Laser Scanning for Emergency First Responders

Evaluating LiDAR Technology in Practice

MSc. Thesis

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Delft University of Technology

Laser Scanning for Emergency First Responders

Evaluating LiDAR Technology in Practice

by

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Cover: Point cloud image of an interior stairwell, acquired with a Zeb Revo RT scanner
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CGI

Abstract

Emergency Response organizations around the Netherlands increasingly use mobile LiDAR scanners (MLS) for tasks such as indoor navigation, 3D mapping, and data acquisition. This gives a compelling reason to investigate how MLS capabilities can be evaluated for indoor emergency response and how current MLS devices meet first responder needs.

In this integrated thesis for MSc. Geoscience-remote sensing and MSc. Communication Design for Innovation, two processes were developed: a technical workflow to evaluate point cloud quality, and an evidence-based theoretical method for comparing MLS capabilities to potential use case scenarios.

Six interviews and focus groups were conducted with first responders from the fire department and the national police to provide the necessary context on their experiences and needs. One relevant characteristic in the indoor emergency response context is the quality of MLS point cloud data. Using point cloud drift as a proxy for indoor point cloud quality, a workflow was established for quantifying the amount of drift in a point cloud. Point cloud data was acquired on the TU Delft campus with three MLS systems: an Intel L515, an iPhone 12 Pro, and a Zeb Revo RT. Applying the drift assessment workflow showed drift values between 0.4cm and 20cm per meter depending on the scanner, with average combined RMS values between 2cm and 12cm. Applying the workflow to additional data will strengthen the conclusions of this analysis.

Lastly, a novel, evidence-based methodology was developed to draw connections between LiDAR scanner attributes and values important to first responders. This methodology was then used to evaluate the suitability of a particular LiDAR scanner for a particular emergency response action. A Pugh Decision Matrix was then used to assess the capabilities of the three laser scanners and their suitability to different first responder use case scenarios. This analysis found that the Intel L515 scanner was the most suitable of the three for the use cases given by emergency first responders.

Summary

Emergency Response organizations around the Netherlands increasingly use mobile LiDAR scanners (MLS) for tasks such as indoor navigation, 3D mapping, and data acquisition. From a developer's perspective, this gives a compelling reason to investigate how MLS capabilities can be evaluated for indoor emergency response, and how current MLS devices meet first responder needs.

In this integrated thesis project for MSc. Geoscience-remote sensing and MSc. Communication Design for Innovation, the research goals were to (1) better understand how and why first responders use mobile laser scanners in their operations, (2) how LiDAR scanner capabilities can be evaluated for indoor emergency response, (3) how suitable current mobile laser scanning capabilities are, and (4) how developers can improve mobile LiDAR scanners to better support first responder operations. To address these topics, a design-based research approach was used, integrating qualitative methods (focus groups and interviews) with quantitative geodata processing methods. First, six interviews and focus groups plus an observational visit were conducted with first responders from the fire department and the national police to provide the necessary context on their experiences and needs.

Next, using point cloud drift as a proxy for indoor point cloud quality, a workflow was established for quantifying the amount of drift in a point cloud. Point cloud data was acquired on the TU Delft campus with three MLS systems: an Intel L515, an iPhone 12 Pro, and a Zeb Revo RT. Applying the drift assessment workflow showed drift values between 0.4cm and 20cm per meter depending on the scanner, with average combined RMS values between 2cm and 12cm and the iPhone 12 Pro having the highest drift at 20.2 centimeters per meter.

Then, a novel, evidence-based methodology grounded in value-sensitive design was developed to draw connections between LiDAR scanner attributes and values important to first responders. This methodology links LiDAR scanner attributes to the values important to first responder operations. These links were then used to evaluate the suitability of a particular LiDAR scanner for a particular emergency response action. This analysis found that the Intel L515 scanner was the most suitable of the three for the use cases given by emergency first responders.

Lastly, that same methodology was used to evaluate the LiDAR needs of police in a hypothetical scenario and turned into a guide that developers can use to consider first responder needs and desires more often in their process.

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Acronyms

BAG	Basisregistratie Addressen en Gebouwen (Register of Buildings and Addresses)	44
BIM	building information model	40
CDI	Communication Design for Innovation	vii
DFV	design for values	
DSI	dienst speciale interventies (special interventions team)	106
FOV	field of view	49
GCP	ground control point	44
GNSS	Global Navigation Satellite System	41
GRS	Geoscience-Remote Sensing	vii
IMU	inertial measurement unit	41
LiDAR	Light Detection and Ranging	1
MLS	mobile laser scanner	6
MP	megapixel	82
MCDM	multi-criteria decision making	98
PD	participatory design	13
PHT	probabilistic Hough transform	74
RGB	red, green, and blue	5
SLAM	simultaneous localization and mapping	41
TLS	terrestrial laser scanner	38
ToF	time-of-flight	4
VSD	value sensitive design	14

1

Introduction

Emergency Response organizations around the Netherlands are increasingly using LiDAR scanners for tasks such as 3D mapping and data acquisition. There are many available LiDAR options on the market, with their own strengths and weaknesses. However, these scanners are not developed with the needs of emergency first responders specifically in mind. This suggests that there are ways in which LiDAR tools could be designed to better support first responder needs. To find out how, it would help to better understand the way that emergency first responders use LiDAR in their work. It is also necessary to find a context-relevant way to evaluate the performance of LiDAR scanners. Addressing a complex, multilayered problem such as this one requires inter-disciplinary thinking and a multi-disciplinary approach.

At its core, the field of Communication Design for Innovation is about using communication theories and design methodologies to understand and solve complex problems. Usually these problems are a tangle of technological, societal, and other factors that make it difficult to solve with a one-size-fits-all solution or from within only one discipline. This is where the need for innovation comes in. Geoscience-Remote Sensing, and in particular the subfield of laser scanning / Light Detection and Ranging, is a constantly-developing technical discipline where new applications of Light Detection and Ranging (LiDAR) techniques are constantly being found, tested, or developed.

That said, technological innovation pursued purely in a technical context is not guaranteed to actually address or solve a particular problem. Solving complex problems often requires a mix of technical knowledge, technological innovation, and an understanding of the values, desires, and fears underlying the problem. Joining the perspective and approach of Communication Design for Innovation (CDI) with a problem in the field of Geoscience-Remote Sensing is a way to bring together the two disciplines and create something with both technical and broader societal value.

What follows is the written report for my joint M.Sc. thesis in the Communication Design for Innovation (CDI) track of the Science Education and Communication Master (Faculty of Applied Sciences), and the Geoscience-Remote Sensing (GRS) track of the Applied Earth Sciences Master (Faculty of Civil Engineering and Geosciences). This is an integrated thesis project, which means that the thesis topic incorporates topics and themes from both disciplines and employs methods of analysis and computation from both disciplines. This project was carried out in collaboration with the IT consulting firm CGI in its Rail Infrastructure division.

This introduction provides some basic background about The Dutch Emergency Response Context and Laser Scanning Principles, both of which are necessary to engage with the research topic. Then it presents the Research Objectives and Research Questions, and provides a Roadmap for the rest of the report.

1.1. The Dutch Emergency Response Context

1.1.1. National Safety and Security Structure

The Netherlands is divided into 25 security regions, each of which is responsible for overseeing the safety and security of residents and local visitors within its borders. The security region organizes the fire brigade and oversees disaster and crisis response operations, bringing together emergency services, governments, companies, and residents (Rijksoverheid.nl, 2022).

Aan deze afbeelding kunnen geen rechten worden ontleend.
Uitgave: Ministerie van Justitie en Veiligheid, november 2019.
Bron: Nederlands Instituut Publieke Veiligheid (NIVP).

Figure 1.1: Map showing the 25 security regions of the Netherlands, with the regions of interest (15 and 17) shown in the blue bounding box.

Figure 1.1 shows a map of the Netherlands divided into 25 security regions. The blue box indicates the two regions in which most first responders contacted for this research are working.

Figure 1.2 shows a schematic of the way that the security regions in the Netherlands are structured at the national and regional levels, including the roles and responsibilities of each entity within the structure.

1.1.2. First Responder Definition

A first responder is someone who is responsible for protecting people, property, and the environment in the early stages of a disaster or an accident (Prati & Pietrantoni, 2010). In the Netherlands, first responders are a combination of personnel from the fire brigade, the police department, and the relevant local municipalities, as well as paramedics **prati2010relation**; **dilo2011data**; **rijksrijksVeiligheidsregio**.

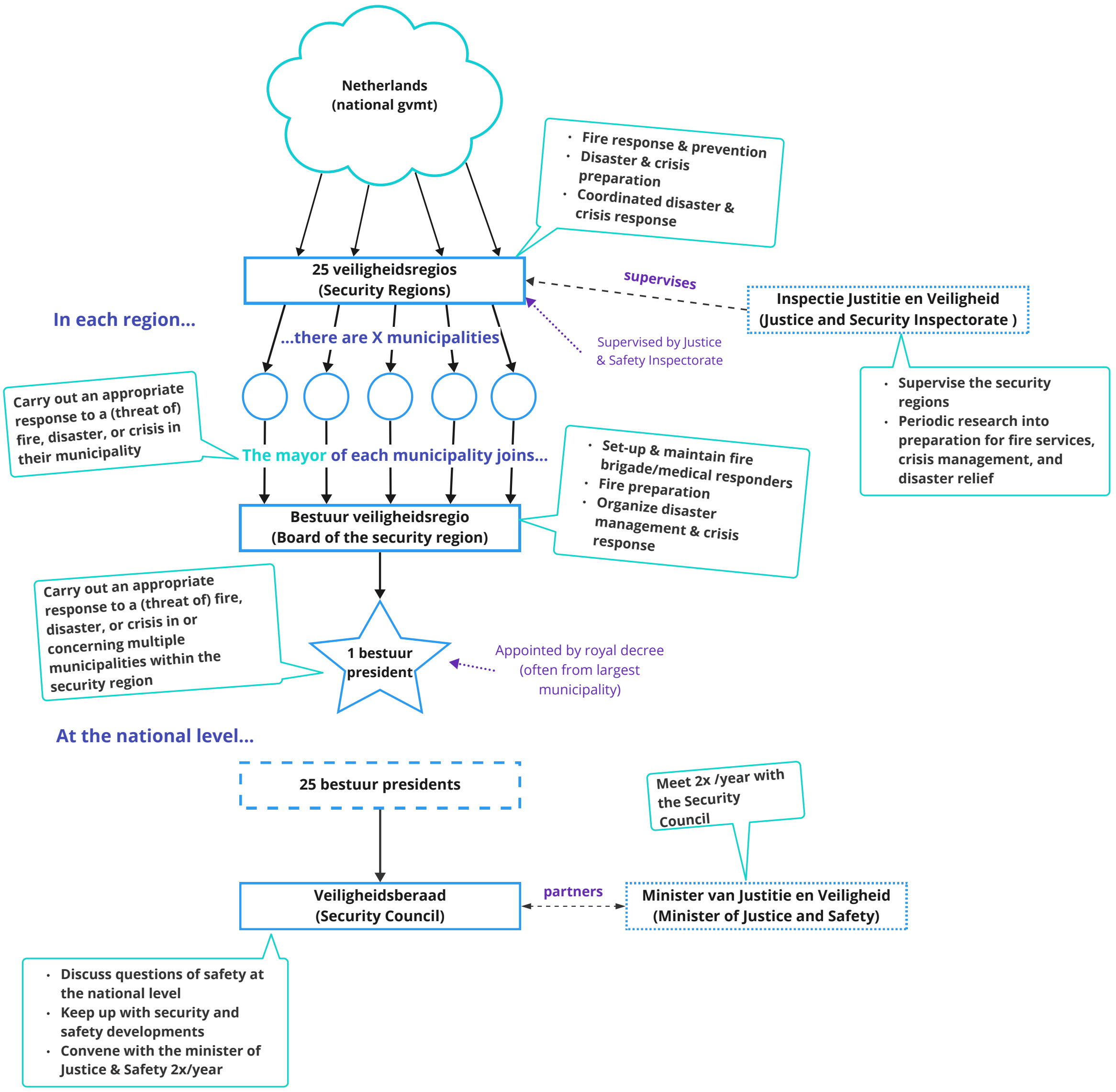


Figure 1.2: Graphic depicting the general structure of the safety governance landscape in the Netherlands, at both regional and national levels.

Based on the type of incident, several processes might be activated, each process involving one or more departments. Depending on the severity and scale of the incident (defined in the GRIP levels (Diehl et al. 2006)), more security regions, ministries or private and public organizations may be involved in the response process **dilo2011data**.

Although "first responders" are often referred to as a monolith in literature relating to technology use in the emergency response context, it can be helpful to consider them as separate groups originating from slightly different organizational contexts. Given that first responder organizations are dispatched differently depending on the type of incident, it is not difficult to imagine that they might also have different needs when it comes to using laser scanning technology in their emergency response actions. This thesis takes the fire brigade and the police department as its target groups within the first responder ecosystem, and touches on the scenarios in which these groups might use laser scanning technology in their typical emergency response actions. For the duration of this report, "first responder" thus refers specifically to police and fire department personnel. i has cheese

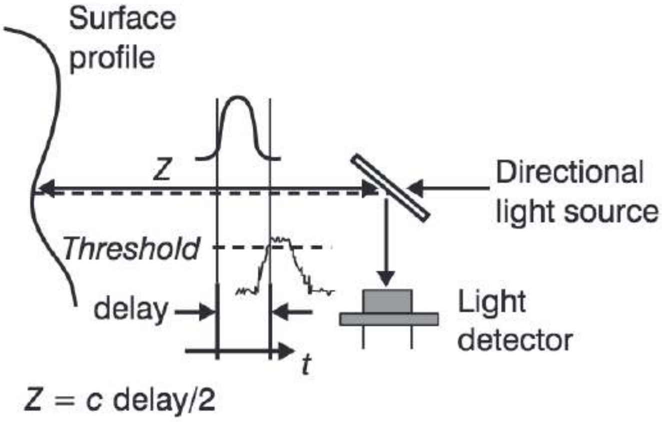


Figure 1.3: Schematic showing the mechanism of time-of-flight LiDAR. Source: Airborne and terrestrial laser scanning, pg. 3

1.2. Laser Scanning Principles

A laser scanner is a remote sensing instrument that produces non-contact measurements of visible, physical objects and spaces Sanchiz-Viel, Bretagne, Mouaddib, and Dassonvalle, 2021. Also known as Light Detection and Ranging (LiDAR), laser scanning uses light emitted in the visible or near-infrared wavelengths (between 400 and 2500 nanometers) Panel, 2008; Rees, 2013. These measurements consist of the geometry of said spaces and objects, but can also include other information such as color, texture, or light reflectance.

Laser scanners generally operate using one of two principles. Time-of-flight (ToF) uses active sensing technology to measure a 3D surface**J.-Angelo-Beraldin_FranÃğois-Blais_Uwe-Lohr_2011**. Triangulation, another optical 3D measurement technique, uses passive sensing technology to the same.

1.2.1. Time of Flight LiDAR

With time-of-flight measurement, also known as Light Detection and Ranging (LiDAR) measurement, the scanner sends a series of short light pulses to map the shape of an object, scene, or space. This principle, explained in its simplest form by Equation 1.1, uses the known values c (the speed of light) and τ (the time delay) to determine the distance from the scanner to the point being measured **J.-Angelo-Beraldin_FranÃğois-Blais_Uwe-Lohr_2011**. The constant n represents the correction factor for the refraction of the light waves as they travel through the air. For most the purposes this factor can be rounded down to a value of 1.

$$\rho = \frac{c}{n}\frac{\tau}{2} \tag{1.1}$$

The time delay represents the time it takes for the light pulse emitted from the laser scanner to travel to the surface it reflects off of and then travel back to the scanner. The range ρ is one half of the time delay and represents the distance between the scanner and the target. In this way, ToF LiDAR creates a 3D image of a surface by recording the distance and location of each reflective surface hit by the light pulses (see Figure 1.3).

1.2.2. Optical Triangulation

Optical Triangulation works by calculating the position of the reflective point based on the relative positions of the laser pulse-emitting source and the detector**J.-Angelo-Beraldin_FranÃğois-Blais_Uwe-Lohr_2011**. (Typically both are situated close to each other on the device.) Knowing the angle of light projection α, the angle of light collection β, and the distance B between the laser source and detector, it is possible to determine the point's distance from the scanning device in terms of (X,Z) coordinates (see Figure 1.4).

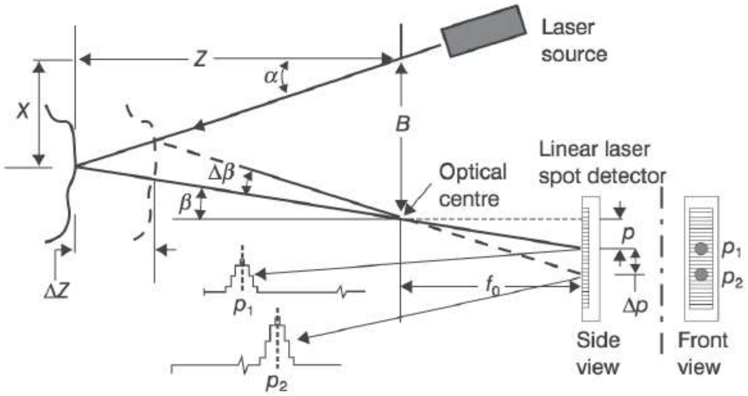


Figure 1.4: Schematic showing the mechanism of optical triangulation. Source: (**J.-Angelo-Beraldin_FranÃğois-Blais_Uwe-Lohr_2011**), pg. 9

(a) Point cloud colored by Z coordinate value

(b) XYZ coordinate points colored by RGB values

(c) XYZ coordinate points colored by Intensity values

Figure 1.5: Three modalities of a point cloud

Usually, systems designed for short ranges of less than 5m (for instance depth cameras such as the) use the optical triangulation principle **J.-Angelo-Beraldin_FranÃğois-Blais_Uwe-Lohr_2011**.

1.2.3. Point Clouds

The measurements captured by a laser scanner, either through ToF or triangulation methods, are usually represented as a point cloud. Point clouds consist of 3D (sometimes 2D) coordinate values (usually expressed in the 3D Cartesian coordinate system) called points Kutterer, 2011; Sanchiz-Viel et al., 2021. Each point represents a real position on the surface being scanned. The points can also include additional information collected by the laser scanner such as red, green, and blue (RGB) or intensity values, or information calculated later on such as normal values.

Figure 1.5 shows a segment of a point cloud that contains multiple properties. The first image shows the cloud as simple XYZ coordinate points. The second image shows the cloud with points colored by RGB values, approximating the true colors observed at the scene. The third image shows the cloud with points colored by intensity values.

1.3. Research Objectives

The aims of this research are to investigate and characterize how emergency first responders currently use LiDAR scanners on the job, to assess how LiDAR technology currently aligns with first responder needs, and to illustrate how developers can (re)design LiDAR technology to better support these needs.

add diagram here

The research objectives along with the Master's discipline they are related to are listed below:

1. Examine how and why first responders currently use LiDAR in their operations **[Part 1, CDI]**
2. Identify what function LiDAR scanners currently serve with respect to communication in the emergency first responder context **[Part 1, CDI]**

3. Develop a workflow to evaluate the quality of LiDAR data with respect to point cloud drift **[Part 2, GRS]**
4. Compare the quality of data from three different LiDAR scanners **[Part 2, GRS]**
5. Construct a method to assess how different LiDAR scanners currently align with first responder needs **[Part 3, CDI / GRS]**
6. Assess how well each LiDAR scanner and its data aligns with first responder needs **[Part 3, CDI / GRS]**
7. Assemble design criteria for creating a LiDAR scanner that would better support first responder needs **[Part 4, CDI]**
8. Infer how improved LiDAR scanners could better help support first responder communication **[Part 4, CDI]**

These research objectives run along two lines. One line focuses on the experiences of first responders related to their use of mobile laser scanners. This is primarily governed by the discipline of Communication Design for Innovation. The other focuses on how to evaluate the quality of mobile laser scanner (MLS) acquisition, data, and data processing as it relates to indoor emergency response. This is primarily governed by the discipline of Geoscience-Remote Sensing. These two lines run in tandem for much of the research process, and then intersect in order to apply the results of the MLS quality assessment to the specific first responder context of this study.

1.3.1. Project Scope

This research is focused on the first responder community within The Netherlands, specifically the fire department and the police. LiDAR devices of interest are limited to mobile laser scanners, although there is some mention of other devices. Likewise, the primary focus is indoor laser scanning, although some results related more to outdoor laser scanning scenarios.

Geographically, this research is centered on the regions of Haaglanden and Rotterdam-Rijnmond (regions number 15 and 17 in Figure 1.1, respectively), where Delft and Rotterdam are located. This is partially due to the fact that they house police and fire departments that are actively involved in innovation and who use or are beginning to use laser scanning technology within their operations.

1.4. Research Questions

Given the research theme and objectives described in section 1.3, the project is broken down into the following research questions and sub-questions:

1. Part 1: Why and how do first responder organizations currently use mobile laser scanning in their operations?
2. Part 2: How can LiDAR sensor, data processing, and data acquisition capabilities be evaluated for indoor emergency response?
    (a) Which metrics and/or point cloud characteristics are useful for assessing point cloud quality with respect to drift?
    (b) What is a suitable workflow for quantifying the drift error present within an interior point cloud?
    (c) How generalizable is that workflow to point clouds from different mobile laser scanners, and does the application of the method differ depending on which MLS system has produced the input point clouds?
    (d) Is there a difference in the amount of drift observed in point clouds from different mobile laser scanning systems?
3. Part 3: How do current mobile laser scanning capabilities measure up to first responder needs?
    (a) Which scanner characteristics are relevant to assessing their suitability for first responder needs?
    (b) How do the capabilities of different MLS systems compare to one another?

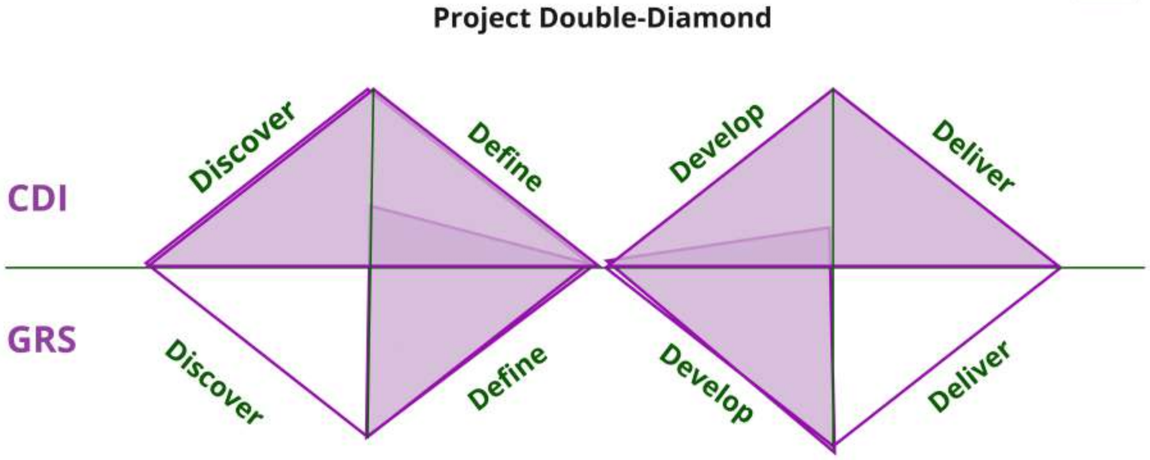


Figure 1.6: Double-diamond diagram illustrating the role that CDI and GRS disciplines play in this thesis project.

   (c) Which MLS system(s) is the best recommendation for the different first responder use cases?

4. Part 4: How can developers improve mobile LiDAR scanners to better support first responder operations during emergencies?

1.5. Approach and Methodology

This thesis takes a design-based research approach to evaluating mobile laser scanning in an emergency context. Design-based research is an educational research framework that switches between generating theory and applying it to a practical problem (Amiel & Reeves, 2008; Roberts & Dick, 2003).

This iterative research process is visualized with the double-diamond concept. There are four stages (Kochanowska & Gagliardi, 2022):

1. The **Discover** phase is exploratory, meant to observe users, understand their goals, and immerse in the problem context.
2. The **Define** phase organizes the findings and frames / adjusts the design challenge.
3. The **Develop** phase uses creativity to come up with different solutions and experiments for user needs, and tests them out.
4. The **Deliver** refines the developed solution with testing, iterations, and/or an implementation plan.

Figure 1.6 illustrates how the phases of this project fit into the double-diamond process. Because the Discover phase is expansive, the diagram diverges. This is where the goal of understanding first responder needs in Part I comes in. The Define phase converges back toward a midpoint in the process, with the goal now clear. This is where the CDI interviews and focus groups (Part I) and the GRS focus on evaluating point cloud drift (Part II) come in. The Develop phase diverges again in Part III, as the CDI and GRS disciplines combine to create an evaluation method for LiDAR scanners. Lastly, the diagram converges again in the Deliver phase. This is where, in Part IV, the methodology from part 3 is applied to give design recommendations to developers.

1.6. Roadmap

This report is structured as one cohesive document, but with four distinct parts that either address the Communication Design for Innovation (CDI) perspective, the Geoscience-Remote Sensing (GRS) perspective, or the integration of the two disciplines. Figure 1.7 visualizes this structure. Each part addresses a particular research question and includes a specific methodology used to arrive at the results for that question. Some of these results are then applied in subsequent parts of the thesis.

