture is used so that the project size can be made within the time constraints. The fact that the previous synthesis project group has explored the East wing of the building means there is previous knowledge of this area, and the project can be built on top of previous references by Dardavesis (2022). This report took advantage of the existing data in the ArcGIS Online platform and enriched new data to the platform in order to establish a continuation of the previous project. The scale of this project is, therefore, focus on the first floor of the building on the East wing. This report showcases the possibility to rescale this procedure to other indoor environments.

Indoor localisation point matching improvement

This report adopts the concept developed by (Dardavesis, 2022). His report takes into account the static ceiling point cloud data to measure the position of the user within the room. The user point cloud will be matched accordingly to the room the person is in. The ceiling contains a specific configuration of point clouds for each room. This report focuses on the available navigable walkable spaces, therefore the scans were switched to eye level. The user scans of this report were taken as selfies" with 360 degrees around them. The reason was to be able to firstly, capture the height of the person standing in the room and secondly, capture the direction of the arm of the person. Unfortunately, the reach of LiDAR scanning by iPhone 13 still has a limitation of having a reach of approximately five metres (Zaczek-Peplinska & Kowalska, 2022). The point cloud matching didn't work in every situation especially in the case that the configuration of tables changed. In future research, the ceilings need to be captured within the user selfie scans to be able to match the position of the user within the room. For further research, the quality of the LiDAR scanning needed to be improved to capture the room more completely (Fig 7.1).

User interface correspondence with target group

Right now the validation process did measure the usability of the tactile map with the user interface implementation for blind people. As already mentioned, this research simulated the preferred target group. In order to really validate the study, a statistically approved amount to blind people have to test the interoperability between the tactile map and the user interface to really qualify the usability.

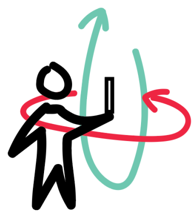


Figure 7.1: New user selfie scan proposal (also considering the ceiling (green) as static point cloud data)

App Implementation

In order to improve the usability of indoor localisation for the user, an integrated app would be an end-product. At the moment the project is mainly split into two parts, the point cloud and raster processing and the ArcGIS and database queries. Ideally, these two sides of the project are combined seamlessly into an app that allows for scans, point cloud matching, and room navigation, with TTS capabilities. There is the possibility of using ArcGIS Indoors on the iPhone to have a map with navigation features. Unfortunately, it will not be possible to have the point cloud matching in the base ArcGIS app.

It is possible, however, to use Esri's developer tools to integrate the maps and data from ArcGIS Online with other codes in order to create an app with all the features desired. This was not feasible within the given time frame but could be the next step.

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APPENDIX A
SWOT ANALYSIS ON EXISTING APPLICATIONS

The SWOT analysis considers the following criteria:

- **Equipment/sustainability:** does the application need extra equipment next to a mobile phone? Equipment must be purchased, maintained and sometimes even replaced, which would lead to extra costs and a less sustainable solution.
- **Equipment/interior:** does the application need equipment that affects the interior of buildings? This criteria is especially important in monumental buildings.
- **Equipment/usability:** do the users need equipment next to their mobile phone? The less material is needed, the more user-friendly the application is.
- **Preparation/sustainability:** is there any preparation needed before being able to use the application (e.g. indoor scan of the building)? The application might be more sustainable without preparation (e.g. a new reference scan must be made when a building has to be renovated). Avoiding preliminary work will also reduce costs.
- **Applicability:** is the application applicable in every indoor environment?
- **Costs:** as mentioned before, equipment and preliminary work will lead to more costs. Also, the application itself is not always available for free. What is the estimated cost of the application (for free, low-cost, affordable, expensive)?
- **Real-time information:** does the application provide real-time information? What is the use of these data (localisation, navigation, object recognition)? Accuracy: does the application give accurate information to the user?
- **Usability/communication:** is the application user-friendly? Which kind of communication techniques are used?
- **Usability/target group:** for which target group is the application designed? Compatibility: is the application both available on Apple and Android?

Application	Description	Strengths	Weakness	Opportunities	Threats
eZwayZ [1]	This application is able to determine the position of the user and allows the user to navigate in the indoor environment. The app uses a pointcloud matching algorithm, in combination with Virtual Reality and 360° photography. Therefore, a reference scan of the indoor environment is needed. The users can scan their environment with their mobile phone to determine their position and from there, a route description is generated. To communicate this information to the user, voice-over and vibrations are used.	• No extra equipment is needed inside the building • Users do not need extra equipment next to their mobile phone No extra costs due to equipment acquisition and/or maintenance • Real-time localisation and itinerary information is provided to the user for navigation purposes • The information given to the users is accurate enough to be able to navigate to their intended destination. • The application is user-friendly for the visually impaired. Voice-over and vibrations are used to communicate the necessary information to the user, together with yellow lines displaying the itinerary on the screen of their mobile phone. • Voice-over and vibrations are used to provide information to the user. As mentioned in section 3.1, these communication tools are appreciated by the blind.	• An indoor scan of the building needs to be done before being able to use the application • The application cannot be used directly: a reference indoor scan is required • The application displays yellow icons representing facilities and yellow lines representing the itinerary within the building. This method is a very user-friendly way to indicate the route and facilities to the visually impaired, but less suitable for the blind.	• The application gives real-time and accurate localisation information to the user by using pointcloud matching. This method is interesting due to the high quality information provided to the user and will be taken into account during the project. • Users are continuously walking with their mobile phone in their hands to scan the environment. The scans are displayed on the screen, together with the itinerary line. This method is also very interesting, but not for the blind. However, scanning the environment while walking can be used to verify if the users are at the correct location while navigating.	• A part of the interface is displaying necessary information to the user, which is not suitable for the blind.