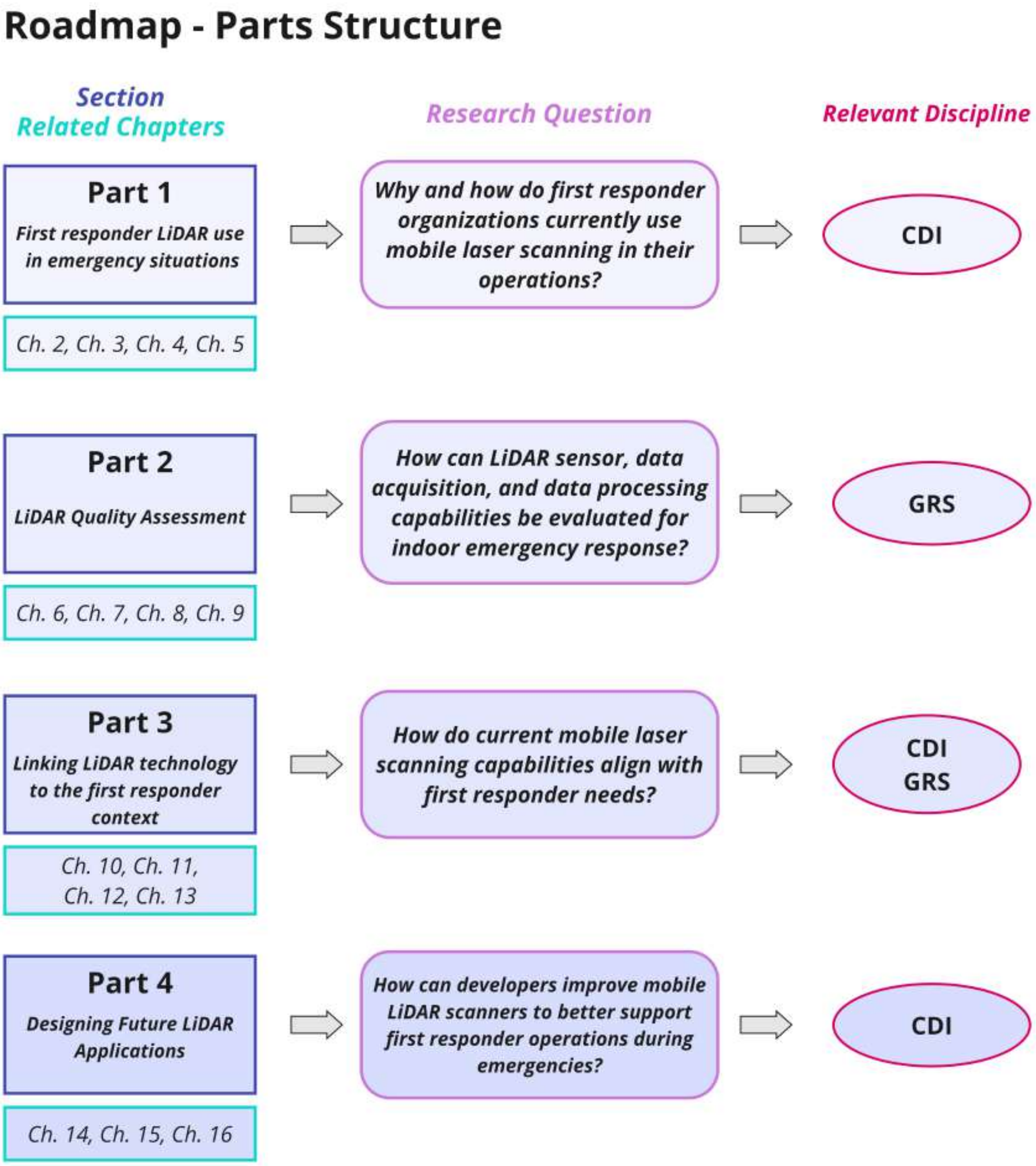


Figure 1.7: Roadmap showing the structure of the thesis report

As seen in Figure 1.7, each part contains multiple chapters and is linked to one or both Masters disciplines.

Part 1 is concerned with first responder LiDAR use in emergency situations.

Part 2 is concerned with a LiDAR quality assessment.

Part 3 is concerned with linking LiDAR scanning technology to the first responder context.

Part 4 is concerned with designing future LiDAR applications.

Lastly, Part V contains a set of integrated conclusions relating to each research question, future work for GRS, and a discussion section related to the overall project.

The overarching introduction, discussion, and conclusion chapters help to make it clear how the two disciplines fit together within the framework of the project. Both committees should read these sections. For the CDI committee, the whole report is being evaluated but some of the technical details within Part 2 may be of more limited interest. For the GRS committee, Part 2 and Part 3 are being evaluated, but Part 1 and Part 4 may be helpful for gaining a fuller understanding the integrated project context and goals. It is also important to note that the discussion section relevant to GRS is split across both Part 2 and Part 3.

Part I

First Responder LiDAR Use in Emergency Situations

2

Background: LiDAR and First Responders

This chapter offers a look at how LiDAR scanning currently relates to work in the emergency first responder field.

2.1. Current LiDAR Usage Context

There are some 28,000 active members of the fire brigades (n.d.) and around 46,000 police officers Jonker and Mouissie, 2023 nationally. These are split into various units based on location and function; not every unit or even location has incorporated laser scanning technology into its operations, and even in the places that have, not every unit member works directly with the laser scanning technology.

There are also six Digital Reconnaissance ("Digitale verkenning") teams in the Netherlands, spread across six different security regions (IJsselland, Twente, Amsterdam-Amstelland, Rotterdam-Rijnmond, Midden en West-Braband, and Zuid-Limburg; see Figure 1.1). These teams are usually more technologically advanced than local or regional first responder organizations, and use various data retrieval techniques to assist first responders nationally. These include laser scanning devices, drones, and other monitoring tools.

The field of emergency or crisis response is an exciting one, especially now with the increasing possibilities offered by integrating drones and laser scanners into first responder repertoires. The process of emergency response is complex, urgent, and uncertain (**smit_creating_2021**).

From an operational standpoint, LiDAR has quite a few benefits: it can produce a point cloud quickly and from a distance, it can produce high-resolution data, and it can be used in the dark(**NOAA-lidar**). It can produce a quick, precise assessment of a building in situations without much light.

The types of tools needed and used by first responders in emergencies varies greatly depending on the regional hazards and the responsibilities and organizational structure of first responders. For example, California, USA is a seismically active area prone to various natural disasters including earthquakes, landslides, flooding, and tsunamis (Kruse et al., 2014). It follows that their emergency scenarios will involve different hazard scenarios than those of the Netherlands, where tsnuamis and earthquakes are not of high concern compared to flooding. Additionally, in the Netherlands, disasters are handled either by the municipal government and first responders, a coalition of responders from multiple safety regions, or nationally, depending on the location and scale of the disaster (Rijksoverheid.nl, 2022).

“For indoor operations, first responder organizations are often forced to gather data themselves as spatial information is seldom readily available (van der Meer, Verbree and Oosterom, 2018)." Usually, relevant structural information about the building such as floor plans, is either outdated or nonexistent (**smit_creating_2021**). Spatial data of the building’s indoor environment are also scarce (**rantakokko2011accurate**; van der Meer, Verbree, & van Oosterom, 2018). At the same time, having access to accurate building maps is crucial for the indoor navigation and tracking systems used by some first responders because it improves their safety and effectiveness while on the go (**parent2022classifying**).

In addition to this scarcity and outdated data, there is the fact that sometimes acquired data requires additional processing before it can render a usable 3D representation of the mapped environment (Luhmann et al., 2013). When software systems exist to support emergency responders in-situ, they are often limited to specific sectors or types of emergencies. In other words, they do not facilitate easy information exchange (**dilo2011data**). Therefore, any simplifications that can be made to the mapping and visualization aspects of the response efforts are likely to be welcome, provided the results are still useful to the emergency responders.

2.2. Developing LiDAR for First Responders

The 2014 study by (Kruse et al., 2014) is an example of a remote project where part of the goal was to design remote sensing tools to the specifications of first responders. They used a relatively simple process of asking members of the target group, via workshops, meetings, and discussions, a variety of questions: what information they needed and when, whether they need answers or data/images, what kinds of sensing platform capabilities are important, what platforms/sensors/data are available, and the utility of baseline data and post-event info. This approach does not appear to be grounded in any particular theory; it was just the way the research team chose to approach gathering the necessary information.

2.3. Problem Statement

LiDAR scanners are increasingly used in emergency response scenarios and/or by emergency first responders. However, the scanners are not necessarily developed with the needs of emergency first responders specifically in mind. This fact impacts the way that first responders use LiDAR in their work, and it also implies that there may be ways in which LiDAR tools could be designed to better support first responder needs.

2.3.1. Research Goal

The first part of the report embodies the CDI perspective and frames the overall topic/focus of the project. The goal of this part is to understand the context around first responder (police and fire department) use of mobile LiDAR technology. How do they use it and what are their experiences with it? The methodology involves a combination of interviews and focus groups and is grounded in the theory of value-sensitive design.

2.3.2. Research Question

The research question that governs Part 1 is, *Why and how do first responder organizations currently use mobile laser scanning in their operations?*

The research objectives for Part 1 are as follows:

- Examine how and why first responders currently use mobile LiDAR in their operations
- Identify what function LiDAR scanners currently serve with respect to communication in the emergency first responder context

The outcome of this section is (1) information on the situations in which first responders (FRs) use LiDAR tools, (2) the values that are important in these situations with respect to the LiDAR tools they use, and (3) pain and plus points related to the use of those tools. Also, (4) the methodology designed to obtain those outcomes (which in theory can be applied to other contexts as well).

3

Methodology: Understanding the LiDAR Use Context

3.1. Research Design

The research question for Part I is answerable in two parts: *why* do first responders use mobile laser scanning, and *how* do first responders use mobile laser scanning. The "Why" refers to LiDAR's characteristics and what benefits it offers as a tool. This includes reasons why you would use mobile LiDAR instead of another tool (digital camera, TLS, etc). For example, that it produces high resolution imagery or that it can be used from afar. The "why" is answered mainly via the interviews and the coding.

The "How" is about the types of situations in which MLS are being used, and about the more generalized role that the tool plays in a first responder team during a response action.

It is answered mainly with the focus group results, specifically the use case scenarios. But it is also answered via the interviews and coding. For this part, the codes should be focused on examples given of MLS use scenarios and on explicit and implicit mentions of the way in which MLS is being used by the FR team. For example how MLS supports operations/FR actions, and maybe who gets to use MLS, who interprets it, and when it is used (meaning more general calculus of when it is useful?)

The research design is a combination of exploratory and case study design, allowing for flexibility in the research process and the application of multiple research methodologies. The research design is supported by a theoretical framework grounded in participatory design and value-sensitive design.

3.2. Theoretical Framework

3.2.1. Participatory Design

Participatory design (PD) was first created as a method to include users in the design process, and to facilitate incorporating their values into design requirements and the resulting created designs (Schuler & Namioka, 1993). At its core, PD is about "addressing...the tension between *what is* and *what could be*"(van der Velden & Mörtberg, 2015, pp.47), (Ehn, 1988). Usually participants in participatory design methods take the role of users and designers, where designers learn the ins and outs of the users' situations while the users express their desired goals and learn how to achieve them technologically (Robertson & Simonsen, 2012). Participatory design consists of multiple different design approaches (Bratteteig & Wagner, 2012) in which the methods allow participants to forecast future use and/or alternative futures of a technology (van der Velden & Mörtberg, 2015). In the use-oriented design approach, the process and the product are equally important and there is strong emphasis on identifying the values and "definitions of use" relevant to the eventual product (Bratteteig & Wagner, 2012; van der Velden & Mörtberg, 2015). The product development process also facilitates participants exploring different definitions of use for the product (Redström, 2008; van der Velden & Mörtberg, 2015).

Value Sensitive Design

Value sensitive design (VSD) is a theory developed to consider human values in the process of technical design. While not strictly a communication theory, it is extremely relevant to this project because of its capability to link the technology to the practical context in this case. The foundational claim of VSD is that "values can be expressed and embedded in technology"(Friedman, Hendry, & Borning, 2017). As an interactional theory, VSD explains that this happens because individuals, organizations, and societies necessarily incorporate their own perspectives, values, and beliefs into the design and implementation of tools and technologies. These tools and technologies then shape human experience and society in turn. Furthermore, VSD posits that technologies both affect people both directly and indirectly, that it is morally significant to think about how values are embedded in technical designs, and that values should be considered early on in the technical design process (Friedman et al., 2017; Friedman, Kahn, & Borning, 2014).

While a full value sensitive design approach involves considering and addressing all of the above, in this project its use more is limited. While there are certainly indirect stakeholders related to the use of laser scanners in emergency response scenarios, they will only be identified briefly in the text and not considered further in the design process. The primary group of interest in this research is the direct stakeholders–those first responders who actively use laser scanners–and what values and value-driven technological features are important to them. Furthermore, rather than analyze and discuss the competing nature of the values identified as important by first responders, this aspect of the process is left aside. For developers bringing a project to completion through the design phase, this would be necessary. However, the application of values in this project is mainly related to assessing the capabilities of different technical instruments with respect to those values. So the tension between different values is not actively incorporated into future design decisions discussed in this project. Lastly, the values identified and considered in this work are not solely related to ethics and morality. A decision was made not to limit the type of value responses given by respondents, but rather to consider all of the values that they named.

That said, this project does follow some of the methods that fall under the umbrella of value-sensitive design. Value sensitive design consists of an "integrative tripartite methodology"(Friedman et al., 2017, p.68), which takes the researcher through multiple iterations of three different investigative phases: the conceptual, the empirical, and the technical (Friedman et al., 2017; Friedman et al., 2014).

The conceptual investigation is concerned with (1) defining the relevant (in)direct stakeholder groups and the ways in which they are affected by the relevant design, (2) determining which values are implicated in these interactions and defining/conceptualizing those values, and (3) deciding how to implement the necessary trade-offs between competing values within the context. *The empirical investigation* focuses on "the human context" surrounding the design and use of the technical tool. This phase of investigation can employ any number of qualitative and quantitative social science research methods and considers how stakeholders prioritize individual and/or competing values. *The technical investigation* focuses primarily on the technology itself. The general position is that a technology is more suited to some activities than others, and more easily supports some values while impeding others. This investigation phase can look at how the technology either supports or detracts from human values, or it can involve proactively designing technical systems to support particular values (usually those that were identified in the conceptual investigation phase).

In the case of this project, the human context refers specifically to the first responder context. While there are many possible questions to focus on, as described above, the focus in this project is on the use context of the technology of interest as well as the current success/suitability of its design.

In the case of this project, the conceptual and empirical investigations were both carried out in this part, Part I, through the interviews and focus group sessions. The technical investigation takes place in Part II and Part III, by way of characterizing the qualities of mobile laser scanners and then assessing how their qualities align with the values uncovered in the first two phases. The empirical and technical investigations were of particular relevance based on the stated research objectives of this project.

Altogether, the above explanation makes clear the extent to which value sensitive design influences the research approach in this project, as well as the elements which were not incorporated.

Values

The Merriam-Webster dictionary defines a value, in the broadest sense, as *"relative worth, utility, or importance"* and as *"a principle or quality intrinsically valuable or desirable"* (**mw:value**). Often in value sensitive design literature a value refers specifically to a "human value," which relates specifically to an ethical or moral judgement held by a human individual, organization, or society (Friedman et al., 2017). Friedman et al. (2014) define a value as referring to *"what a person or group of people consider important in life."* For the purposes of this research we will adapt this definition slightly, to *"what a person, group of people, or organization considers important in a given context."* This definition can be further scoped down to apply to first responders in The Netherlands and to their respective organizations (the police and fire departments).

So, for the purposes of this project, the working definition of a value can be described as *"what emergency first responders in The Netherlands consider important in relation to using laser scanning instruments in a given emergency situation."* This working definition shows one of the key ways in which this project's methodology differentiates itself from some other applications of value-sensitive design: because the ultimate goal of this methodology is to analyze the technology usage behavior of a particular stakeholder group, all of the values expressed by this group are of interest—not just the ethical and moral values.

Identifying Stakeholders

One important part of the value sensitive design process is the identification of the direct and indirect stakeholders in the process. Direct stakeholders are the people who interact directly with the technology or technological output in question. Indirect stakeholders are people who are impacted by the technology, but never directly interact with it (Friedman et al., 2014). In this context, the direct stakeholders are the emergency first responders who using MLS on the job. In the case of the fire department, this includes drone pilots, payload operators, team coordinators, and observers: the people within the digital exploration team who actively work with the drones and LiDAR scanners. Indirect stakeholders can include (1) the commanding officers who receive information from the coordinator about what the LiDAR images mean; (2) firefighting personnel who do not use drones or LiDAR but whose actions are directed based on the information they provide; and (3) any (potential) victims or vulnerable people in the incident whose well-being depends on the actions and decisions of the LiDAR-informed first responders.

In the case of the police, the groups of direct and indirect stakeholders are virtually identical. The main difference is the addition of another group of indirect stakeholders, namely the people such as lawyers and judges who occasionally receive LiDAR images or products derived from LiDAR as evidence in court.

Friedman et al. (2014) recommend giving priority during the conceptual investigation phase to indirect stakeholders strongly affected (benefited or harmed) by the technology. Generally, this is important, especially in an emergency response context, where the technology may be used to save the lives of indirect stakeholders. In the case of this project, the relevant technology is not directly used to interact with victims (for example by pulling them out of a burning building). Rather, the most affected indirect stakeholders are the commanding officers and peer first responders who receive information and/or orders based on the output of the LiDAR device. This is likely why few of the relevant values named by later in this chapter by first responders were related to vulnerability issues such as privacy or trustworthiness. The only one was safety, and it was mentioned both in the context of victim safety and first responder safety.

3.3. Overview of Methods

Following from the theoretical framework, multiple methods were used to pursue the research goals. Figure 3.1 shows the three-tiered approach used to address research questions in this part and Part III of this project.

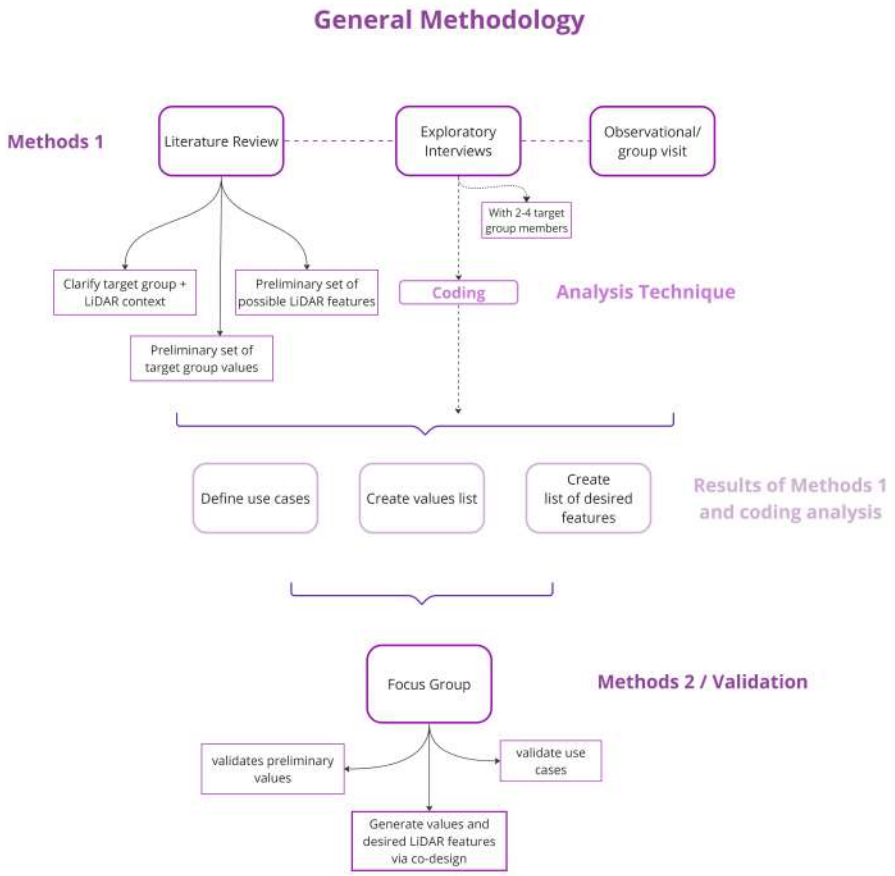


Figure 3.1: Flowchart depicting the general project methodology for research questions one and five.

The methods include literature review, interviews, focus groups, and coding analysis.

3.3.1. Literature Review

The purpose of the literature review at this stage was to find evidence or mentions of three things in the literature:

1. Examples of values declared to be important for first responders / in emergency response scenarios
2. Examples of any LiDAR / scanning / processing features that first responders have already expressed interest in (ie. if there has been a study very similar to this one already)
3. Examples of ways in which LiDAR is already being used in emergency response scenarios and/or to support first responder operations

Topics searched for include:

- Collaboration between a technology/product developer and a specialized target user.
- Lidar tools used by first responders
- Value-sensitive design applied to LiDAR tech
- Value-sensitive design applied to first responder context

Keyword combinations used in the Scopus search include:

- "developing AND a AND lidar AND tool AND for AND emergency AND first AND responders" : 0 results
- "lidar AND emergency AND response" : 94 results

3.3.2. Interviews

The Interviews were used to answer the research question by posing questions to respondents that answered both the *why* and the *how*. Friedman et al. (2014) suggest using stakeholder interviews during the empirical investigation phase (of value sensitive design) to better understand stakeholder perspectives on the context, technology, or proposed design at hand.

Semi-structured interviews provide a clear, directed plan for interacting with respondents, as well as ensuring that the responses will be somewhat standardized. At the same time, they allow the interviewer enough flexibility to change course during the interview and gather new and/or unexpected information if the opportunity arises (Friedman et al., 2014).

In chapter 5 (pg. 138), Babbie discusses the need to identify which dimensions of a concept or variable are of interest for the research and data collection processes. The interview and focus group questions were designed to investigate different aspects of the topics that can help answer the research questions. For example, the question “As a team, do you arrive on the scene of an incident right away?" was designed to elicit information about the timing of LiDAR use with respect to an incident. A more detailed explanation of the intention behind the interview and focus group questions can be found in section A.2.

Sampling Strategy

The sampling strategy for finding interview and focus group participants was a mix of snowball and judgemental sampling (Babbie, 2016). Judgemental sampling, because I specifically sought out members of the fire department and police communities in the Netherlands who had at least some knowledge of LiDAR. Snowball sampling, because I started by emailing people affiliated with TU Delft and CGI, who were able to put me in touch with other people who were able to direct me further in my search. The choice of eventual participants was moderated by the constraints of available project time and the respondents’ demonstrated interest and willingness to participate.

In the process of reaching out to members of the police and fire departments involved or familiar with LiDAR, I found myself being directed to some of the same people multiple times. I was also told by one contact I that ended up interviewing, that they had seen my email going around in multiple email threads and that they had contacted me themselves because they saw that they could be of help based on the information I was seeking. I took this statement as a suggestion that my requests had saturated, if not the entire national LiDAR-first-responder community, at least a subset of it. In another instance, a member involved in fire department LiDAR activities was referred to me both by a regional fire department colleague of theirs, and by a member of the police community in an entirely different (and relatively distant) safety region. Again, this seems to indicate that my requests for respondents managed to circulate relatively widely among the community.

Approach to Questioning

The interviews conducted were exploratory, meaning that they were meant to provide information about the first responder context of the case study that would help to narrow the project’s focus. They were semi-structured interviews, which allowed the focus to be centered on the known theme—LiDAR use in emergency response situations—while at the same time allowing ample room for new insights and thematic directions to surface.

There were four exploratory interviews conducted, two with members of the Rotterdam-Rijnmond regional fire department, and two with members of the national police. Due to the timing of the unfolding of the CDI phase of the project, the way that the scope of the project developed, and the differing process by which contacts were found in each agency, the first two interviews were conducted with members of the fire department. The interviews were conducted with informed consent, and an example consent form can be found in subsection A.1.1. *Note: due to the privacy agreements listed on the informed consent forms, interview transcripts are only available to the research team and will not be attached in the appendix.*

The first interview, conducted in March 2023, also occurred six months before the third interview, which in September 2023 was the first moment data collection with members of the police became possible. Until this time, the CDI phase of the project (in particular the design component) was not quite clear. This interview marks the end of the purely exploratory phase of the project; around this time the focus on values took more shape and the subsequent analyses followed from there in a more streamlined fashion. (See section A.5 for a visual representation of the project iterations that occurred before arriving at the final iteration enumerated in this report.)

The fourth interview, conducted with a member of the national police in December 2023, was therefore the only one which took place after the exploratory phase was more or less complete. At that point in the project, the focus on value-sensitive design and first responders' situational values and the formulation of the LiDAR use cases had already been established. This meant that the fourth interviewee was also asked to describe common LiDAR use cases and consider the most important values related to each use case, in addition to serving as a more general source of insight into police use of LiDAR tools.

Data Source	Date of Interview	Organization
Interviewee A1	March 2023	Fire department
Interviewee A2	June 2023	Fire department
Observational Visit	August 2023	Fire Department
Interviewee A3	September 2023	National Police
Interviewee A4	December 2023	National Police

Figure 3.2: Table showing information about the interviewees.

Figure 3.2 gives an overview of the timing of the four interviews as well as an observational visit. It also shows the team or general area of expertise of each respondent.

Sequence of Interviews

Data collection and analysis were conducted in a bit of a cyclical manner. The first two interviews, both of which were with fire department contacts, at first served an exploratory function. The goal was to understand the general context of first responder use of laser scanning, as well as to determine how and whether the precision and accuracy of point cloud data was important. The answers to the latter influenced the direction of the GRS and CDI research focus, goals, and objectives. The answers to the former served as a foundational understanding of the project and technological use context; effectively a combination of conceptual and empirical investigations. The third interview served an exploratory function for the same topics and goals, but in the police context rather than the fire department context.

The thoughts and experiences expressed in these interviews influenced aspects of the focus groups conducted in December and January. Mainly by providing initial use cases and relevant values to be validated by participants in the first and second parts of the itinerary/program.

For consistency's sake, the last interview–which was conducted much later (also in December)–investigated most of the same topics as the first three. However, by then, the focus of the CDI research had shifted towards a values-based assessment of first responder needs. So, some additional questions were added to the protocol to address that topic. This means that the last interview was more directed than purely exploratory.

Later on, in the more advanced stage of data analysis and interpretation, the interviews were used as source material for coding. The earlier interview transcripts could still be used to glean insights about values. But because the focus on values was identified after the collection of this data, to do so, the coding had to be used a bit more implicitly.

3.3.3. Coding Analysis

The transcripts were interpreted using coding to explain the reasons why first responders use LiDAR. The codes were focused on explicit or implicit mentions of the characteristics of MLS and of ways in which MLS is more useful than a different type of tool. The coding tree for this analysis is in section A.6.

Coding for the how and the why

The batch of coding dedicated to answering research question 1 (how and why first responders use LiDAR) pursued thematic analysis via an open approach. The open (or inductive) approach complements thematic analysis, which uses induction to interpret the data with respect to particular research questions. The data collection was heavily framed by the research questions, by way of the questions included in the interview protocols and the activities included in the focus group sessions. However, the data itself was analyzed without a predefined list of codes, concepts, and themes. While I did have some preliminary categories in mind based on the conceptualization of the "how" and "why" components of the research question, the codes arose from the data itself and those categories were subject to change based on the codes.

Altogether, coding for this question involved a mix of descriptive, structural, and provisional coding. Descriptive coding is best used to catalog the variety of opinions expressed by multiple respondents, while structural coding is a foundational coding method that allows the researcher to index and label data that might be relevant to a particular analysis (Saldana 2016).

The interview questions, and to a lesser extent the questions guiding the activities and discussion during the focus groups, were used to create the thematic and keyword-based categories used in the coding analysis. For example, the question "How does laser scanning factor into the work [that members of the fire department's digital exploration team] do?" translates into the coding category of "Lidar:how," which is concerned with the role that LiDAR plays as a tool within the emergency first responder arsenal.

Although indirectly related to this research question, there were also some categories of information that seemed relevant to consider. Namely, "direct and indirect stakeholders," "people/positions who use LiDAR," "Required LiDAR training," "main purpose(s) of LiDAR / drone use," "Type of LiDAR tool(s) used," "type(s) of images worked with," "Timing of LiDAR use with respect to an incident," "data resolution and/or precision," "about point cloud drift," and "desired LiDAR features." **reference coding tree, code list, etc here**

Coding for value definitions

The batch of coding dedicated to cataloging first responder definitions of values pursued *content analysis* via a *directed approach*. Content analysis means that the focus is on understanding the context and meaning behind certain concepts, and the directed (or deductive) approach means that it begins with codes taken from theory and prior observation. In this case, the initial codes were derived from the values named in the focus groups. This is because the objective of the coding session was to identify the meanings and definitions that respondents ascribed to these values. Two types of coding were used to achieve this goal: provisional coding, which begins with a provisional list of codes derived (in this case) from prior investigation; and values coding, which is meant to identify the subjective perspectives of participants with respect to their cultural values, attitudes, and beliefs (Gable, Wolf, Gable, & Wolf, 1993; Saldaña, 2016).

The list of initial codes for the fire department is as follows: Safety, 3D Data, Interpret(ability), Maneuver(ability), (Data) Reliability, (Data) Consistency, (Data) Clarity, Access, Effective(ness), Efficiency/Efficient, Time/Timing/Speed, (GPS) Reception

The list of initial codes for the police is as follows: Safety, Response Time, User-friendliness, Data Transfer, Visualization Capabilities, User Preparation / Training, Objectivity, Information, Data Sharing, Visual Editability / Modification, Overview / Focus

3.3.4. Observational Visit

In August 2023 I conducted a site visit with the Digital Exploration Team of veiligheidsregio Rotterdam-Rijnmond during one of their regular practice sessions. This was a descriptive observation that also fulfilled some focused observation functions (answering research questions, deepening researcher knowledge, and serendipitous findings). The team is comprised mostly of firefighters and their job is to “make the work of firefighters less dangerous and make the job more efficient" (interviewee A2) by using aquatic, terrestrial, and airborne drones.

I was still relatively new to the context at this point, so the primary goal was to get a sense of how the fire department used LiDAR technology in the field. The second goal was to hear from different team members about what information and interface elements or software features they would find useful in their work. Lastly, I wanted to determine whether the group was a good candidate for a focus group.

All of these goals were achieved, and I also gained other insights including about the training hierarchy, who uses and interprets the LiDAR imagery, and that the team is still investigating how they can best use LiDAR. I also got a chance to fly the Elios 3 drone used in the team’s operations (see Figure 3.3).

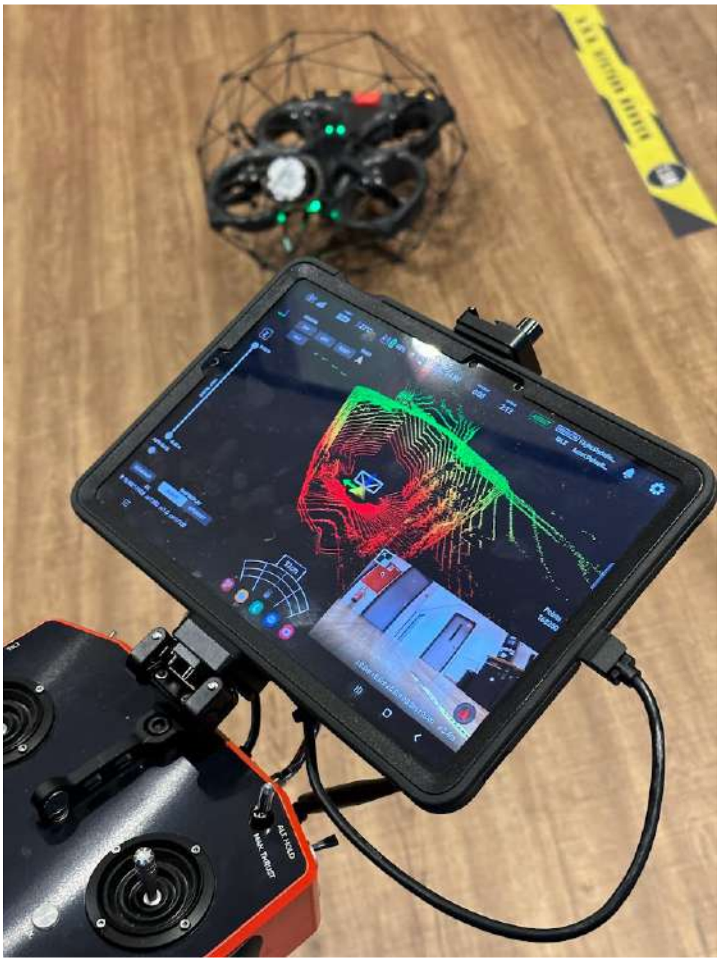


Figure 3.3: Viewer screen of the Flyability Elios 3 drone used by the Rotterdam Fire Department.

Some notes from the observational visit can be found in section A.3. The value of this visit can be explained by van der Velden and Mörtberg (2015)’s concept of situation-based action. I was able to learn more about the study context by engaging as a participant-observer with members of the target group.

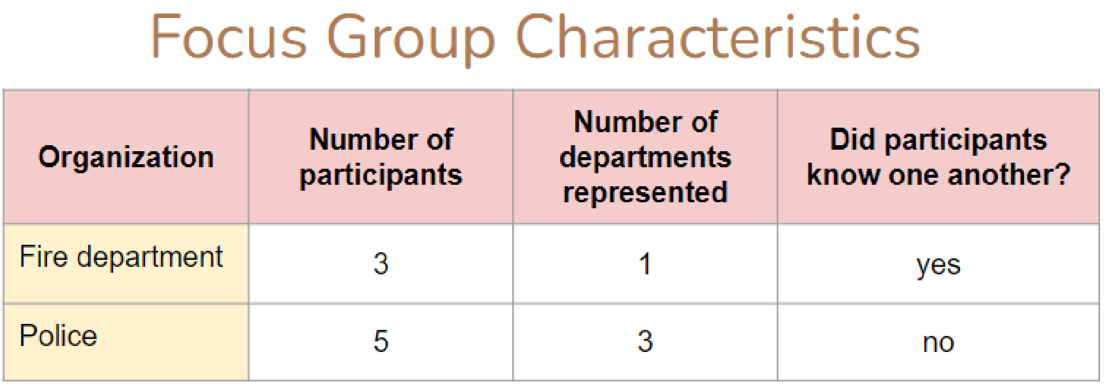
3.3.5. Focus Groups

The focus groups were the final method of analysis in the chain of operations. As a data collection method, focus groups offer an opportunity to gather in-depth information about respondents’ thoughts, perspectives, and/or feelings about a given issue, while also immediately highlighting potential differences of opinion within the group (Rabiee, 2004). Participants were selected on the basis of their having relevant things to say about the topic, as well as their willingness and potential comfort with participating in a group discussion (**richardson2001question**). Informed consent was obtained before and after the session. An example consent form can be found in subsection A.1.2.

There were two focus groups, one for each organization and both conducted virtually via Microsoft Teams. The focus group for the fire department was virtual by request. The police department focus group was virtual by logistical necessity, because the participants were from different departments and spread across different parts of the Netherlands. Each focus group started with brief introductions as participants joined the call, followed by a short introductory presentation that introduced the researcher (me), research question, general theoretical concepts of value-sensitive design, and an agenda and ground rules for the discussion. After about 15 to 20 minutes, the group transitioned to Miro for the remainder of the session. Typically, the dynamics within the group of respondents are a key point of interest (Rabiee 2004) and serve as an important part of the generated data. However in the case of this project, the focus groups more closely resembled group interviews with interactive activities. It was most important that participants were able to express their personal thoughts and experiences both verbally and via the activities. After participants had some time to work individually, there was time to briefly elaborate and discuss with one another as time allowed.

About the participants

There were three participants for the fire department focus group, and five participants for the police focus group. However, in each group there was at least one participant who was on duty at the time of the focus group. In the case of the police focus group, that person was only able to be present for about half of the session and was unable to add elements to the Miro board due to participating from inside the police vehicle.



Focus Group Characteristics

Organization	Number of participants	Number of departments represented	Did participants know one another?
Fire department	3	1	yes
Police	5	3	no

Figure 3.4: Table showing different characteristics of the two focus groups.

Although there was not much flexibility in terms of who the participants were (particularly on the fire department side), thought was still given to the way that relationships between participants might influence the dynamic during the session. Culturally, the Netherlands has a relatively flat and non-hierarchical working culture which is a plus in this particular scenario. But of course, people are still likely to be a bit hesitant to directly contradict their superior, especially when it comes to discussing for example the values underlying their work operations and ranking the importance of such values. So in that sense, it is helpful to have respondents who are on relatively equal footing.

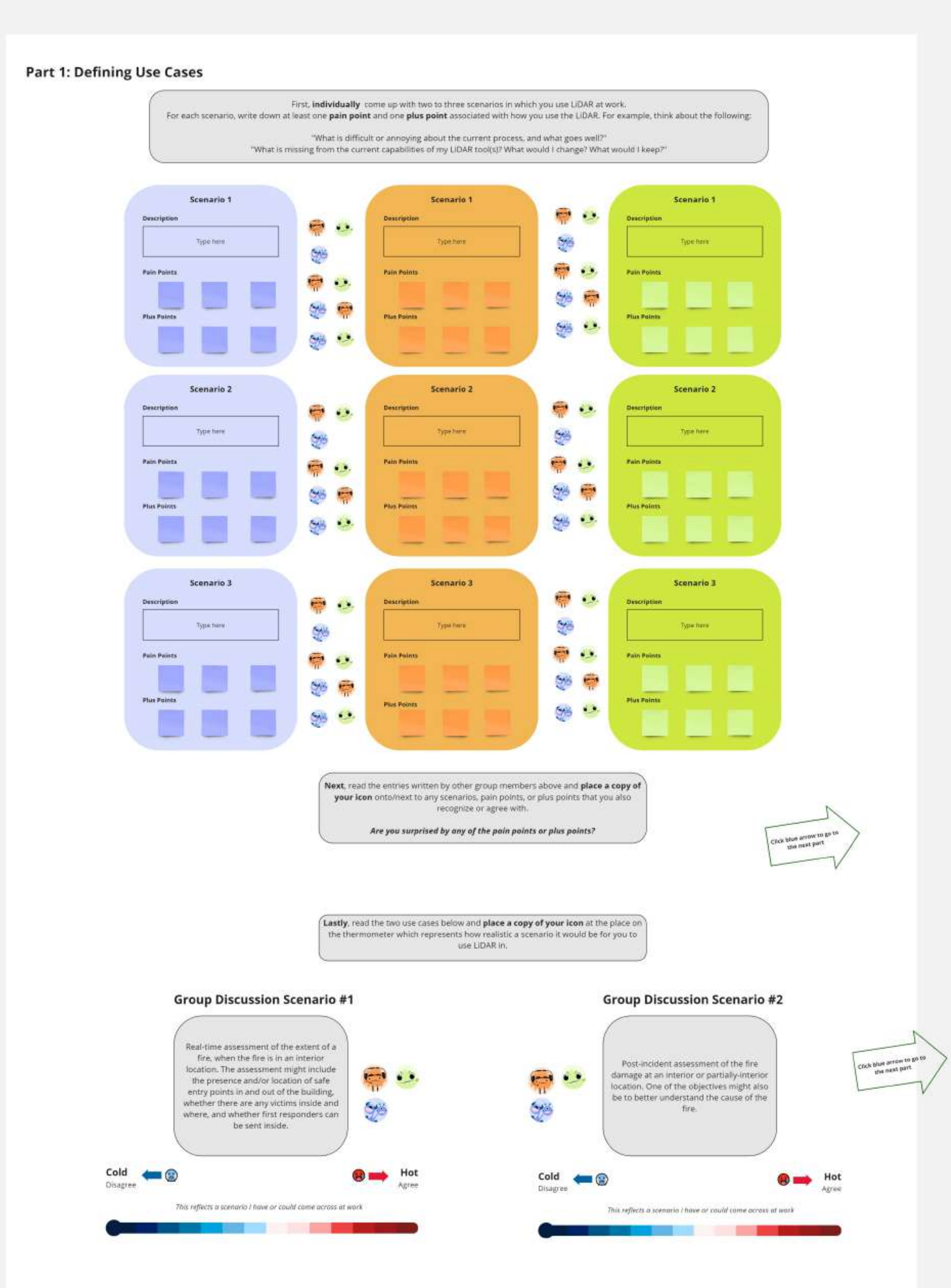
Session Design

The focus group session was designed to be interactive, with various opportunities for participants to write down their own thoughts and experiences as well as to read or hear those of other participants and then express opinions or dis/agreement with them. It could perhaps be better described as an interactive group discussion than a focus group, since the primary data of interest were the responses of each participant, and not the ways that participants interacted with one another.

The session consisted largely of open-ended questions. Some questions asked participants to use a Likert scale to express their opinions on a statement. Each round of the focus group had a specific purpose and was governed by a few guiding questions. These questions can be seen in the focus group planning document in section A.4.

Round 1: Use Cases

In the first round of the focus group, participants defined scenarios in which they use LiDAR at work and reflected on the negative and positive aspects of LiDAR in those situations. Figure 3.5 shows a blank example of this section of the Miro board.



First, **individually** come up with two to three scenarios in which you use LiDAR at work.
For each scenario, write down at least one **pain point** and one **plus point** associated with how you use the LiDAR. For example, think about the following:

"What is difficult or annoying about the current process, and what goes well?"
"What is missing from the current capabilities of my LiDAR tool(s)? What would I change? What would I keep?"

Next, read the entries written by other group members above and **place a copy of your icon** onto/next to any scenarios, pain points, or plus points that you also recognize or agree with.

Are you surprised by any of the pain points or plus points?

Lastly, read the two use cases below and **place a copy of your icon** at the place on the thermometer which represents how realistic a scenario it would be for you to use LiDAR in.

Real-time assessment of the extent of a fire, when the fire is in an interior location. The assessment might include the presence and/or location of safe entry points in and out of the building, whether there are any victims inside and where, and whether first responders can be sent inside.

Post-incident assessment of the fire damage at an interior or partially-interior location. One of the objectives might also be to better understand the cause of the fire.

This reflects a scenario I have or could come across at work

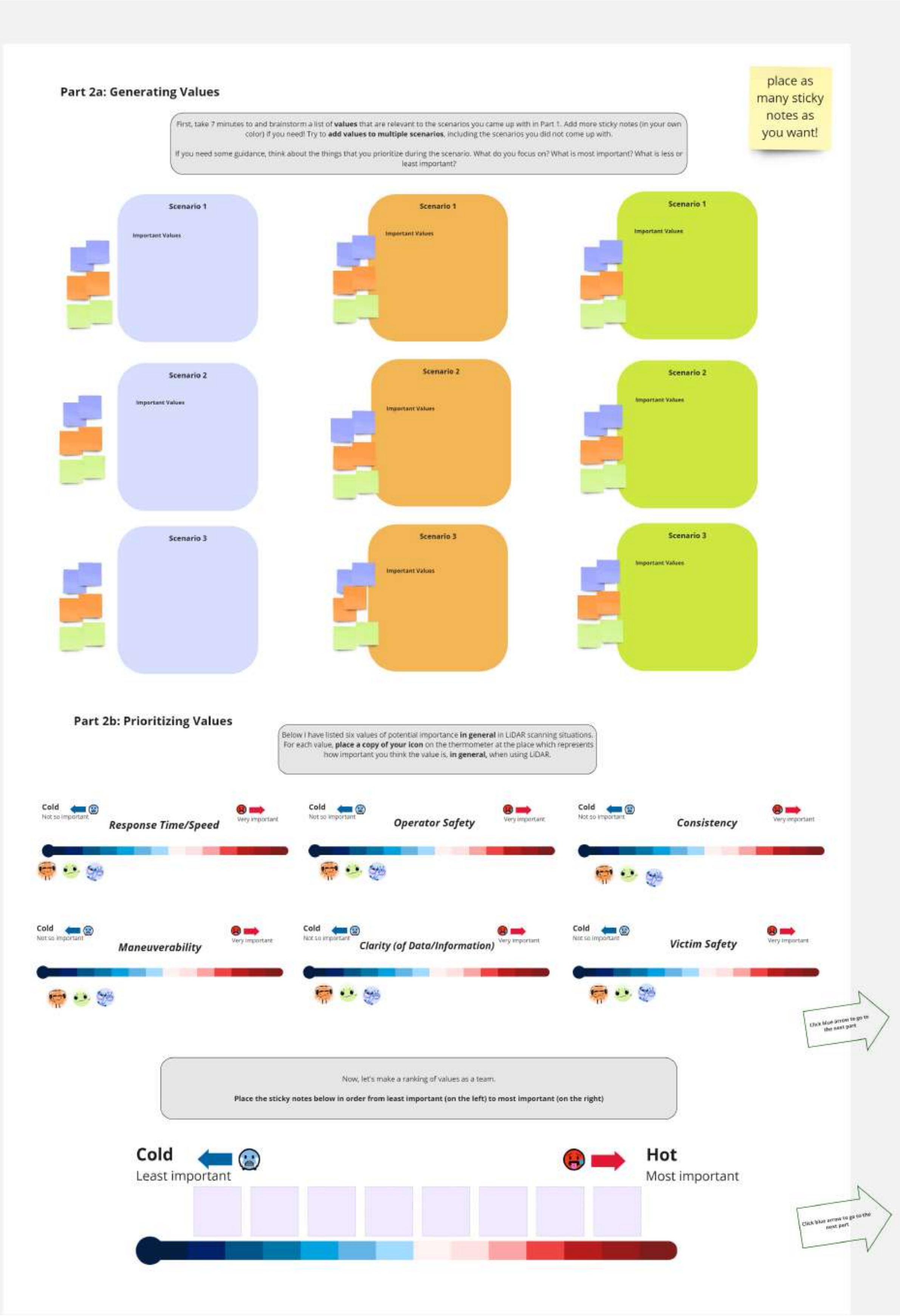
This reflects a scenario I have or could come across at work

Figure 3.5: The Miro board setup for the first round of the focus group.

Then participants commented on two predefined use cases. They indicated the degree to which they felt they could encounter the use case at work. The thermometer was chosen as a way for participants to show agreement with the elements of the board that I proposed. Using a visual spectrum from hot to cold rather than framing it as "agree/disagree" allows participants more leeway in deciding how much they do or do not identify with the presented statement.

Round 2: Values

In the second round of the focus group, participants focused on identifying and prioritizing values. Figure 3.6 shows a blank example of this section of the Miro board.



Part 2a: Generating Values

First, take 7 minutes to and brainstorm a list of **values** that are relevant to the scenarios you came up with in Part 1. Add more sticky notes (in your own color) if you need! Try to **add values to multiple scenarios**, including the scenarios you did not come up with.

If you need some guidance, think about the things that you prioritize during the scenario. What do you focus on? What is most important? What is less or least important?

place as many sticky notes as you want!

Part 2b: Prioritizing Values

Below I have listed six values of potential importance **in general** in LiDAR scanning situations. For each value, **place a copy of your icon** on the thermometer at the place which represents how important you think the value is, **in general**, when using LiDAR.

Now, let's make a ranking of values as a team.

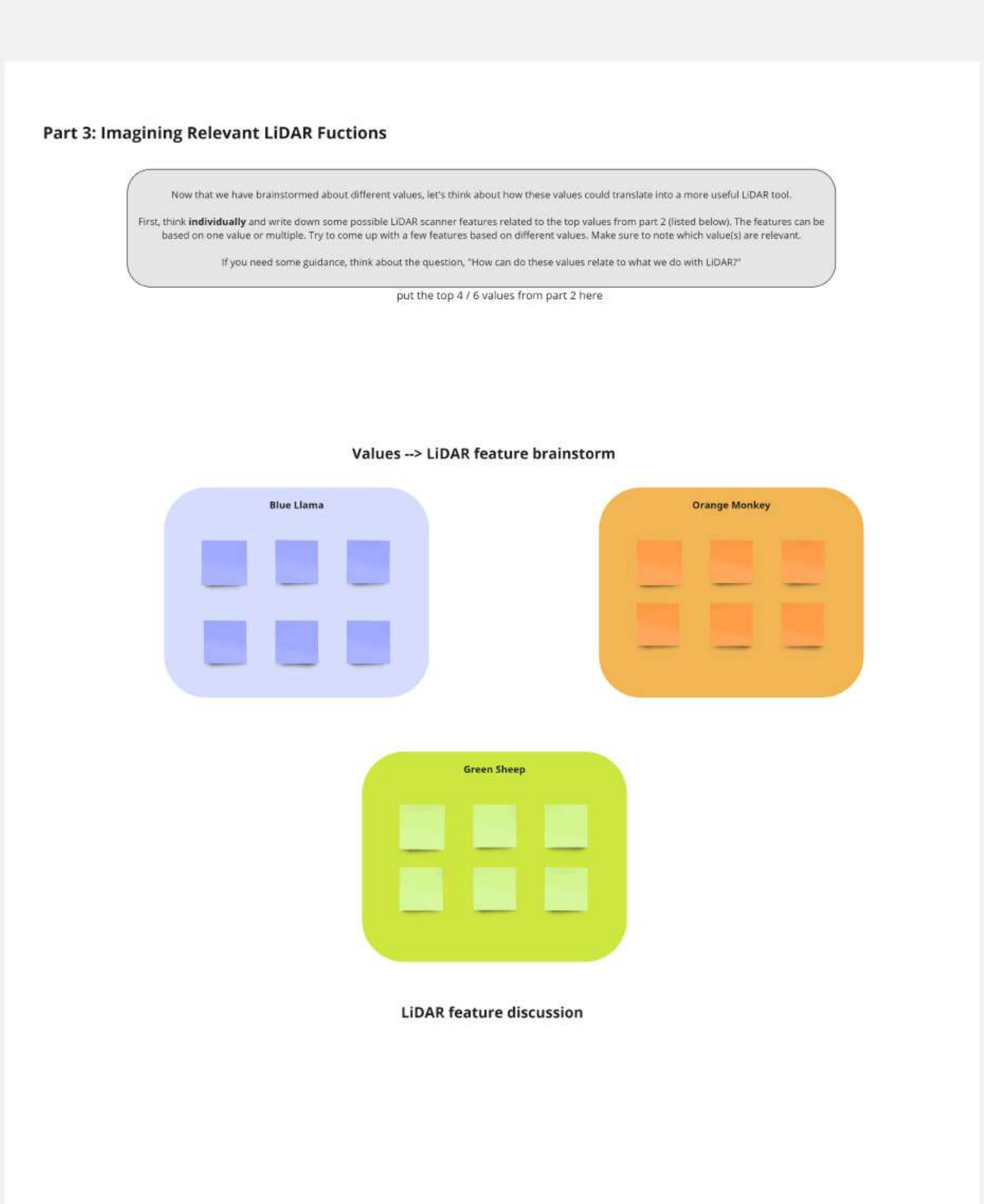
Place the sticky notes below in order from least important (on the left) to most important (on the right)

Figure 3.6: The Miro board setup for the second round of the focus group.