Application	Description	Strengths	Weakness	Opportunities	Threats
NaviLens [2]	This application describes objects (products and facilities) in the surrounding environment. Therefore, large QR codes are placed near these objects. Users can scan these QR codes and hear the information about the objects via voice-over.	• Users do not need extra equipment next to their mobile phone • Using QR codes is a relatively sustainable solution. They are not complex and only consist of paper and ink (with eventually extra materials to optimise the design). • The production costs of QR codes are not very expensive due to their simplicity, which usually lead to lower acquisition costs. • The application is able to provide context related real-time information (e.g. available facilities and objects around the user) • Users do not necessarily need the information or visualisations displayed on their screen. Voice-over is used to communicate the information to the user. • Voice-over is used to provide information to the user. As mentioned in section 3.1, this communication tool is appreciated by the blind. • This application is compatible with Android and Apple, and free of charge.	• QR codes are posted on visible places, such as walls. These might affect the interior of the building. • QR codes need to be put up. The QR codes might not be too expensive, but there might be some labour costs. • The application cannot be used directly: QR codes are required • The application provides real-time information, but not accurate information. The user can scan the QR codes from a distance of 20 m. This means that accurate localisation information cannot be provided using this method. • Large QR codes are easier to find for the visually impaired. However, they are still difficult to identify for the blind.	• QR codes might be used to identify objects or facilities in the surrounding environment of the user.	• As stated in the fourth point of the weaknesses, using QR codes for localisation (and also navigation) purposes for the blind is not the most suitable solution due to the large scanning range.

Application	**Description**	**Strengths**	**Weakness**	**Opportunities**	**Threats**
Speechlabel [3]	This application allows users to scan labels and hear information about the products on which the labels are attached via voice-over. It works with products from the grocery, and also with personal items. Users can buy labels, attach them and connect them with a description via the app.	• Users do not need extra equipment next to their mobile phone • Using labels is a relatively sustainable solution. They are not complex and only consist of paper and ink (with eventually extra materials to optimise the design) or are already on the products from groceries. • The production costs of labels are not very expensive due to their simplicity, which usually lead to lower acquisition costs. • The application is able to provide context related real-time information (e.g. objects around the user) • Users do not necessarily need the information or visualisations displayed on their screen. Voice-over is used to communicate the information to the user. • Voice-over is used to provide information to the user. As mentioned in section 3.1, this communication tool is appreciated by the blind. • This application is compatible with Android and Apple, and free of charge.	• Attaching labels to objects requires a lot of work • The application cannot be used directly: labels are required • Finding the labels on objects might be challenging for the user	• Labels might be used to identify objects or facilities in the surrounding environment of the user.	• This application is more designed for object identification than localisation or navigation purposes.

Application	Description	Strengths	Weakness	Opportunities	Threats
Seeing AI [4]	This application recognises text, colours, objects and light strength through AI and describes them to the user. Users can scan what they are facing and the information will be transmitted via voice-over.	• No extra equipment is needed inside the building • Users do not need extra equipment next to their mobile phone • No extra costs due to equipment acquisition and/or maintenance • No preparation is needed before the application can be used • The user can directly use the application in every indoor environment • Acquisition costs are low: no preparation and/or equipment costs • This application is compatible with Apple, and free of charge. • This application provides real-time and accurate information to the user for object and text identification • Voice-over is used to provide information to the user. As mentioned in section 3.1, this communication tool is appreciated by the blind. • This application is designed for the visually impaired and blind.	• The identification time is dependent on the network connection. • This application is not compatible with Android	• This application could be used to identify marking-points • This application could be used to read indication boards, which could give an indication to the users if they are in the right direction.	• This application is designed for object identification, and not for localisation or navigation purposes.

Application	**Description**	**Strengths**	**Weakness**	**Opportunities**	**Threats**
Lookout: Assisted Vision [5]	This application recognises products (from grocery stores), text, valuta and objects through AI and describes them to the user. Users can scan what they are facing and the information will be transmitted via voice-over.	• No extra equipment is needed inside the building • Users do not need extra equipment next to their mobile phone • No extra costs due to equipment acquisition and/or maintenance • No preparation is needed before the application can be used • The user can directly use the application in every indoor environment • Acquisition costs are low: no preparation and/or equipment costs • This application is compatible with Android, and free of charge. • This application provides real-time and accurate information to the user for object and text identification • Voice-over is used to provide information to the user. As mentioned in section 3.1, this communication tool is appreciated by the blind. • This application is designed for the visually impaired and blind.	• The identification time is dependent on the network connection. • This application is not compatible with Apple	• This application could be used to identify marking-points • This application could be used to read indication boards, which could give an indication to the users if they are in the right direction. • Could be used to give information about the rooms (e.g. function, number of tables or doors)	• This application is designed for object and text identification, and not for localisation or navigation purposes.