Participants were asked to name the values that they considered relevant to the emergency scenarios in which they use LiDAR. A value was defined for them as “What you prioritize in a certain situation." Next, participants ranked how important they considered each of a set of six values. Lastly, participants used the top six highest-ranked values as a starting point to brainstorm LiDAR features that they would like to see.

Round 3: Tool Building

In the third and final round of the focus group, participants focused on linking the identified values to LiDAR features they would like to see. Figure 3.7 shows a blank example of this section of the Miro board.



Part 3: Imagining Relevant LiDAR Fuctions

Now that we have brainstormed about different values, let's think about how these values could translate into a more useful LiDAR tool.

First, think **individually** and write down some possible LiDAR scanner features related to the top values from part 2 (listed below). The features can be based on one value or multiple. Try to come up with a few features based on different values. Make sure to note which value(s) are relevant.

If you need some guidance, think about the question, "How can do these values relate to what we do with LiDAR?"

put the top 4 / 6 values from part 2 here

Values --> LiDAR feature brainstorm

LiDAR feature discussion

Figure 3.7: The Miro board setup for the third round of the focus group.

Validation

In addition to gathering information from participants, the focus groups were a way to validate the use cases and organizational/operational values that I had generated from the literature, interviews, and site visit. Certain areas of/activities on the Miro board were designed to act as direct validation for specific concepts. ***[go into more detail/say which parts?]*** Additionally, the answers given by participants during the session also served as indirect validation for certain concepts. For example, the answers written on sticky notes in "Part 2a: Generating Values" on the Miro board provide indirect validation of the values that I extracted from the interview transcripts. This indirect validation occurs through a comparison of the values in my list with the values written down by participants. If the values in my list appear in the list of those mentioned by participants, they have been validated. In contrast, in "Part 2b: Prioritizing Values", participants are asked to directly comment on values that I present to them. This results in a direct validation of the values.

4

Results

4.1. Use Cases

One of the results of the interviews conducted with first responders was gaining insight into the ways in which they use or consider using LiDAR scanning. These use cases represent different types of scenarios in which first responders, specifically police operatives and firefighters, are likely to use LiDAR scanning.

Figure 4.1 is a word cloud showing the words participants used related to LiDAR use cases. It does not provide a complete picture of the mentioned use cases, but topics such as traffic incidents, forensics, crime scene analysis, and investigation are all mentioned.

Figure 4.2 shows various use cases for the police and the fire department, compiled from a combination of interview data, focus group data, and information gathered during the observational visit.

4.2. Use Case Rankings

In the first round of the focus group participants also commented on two predefined use cases. Participants indicated the degree to which they felt they could encounter the use case at work. Figure 4.3 shows the results from the fire department focus group. (Due to time constraints, this part was skipped during the police department focus group.) Note that the proposed use cases are the same ones presented in the results in section 4.1.

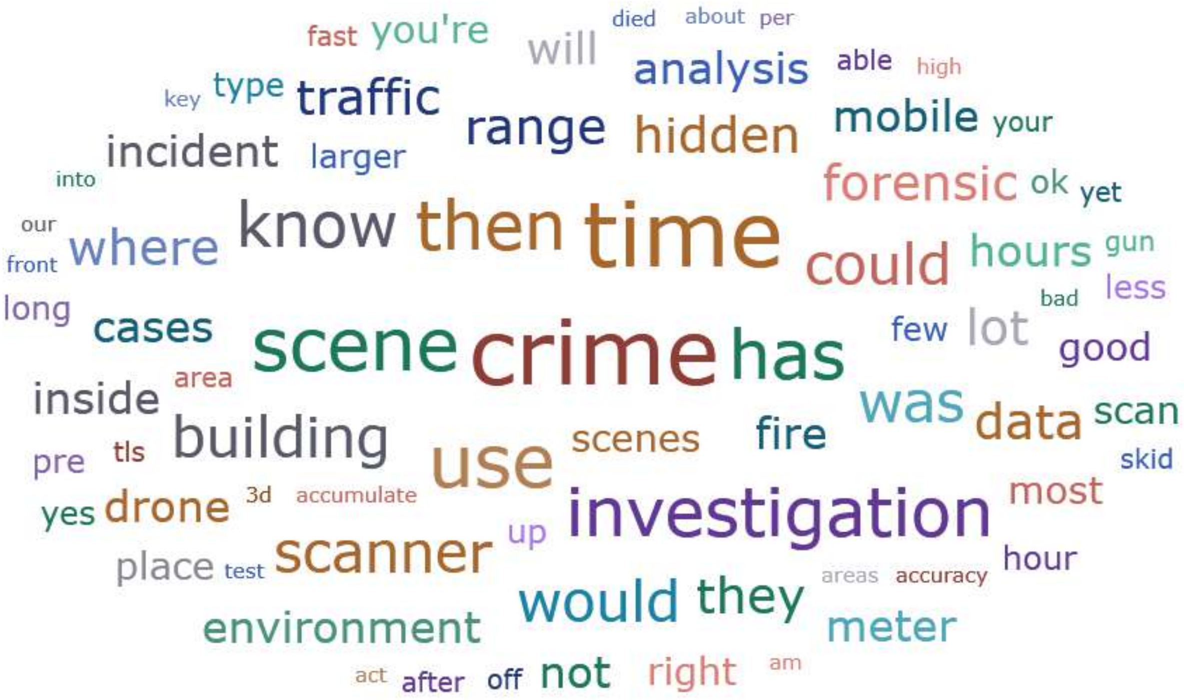
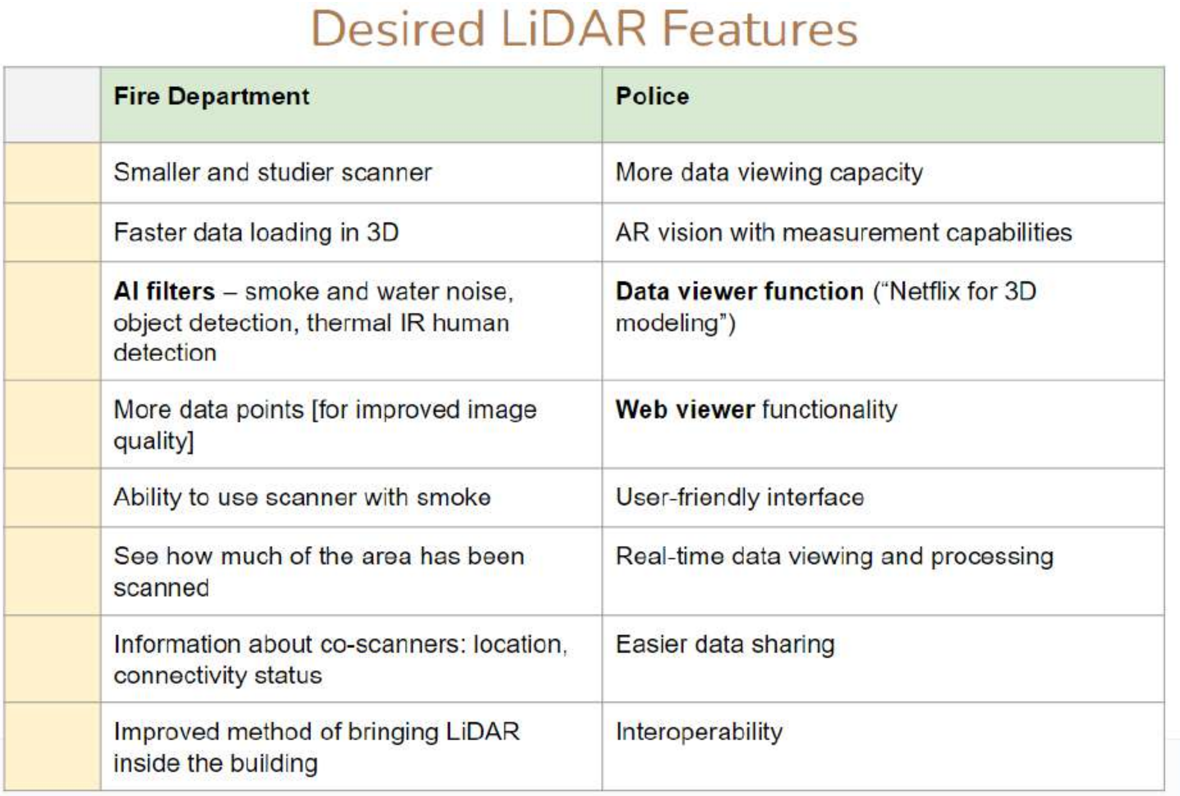


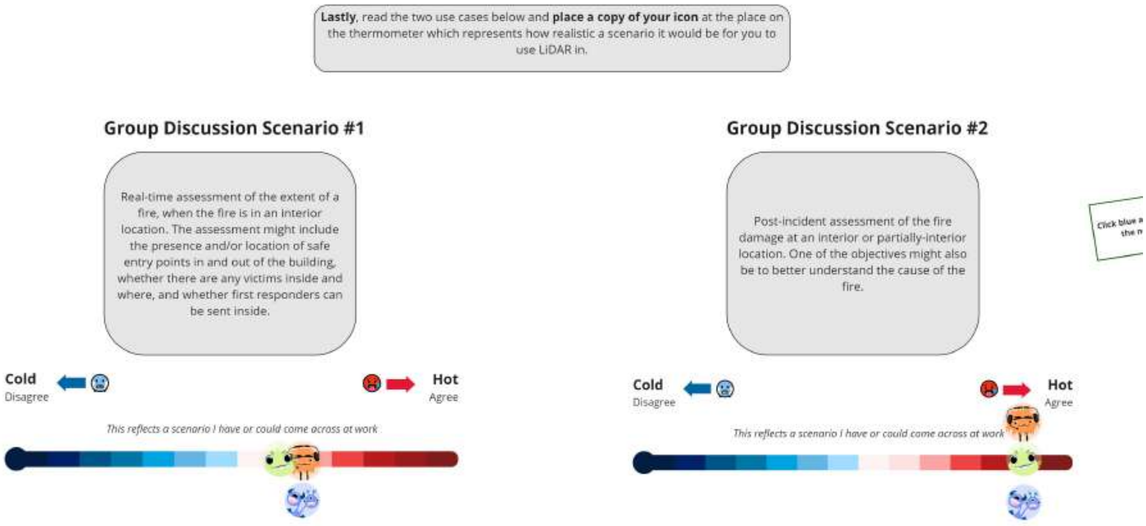
Figure 4.1: Word cloud showing the various LiDAR use cases described by emergency first responders, sized according to the relative number of mentions



Desired LiDAR Features

	Fire Department	**Police**
	Smaller and studier scanner	More data viewing capacity
	Faster data loading in 3D	AR vision with measurement capabilities
	AI filters – smoke and water noise, object detection, thermal IR human detection	**Data viewer function** ("Netflix for 3D modeling")
	More data points [for improved image quality]	**Web viewer** functionality
	Ability to use scanner with smoke	User-friendly interface
	See how much of the area has been scanned	Real-time data viewing and processing
	Information about co-scanners: location, connectivity status	Easier data sharing
	Improved method of bringing LiDAR inside the building	Interoperability

Figure 4.2: Chart showing the various LiDAR use cases described by emergency first responders



Lastly, read the two use cases below and **place a copy of your icon** at the place on the thermometer which represents how realistic a scenario it would be for you to use LiDAR in.

Group Discussion Scenario #1

Real-time assessment of the extent of a fire, when the fire is in an interior location. The assessment might include the presence and/or location of safe entry points in and out of the building, whether there are any victims inside and where, and whether first responders can be sent inside.

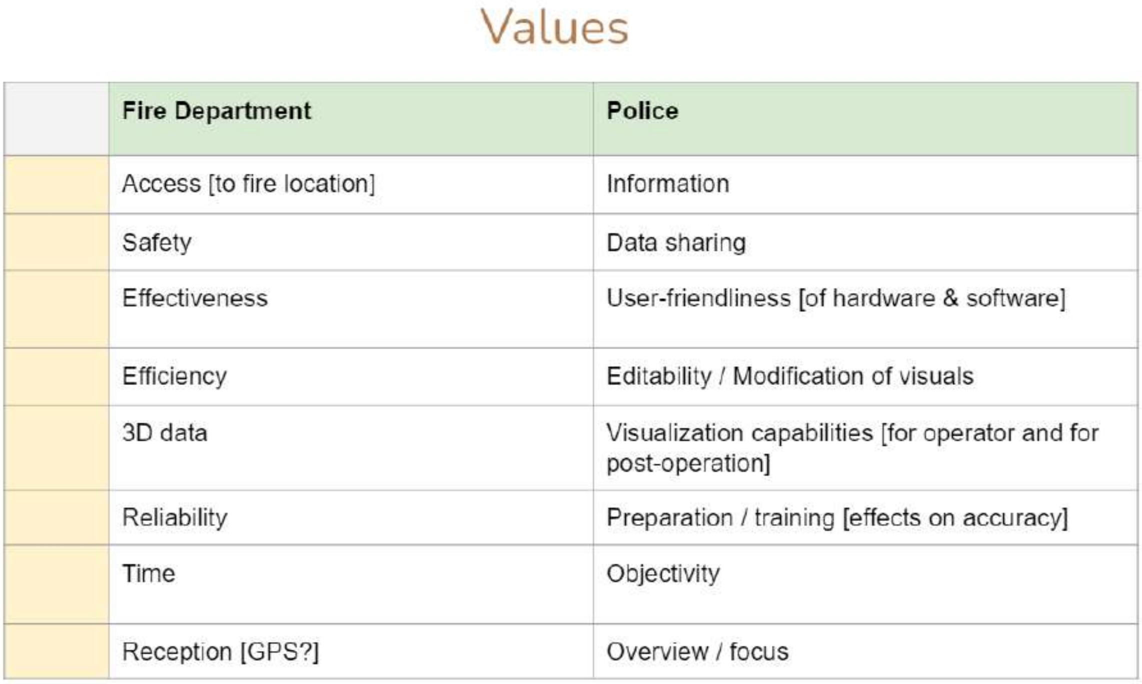
Group Discussion Scenario #2

Post-incident assessment of the fire damage at an interior or partially-interior location. One of the objectives might also be to better understand the cause of the fire.

Figure 4.3: Figure showing the degree to which participants feel they could encounter each use case at work.

4.3. Values

In the second round of the focus group, participants focused on identifying and prioritizing values. The values shown in Figure 4.4 were named by focus group participants as being relevant to the emergency scenarios in which they use LiDAR.

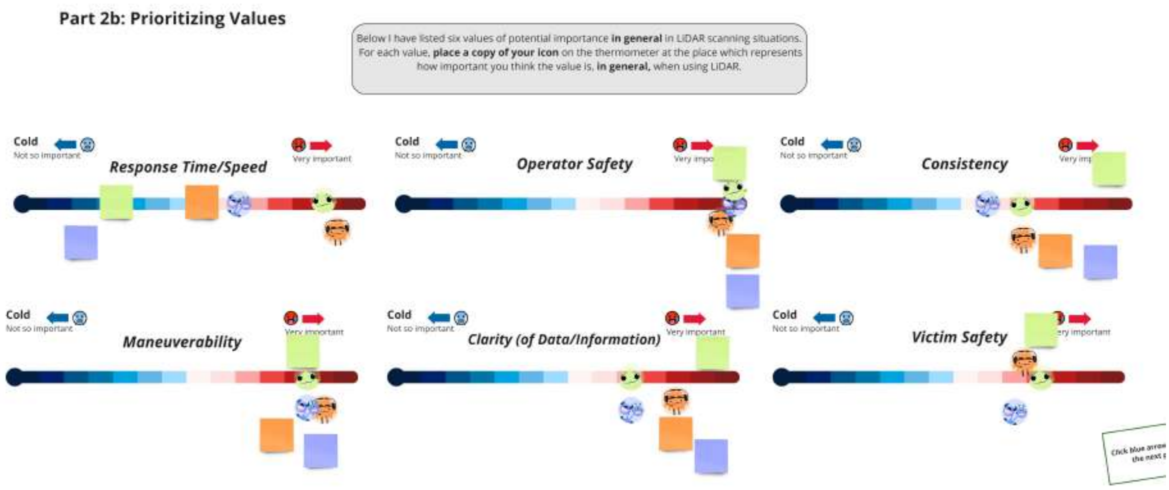


Values

	Fire Department	Police
	Access [to fire location]	Information
	Safety	Data sharing
	Effectiveness	User-friendliness [of hardware & software]
	Efficiency	Editability / Modification of visuals
	3D data	Visualization capabilities [for operator and for post-operation]
	Reliability	Preparation / training [effects on accuracy]
	Time	Objectivity
	Reception [GPS?]	Overview / focus

Figure 4.4: Table of the values named by focus group participants as relevant to the scenarios in which they use LiDAR.

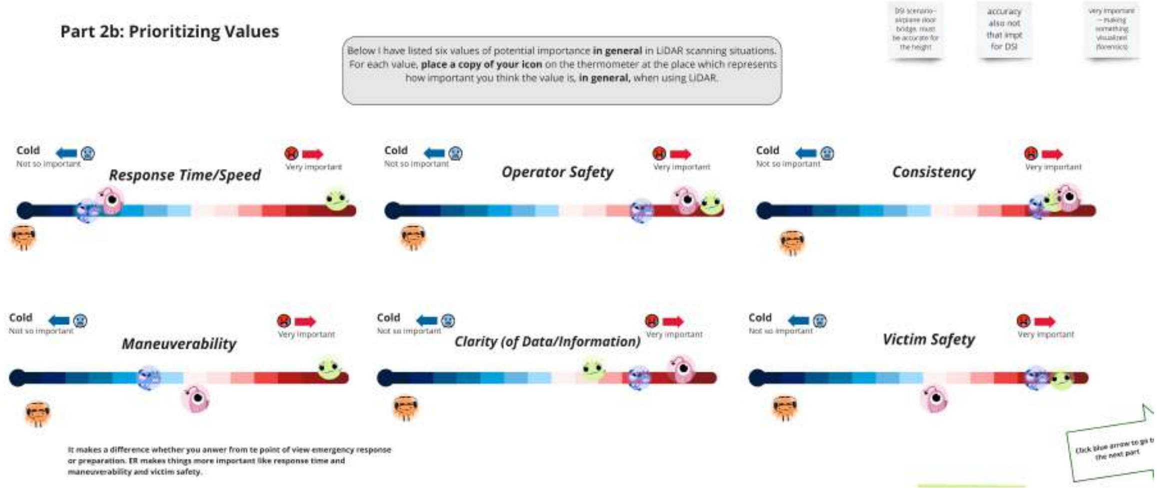
Next, participants ranked how important they considered each of a set of six values. Figure 4.5 shows the results for the fire department and Figure 4.6 shows the results for the police department.



Below I have listed six values of potential importance **in general** in LiDAR scanning situations. For each value, **place a copy of your icon** on the thermometer at the place which represents how important you think the value is, **in general**, when using LiDAR.

Figure 4.5: Figure showing the value importance rankings made by participants in the fire department focus group.

The fire department respondents made a distinction between the importance of the values during a fire (icons) vs. after a fire (post-its). For the fire department, every value except for one (response time/speed) was marked in the top half of the importance scale, for both timeframes. The opinions of different participants were also often clustered in similar areas.



Below I have listed six values of potential importance **in general** in LiDAR scanning situations. For each value, **place a copy of your icon** on the thermometer at the place which represents how important you think the value is, **in general**, when using LiDAR.

DSI scenario– airplane door bridge, must be accurate for the height

accuracy also not that impt for DSI

very important – making something visualized (forensics)

It makes a difference whether you anwer from te point of view emergency response or preparation. ER makes things more important like response time and maneuverability and victim safety.

Figure 4.6: Figure showing the value importance rankings made by participants in the police focus group.

The police department approached the exercise as the importance of the values during LiDAR use scenarios in general. They had a much wider spread of opinions about the different values – only half of the values were consistently marked in the top half of the importance scale. There was also more variation between participants in how they ranked values, with clustering on half the values and more varied opinions on the other half.

Lastly, the top ranked values shown in Figure 4.7 were ranked by focus group participants as representing the most important values during emergency scenarios in which they use LiDAR. The participants subsequently used these values as a starting point to brainstorm LiDAR features that they would like to see.

Top Values

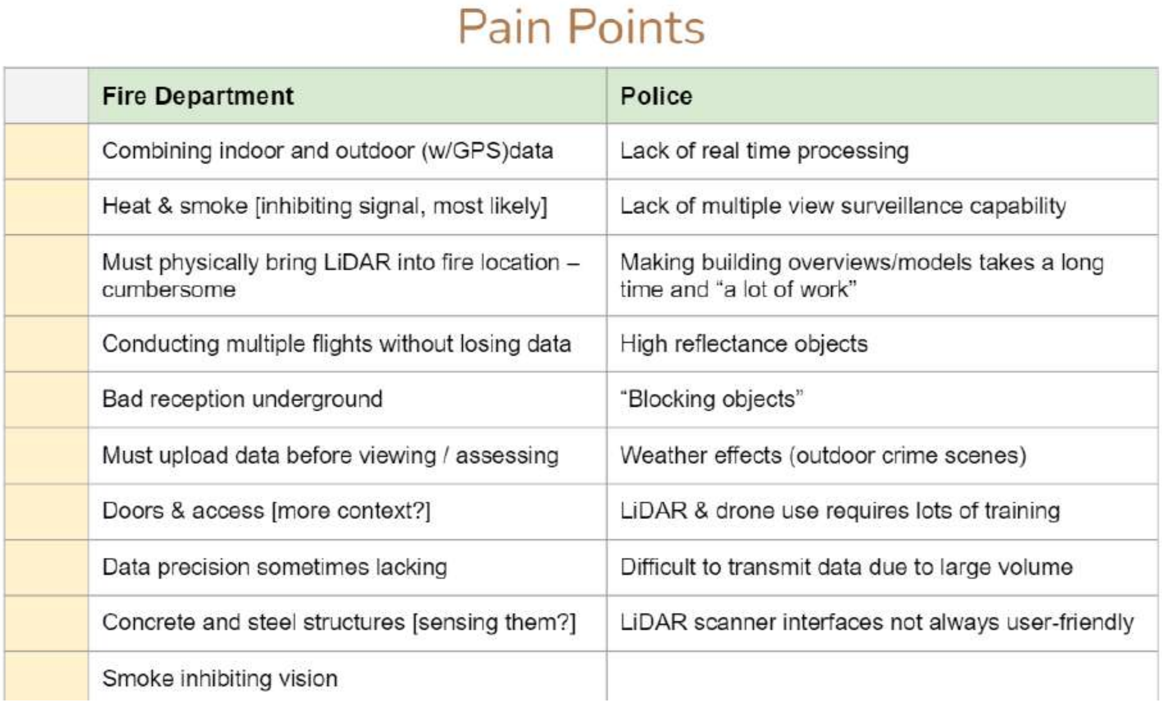
	Fire Department	Police
1	Safety	Operator / victim safety
2	3D data	Response time
3	Maneuverability	User-friendliness
4	Reliability	Data transfer
5	Consistency	Visualization capabilities
6	Clarity of data / information	Preparation / training [effects on accuracy]

Figure 4.7: Table of the 6 most important values as ranked by focus group participants.

4.4. Pain Points

The following results were obtained during the focus group sessions.

In the first round of the focus group, participants defined scenarios in which they use LiDAR at work and reflected on the negative and positive aspects of LiDAR in those situations. Figure 4.8 shows the pain points that participants identified across scenarios. Figure 4.9 shows the positive aspects that they identified.



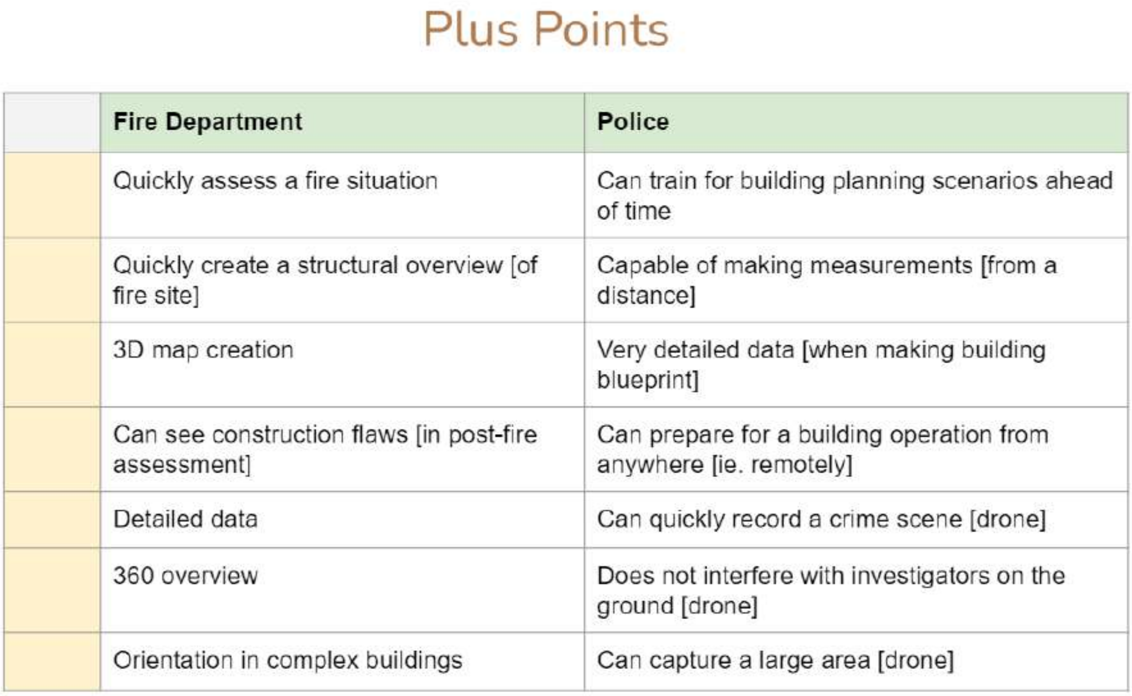
Pain Points

	Fire Department	Police
	Combining indoor and outdoor (w/GPS)data	Lack of real time processing
	Heat & smoke [inhibiting signal, most likely]	Lack of multiple view surveillance capability
	Must physically bring LiDAR into fire location – cumbersome	Making building overviews/models takes a long time and “a lot of work”
	Conducting multiple flights without losing data	High reflectance objects
	Bad reception underground	“Blocking objects”
	Must upload data before viewing / assessing	Weather effects (outdoor crime scenes)
	Doors & access [more context?]	LiDAR & drone use requires lots of training
	Data precision sometimes lacking	Difficult to transmit data due to large volume
	Concrete and steel structures [sensing them?]	LiDAR scanner interfaces not always user-friendly
	Smoke inhibiting vision	

Figure 4.8: Table showing the pain points that participants experience while using LiDAR in different scenarios.

4.5. Plus Points

The following plus points were identified during the focus group sessions.



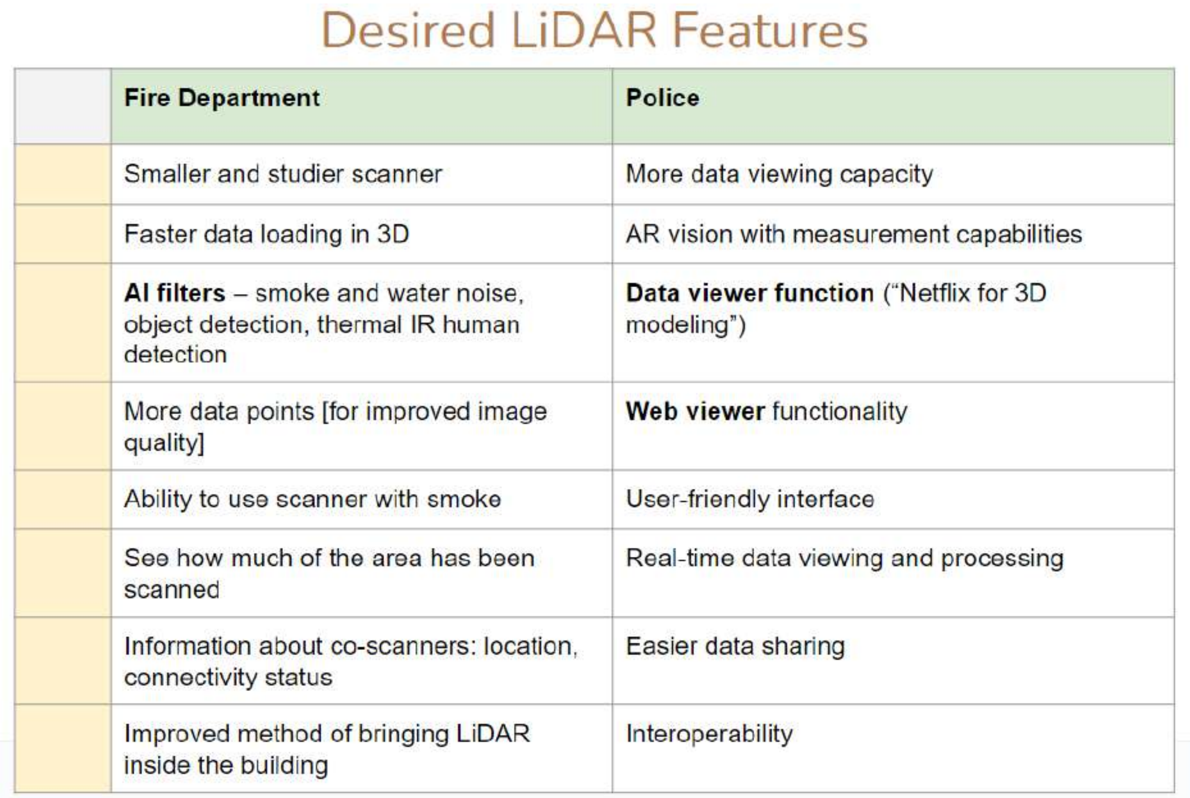
Plus Points

	Fire Department	**Police**
	Quickly assess a fire situation	Can train for building planning scenarios ahead of time
	Quickly create a structural overview [of fire site]	Capable of making measurements [from a distance]
	3D map creation	Very detailed data [when making building blueprint]
	Can see construction flaws [in post-fire assessment]	Can prepare for a building operation from anywhere [ie. remotely]
	Detailed data	Can quickly record a crime scene [drone]
	360 overview	Does not interfere with investigators on the ground [drone]
	Orientation in complex buildings	Can capture a large area [drone]

Figure 4.9: Table showing the plus points that participants experience while using LiDAR in different scenarios.

4.6. Desired Features

In the third and final round of the focus group, participants focused on linking the identified values to LiDAR features they would like to see.



Desired LiDAR Features

	Fire Department	**Police**
	Smaller and studier scanner	More data viewing capacity
	Faster data loading in 3D	AR vision with measurement capabilities
	AI filters – smoke and water noise, object detection, thermal IR human detection	**Data viewer function** ("Netflix for 3D modeling")
	More data points [for improved image quality]	**Web viewer** functionality
	Ability to use scanner with smoke	User-friendly interface
	See how much of the area has been scanned	Real-time data viewing and processing
	Information about co-scanners: location, connectivity status	Easier data sharing
	Improved method of bringing LiDAR inside the building	Interoperability

Figure 4.10: Table showing different LiDAR features that participants would like to see in their tools.

5

Interpretation of Results

5.1. Observations about the values data

5.1.1. Differing focuses

The data from police participants indicates that they seem to focus more on the user experience and usability of the laser scanner than fire department participants do. Two of the top police values are explicitly related to the user: 3. User-friendliness and 6. User Preparation/training. Additionally, 5. Visualization Capabilities and a few other values relate to the user experience indirectly by way of dictating ease of interpreting the scanner outputs [**fact check this against all data**]. In contrast, only one value from the fire department, subsection 13.2.1, relates to the user, and that has to do with the physical user experience of the scanner rather than the software interface / data acquisition aspects of the user experience. It also relates less to the user than you might think, because typically the fire department uses remote-controlled laser scanners.

On the other side, the fire department seems to focus more on the actual qualities and properties of the data than the police do. Three of the top fire department values relate in some way to the quality of the data (4. Reliability, 5. Consistency, and 6. Clarity of Data / Information), as well as one of the other named values (namerefPart3-subsec-effectiveness). A fourth top value, (namerefPart3-subsec-3Ddata), is related to properties of the data. Although the police did name Objectivity as one of their (non-top) values, they appear to be more concerned with the ability to share the captured data (4. Data Transfer, Data Sharing).

One reason for the differing focuses between agencies could be differences in the typical workflows. The fire department tends to use LiDAR scanners mounted on a remote-controlled device, so maneuverability is important insofar as it relates to the device being able to handle the scanner. The fire department was also quite familiar with the technical capabilities and possibilities of LiDAR, which could explain why they were less concerned with the user experience and more focused on the quality of the data itself. In addition, it is possible that a larger portion of scenarios in which they use LiDAR are urgent with the possibility of bodily harm, leading to more concern over how well the captured data represents the scene. (Compare this to the police use case scenarios, which infrequently involve real-time hostile interventions and often use LiDAR for precisely documenting a scene before or after an incident, when there is usually no victim in imminent danger.)

The use case scenarios described by the police were more likely to involve multiple departments, parties, or operatives. This could mean that collaboration across multiple parties is more frequent, which would also require being able to transfer data and create and share visualizations quickly and easily. That said, participants from both agencies expressed a desire for easy-to-understand visuals, because not everyone has experience with creating or interpreting LiDAR images.

5.1.2. Lack of focus on Accuracy

Interestingly enough, accuracy was not mentioned in either focus group as an important value, and did not come up in conversation until I mentioned it myself.

6

Short Discussion

In both the interviews and the focus groups, the topic of research was described as being mainly concerned with indoor applications of mobile laser scanning. This was done to limit the scope of the research and to try to align it as much as possible with the initial focus of the technical part of the report (LiDAR Quality Assessment). However, for the most part respondents spoke about all of their LiDAR use, which usually included outdoor MLS scenarios and sometimes also mentioned terrestrial laser scanner (TLS) use. This is because the specific use of indoor MLS tended to be limited and in many cases is not the bulk of the LIDAR use being taken on by the departments. In the end the scope for the CDI report includes indoor and outdoor MLS use, so these responses were helpful and relevant. However the caveat is that because the data was collected with a narrower focus in mind, some additional information about the full breadth of LiDAR use might be missing due to respondents editing down some of their information to primarily focus on indoor LiDAR applications. Thus, if further work was conducted on this topic it might be wise to explicitly include that broader scope of LiDAR usage.

6.1. Implications for Emergency Management

Zlatanova, van Oosterom, and Verbree (2004) identify three aspects of geoinformation for disaster management that are important for supporting the work of first responders in disaster scenarios: data discovery (finding and acquiring the necessary information for a user on the fly), data preparation (making sure the data is in a form appropriate for the entity requesting it), and data export (striving to make sure it is standardized to as high a degree as possible). At first glance, the first responder LiDAR use covered in this project relates largely to data discovery. After all, much of understanding how and why first responders use LiDAR relates to the types of situations in which they need to find information, and to the reasons they use a specific tool (laser scanners) to acquire that information. Interestingly, though, many of the values and top values named by the police are actually quite relevant to data preparation, data export, or both. Values like “data transfer" or “visualization capabilities" have less to do with acquiring data at a specific location, and more to do with what happens to and can be done with the data after acquisition. Similarly, many of the plus points mentioned by the police and even the fire department relate to the detailed nature of the point cloud data and the fact that it allows them to create an overview of an area or scenario for further assessment. These are relevant to data discovery, but also bleed over into data preparation by virtue of relating to what is made with the data. Many of the pain points expressed by both agencies explicitly have to do with processing and transmitting data (“must upload data before viewing/assessing," “‘lack of real time processing," “Difficult to transmit data due to large volume"). This all suggests that (1) LiDAR scanners currently serve first responder data discovery needs very well relative to the data preparation and data export needs; and (2) there is much room for improvement when it comes to supporting the processing, use, and sharing of this data among first responders and/or operatives, and even between emergency services agencies during a larger crisis. Part IV further explores how LiDAR capabilities can be improved.

Part II

LiDAR Quality Assessment

7

Background: Indoor LiDAR Scanning

This part of the project focuses on assessing the quality of point cloud data concerning emergency response efforts. To make addressing this question more feasible, the scope is limited to interior point cloud data acquired with mobile laser scanners. This more limited scope also reflects a significant subset of the LiDAR usage described by emergency first responders in First Responder LiDAR Use in Emergency Situations.

This chapter discusses some background necessary for understanding the technical analyses that follow in LiDAR Quality Assessment and Linking LiDAR Technology to the First Responder Context. First, there is an overview of concepts relevant to 3D mapping of indoor spaces, followed by a discussion of point cloud drift. The chapter ends with an explanation of some theoretical concepts used in the quantitative analyses described in section 8.2.

7.1. 3D Indoor Mapping Methods

3D indoor laser scanning is a growing field of study that comprises many areas of research, including the detection and extraction of floor plans and structural elements from point clouds (**nikoohemat_indoor_2019**; Balado, Díaz-Vilariño, Arias, & Garrido, 2017; Pouraghdam, Saadatseresht, Rastiveis, Abzal, & Hasanlou, 2019); the suitability of different mobile mapping systems for indoor mapping (**hubner_evaluation_2020**; Keitaanniemi et al., 2021; Salgues, Macher, & Landes, 2020) and emergency response (B.-P. Smit, Voûte, & Verbree, 2021); and methods of (near) real-time indoor positioning (Hess, Kohler, Rapp, & Andor, 2016; Oostwegel, 2020; Sarlin et al., n.d.; Zhang & Singh, 2014), among others.

There are many applications of 3D mapping of indoor environments, from documenting construction progress to mapping hazardous sites to building information model (BIM) (**keitaanniemi_combined_2021**; **karam2018evaluation**).

In the context of this project, indoor mapping concerns (1) the techniques and tools used to create a close representation of an indoor space and (2) the process of positioning this representation within a georeferenced coordinate system.

There are many technologies that can be used to measure and map indoor environments, including terrestrial laser scanners, mobile laser scanners, depth cameras, and photogrammetry. (**keitaanniemi_combined_2021**)

7.1.1. Terrestrial Laser Scanning

A terrestrial laser scanner (TLS) is a laser scanner that collects dense, 3D spatial data of an object or environment in the form of a point cloud (**yang_analytical_2018**). For the purposes of this report, TLS refers specifically to a static terrestrial laser scanner, the most popular laser scanning system for tasks including building documentation (De Geyter, Vermandere, De Winter, Bassier, & Vergauwen, 2022). TLS produce detailed, high-quality point clouds with both high accuracy and high precision (for example, millimeter-level accuracy and no point cloud drift), leading to TLS point clouds often being used as reference data for scans of indoor environments (Keitaanniemi et al., 2021), (De Geyter et al., 2022). However, this option comes at a cost of time and logistical complexity, especially in environments which are large and/or complex in their layout. This is because to acquire sufficient data to produce a robust point cloud of an entire environment, TLS scans must be made from multiple scanning positions to ensure full coverage (**keitaanniemi_combined_2021**). In a relatively small room, this may entail making scans from two positions, but that quickly increases as the size of the environment increases. For these reasons, alternate sources of reference data may need to be considered, depending on the scale and goals of the project and scanning environment.

7.1.2. Mobile laser scanning

A mobile laser scanner (MLS) is a type of mobile mapping system that uses a Light Detection and Ranging (LiDAR) sensor to acquire 3D data while on the move (**nocerino_investigation_2017**). Typically, an MLS includes some combination of the following components: an imaging unit containing laser scanners and/or digital cameras; an inertial measurement unit (IMU) and a Global Navigation Satellite System (GNSS) unit for orientation, navigation, and spatial referencing; and an operating system or other unit for temporal referencing(Kutterer, 2011). They often also include an RGB camera that can obtain color images or information about the scene to be scanned (**nocerino_investigation_2017**; **karam_design_2019**).

The biggest advantage of using an MLS is that they do not require fixed scanning positions or physical scanning stations like a TLS does, making it much easier and faster to acquire scenes of a given environment–especially an indoor one(Kutterer, 2011). One of the drawbacks compared to a TLS is that MLS scans have both a lower point density and higher measurement noise (**salgues_evaluation_2020**). Even still, MLS are a promising tool for data gathering in emergency response contexts because they can quickly produce detailed images and point clouds of environments on the fly. This ability also lends itself to promising potential applications such as updating and/or streaming such images in real time during a rescue operation (**smit_creating_2021**; **dilo2011data**).

7.1.3. Depth Cameras

Depth cameras use two cameras placed a few centimeters apart to detect features within a scene, and then calculates the depth of that point in space using optical triangulation. A depth camera stores a Z value for each (X,Y) pixel within the image, with Z representing the distance from the camera to the object pictured in the scene. The resulting depth map is usually represented as a grayscale intensity map of the scene with values from 0 to 255 (**Depth-Sensing-Overview**). Depth information can also be represented as a 3D point cloud. Instead of storing Z information for each pixel, a 3D point cloud contains (X,Y,Z) coordinate points that represent the actual surface(s) of the objects in the scene (**Depth-Sensing-Overview**).

Typically, depth cameras are implemented to support visual SLAM algorithms that use RGB cameras, which tend to be sensitive to lighting conditions and perform poorly in the "textureless" areas common in indoor environments. (**karam_design_2019**) However, depth cameras tend to have a short range, capturing only object depths within a few meters of the camera (Fu, Mertz, & Dolan, 2019). This characteristic poses difficulties when scanning larger indoor spaces.

7.2. SLAM

One of the challenges related to indoor mapping is being able to accurately geolocate the position of the resulting point cloud(Kutterer, 2011). GNSS signals are known to be easily jammed in dense urban environments(Rantakokko, Handel, Fredholm, & Marsten-Eklof, 2010). Because GNSS positioning does not work inside of buildings, accurately referenced indoor maps are difficult to generate (**karam2018evaluation**). Collecting the position and orientation of the laser scanner at the time of each individual measurement can help rectify this problem by producing a detailed spatial and temporal record of the laser scanner's movements relative to the scene being mapped (Kutterer, 2011).

divide into two sections SLAM, or Simultaneous Localisation and Mapping, refers to a relative positioning technique which can be used to map both an indoor environment and the position of the sensor at the same time (**karam_design_2019**; **servieres2021**). Most MLS make use of a simultaneous localization and mapping (SLAM) algorithm to track the trajectory of the scanner as it moves through a space. The SLAM algorithm uses this trajectory data to determine the scanner's relative location at the time of each measurement. The Microsoft HoloLens uses a SLAM algorithm to correct for pose drift, as do many other mobile laser scanners on the market (Khoshelham, Tran, & Acharya, 2019). One of the issues with SLAM algorithms is that they are vulnerable to drift error (Bassier, Yousefzadeh, & Van Genechten, 2015). In addition, in featureless zones they can lose tracking capabilities and are prone to failure in areas with high similarity with one another (Bassier et al., 2015).

"SLAM's goal is to obtain a global and consistent estimate of a device's path while reconstructing a map of the surrounding environment" (**servieres2021**). Put in another way, SLAM can place digital objects in a physical location–it acts as the mechanism for joining the digital world within a scanning device to the physical world around it.

There are two main types of SLAM algorithms: visual SLAM and LiDAR SLAM. Visual SLAM uses visual camera inputs to calculate the sensor's position and orientation relative to its surroundings, while at the same time mapping the environment. It can also keep track of a particular feature throughout the trajectory and use that to triangulate the camera's position (**servieres2021**). LiDAR SLAM works similarly, but uses a laser to measure the distance to objects in the environment and generate a high-precision point cloud as a result. LiDAR SLAM is known to be faster and more accurate than visual SLAM, able to produce data with survey-quality accuracy.

SLAM-enabled mobile laser scanners fall into three categories related to their mode of operation: handheld sensors, backpack sensors, and trolley sensors (Bassier et al., 2015; Karam, Vosselman, Peter, Hosseinyalamdary, & Lehtola, 2019; Keitaanniemi et al., 2021). Handheld and backpack sensors, in particular, are well-suited to indoor environments because they allow the user to maneuver around common features of indoor environments, such as corners, steps, and stairways. This research makes use exclusively of handheld scanners.

7.3. Point Cloud Drift

Indoor SLAM-based scans can result in some misalignment between the point cloud result and the real environment due to the cumulative effect of the scanner moving while scanning. Figure 7.1 illustrates what this misalignment looks like when juxtaposing a 2D floor plan of a building with a 3D mesh of the same area. The areas inside the red circles show the clearest instances of misalignment. This misalignment will be referenced as drift error in the context of this project.

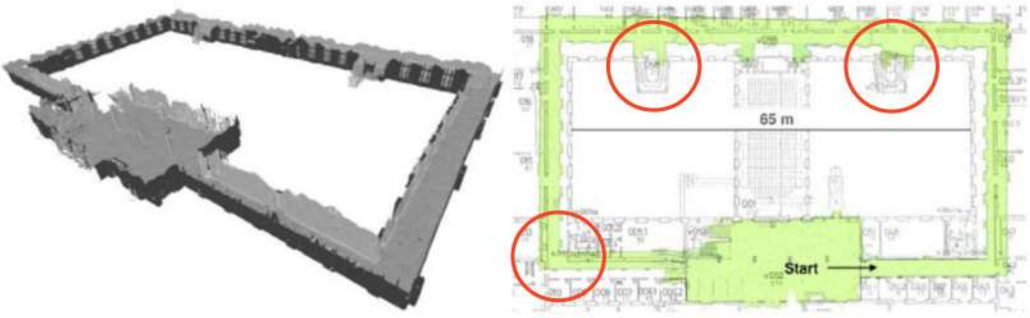


Figure 7.1: Example of the misalignment occurring in a Microsoft HoloLens scan due to drift. (**Source**: P. Hübner, S. Landgraf, M. Weinmann, and S. Wursthorn, *Evaluation of the Microsoft HoloLens for the Mapping of Indoor Building Environments.* 2019.)

Drift error is essentially an error with respect to a device's tracking capacity (**hubner_evaluation_2020**). It signifies that the device's internal positioning estimation (with respect to the device's own coordinate system) has deviated from the actual position of the device in the local coordinate system.

Drift error is not constant across all indoor scanning situations. For example, Hubner et al. 2020 (**hubner_evaluation_2020**) found a drift error of roughly 2.4 meters on a 287 meter trajectory when using a Microsoft Hololens. However, (Oostwegel, 2020) Oostwegel 2020 found a mean drift error of about 70cm on a 340 meter trajectory when using the same type of laser scanner.

7.3.1. Evaluation

Hubner et al. 2020 evaluated the tracking capability of the Microsoft HoloLens by comparing the device's estimated trajectory, and its ground truth trajectory (**hubner_evaluation_2020**). This is similar to evaluating the drift, but using trajectory data rather than the point clouds themselves. The same team also evaluated the accuracy of the HoloLens in indoor mapping cases by calculating the Euclidean distance between each point in the scanned data and the nearest point in a groundtruth point cloud made by a TLS (**hubner_evaluation_2020**). Given a full reference point cloud, this evaluation method is useful. However in an emergency response scenario it is unlikely that first responders will have a full reference point cloud available. More likely, although not guaranteed, is the presence of floor plans or a georeferenced point cloud or building model.

7.3.2. Loop Closure

There are various methods to address point cloud drift, including using loop closure and spatial matching to align the points correctly and thereby reduce the drift error (**hubner_evaluation_2020**; **servieres2021**; **oostwegel_indoor_2020**). Loop closure refers to the practice of ending a laser scan at the exact location where the scan started, thereby capturing the points in that area twice (Burgard, Stachniss, Arras, & Bennewitz, 2023). The scanner's SLAM algorithm will recognize the already-mapped area and associate the first group of points with the newly-overlapping ones (Bassier et al., 2015; Burgard et al., 2023). Closing the loop allows the SLAM algorithm to reduce any drift in the estimates of the map and the device trajectory through the use of bundle adjustment, producing a consistent and global estimate of the scanning device's path (**servieres2021**; Bassier et al., 2015). This allows it to calculate any drift or tracking errors present in the scan and make the necessary corrections by reducing the uncertainties between the predicted and observed sensor measurements (Burgard et al., 2023). Figure 7.2 shows "the advantage of loop closing": the image on the left shows a trajectory through a presumably square walking route that becomes increasingly crooked with time, culminating with a clear misalignment between two sections of the same hallway. The figure also indicates that over the course of the trajectory, the uncertainty of the sensor's pose also drastically increases. This trajectory was captured right before the loop was closed, meaning that the last measured position of the scanner was not quite in the same place as the first one. The image on the right side shows the same trajectory after the loop has been closed. In this instance, the trajectory is more or less straight as it passes through each hallway, and the previous pose uncertainty is no longer visible.

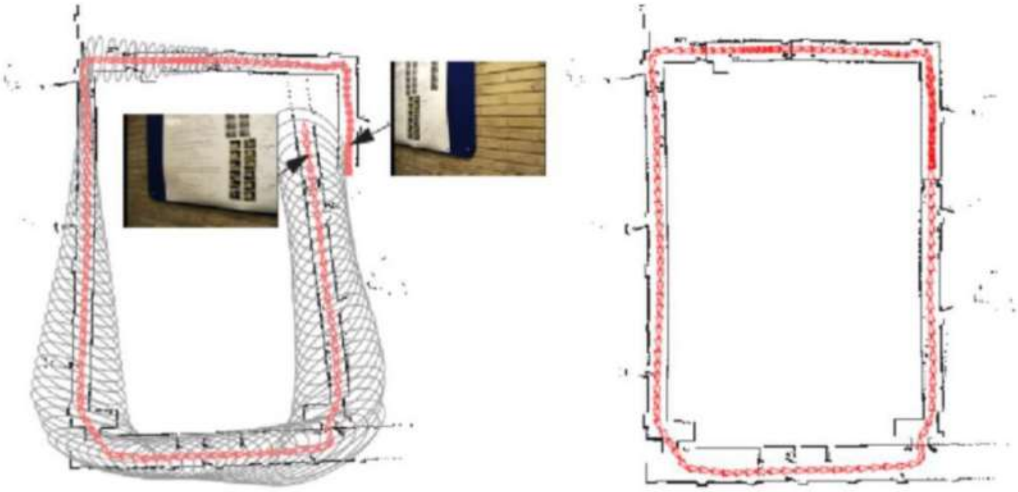


Figure 7.2: Demonstration of the way that loop closure reduces potential positioning uncertainty within a scan. (**Source**: Smit, Bart-Peter, "Creating Remote Situation Awareness of Indoor First Responder Operations using SLAM," GIMA, 2020.)