Application	Description	Strengths	Weakness	Opportunities	Threats
Envision AI [6]	This application recognises surrounding objects, text and even faces through AI and describes them to the user. Users can scan what they are facing and the information is transmitted via voice-over. Envision AI also provides glasses that have the same functions and allow users to be hands-free. However, they are quite expensive compared to the application that is available for free.	• No extra equipment is needed inside the building • Users do not need extra equipment next to their mobile phone • There is also a possibility to use envision glasses instead of the application, which is even more user-friendly, but costs around € 2.500,00. The glasses are not taken into account in this project because the focus lies on the development of an application. • No extra costs due to equipment acquisition and/or maintenance • No preparation is needed before the application can be used • The user can directly use the application in every indoor environment • Acquisition costs are low: no preparation and/or equipment costs • This application is compatible with Android and Apple, and free of charge. • This application provides real-time and accurate information to the user for object, text and face identification • Voice-over is used to provide information to the user. As mentioned in section 3.1, this communication tool is appreciated by the blind. • This application is designed for the visually impaired and blind.	• The identification time is dependent on the network connection.	• This application could be used to identify marking-points • This application could be used to read indication boards, which could give an indication to the users if they are in the right direction. • This application could be used to give information about the occupancy of a room	• This application is designed for object, face and text identification, and not for localisation or navigation purposes.

Application	Description	Strengths	Weakness	Opportunities	Threats
TapTapSee [7]	This application identifies surrounding objects through AI and describes them to the user. Users can scan what they are facing and the information is transmitted via voice-over.	• No extra equipment is needed inside the building • Users do not need extra equipment next to their mobile phone • No extra costs due to equipment acquisition and/or maintenance • No preparation is needed before the application can be used • The user can directly use the application in every indoor environment • Acquisition costs are low: no preparation and/or equipment costs • This application is compatible with Android and Apple, and free of charge. • This application provides real-time and accurate information to the user for object and text identification • Voice-over is used to provide information to the user. As mentioned in section 3.1, this communication tool is appreciated by the blind. • This application is designed for the visually impaired and blind.	• The identification time is dependent on the network connection.	• This application could be used to identify marking-points • This application could be used to read indication boards, which could give an indication to the users if they are in the right direction. • This application could be used to give information about the occupancy of a room	• This application is designed for object, face and text identification, and not for localisation or navigation purposes.

Application	Description	Strengths	Weakness	Opportunities	Threats
Lazarillo [8]	The app allows users to determine their position and navigate in out- and indoor environments. Outside, the app uses GPS, inside it uses Bluetooth Beacons. The app provides information about their location (e.g. facilities in the area) and gives route descriptions to the user via voice-over.	• Bluetooth Beacons are needed for indoor positioning, which are small and do not affect too much the interior of the building • Bluetooth Beacons are easy to install, require low maintenance and do not need electronic connections • Users do not need extra equipment next to their mobile phone • Acquisition costs are affordable for large organisations. • This application provides real-time and accurate information to the user for object identification, positioning and navigation. • This application is compatible with Android and Apple, and free of charge. • Voice-over is used to provide information to the user. As mentioned in section 3.1, this communication tool is appreciated by the blind. • This application is designed for the visually impaired and blind. • This application is not only for indoor positioning, but also for outdoor positioning. The indoor and outdoor environments are connected to each other. • This application is also used for object identification	• Bluetooth Beacons needs to be installed before being able to use the application • The application cannot be used directly: Bluetooth Beacons are required • Acquisition costs might be expensive for private use.	• Bluetooth Beacons are interesting for this project. Their specifications are beneficial: small, accurate, and low in maintenance.	• Bluetooth Beacons need to be purchased

Application	Description	Strengths	Weakness	Opportunities	Threats
Be my eyes [9]	This application allows users to video call volunteers to ask them for help in identifying the objects they are facing and navigating.	• No extra equipment is needed inside the building • Users do not need extra equipment next to their mobile phone • No extra costs due to equipment acquisition and/or maintenance • No preparation is needed before the application can be used • Involving volunteers leads to social talk and maybe even new relations, which is very valuable. • This application is compatible with Android and Apple, and free of charge. • This application provides real-time information to the users on their surrounding environment, objects and documents. • This application is designed for the visually impaired and blind.	• Volunteers must be available to be able to use this application	• Opportunity for volunteers to contribute to this project for the blind to see	• One of the objectives is to create more autonomy for the visually impaired and blind. Involving volunteers will not contribute to that.

[1]https://eZwayZ.com
[2]https://www.navilens.com/en/
[3]https://speechlabel.com/en
[4]https://www.microsoft.com/en-us/ai/seeing-ai
[5]https://play.google.com/store/apps/details?id=com.google.android.apps.accessibility.revealhl=en$_U Sgl = US$
[6]https://www.letsenvision.com/
[7]https://taptapseeapp.com/
[8]https://lazarillo.app/
[9]https://www.bemyeyes.com/

APPENDIX B

PROJECT ORGANISATION

B.0.1 Contributions and Responsibilities

Table B.1. shows the roles and responsibilities for each member. At the beginning of the project, the tasks were divided by strength and interest of the team members and presented in the Project Initiation Document (PID). The roles have slightly changed during the project.

Each week a meeting was organised with the supervisors and the client. To ensure equal responsibilities, members took turns presenting the results achieved so far and taking notes.