The main drawback to using loop closure to solve drift is that in some situations, it may not be possible to return to the scanning start point and end the scan there. For example, closing the loop is not necessarily realistic in an emergency scenario where first responders are evacuating people or exploring a space, or where they need to exit the structure from a different place than which they entered due to safety concerns or changes in the surrounding environment. Certain environments also tend to make loop closure more difficult, for example, long hallways (Balado et al., 2017; Karam et al., 2019).In such cases, using control points such as checkerboard or spherical targets is another way to ensure the quality of the alignment of the final scan. The control points are placed throughout the environment, their coordinates are measured with a method more accurate than the MLS, and the control points are then captured in the environment during scanning (Maboudi, Bánhidi, & Gerke, 2018). However, in an emergency response context, it is impractical to prepare and measure the control point locations on-site before or during an incident. There is therefore a need for additional ways to correct the point cloud drift that occurs in scans of indoor environments when SLAM algorithms are unable to acquire the information necessary to produce corrections on their own.

7.3.3. Georeferencing

Georeferencing is a way to ensure that data is properly located in geographical space. Point clouds acquired without GNSS need to be georeferenced to link them to the true location of the scene represented in the point cloud. Georeferencing interior point cloud data can be challenging due to the lack of ground control point (GCP) with which to execute the process (**parent2022classifying**). Despite the convenience and mobility offered by mobile laser scanners, georeferencing needs still mean that often MLS usage is tied to the use of a TLS scan for point cloud registration (Bassier et al., 2015). However, in emergency response scenarios setting up a TLS measurement campaign is not practical, nor is it practical to assume that high-quality TLS data of the given building/location's exterior will be available to first responders. Therefore, these options were not considered as part of the georeferencing workflow. It is more likely that a scan can begin outside, capturing part of the building or structure's facade which can subsequently be georeferenced either to a georeferenced point cloud or photo, or to control points taken with a handheld GPS device if available. The other option is to use the open-source 3D Basisregistratie Addressen en Gebouwen (Register of Buildings and Addresses) (BAG) or 3D **bgt!** (**bgt!**) datasets, which include virtually all buildings and structures in the Netherlands. In order to most closely mimic an emergency response scenario, georeferencing was conducted via a combination of control points and cloud to cloud registration. Bassier et al. 2015 also suggest this approach to data georeferencing, stating that adding GPS measurements to geo-located projects can both georeference the data and increase accuracy.

Cloud-to-cloud georeferencing, in which a non-referenced cloud is aligned with an already-georeferenced cloud, happens, is faster and requires collecting fewer data than using control points, targets, a TLS or some combination of the three. One study compared the accuracy of cloud-to-cloud registration and registration using a survey network for two different sets of TLS data, and found that the cloud-to-cloud method differed from the survey network method on the order of < 6mm RMSE in the X- and Y-directions and <20mm RMSE in the Z direction. The deviation was more pronounced in the z-direction due to the fact that the variance was [higher/lower – more concentrated at the floor and ceiling]. They also found that integrating GPS measurements, for example via the use of measured ground control points, greatly minimized the bending deviations in the z-direction (Bassier et al., 2015).

7.4. Theoretical Concepts

7.4.1. Iterative Closest Point

The iterative closest points algorithm is a method of point cloud registration. It works by iterating over the transformation matrix that will minimize the distance between the points in the datasets being aligned.

7.4.2. RANSAC

Random Sample Consensus (RANSAC) is an iterative shape detection algorithm. It is used to identify simple shapes, such as lines and planes, within a point cloud (Ledoux, Peters, Ohori, & Pronk, 2023). RANSAC works by randomly sampling the input cloud within a minimum number of points, and testing whether each point is close enough to the desired shape to be an inlier.

7.4.3. Alpha Shapes

Alpha shapes are essentially a convex hull, which is the outer shape of a given set of points (Ledoux et al., 2023).

7.4.4. Hough Transforms

Hough Line Transform

The Hough Line Transform (Duda & Hart, 1972) uses a voting algorithm to detect shapes or simple features in an image. To do so, the input points are transformed from the image space into the parameter space. The Hough Line transform is robust to noise and occlusion (Henderson, Ingleby, & Ford, 1997), which makes it useful for indoor mapping.

Probabilistic Hough Transform

The Probabilistic Hough Transform optimizes its calculations to require less computational power than the Hough Line Transform, by only considering a random subset of the points (Galamhos, Matas, & Kittler, 1999).

7.5. Problem Statement

Indoor Laser scanning encounters a specific set of challenges. One of these is the lack of GPS access indoors, which can impact the quality of the data. SLAM algorithms were designed to correct this problem, but require careful scanning practices (ie. closed loop, multiple loops if possible) that cannot always be guaranteed in an emergency situation. Without SLAM, the data quality suffers. So this part of the thesis investigates how to assess the quality of indoor LiDAR data acquired without using SLAM.

The goal of this second part of the report is to develop a method to evaluate the quality of LiDAR data in terms of point cloud drift. The second goal is to use this method to compare the quality of data from three different LiDAR scanners.

7.6. Research Question

The overarching question addressed in this part of the project is

How can LiDAR sensor, data acquisition, and data processing capabilities be evaluated for indoor emergency response?

The sub-questions are as follows:

1. Which metrics and/or point cloud characteristics are useful for assessing point cloud quality with respect to drift?
2. What is a suitable workflow for quantifying the drift error present within an interior point cloud?
3. How generalizable is that workflow to point clouds from different mobile laser scanners, and does the application of the method differ depending on which MLS system has produced the input point clouds?
4. Is there a difference in the amount of drift observed in point clouds from different mobile laser scanning systems?

The research objectives are to

1. Develop a workflow to evaluate the quality of LiDAR data with respect to point cloud drift
2. Compare the quality of data from three different LiDAR scanners

The outcomes are (1) a qualitative and quantitative methodology for assessing point cloud quality, and (2) an application of these methodologies to point clouds from three different scanners.

8

Point Cloud Quality Assessment Methodology

We have established that assessing the quality of a point cloud here means identifying and measuring the point cloud drift present in the point cloud. Figure 8.1 shows the general workflow for the point cloud quality assessment methodology.

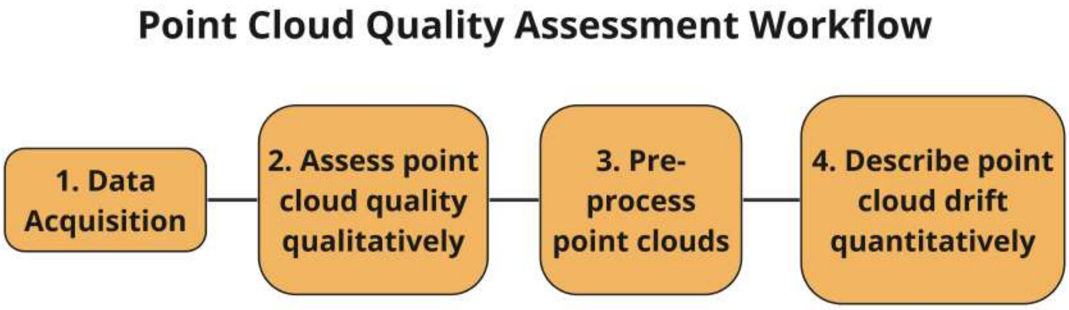


Figure 8.1: Flowchart depicting the general project methodology.

First, point cloud data was acquired from the study location using three different mobile laser scanners. Second, the point cloud quality was assessed qualitatively for the presence of point cloud drift and other distortions. Third, pre-processing methods were applied to the point clouds to prepare them for further analysis. Lastly, a computational workflow was designed to quantitatively describe the point cloud drift and then applied to the acquired point clouds.

8.1. Data Acquisition and Description

8.1.1. Acquisition location

TU Delft's old applied sciences (TNW) building, also known as Building 22, was chosen as the scanning location for this project. (The descriptions for the other candidate locations can be found in section B.1.)

The most important factor in choosing a location was whether there was enough room in the building's layout to allow for walking multiple different trajectories with the same starting and ending points. In addition, the possibility to walk trajectories with an open loop (ie. one with different starting and ending points) was also important because at this stage in the research it was not clear whether that would also be part of the scanning protocol/research methodology. The TNW building fulfilled this requirement best out of the options considered. The presence of multiple long hallways spanning the length and width of the building also allows for commentary/observations about how the different MLS scanners function in relatively uniform, "non-distinct" environments (in which they historically perform less well). The full descriptions of the TNW building is below (subsection 8.1.1, and the descriptions for the other candidate locations can be found in section B.1

Faculty of Applied Sciences (building 22): Lorentzweg 1, 2628 CJ Delft

(a) the TNW main entrance

(b) On the left, one part of the long hallways that stretch along the front of the building (perpendicular to the windows visible in Figure 8.2a
)

Figure 8.2: The (a) exterior and (b) interior of the old applied science building on TU Delft campus.

The TNW building is larger than Echo and EEMCS, covering almost twice as much ground. (See a comparison of the building sizes in Figure 8.3, with the TNW building in the green circle, EEMCS in the yellow circle, and the empty plot of the Echo building in the magenta circle.) The front of the building is covered by five uniform rows of square windows that stretch along the entire facade. The sides vary with respect to the window arrangements, and the back side has a five-pronged shape (visible in Figure 8.3 and Figure 8.9). For the most part, the bottom edge of the windows is roughly **1 meter [check]** above the interior floor height of the building. There are two widely-used entrances: a main entrance in the front of the building (pictured in Figure 8.2a) and a side entrance on the left side of the building; both are located at the top of a small set of stairs. In addition, there are multiple back entrances accessible with a building key card.

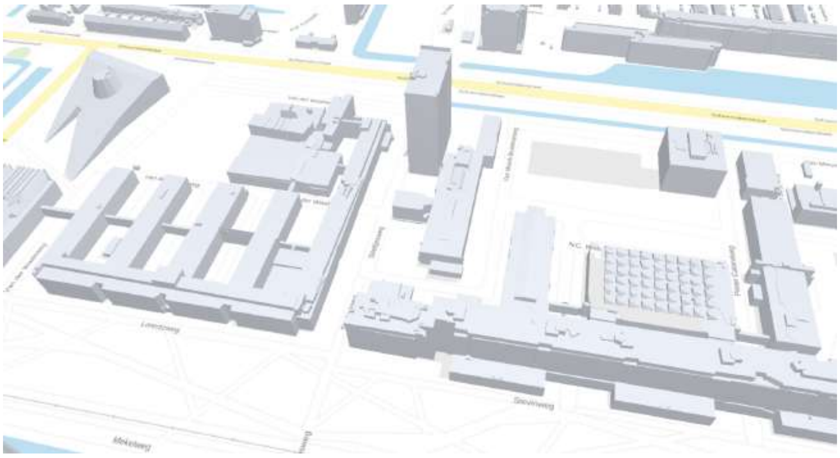


Figure 8.3: 3D BAG (see subsection 8.1.5) image of the TNW building (green), EEMCS (yellow), and the plot where the Echo building was eventually built (magenta). At the time of the airborne LiDAR campaign that collected the data used in these 3D BAG models, the Echo building had not yet been built, thus only the outline of the building plot is visible.

The interior of the building is characterized by long hallways along the front side of the building, with five wings branching off of it in the form of perpendicular hallways. Each hallway/wing contains

Scanner	Company	Cost	Sensor type	Capture Range	Average Error	Resolution
Zeb Revo RT	Geoslam	€26,000.00	ToF LiDAR	0.6m – 30m	up to 6mm	0.625° x 1.8° angular resolution
L515	Intel	€649.00	ToF Lidar, Depth Sensing	0.25m – 9m	5mm avg error at 1m distance w/2.5mm std deviation; 14mm avg error at 9m distance w/ 15.5mm std deviation	• 1024 pixels x 768 pixels (Depth camera) • 1920 pixels x 1080 pixels (RGB frame)
iPhone 12 pro	Apple	€1,100.00	Direct ToF LiDAR	5m	+/- 1cm for objects 10cm object detection limit is 5cm	• 2532 pixels x 1170 pixels at 460ppi • 0.2° x 0.2° angular resolution

Table 8.1: Table showing some of the most important scanner specs.

meeting rooms, classrooms, offices, and lab/research spaces. The wings are connected to one another by hallways, passageways, and/or staircases. For example, there are at least four entrances and exits that can be used to chart the scanning trajectory. In addition, the entire [sq footage] building is connected from the inside via a system of large and narrow hallways. Multiple stairway levels also make it possible to either easily create a closed loop or chart a unique scanning path through the building. All in all, the TNW building's structure and layout is well-suited to the kind of data collection required for this project. "The Faculty of Applied Science has several departments that are sharing six wings and those wings consist of around 1200 spaces. The building consists of a front block (main building) and five wings (A, B, C, D, and E) attached to it. Each wing has multiple emergency exits, and all wings are connected by the main building and the bridges located on the first floor" (Alattas et al. 2020).

8.1.2. Scanning Protocol

Scanning was carried out in two campaigns on four separate days on the TU Delft campus. Open-loop scans were made using a few different routes through the TNW building. Some were only on the ground floor and some also included the first floor, and for the most part started and ended outside. The same routes were followed with each of the 3 scanners. About half of the trajectories started outside or inside the side entrance (near segment 0 in 9.1), and then passed through the hallways along the wall of the building to stop at the main entrance ((near segment 3 in 9.1). The other half of the trajectories had the opposite route, starting at the main entrance and ending at the side entrance. Control points outside the building were measured with GNSS with the Leica GS18-i. Parts of the building façade were photographed to retrieve GPS coordinates via photogrammetry.

Literature about scanning indoor environments also provides a number of tips for producing the most accurate, detailed, and artifact-free scans possible:

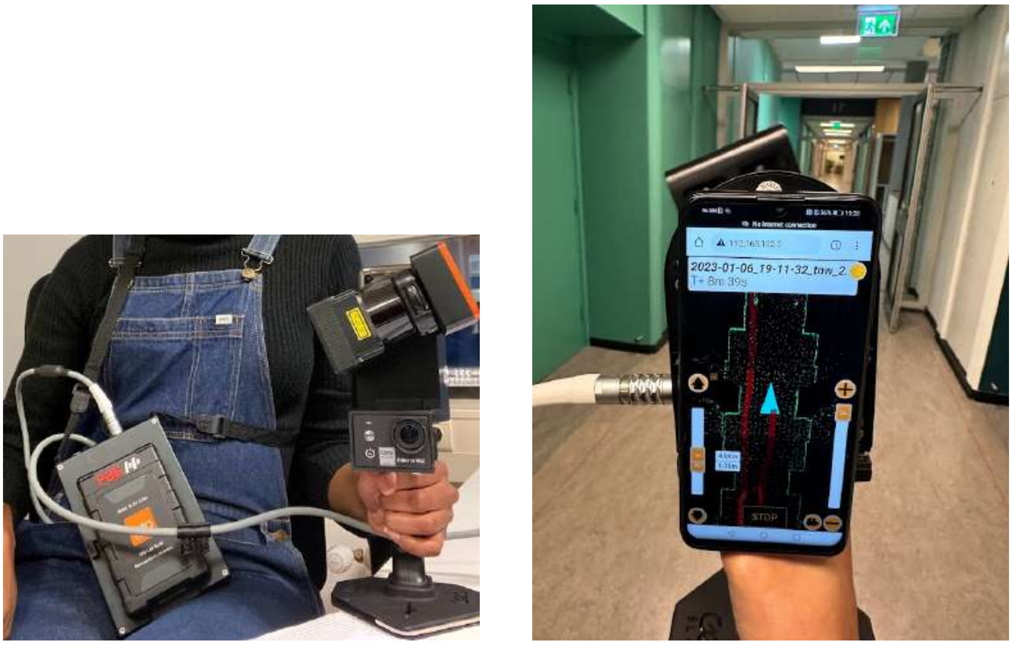
- Begin and end scan at tie points made using GNSS sensor
- Walk slowly enough to ensure that the scanner rotates to get full coverage of the surroundings with each step
- Checkerboard targets (Maboudi et al, 2018)
- Perform a scanning trajectory within a room rather than just quickly entering and exiting (Keitaanniemi et al, 2021)
- Perform multiple loops during acquisition (Maboudi et al, 2018)

As the goal was to simulate a realistic-to-negative acquisition environment, these guidelines were neglected. With the exception of the checkerboard targets, which were scanned to use during georeferencing. A copy of the scanning protocol used during data acquisition can be found in section B.3.

8.1.3. Mobile Laser Scanners

Three mobile laser scanners (MLS) were used to capture the indoor point clouds used for this research. Table 8.1 gives a few important specifications for the scanners, which are further described in the following subsections. (Note: additional scanner attributes are discussed in Comparing Scanner Attributes and Scanner Attribute Comparisons.)

ZEB-REVO RT



(a) (b)

Figure 8.4: The Zeb Revo RT handheld LiDAR scanner

The Zeb Revo RT is a lightweight, handheld mobile mapping system designed by GeoSLAM and released in 2018. Co-founded by Australia's national science agency (CSIRO), GeoSLAM has developed the Zebedee line of portable, handheld laser scanners which includes the Zeb Revo RT (CSIRO, n.d.). The scanner uses ToF measurement at a wavelength of 905nm. Its sensor has a resolution of 0.625° (horizontal) by 1.8° (vertical), with a 360° (horizontal) x 270° (vertical) field of view (FOV) (**salgues_evaluation_2020**; **ZebRevo-factsheet**). The Zeb Revo RT used for this project is not capable of recording intensity or RGB information (although the latter is possible with the purchase of an optional GoPro camera); the point cloud output is strictly 3D positional coordinates.

Intel L515

The Intel L515 is a small, handheld depth camera with RGB and Infrared capabilities ("Intel® RealSense (TM) LiDAR Camera L515", 2021). In addition to XYZ coordinates, it can also capture RGB and Intensity values. Introduced in 2020, the Intel L515 uses a combination of ToF and depth sensing, and its laser works at a wavelength of 860nm. The depth sensor has a resolution of 1024 pixels (horizontal) by 768 pixels (vertical), with a 70° (horizontal) x 55° (vertical) FOV ("Intel® RealSense (TM) LiDAR Camera L515", 2021). The RGB sensor has a resolution of 1920 pixels (horizontal) and 1080 pixels (vertical), with a 2 Megapixel camera.

(a)

(b)

Figure 8.5: The Zeb Revo RT handheld LiDAR scanner

Apple iPhone 12 Pro

Introduced in 2020, Apple's iPhone 12 Pro and iPhone 12 Pro Max include a LiDAR sensor as part of the built-in camera options for the first time. The iPhone thus has both LiDAR and RGB capabilities, allowing it to produce RGB point clouds. Figure 8.6 shows the back side of the Apple iPhone 12 Pro Max; visible are its 3 camera lenses, the flash (top right corner), and the LiDAR scanner (bottom right corner). At the time of writing, Apple has not made detailed specifications for the iPhone 12 Pro's LiDAR system publicly available (**diaz-vilarino_3d_2022**). However, some of this information can be gathered from estimations and studies which have tested and/or tried to determine the system's capabilities.

Figure 8.6: Back side of the Apple iPhone 12 Pro Max, showing its 3 camera lenses and the LiDAR scanner; Daniel Acker/Bloomberg, from this Forbes article

The iPhone 12 Pro uses direct time of flight LiDAR measurements (**luetzenburg_evaluation_2021**) with a wavelength in the 800nm range(Rangwala, 2020). The sensor has a resolution of 2532 pixels (horizontal) by 1170 pixels (vertical) at 460 points per inch(**iphone-lidar-specs**), with a 0.2° (horizontal) x 0.2° (vertical) angular resolution and a 120° (horizontal) x 30° (vertical) angular FOV (Rangwala, 2020). For example, and the capture range was given by (**diaz-vilarino_3d_2022**), (Razali, Idris, Razali, & Syafaun, 2022), and (Rangwala, 2020), and the average error was given by (**luetzenburg_evaluation_2021**).

At the time of writing, it is only possible to use the LiDAR sensor via one of various 3rd-party apps available on the Apple Store. In this case, the iPhone scans were made using the Scaniverse App.(**Scaniverse**)

8.1.4. Other Tools

CloudCompare

CloudCompare software was used for visualizing the point cloud data as well as for many of the preprocessing and alignment tasks described in subsection 8.3.2. In addition, CloudCompare was used to georeference the point cloud data collected at the TNW building.

Dot3D Pro
Dot3D is a proprietary point cloud processing software and"complete professional 3D scanning application for all Windows and Android devices equipped with DPI/RealSense 3D cameras" (LLC, 2023).

A free trial of Dot3D Pro software was used to capture the L515 point clouds and export them to .las format because the native Intel RealSense Viewer software was incompatible with my laptop. Dot3D offers an option to optimize scans before saving and/or exporting them. However, because it is not clear what exactly their optimization process entails, the raw, non-optimized versions of the point clouds were exported and used as the basis for all pre-processing and analysis.

Leica GS18i
The Leica GS18i is a pole-mounted GPS unit with a built-in photogrammetric camera. This instrument was used to measure the precise locations of the control points during mobile laser scanning, so that those scans could later be georeferenced (2020).

The Leica GS18i has a general device accuracy of $8mm+1ppm$ in the horizontal direction and $15mm+1ppm$ in the vertical direction (for kinematic observations, which is what was used). It has an accuracy of 2cm to 3cm in 2D when using the imaging function from between 2m and 10m from the object. (2020)

Leica Infinity
Leica infinity software was used to extract the GPS coordinates measured at the TNW building with the Leica GS18i, so that they could be used for further analysis.

Python
The Python programming language (version 3.10.10) was used to examine and analyze the point cloud data. Programming scripts were written to do tasks such as extracting floor planes from point clouds (as seen in Figure 8.21) and comparing the distances between observed and reference wall edges. Relevant libraries include numpy, open3d, geopandas, and scikit-image.

QGIS
QGIS is a free, open-source GIS and spatial analysis software (QGIS.org, 2022a). The software can view, create, analyze, and export combinations of vector data and raster data; compose maps; and perform various spatial analyses (QGIS.org, 2022b). It also has some basic point cloud visualization capabilities, although it was not used for that purpose in this project. QGIS (version 3.22) was used primarily to digitize the floor plans of the study area as shown in Figure 8.7.

8.1.5. Reference Data

This project required reference data that both situates the TNW building properly in geographic space and represents the building correctly in terms of its shape and dimensions. To achieve this, a combination of interior floor plans provided by the university and 3D building model data from 3D BAG was used (Peters, Dukai, Vitalis, van Liempt, & Stoter, 2022). Figure 8.7 shows one of the pages of the floor plan, while Figure 8.9 shows the 3D BAG model of the study area.