Team member	Role
Leo Kan	Data acquisition manager, coding, presentation
Louis Dechamps	ArcGIS manager, coding, tactile map
Maren Hengelmolen	Technical manager, coding, tactile map
Yue Yang	Technical manager, coding, tactile map
Marieke van Esch	Project manager, coding, presentation

Table B.1: Roles of each team member

In addition to the specific role which is related to the responsibility, several tasks following were spread within the team members as equal as it could be:

- data acquisition
- pre-processing LiDAR data to extract floor maps

- matching algorithm from user point cloud to reference point cloud
- ArcGIS implementation
- user interface (tactile map, audio and demo)
- user testing and validation
- writing on the final report

Colleague	Role	Task
Edward Verbree	Consulting role	Consulting role for the whole project process and content
Niels van der Vaart	Consulting role software	Consulting for the use of ArcGIS pro and ArcGIS Indoors
Vincent van Altena	Consulting role	Consulting role
Ellen Zieleman	Consulting role for visually impaired people perception	Consulting role if we have questions about the perception of visually impaired people
Ioannis Dardavesis	Consulting role and supplier for detection of the indoor environment	Consulting role for process and supplier of point cloud matching algorithm

Table B.2: Major contribution and responsibilities of each supervisor and client

B.0.2 Contributions and Responsibilities

Meetings

The group kept record of the availability of each team member. Therefore, two Whatsapp groups were made: one with only the team members, and another one with E. Verbree included. Also, the group was making use of an availability schedule in Google Document shared in Drive.

The following weekly meetings were planned:

- Group meetings on Monday afternoon, Tuesday morning, and Friday morning
- Meetings with supervisors and/or client on Wednesday morning at 9 am

The group tried to meet as much as possible at the faculty of Architecture in Delft. In the case meetings in person were not possible, Zoom or Microsoft Teams were used.

Content

To share documents and work together, the team used the following platforms:

- Drive was the main platform and was mainly used to share documents (e.g. PID, weekly presentations) and data (e.g. pointclouds, raster files)

- Github was used to share Python codes

- Overleaf was used to write the final PID and report

B.0.3 Time management

When creating the time schedule, some issues have already been taken into account. But there are still some unexpected problems, which leads to the fact that some tasks took more time than expected, such as the licence of ArcGIS Indoors which is different from the regular ArcGIS Pro licence, lidar data collected which is not accurate enough and supplementary collection is needed, unexpected technical issues when setting up arduino module.

The first version of the timeline was before the midterm, and different phases within our research were basically completed based on the work plan per week. However, because of the issues mentioned above, the timeline was adapted a bit to the second version that ensured the realisation of the project completion. All aspects of the project have been worked on collaboratively with the whole team. However due to the amount of work, different couples of persons were divided into groups working on the target tasks. In the Gantt Diagram our task division is shown in a more visually appealing way, see fig .

		Lead team member	1	37	38	39	40	41	42	43	44	45
		Week no.	1	2	3	4	5	6	7	8	9	10
Work Package (WP) / Deliverable (D)/ Task (T)												
WP1	**Literature review**											
T1.1	Data literature	all										
T1.2	Previous projects	all										
WP2	**Data acquisition**											
T2.1	Lidar data	1,3,4,5										
WP3	**Data processing**											
T3.1	Data Processing Lidar	1,2,3,4,5										
T3.2	Point cloud reference matching	1,3,4,5										
T3.3	Data Processing ArcGIS	2,5										
T3.4	User interface (tactile map, audio and demo)	all										
WP4	**Dissemination /communication**											
D4.1	Presentation preparation											
D4.0	Reporting	all				PID		Mid-term				Geo day
T4.1	Meetings	all										
WP5	**Management /Coordination**											
	Coordination	Take turns										

Legend
Deliverables
Activity

Team member nr.:
1. Leo Kan:
2. Louis Dechamps
3. Maren Hengelmolen
4. Yue Yang
5. Marieke van Esch

B.0.4 Related courses

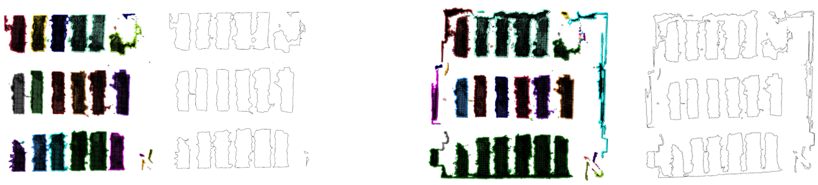
The synthesis project was completed in the first quarter of the second year of the master Geomatics at the TU Delft. Knowledge from courses given in the first year is integrated into the synthesis project.

- GEO1001 Sensing Technologies: acquisition methods of 3D pointclouds
- GEO1002 GIS and Cartography: data representation and A* star algorithm
- GEO1000 Python Programming for Geomatics: programming in Python
- GEO1006 Geo Database management Systems: databases, semantics
- GEO1015 Digital terrain modelling: extracting walkable spaces from 3D point clouds and point cloud matching algorithm
- GEO1003 Positioning and Location awareness: location and context awareness, indoor location and navigation
- GEO1007 Geo-web Technology

APPENDIX C

BOUNDARY EXTRACTION USING ALPHA-SHAPE ALGORITHM

In order to find the concave hull containing a set of points, alpha-shape algorithm is used. The collected point cloud is filtered according to the height constraints, and the point cloud near the table height is obtained. One more thing to mention is that the point clouds filtered are both with and without walls, and are processed parallel in the steps followed, taken room C as an example (Figure C.1). This makes it easier to determine the global location of extracted tables in the indoor environment when using the output file generated from the point cloud with walls. Then the point cloud is reprojected on the same level for the boundary extraction. After obtaining the pre-processed point cloud, an alpha-shape algorithm is used to extract the scene from the point cloud. The output file is saved as a svg file, and further converted to autoCAD format.



(a) (b)

Figure C.1: (a) Extracted CAD file without wall (b) Extracted CAD file with wall

In this approach, the parameters of alpha-shape are adjusted to find the optimal one. It's worth noting that nearby tables are joined together as the parameter increases, while a single table is split as the parameter decreases. However, the algorithm still has limits in this project, and there are still some problems to be solved. One is that there are some duplicated lines in the generated files. Cleanup of the file is performed in Rhinoceros using the command SelDupAll. This can be further improved to enable automatic cleanup. Another problem is that the extracted table outlines are not ideal straight lines. One reason for this is outliers, but also the limitations of the algorithm itself. The final output provides an approximate layout of the static objects in the room and will be imported into ArcGIS as a reference.

APPENDIX D

AUDIO INSTRUCTIONS

Voice instructions made by Ellen Zielenman 25-10-2022

Hi everybody. My name is Ellen and I am blind. I would like to give you some tips and tricks for the exercise to navigate as a blind person. Soon you will be blindfolded and you will receive a stick or an umbrella and in this way you will navigate. It is important to place the stick in your right hand and by taking each step you have to touch with the stick in a stroke pattern, from left to right and from right to left in order to perceive inequalities in pavement or encountering obstacles. If you are navigating with sound, it is important to listen to the full recording with the steps. If you don't do this, it can happen that you miss a step in the direction while walking. When you are walking your mind could be occupied with the walking instead of having full attention to the instructions. Next to using your stick you could make use of other senses like your ears: what do you hear? Are you walking towards the sound or not? You could also use your sense of smell: do I encounter a coffee machine for example. This could be a clue of a point of recognition or a landmark. What is handy if you are within or encountering a room. You have to detect the door opening and the wall attached to it. In this way you can immediately encounter if there are plants available or closets or tables. You could also ask if there are people present within the room. If this is not applicable in your application you can just ask this. I hope I have informed you enough for this exercise and I wish you the best of luck! Kind regards, Ellen.

APPENDIX E

QUESTIONNAIRE VALIDATION

Questionnaire

1. User on the go system is simple to use
   (1 = difficult, 5 = simple)
   1 2 3 4 5

2. The information that is given is relevant to my needs
   (1 = not-relevant, 5 = relevant)
   1 2 3 4 5

3. I have an understanding of the function of the room (context awareness)
   (1 = good understanding, 5 = no understanding)
   1 2 3 4 5

4. It is easy to follow the descriptions
   (1 = difficult, 5 = easy)
   1 2 3 4 5

5. It is efficient in terms of time required to find my destination
   (1 = not-efficient, 5 = efficient)
   1 2 3 4 5

6. It is efficient and I feel confident with finding my way with this application
   (1 = not-confident, 5 = confident)
   1 2 3 4 5

7. Overall I liked the system
   (1 = I dislike it , 5 = I love it)
   1 2 3 4 5

8. User on the go system is simple to use
   (1 = difficult, 5 = simple)
   1 2 3 4 5

Results

Question	Results
1. User on the go system is simple to use	3.5
2. The information that is given is relevant to my needs	3.5
3. I have an understanding of the function of the room (context awareness)	3.5
4. It is easy to follow the descriptions	4
5. It is efficient in terms of time required to find my destination	3.5
6. It is efficient and I feel confident with finding my way with this application	3.5
7. Overall I liked the system	3.5