Digitizing

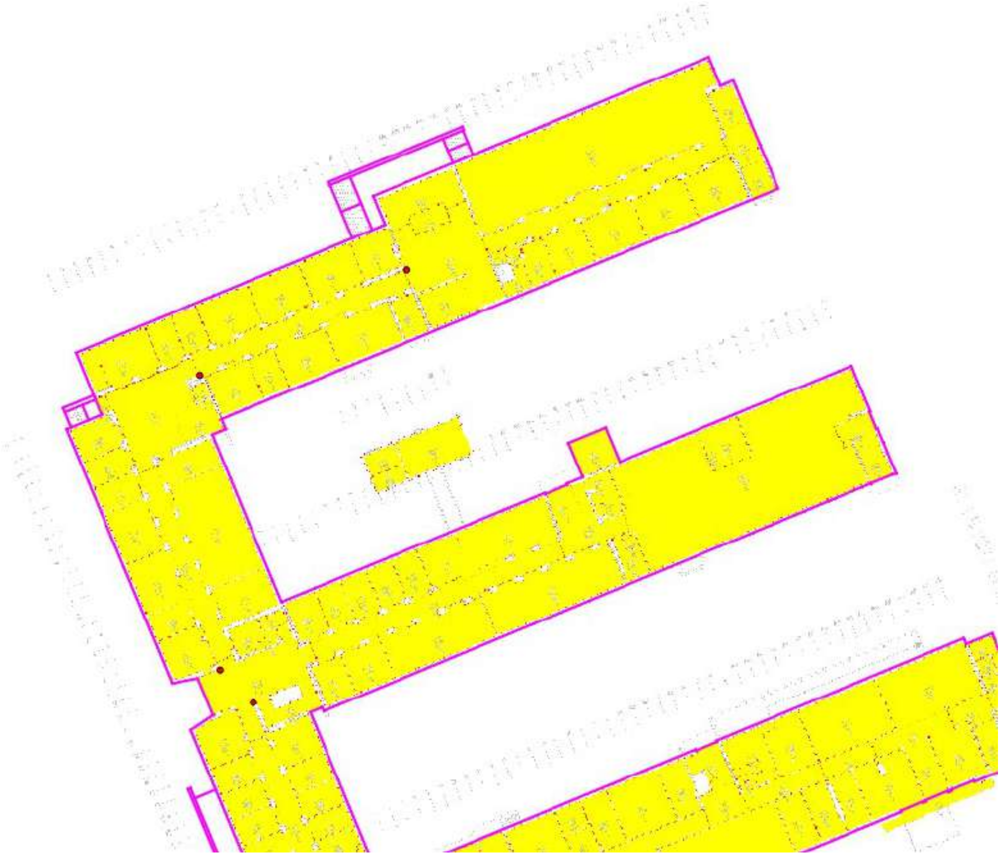
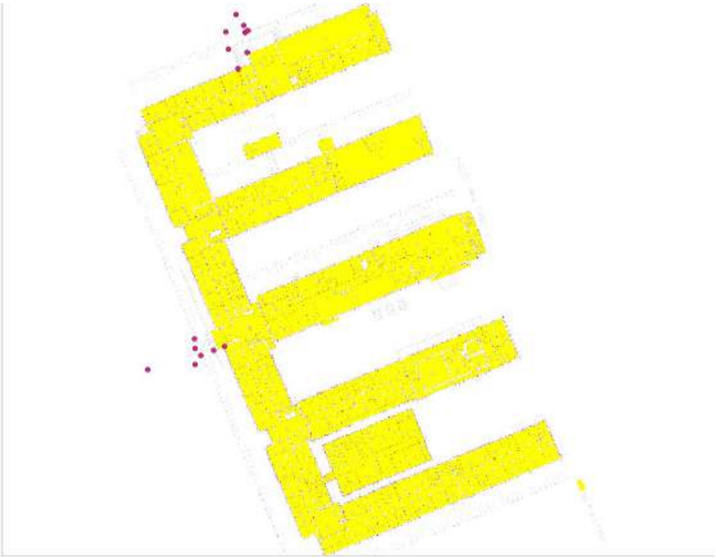


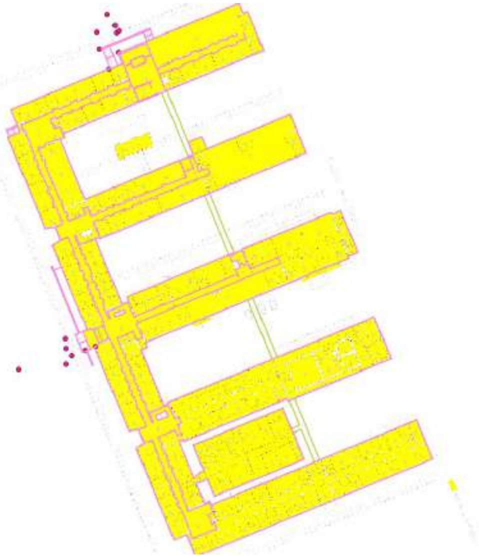
Figure 8.7: Part of the ground floor floor plan, in the process of being digitized. The thin red lines represent interior rooms, and are marked on the original floor plans. The thick purple lines are polylines (added in QGIS) used to represent exterior boundaries of the building.

Because the floor plans were provided in PDF form, they needed to be digitized before they would be suitable for use in a reference capacity. Using QGIS, the fire door segments were split from the other interior wall segments. Then the interior hallway and wall segments were merged as much as possible into a single line feature. Merged all fire door line segments into one multiline feature with the same wall type value
Classified the floor plan wall segments into the following types (across layer type):

Note that doors are not distinguished from hallway/interior walls, because it was not necessary for this analysis. Figure 8.8 shows three steps in the process of digitizing the floor plans.



(a) The ground floor of the floor plan, with the GPS control points overlaid in pink



(b) The ground floor exterior and interior walls are now digitized, in pink. The brown-yellow lines represent the glass walkways present on the first floor of the building.

Figure 8.8: Three digitized layers of the TNW floor plan.

Georeferencing the Reference Data

The floor plans also lacked a scale, coordinates, or any indication of georeferencing. To remedy this, the floor plans were georeferenced to the 3D BAG model of the Applied Sciences building in the **RD-New (EPSG:28992)** reference frame. Shown in Figure 8.9, the 3D BAG model used for the georeferencing was in the 2.2 Level of Detail, which includes detail in the elevated building parts above the terrain.

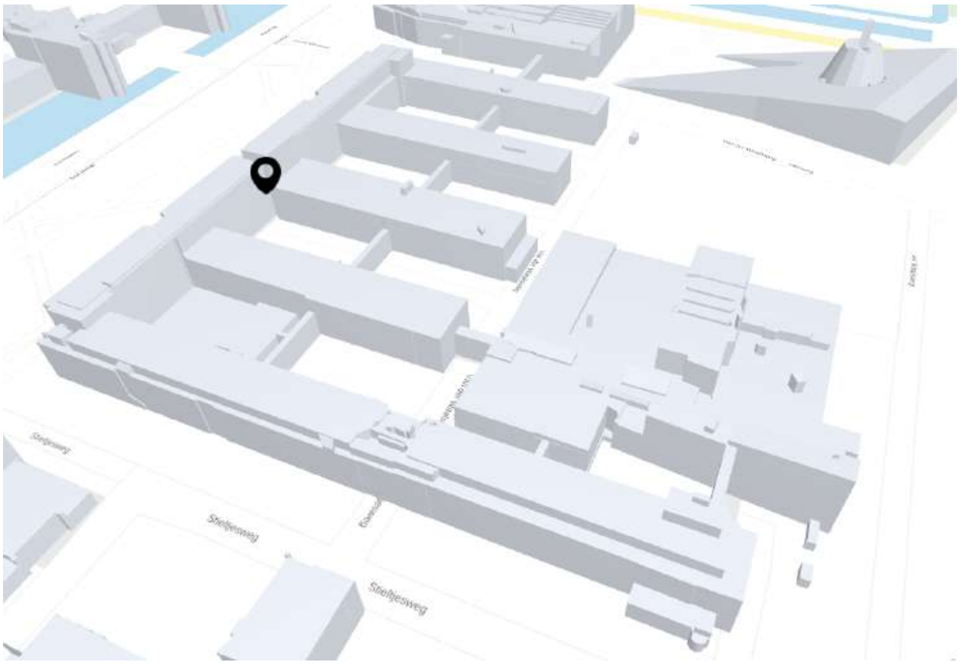


Figure 8.9: 3D BAG model of the TNW building at LoD 2.2.

8.1.6. Data Description

In total, 28 point clouds were acquired from the three mobile laser scanners. Of these, 6 were unusable fragments and 4 others only included outdoor areas of the building. Six point clouds (2 from each scanner) were chosen to use as examples for the analyses in this section. Table 8.2 shows a few characteristics of six of the example point clouds, and a full description of all collected point clouds can be found in **??** in section B.7.

Point Cloud	Scanner	Number of points	Contains outdoor area?	RGB Data	Intensity Data
1	Zeb Revo RT	17,332,858	no	no	no
2	Zeb Revo RT	15,956,913	yes	no	no
3	iPhone 12 Pro	775,466	yes	yes	no
4	iPhone 12 Pro	603,226	yes	yes	no
5	Intel L515	36,174,509	yes	yes	yes
6	Intel L515	57,877,272	no	yes	yes

Table 8.2: Some information about the six example datasets.

In the sections below are examples of what a point cloud from each scanner looks like.

Zeb Revo RT

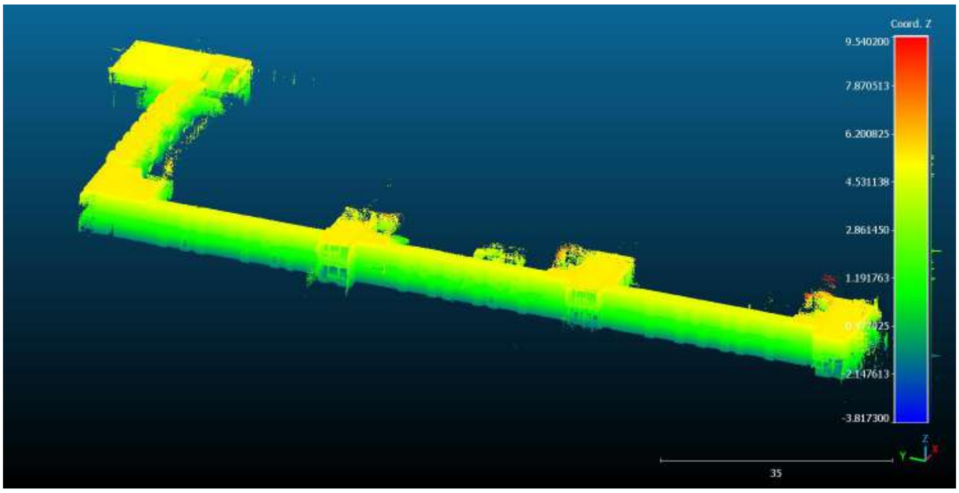


Figure 8.10: Example of a Zeb Revo RT point cloud, colored according to Z coordinate value (in m above the geoid). The color scale goes from dark blue at the lowest Z value to red at the highest Z value.

Intel L515

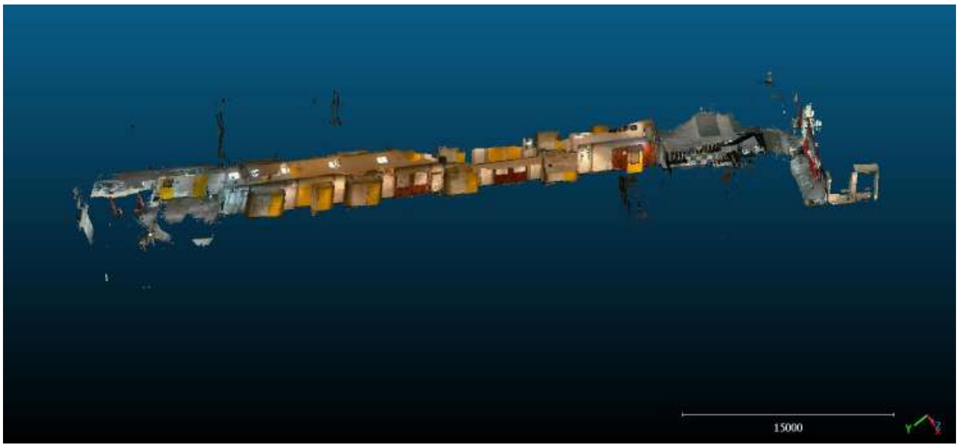


Figure 8.11: Example of an Intel L515 point cloud with RGB coloring.

iPhone 12 Pro

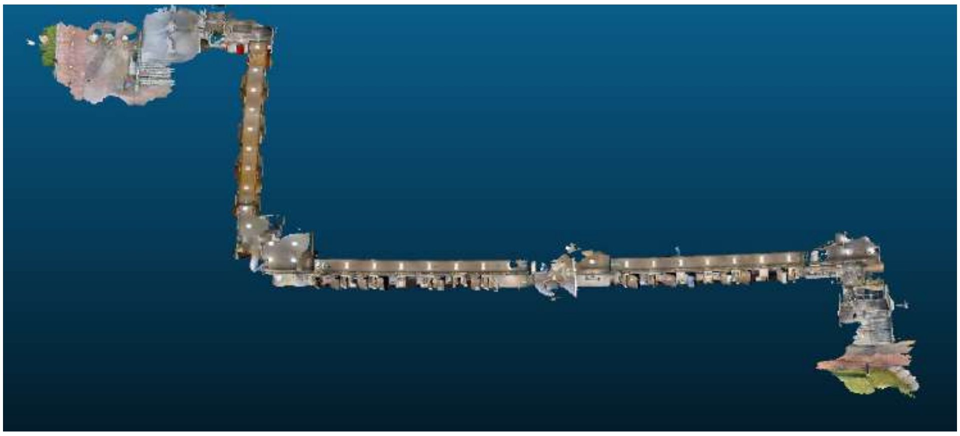


Figure 8.12: Example of an iPhone 12 Pro point cloud with RGB coloring.

8.1.7. Data Artifacts

A data artifact is a feature occurring in a point cloud that misrepresents the true scene and/or reduces the accuracy of certain areas of the data (Tang et al. 2007). The following are some examples of the data artifacts occurring in each type of scan.

iPhone

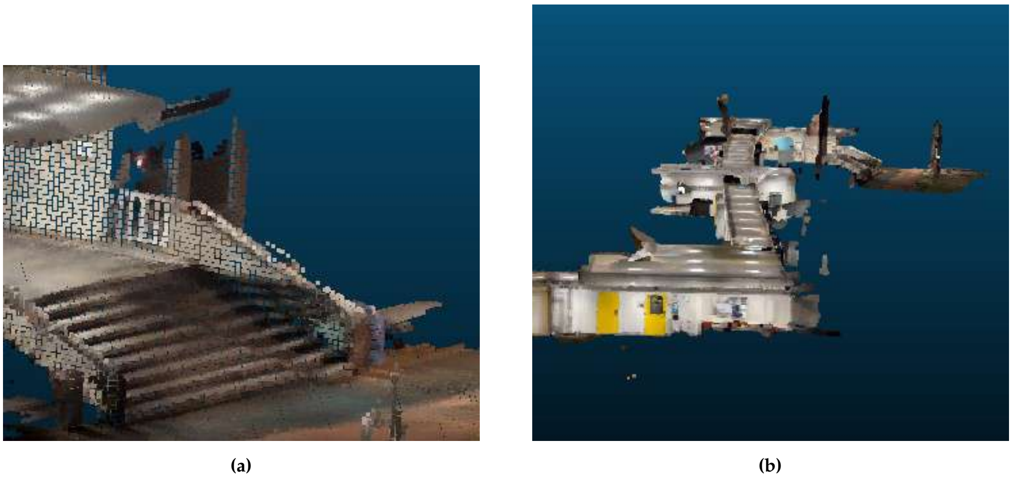

(a) (b)

Figure 8.13: Examples of artifacts from the iPhone 12 Pro

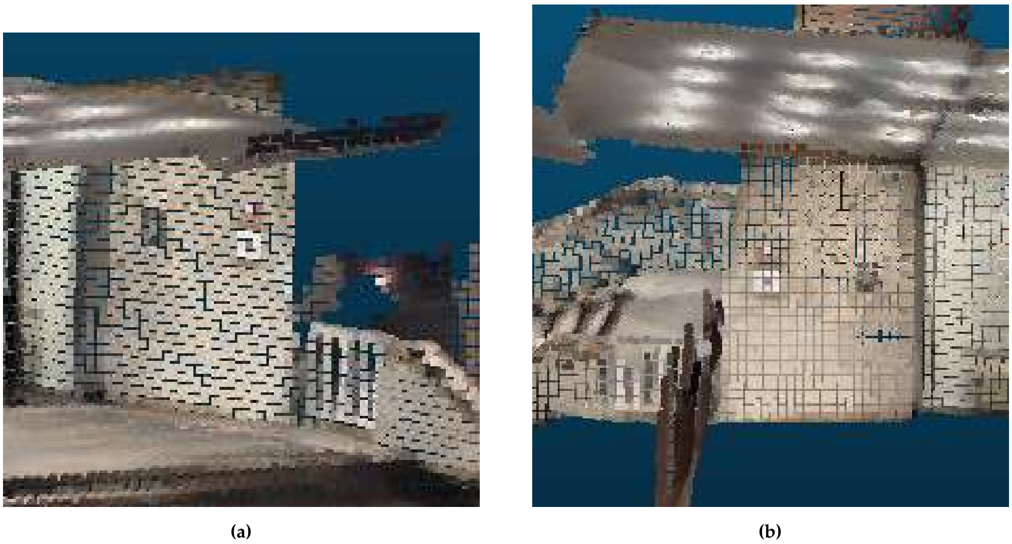

(a) (b)

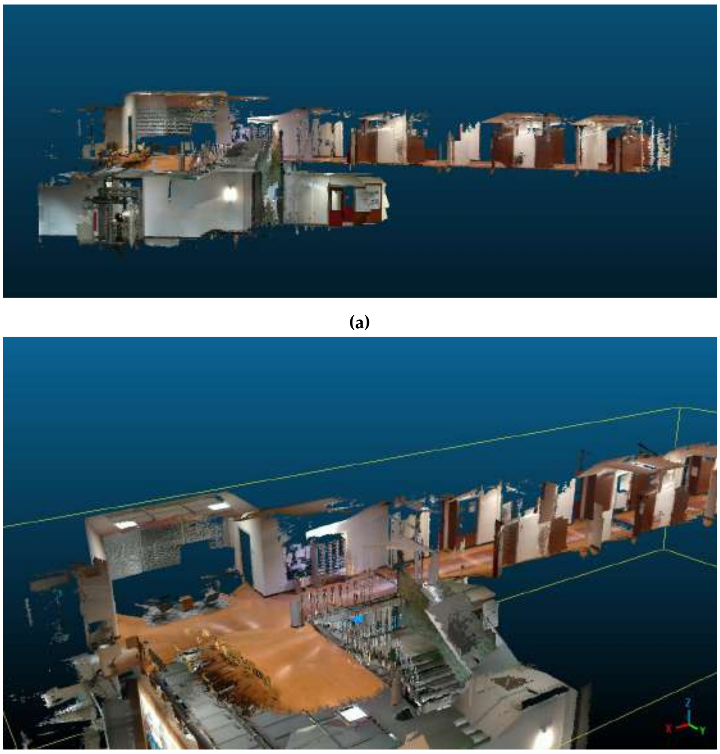
Figure 8.14: Examples of artifacts from the iPhone 12 Pro

Looking at the iPhone 12 Pro scans, there are also a few artifacts worth taking note of. **Artifact 1:** In Figure 8.13a, the wall along the side of the stairwell at the head entrance is completely shadowed (rather than being white) and it appears that the stairs have been falsely mirrored onto the wall surface.

Artifact 2: In Figure 8.13b, when you look along the length of the hallways you can see the places along the trajectory where it bends inward rather than staying straight. This is likely an expression horizontal drift affecting the images.

Artifact 3: In Figure 8.14, the paper target placed on the left (when exiting the building) exterior wall at the top of the main entrance stairwell is clearly visible. However, the back side view of that same wall also shows the target, which means that the wall thickness and features of the other side of the wall were not recorded during the scanning. This is not surprising because no special care was taken to scan that portion of the wall after exiting the building. But it is (1) an important note to consider when visually interpreting scenes taken with iPhone LiDAR, and (2) an important reminder to scan both sides of such exterior walls whenever possible in a real collection scenario to minimize the chance of misinterpreting the resulting images.

Intel L515



(a)

(b)

Figure 8.15: Examples of artifacts from the Intel L515 scanner.

Depth cameras tend to struggle when confronted with highly-reflective (ie. bright) surfaces, transparent surfaces, and larger distances (Fu et al., 2019). These conditions lead to holes and large missing areas within the resultant depth map, which can be seen in many of the Intel L515 scans. Figure 8.15 shows a few examples of different data artifacts common to the Intel L515 scans: low ceiling coverage, holes or missing patches in the walls, and distorted/unresolved features to name a few.

Zeb Revo RT

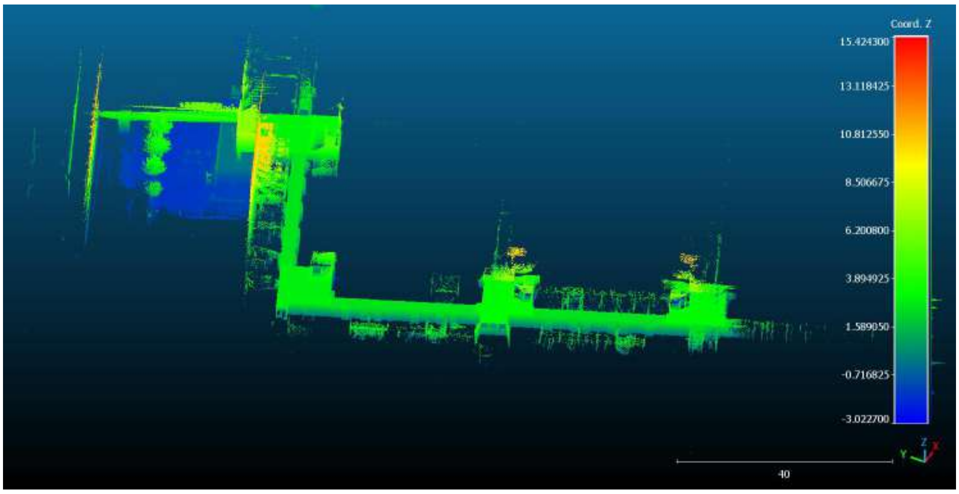


Figure 8.16: Example of reflectance noise from the Zeb Revo RT scanner.

The Zeb Revo RT's long range, coupled with the presence of many windows and a few glass walkways, led to noise due to reflectance scattering as the primary artifact. Much of this was able to be removed during the pre-processing stage.

8.2. Qualitative Assessment

This section describes the procedure used to do a qualitative assessment of the acquired point clouds. It is a relatively simple assessment of whether the scanner produced an accurate representation of the scene. In examining a point cloud, sometimes it is possible to recognize point cloud drift with the naked eye. This has to do with the topographic quality of the point cloud, ie. whether elements (say, a staircase, chair, or wall) in the scene visually appear where and in the shape that they should. Although there are many possible metrics of topographic quality, those chosen are characteristics relevant to point cloud drift.

Looking at each point cloud in a 3D viewer, we found the most prominent distortions within the image and answered each question with a score between 1 and 3. 1 means not present, 2 means moderately present, and 3 means heavily present.

Q1. Visible hallway warping (horizontal)?

When looking at the point cloud in a top-down, bottom-up, or front/back view, is the hallway visibly warped or bent in the horizontal direction? Figure 8.13b is an example of moderate horizontal warping.

Q2. Visible hallway bending or tilting (vertical)?

When looking at the point cloud in a front/back or side view, does the hallway visibly bend or tilt up or down? Do the heights of the hallway floor and ceiling appear to stay constant with respect to the ground?

Q3. Visible bending or twisting of hallway walls?

When looking at the point cloud in a front/back or side view, do the walls of the hallway twist or tilt in a direction that makes the orientation no longer perpendicular to the floor, ceiling, or ground? Figure 8.17 is an example of heavily-visible hallway twisting.

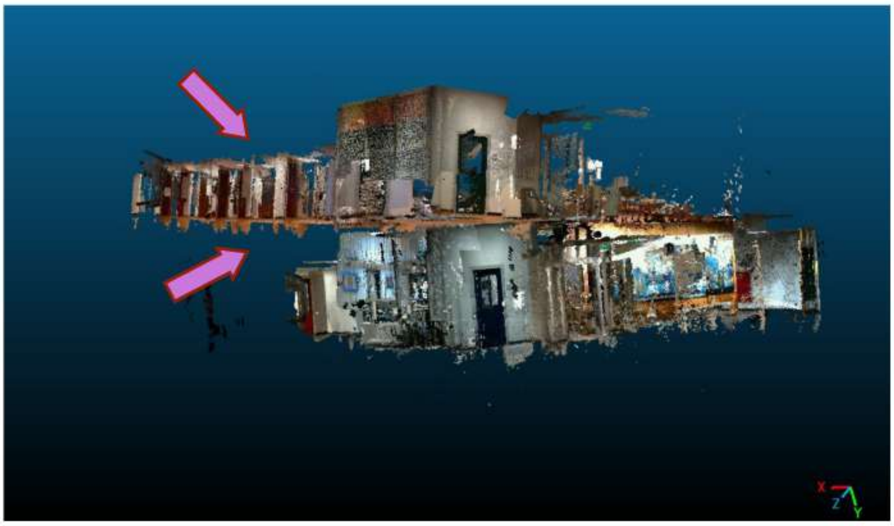


Figure 8.17: Example of heavily visible hallway twisting.

Q4. Uneven thickness in walls and beams?
Do walls, beams, or other structural elements have the same thickness from one end to the other?

8.3. Quantitative Assessment

This section details the computational workflow applied to the point clouds after acquisition. This workflow starts with Point Cloud Georeferencing and Pre-processing, and then moves on to various operations which together comprise the Drift Assessment Workflow.

In contrast to the Qualitative Assessment, the quantitative drift assessment is related to the metric quality of the point cloud. This is clear from its focus on measuring the amount of drift in spatial units, in terms of alignment with or deviation from ground truth data such as floor plans and GPS points.

8.3.1. Point Cloud Georeferencing

The first step in performing a quantitative assessment of the data was to georeference the point clouds. This ensured that they can be accurately compared to the ground truth data.

The GNSS image points and gcp measured with the Leica GS18i were used to georeference the data to the **RD-New (EPSG:28992)** reference frame.(subsection B.8.1 discusses how the Leica GS18i data was processed in QGIS.) There were 15 GCP collected in total, half on the front side of the building and the other half on the aula side. The orthometric height values were adjusted to compensate for the height of the traffic cones and the wine bottles used to mark the location of the control points in some of the LiDAR point clouds. The adjusted height field for the cones was calculated by applying an offset of 46cm to the height, and for the wine bottles the offset was 32.5cm.

The most important aspect of this georeferencing process is that each point cloud is only georeferenced on the starting side of its scanning trajectory. This is because the data collection simulates a scenario in which first responders do not have the time or ability to close their data acquisition loop. It is thus expected that at the end of the scanning trajectory, there will be misalignment between the point cloud and the ground control points–this misalignment is the drift which can subsequently be measured with the drift assessment workflow.