Table E.1: Questionnaire Results

APPENDIX F

PYTHON CODE

```python
# -------- POINT CLOUD MATCHING / A* ALGORITHM --------

from typing import Sequence
from cv2 import threshold
from matplotlib import colors
import numpy as np
from plyfile import PlyData, PlyElement
import open3d as o3d
import glob
import time
import copy
import sys
import os
from difflib import SequenceMatcher
from pathfinding.core.diagonal_movement import DiagonalMovement
from pathfinding.core.grid import Grid
from pathfinding.finder.a_star import AStarFinder



### 1. Pointcloud matching (code from Ioannis Dardavesis)
def display_inlier_outlier(cloud, ind):
    inlier_cloud = cloud.select_by_index(ind)
    outlier_cloud = cloud.select_by_index(ind, invert=True)
    print("Showing outliers (red) and inliers (gray): ")
    outlier_cloud.paint_uniform_color([1, 0, 0])
    inlier_cloud.paint_uniform_color([0.8, 0.8, 0.8])
    o3d.visualization.draw_geometries([inlier_cloud, outlier_cloud])

def draw_registration_result(source, target, transformation):
```

```python
    source_temp = copy.deepcopy(source)
    target_temp = copy.deepcopy(target)
    source_temp.transform(transformation)
    source_temp.paint_uniform_color([1, 0.706, 0])
    target_temp.paint_uniform_color([0, 0.651, 0.929])
    print(o3d.geometry.PointCloud.get_center(source_temp))
    print(o3d.geometry.PointCloud.get_center(target))
    o3d.visualization.draw_geometries([source_temp, target_temp])

def preparation(pc, voxel_size):
    """"Downsampling, normals,fpfh,inliers"""
    print(len(np.asarray(pc.points)))
    radius_normal = voxel_size * 1.5
    voxel_down_pcd = pc.voxel_down_sample(voxel_size)
    cl, ind = voxel_down_pcd.remove_statistical_outlier(nb_neighbors=30, std_ratio=1)
    plane_model, inliers = cl.segment_plane(distance_threshold=0.4, ransac_n=3, num_iterations=1000)
    [a, b, c, d] = plane_model
    inlier_cloud = cl.select_by_index(inliers)
    inlier_cloud.paint_uniform_color([1.0, 0, 0])
    outlier_cloud = cl.select_by_index(inliers, invert=True)
    outlier_cloud.estimate_normals(o3d.geometry.KDTreeSearchParamHybrid(radius=radius_normal,
                                                                      max_nn=50))
    radius_feature = voxel_size * 3
    pc_fpfh = o3d.pipelines.registration.compute_fpfh_feature(outlier_cloud,
    o3d.geometry.KDTreeSearchParamHybrid(radius=radius_feature, max_nn=100)) #radius_feature

    return pc, outlier_cloud, pc_fpfh

# GLOBAL REGISTRATION WITH RANSAC
def execute_global_registration(outlier_user, outlier_db, source_fpfh, target_fpfh, voxel_size):
    distance_threshold = voxel_size * 1.5
    result = o3d.pipelines.registration.registration_ransac_based_on_feature_matching(outlier_user,
    outlier_db, source_fpfh, target_fpfh, True, distance_threshold,
    o3d.pipelines.registration.TransformationEstimationPointToPoint(False), 3,
    [o3d.pipelines.registration.CorrespondenceCheckerBasedOnEdgeLength(0.9),
    o3d.pipelines.registration.CorrespondenceCheckerBasedOnDistance(distance_threshold)],
    o3d.pipelines.registration.RANSACConvergenceCriteria(100000, 0.999))
    return result

# COLORED ICP
def refine_registration(source, target, source_fpfh, target_fpfh, voxel_size):
    distance_threshold = voxel_size * 3
    voxel_radius = [0.1, 0.15, 0.2]
    max_iter = [15, 30, 50]
    for scale in range(3):
        iter = max_iter[scale]
        radius = voxel_radius[scale]
        source_down = source.voxel_down_sample(radius)
        target_down = target.voxel_down_sample(radius)
        source_down.estimate_normals(o3d.geometry.KDTreeSearchParamHybrid(radius=radius * 2,
        max_nn=30))
        target_down.estimate_normals(o3d.geometry.KDTreeSearchParamHybrid(radius=radius * 2,
        max_nn=30))
```

```python

        result = o3d.pipelines.registration.registration_colored_icp(
            source_down, target_down, radius, result_ransac.transformation,
            o3d.pipelines.registration.TransformationEstimationForColoredICP(),
            o3d.pipelines.registration.ICPConvergenceCriteria(relative_fitness=1e-6,
            relative_rmse=1e-6, max_iteration=iter))
    return result

def pointcloud_matching(user_scan):
    start = time.time()
    voxel_size = 0.15
    pcd_user = o3d.io.read_point_cloud('{}'.format(user_scan))
    pcd_user.estimate_normals(o3d.geometry.KDTreeSearchParamHybrid(radius=voxel_size * 2, max_nn=30))
    #voxel_size * 2
    pcd_user, outlier_user, source_fpfh = preparation(pcd_user, voxel_size)
    global result_ransac
    path = "C:/pythonProject/synthesisproject0/"
    all_files = glob.glob(path + "*.ply")
    fitness = {}
    for pc_db in all_files:
        pcd_db = o3d.io.read_point_cloud("{}".format(pc_db))
        pcd_db.estimate_normals(o3d.geometry.KDTreeSearchParamHybrid(radius=voxel_size * 2, max_nn=30))
        pcd_db, outlier_db, target_fpfh = preparation(pcd_db, voxel_size)
        result_ransac = execute_global_registration(outlier_user,
        outlier_db, source_fpfh, target_fpfh, voxel_size)
        pcd_user.paint_uniform_color([1, 0.706, 0])
        pcd_db.paint_uniform_color([0, 0.651, 0.929])
        result_icp = refine_registration(pcd_user, pcd_db, source_fpfh, target_fpfh, voxel_size)
        draw_registration_result(pcd_user, pcd_db, result_icp.transformation)
        print(result_icp)
        pc_db = pc_db.split('\\')
        pc_db_1 = pc_db[1].split('-')
        fitness[str(pc_db_1[0])] = result_icp.fitness
        max_key = max(fitness, key=fitness.get)
    print("Time elapsed: {:.4f}".format(time.time() - start))
    print(max_key)

    return max_key

### 2. A* algorithm
## 2.1. Route description
def west(next_x, next_y, Wx, Wy, Ex, Ey, Nx, Ny, Sx, Sy):
    if next_x == Wx and next_y == Wy:
        new_direction = "west"
        step = "forward"

    if next_x == Ex and next_y == Ey:
        new_direction = "east"
        step = "backwards"

    if next_x == Nx and next_y == Ny:
        new_direction = "north"
        step = "to the right"
```

```python

    if next_x == Sx and next_y == Sy:
        new_direction = "south"
        step = "to the left"

    return new_direction, step


def east(next_x, next_y, Wx, Wy, Ex, Ey, Nx, Ny, Sx, Sy):
    if next_x == Wx and next_y == Wy:
        new_direction = "west"
        step = "backwards"

    if next_x == Ex and next_y == Ey:
        new_direction = "east"
        step = "forward"

    if next_x == Nx and next_y == Ny:
        new_direction = "north"
        step = "to the left"

    if next_x == Sx and next_y == Sy:
        new_direction = "south"
        step = "to the right"

    return new_direction, step


def north(next_x, next_y, Wx, Wy, Ex, Ey, Nx, Ny, Sx, Sy):
    if next_x == Wx and next_y == Wy:
        new_direction = "west"
        step = "to the left"

    if next_x == Ex and next_y == Ey:
        new_direction = "east"
        step = "to the right"

    if next_x == Nx and next_y == Ny:
        new_direction = "north"
        step = "forward"

    if next_x == Sx and next_y == Sy:
        new_direction = "south"
        step = "backwards"

    return new_direction, step


def south(next_x, next_y, Wx, Wy, Ex, Ey, Nx, Ny, Sx, Sy):
    if next_x == Wx and next_y == Wy:
        new_direction = "west"
        step = "to the right"

```

```
    if next_x == Ex and next_y == Ey:
        new_direction = "east"
        step = "to the left"

    if next_x == Nx and next_y == Ny:
        new_direction = "north"
        step = "backwards"

    if next_x == Sx and next_y == Sy:
        new_direction = "south"
        step = "forward"

    return new_direction, step

def algorithm(direction, next_x, next_y, Wx, Wy, Ex, Ey, Nx, Ny, Sx, Sy):
    if direction == "west":
        new_direction, step = west(next_x, next_y, Wx, Wy, Ex, Ey, Nx, Ny, Sx, Sy)
    if direction == "east":
        new_direction, step = east(next_x, next_y, Wx, Wy, Ex, Ey, Nx, Ny, Sx, Sy)
    if direction == "north":
        new_direction, step = north(next_x, next_y, Wx, Wy, Ex, Ey, Nx, Ny, Sx, Sy)
    if direction == "south":
        new_direction, step = south(next_x, next_y, Wx, Wy, Ex, Ey, Nx, Ny, Sx, Sy)

    return new_direction, step

def route_description(steps):
    i = 0
    description = []
    for s in range(len(steps)):

        if s != 0 and steps[s] == steps[s-1] or s != (len(steps)-1) and steps[s] == steps[s+1]:
            i += 1
            tmp = steps[s]

            if steps[s] != steps[s+1]:
                d = "{} steps {}".format(s, steps[s])
                description.append(d)

        else:
            i=0
            d = "1 step {}".format(steps[s])
            description.append(d)

    return description

## 2.2. A* algorithm
def A_star(raster, correction, initial_direction):
    #Clean data
    arr = np.loadtxt(raster)
    arr = np.around(arr, 2)
    arr = arr + correction
    arr_obj = arr
```

```
    arr = np.rint(arr)
    #print(arr)

    arr.tolist()

    grid = Grid(matrix = arr)
    start = grid.node(0, 0)
    end = grid.node(0, 20)

    finder = AStarFinder(diagonal_movement = DiagonalMovement.never)
    path, runs = finder.find_path(start, end, grid)

    print('operations:', runs, 'path length:', len(path))
    print(grid.grid_str(path=path, start=start, end=end))
    print('Path:', path)

    steps = []
    direction = initial_direction

    for p in range(len(path)-1):
        x, y = path[p][0], path[p][1]
        next_x, next_y = path[p+1][0], path[p+1][1]

        Wx, Wy = x - 1, y
        Ex, Ey = x + 1, y
        Nx, Ny = x, y - 1
        Sx, Sy = x, y + 1

        new_direction, step = algorithm(direction, next_x, next_y, Wx, Wy, Ex, Ey, Nx, Ny, Sx, Sy)
        steps.append(step)

        x, y = next_x, next_y
        direction = new_direction

    #print(steps)
    itinerary = route_description(steps)
    print(itinerary)

if __name__ == "__main__":
    print('1. Pointcloud matching algorithm')
    user_scan = 'C:/pythonProject/synthesisproject0/venv/User_scans/RoomU_user.ply'
    matched_room = pointcloud_matching(user_scan)

    #print('2. A* algorithm')
    raster = "{}.txt".format(matched_room.split('.ply')[0])
    initial_direction = "east"
    correction = 1.35
    A_star(raster, correction, initial_direction)
```

```
# -------- QUERYING ARCGIS ONLINE -------

from arcgis.features import FeatureLayerCollection
```

```python
from arcgis.gis import GIS
from IPython.display import display
import pyttsx3
engine = pyttsx3.init()


print("ArcGIS Online as anonymous user")
gis = GIS()
print("Logged in as anonymous user to " + gis.properties.portalName)

items = gis.content.search('Indoors Pathways Prototype_WFL1',
item_type="Feature Layer", outside_org=True)
for item in items[:3]:
    display(item)

search_results = gis.content.search('title: Indoors Pathways Prototype_WFL1',
                                    'Feature Layer')
display(search_results[0])

synthesis_item = search_results[0]
synthesis_layers = synthesis_item.layers
display(synthesis_layers[3])
units_layer = synthesis_layers[3]
query_result1 = units_layer.query(where='LEVEL_ID=1')
query2 = units_layer.query(where="Level_ID=1")
synthesis_l1 = synthesis_layers[3]

# create feature set
synthesis_l1_fset = synthesis_l1.query(where = 'OBJECTID < 6')

# get features
synthesis_l1_features = synthesis_l1_fset.features

# display feature attributes
attributes = synthesis_l1_features[0].attributes

print(attributes["UNIT_ID"], "functions as a", attributes["USE_TYPE"])

# TTS read output
engine.say(attributes["UNIT_ID"]+" functions as a "+attributes["USE_TYPE"])
engine.runAndWait()
```

```python
# -------- VECTORIZING THE AVERAGE HEIGHT RASTERS -------


import PIL.Image as Image
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
import cv2


```

```
# txt to array
txt_array = np.loadtxt('data/roomU_raster_matrix.txt')

# replace array items according to height conditions
def arrayToimage(txt_array):
    # dataframe for check
    dataframe_txt_array = pd.DataFrame(data=txt_array)
    print('txt_array\n', dataframe_txt_array)

    data = txt_array
    height = -1.00625
    data[data > height] = 0 #black
    data[data <= height] = 255 #white

    # dataframe for check
    dataframe_new_img = pd.DataFrame(data=data)
    print('new_image\n', dataframe_new_img)
    return data


# data to binary image
def new_image(txt_array):
    data = arrayToimage(txt_array)

    new_image = Image.fromarray(data)
    plt.imshow(data, cmap=plt.cm.gray) #interpolation="nearest"
    new_image.show()

    if new_image.mode == "F":
        new_image = new_image.convert('L')
    new_image.save('data/new_image.jpeg', quality=95, subsampling=0)

    return new_image


# resize the image
def image_resize(txt_array):
    image = new_image(txt_array)

    titles = ['Original Image']
    images = [image]

    plt.imshow(images[0], 'gray')
    plt.xticks([])
    plt.yticks([])
    plt.savefig("data/resize.jpeg", dpi=300)
    plt.show()

    if ord("q") == (cv2.waitKey(0) & 0xFF):
        plt.close()
    return


```

```python
# vectorize the image
def vectorization(path):
    img = cv2.imread(path)
    (h, w) = img.shape[:2]
    hsv = cv2.cvtColor(img, cv2.COLOR_BGR2HSV)
    edged = cv2.Canny(hsv, 100, 200)
    contours, hierachy = cv2.findContours(edged, cv2.RETR_LIST, cv2.CHAIN_APPROX_NONE)

    idx = 0
    for c in contours:
        plt.plot(c[:, 0, 0], h - c[:, 0, 1], linewidth=2)
    plt.axis('off')
    plt.show()
    plt.savefig("data/vectorization.svg", format="svg")

    return 0


def main():
    image_resize(txt_array)

    path = 'data/resize.jpeg'
    vectorization(path)


if __name__=="__main__":
   main()
```

APPENDIX G

ARDUINO

The dynamic user representation was tested on the 3D printing model by using a small Arduino actuator (DC12V 5N Solenoid).

The open-source Arduino software (IDE) is used to compile the code, and the executed code is from controlling-a-solenoid-valve-with-arduino. The code can control the movement of the actuactor.

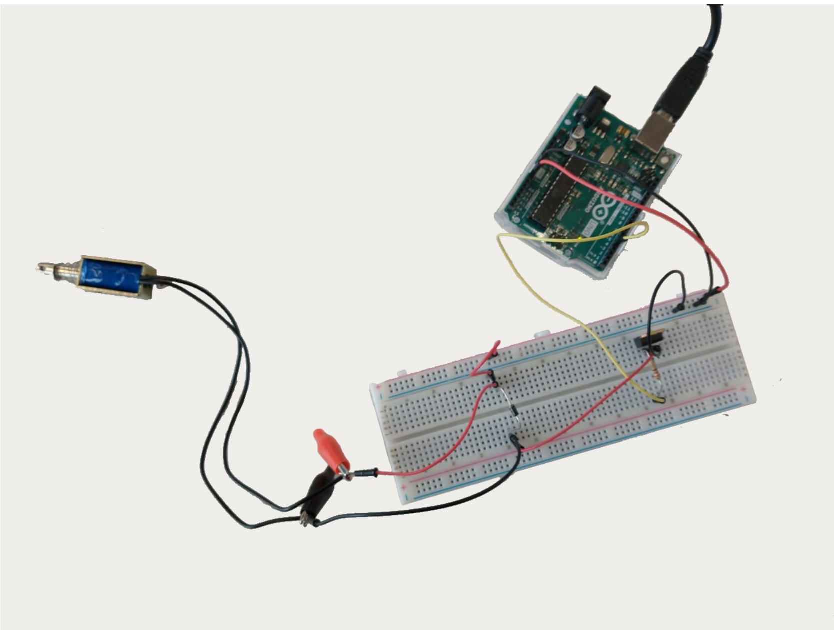


Figure G.1: Test setup Arduino

```
int solenoidPin = 4; //This is the output pin on the Arduino we are using

void setup() {
// put your setup code here, to run once:
pinMode(solenoidPin, OUTPUT); //Sets the pin as an output
}

void loop() {
// put your main code here, to run repeatedly:
digitalWrite(solenoidPin, HIGH); //Switch Solenoid ON
delay(1000); //Wait 1 Second
digitalWrite(solenoidPin, LOW); //Switch Solenoid OFF
delay(1000); //Wait 1 Second
}
```

Figure G.2: Arduino code from https://bc-robotics.com/tutorials/controlling-a-solenoid-valve-with-arduino/

Colophon

This document was typeset using LaTeX, using the KOMA-Script class `scrbook`. The main font is Palatino.