The ground control points were visible at the starting side of three of the six example clouds, so these clouds were directly georeferenced to the ground control points with an average RMS around 2cm. The other example clouds were first roughly aligned with the newly-georeferenced clouds using point picking of targets and other visible, easily-identifiable structural features such as stairs and benches. Next, fine alignment was applied to the newly-aligned point clouds using the ICP algorithm. This process of rough alignment followed by fine alignment produces a closer alignment between the two clouds which improves the basis for the subsequent analysis(**salgues_evaluation_2020**; **luetzenburg_evaluation_2021**).

8.3.2. Pre-processing

Each scan is pre-processed according to the following steps:

1. SOR filter to remove noise if needed (mainly for Zeb Revo due to longer range, Intel due to short range)
2. Subsample randomly to 10million points
3. Add Z coord as scalar field
4. Compute normals using 2D triangulation
5. Orient normals with minimum spanning tree
6. Save Nx, Ny, and Nz as scalar fields
7. Add dip angle and dip direction as scalar fields
8. Save the cloud as .ply file

Later, when the point clouds are loaded into Python to begin the drift assessment outlined in **??**, an additional pre-processing step is applied: the input point cloud is uniformly downsampled by way of voxel downsampling. A voxel, or volume pixel, is a representation of a data point in a 3-dimensional uniform grid space. Voxel downsampling works by creating a regular voxel grid and containing the point cloud points within the nearest voxel. Then a single point is generated per voxel by averaging all the points within that voxel, resulting in a downsampled version of the input point cloud(**Open3d-voxel**).

8.3.3. Drift Assessment Workflow

The performance of a SLAM system is generally evaluated by one of two methods: comparing the system's map output to a ground truth version (Sturm, Engelhard, Endres, Burgard, & Cremers, 2012), or to compare the estimated camera/sensor motion with its true trajectory (**hubner_evaluation_2020**; Sturm et al., 2012). The latter typically employs the relative pose error (RPE) and the absolute trajectory error (ATE) as metrics, while the former can be computed quantitatively but is often simply compared visually (in similar ways to what was done in section 8.2)(Sturm et al., 2012). The difference with this project is that we are not interested in assessing the quality of the SLAM algorithm, as the assumption is that SLAM algorithms will not be reliable in a real-time scenario in which loop closure is not a priority and perhaps not even an option. However, we are interested in assessing the quality of the system output, which can be assessed using similar means.

What follows here is a description of the steps followed to arrive at an assessment of the drift via the metrics shown in section 9.2. The goal is to bring the point cloud data and the digitized ground truth data together, manipulating them into complementary formats which can then be compared. Refer to **??** as a guide. These analyses were conducted in Python.

First, the **pre-processed point cloud** is loaded into the program. In this example it is an iphone point cloud.

Figure 8.18: Full point cloud.

Create Bounding Box

Next, a bounding box is created from the corners of the region of interest (ROI) polygons shown in **??**. This operation required writing a function to define an Open3d bounding box using the corners of the polygon as an input.

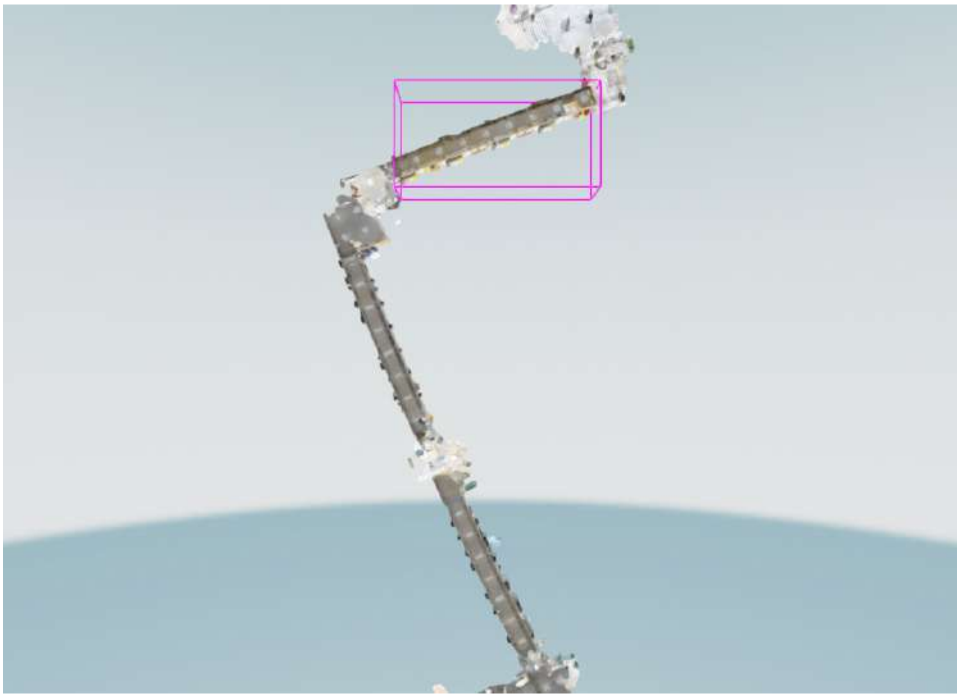


Figure 8.19: Bounding box overlaid on the full point cloud.

The bounding box shown in Figure 8.19 represents the first segment in the sequence of hallway segments which will be compared to ground truth data.

Crop Point Cloud

Next, the point cloud is cropped to the extent of the bounding box. This will be repeated for each of the ROIs within the point cloud's extent, so that in the end there are 2 to 5 cropped segments of the point cloud ready to be compared.

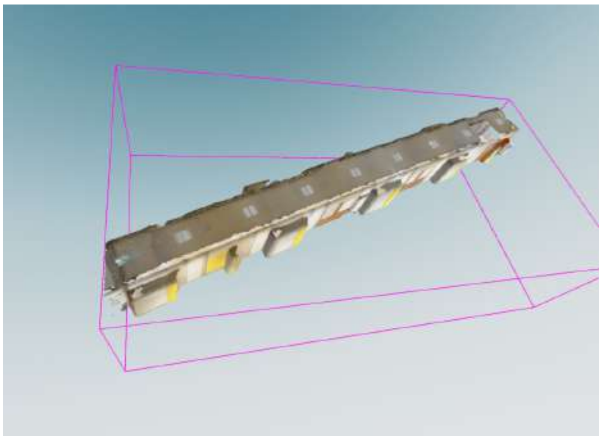


Figure 8.20: Point cloud cropped to the bounding box extent

Floor Extraction

Now that the point cloud is cropped, it is much smaller and therefore easier to deal with computationally. Using RANSAC, the floor plane is extracted from the point cloud.

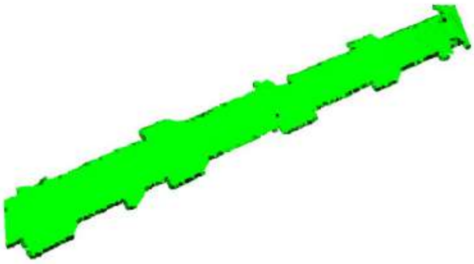


Figure 8.21: A RANSAC-extracted floor plane

Wall Extraction

The site for drift comparison is the walls, so next they need to be extracted from the point cloud.

Alpha Shape Method The alpha shape algorithm was used to do so. Using the extracted floor plane (in point cloud form) as an input results in a 2-dimensional approximation of the location of the walls.

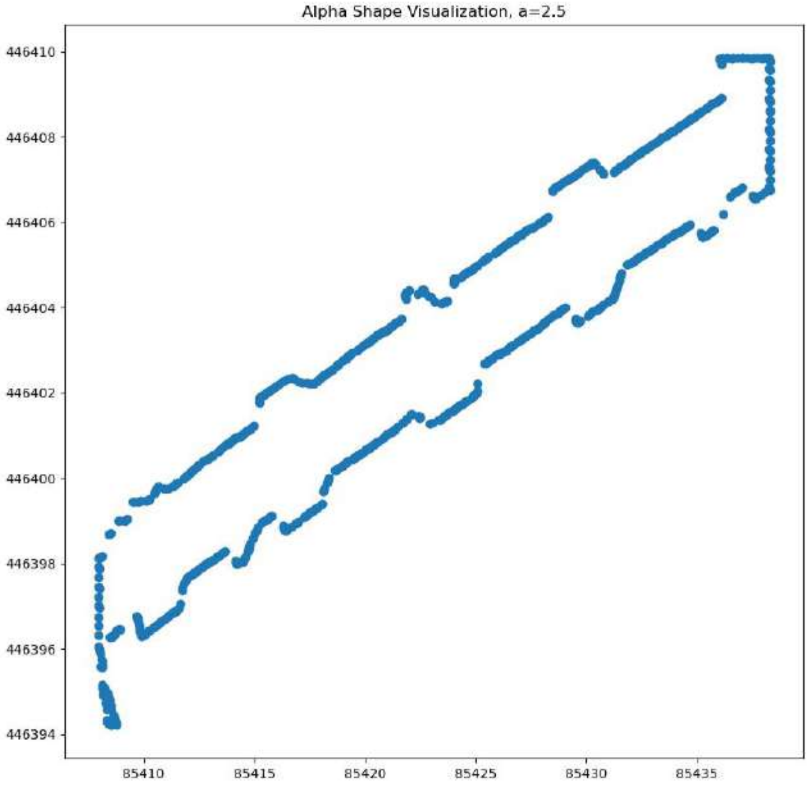
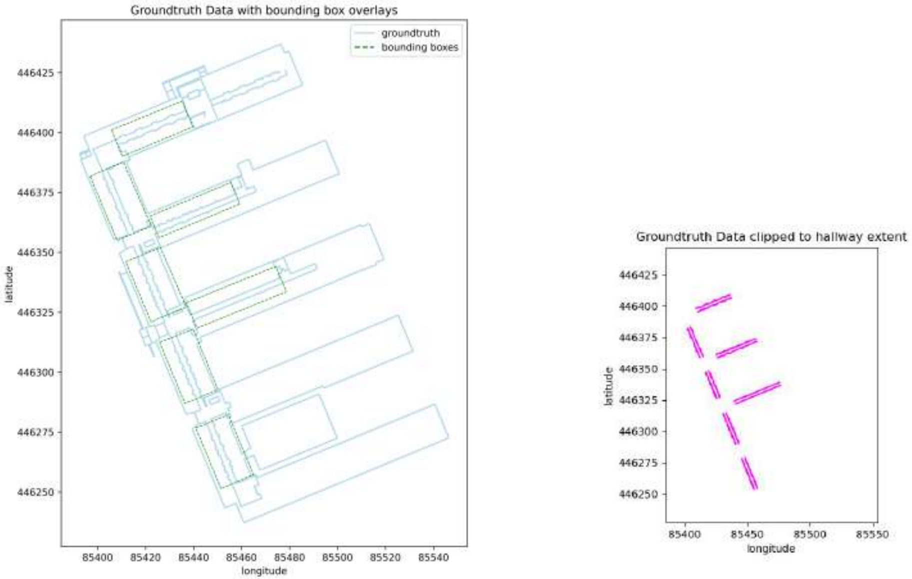


Figure 8.22: The boundary points of the wall as estimated with an alpha parameter of $\alpha = 2.5$

The alpha shape algorithm requires a parameter value for α, which was determined through experimentation to be $\alpha = 2.5$.

Prepare the Groundtruth data

The digitized ground truth data (discussed in subsection 8.1.5) is already in vector form, but it needs to be transformed to match the extent of the point cloud data. To do that, geopandas and matplotlib were used to crop the extent of the ground truth data to the same bounding box as the point cloud data. Figure 8.23 shows the groundtruth data clipping process: in Figure 8.23a, the light blue lines of the floor plan walls are overlaid with the dark green boundaries of the hallway bounding boxes. In Figure 8.23b the ground truth data is cropped to the extent of the bounding boxes, leaving only the two walls needed to make the drift comparison.



(a) TNW floor plan with hallway bounding boxes overlaid

(b) Ground truth data clipped to the extent of the bounding boxes

Figure 8.23: Visualisation of the ground truth clipping process

Comparisons with Groundtruth

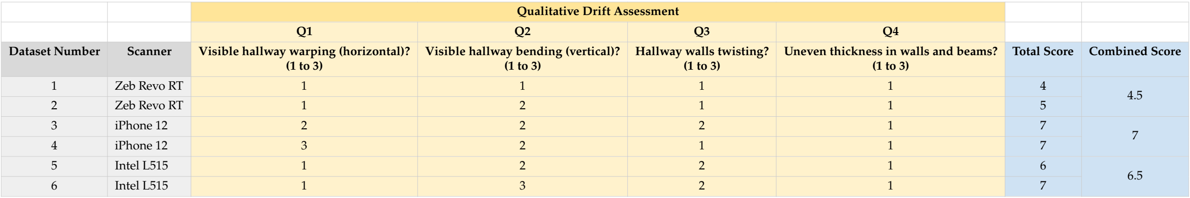
With the initial point cloud and the digitized ground truth data now in a mutually compatible form, they can be compared to one another. section 9.2 contains the comparison results.

9

Point Cloud Assessment Results

This chapter contains the results of the point cloud quality assessment results. First the results of the qualitative assessment are shared. Then the results of the quantitative drift assessment are shared.

9.1. Qualitative Assessment



		Qualitative Drift Assessment					
		Q1	Q2	Q3	Q4		
Dataset Number	**Scanner**	**Visible hallway warping (horizontal)? (1 to 3)**	**Visible hallway bending (vertical)? (1 to 3)**	**Hallway walls twisting? (1 to 3)**	**Uneven thickness in walls and beams? (1 to 3)**	**Total Score**	**Combined Score**
1	Zeb Revo RT	1	1	1	1	4	4.5
2	Zeb Revo RT	1	2	1	1	5	
3	iPhone 12	2	2	2	1	7	7
4	iPhone 12	3	2	1	1	7	
5	Intel L515	1	2	2	1	6	6.5
6	Intel L515	1	3	2	1	7	

Table 9.1: Results of the qualitative drift assessment applied to the six example point clouds. The iPhone Pro 12 exhibits the most visible drift, followed by the Intel L515 and then the Zeb Revo RT.

Table 9.1 shows the qualitative quality assessment of the six example point clouds. The point clouds are scored from based on four criteria, with 1 being no or almost no presence of the distortion, 2 being moderate presence of the distortion, and 3 being heavy presence of the distortion. The total score for each point cloud and for each scanner as a whole is then given. The iPhone Pro 12 narrowly exhibits the most visible drift and distortion, with a score of 14, followed by the Intel L515, with a score of 13, and then the Zeb Revo RT, with a score of 9. See section 10.4 for further discussion.

9.2. Quantitative Drift Assessment

This section shows the results of the drift assessment workflow applied to some example point clouds (described in Data Description). First are the visualizations, followed by a short discussion of drift values and their validity.

Figure 9.1 shows the interior layout of the TNW building. The light blue represents the interior and exterior walls of the building. The green bounding boxes cover the hallway comparison sites. No point cloud contains all of the segments. All point clouds except for one were taken starting from the side entrance (near segment 0) and moving towards the main entrance (between segments 2 and 3). The other was taken starting at the main entrance.

Figure 9.2 shows the alpha shapes of each scanner at segment 0. The acquired data is in green, and the ground truth data is in pink underneath. The units are in meters latitude and longitude. There is very little deviation apparent in the Zeb Revo RT data. There is a noticeable deviation at the beginning of dataset 3, where the iPhone starting point does not match up with the ground truth data. This is surprising because drift error should accumulate from a common starting point with the groundtruth data. This dataset offset in starting points could be partially due to georeferencing error. There does not appear to be much deviation in the Intel data, but it also stops short due to acquisition problems.

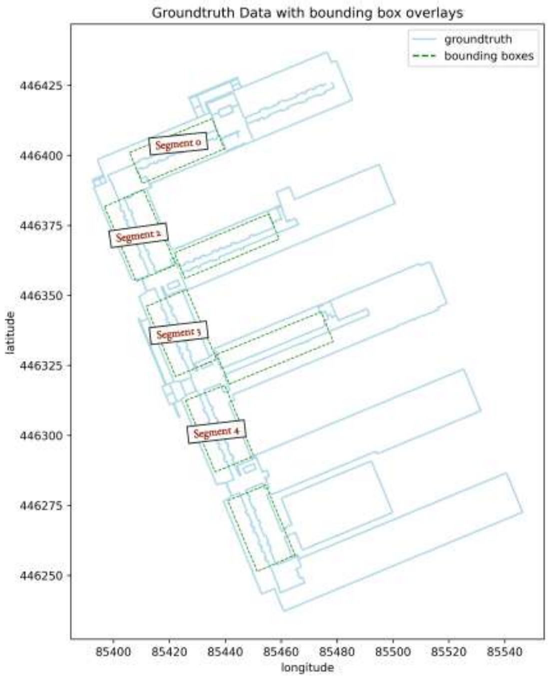


Figure 9.1: Map key showing the locations of the different hallway segments on the ground floor of the study area. These segments were evaluated for point cloud drift.

Figure 9.3 shows point cloud drift recorded along hallway segment 1. Again the Zeb Revo RT scan shows minimal drift, although there is some visible at the end of the trajectory. Both iPhone scans show prominent drift on the order of 3-5 meters. Interestingly, the drift directions of the two iPhone scans are opposite.

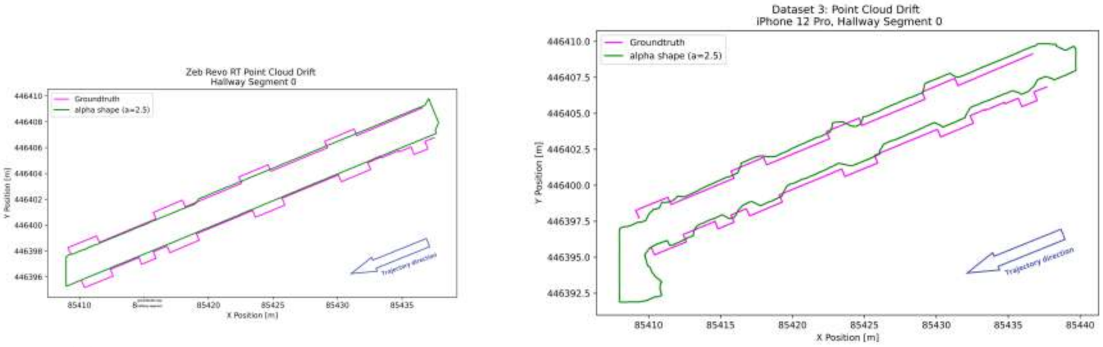
Figure 9.4 shows point cloud drift recorded along hallway segment 2. Here, the Zeb Revo RT scan shows slightly more displacement than in segment 1, although it is still on the order of a few centimeters. iPhone dataset 3 was slightly cut off by the bounding box. The drift in dataset 4 was so extreme that the bounding box for the segment had to be adjusted in order to keep the point cloud in view. This is shown in Figure 9.5.

Figure 9.6 shows the lone point cloud acquired on segment 3, with an Intel L515 scanner. Although this is the first (and only) segment in the trajectory, the drift is quite visible.

Drift Values and Validity

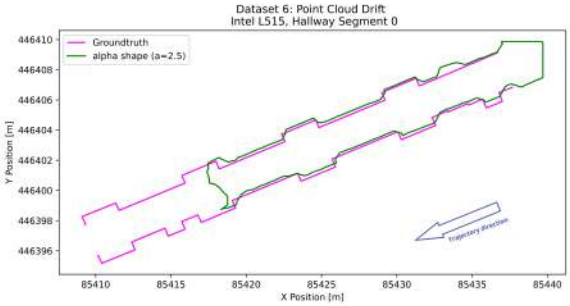
Drift values were calculated as the average distance between the ground truth wall segments and the extracted wall segments (Okorn, Pl, Xiong, Akinci, & Huber, 2010), over the length of the hallway segment. The distance between groundtruth and extracted wall segments was measured at the endpoints of the hallways.

Table 9.2 gives the average horizontal endpoint displacement and horizontal drift per meter for each segment. (Table B.2 shows the full table of quantitative drift results: the hallway length, the displacement



(a) Drift from the Zeb Revo RT scanner along hallway segment 0.

(b) Drift from the iPhone 12 Pro scanner along hallway segment 0.



(c) Drift from the Intel L515 scanner along hallway segment 0.

Figure 9.2: Visualisation of drift occurring across hallway segment 0.

Segment	Hallway Length (m)	Avg endpoint displacement (m)	Avg drift per meter (cm/m)
0	30.779	0.975	2.377
1	26.337	3.536	13.426
2	23.95	7.063	24.575
3	26.115	1.155	4.423

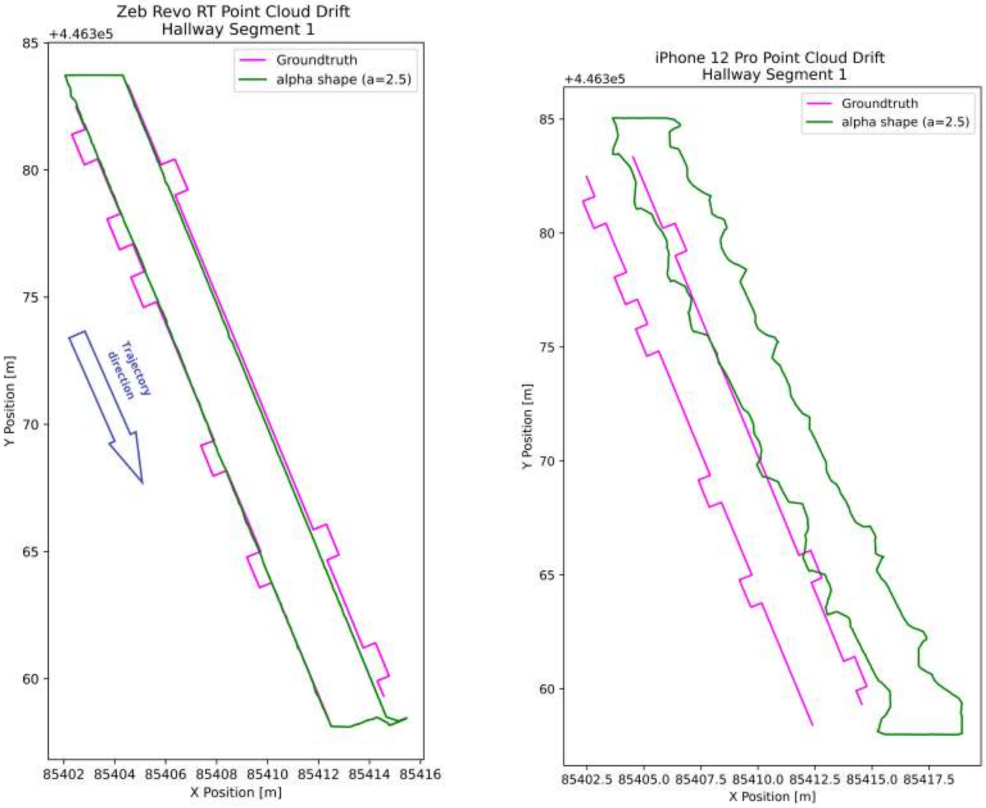
Table 9.2: Table showing the average endpoint displacement and average horizontal drift per meter in each hallway segment.

of each hallway endpoint, and the average drift per meter.)

As expected, the average drift increases with each segment. This makes sense because point cloud drift should accumulate along the length of a trajectory (**hubner_evaluation_2020**). The average drift is lower in segment 3 because that was the first segment of a new trajectory.

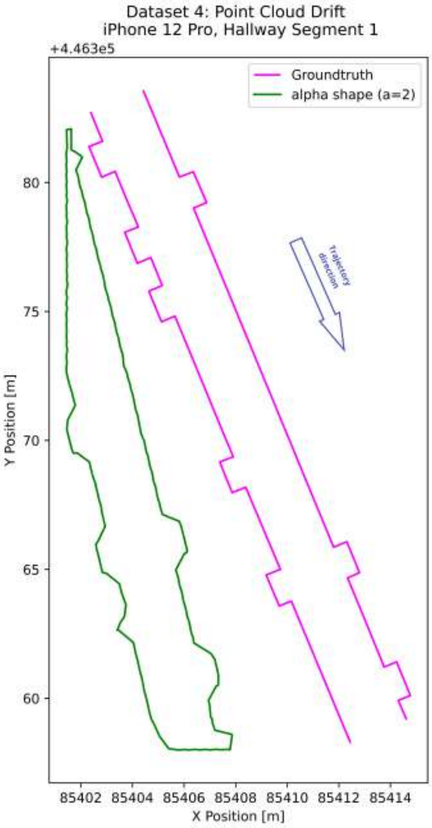
Table 9.3 gives the average horizontal endpoint displacement and horizontal drift per meter for each scanner. In summary, the results clearly show that the iPhone 12 pro has the highest average drift per meter at 20.2 cm/m–almost 10 times as much as the Intel L515 at 2.6cm/m. This is a drastic difference, and warrants analysis of additional iPhone 12 scans to determine whether the two point clouds used in this analysis were outliers. An investigation of iPad Pro LiDAR indoor mapping capabilities found that some deviations in some walls of their study area might have been caused by trajectory reconstruction errors (**diaz-vilarino_3d_2022**). On the other hand, the Zeb Revo RT exhibits very low drift, on the order of 4 millimeters. This makes sense because the Zeb scanner used for data collection was unable to make open-loop scans. Therefore, all scans were closed-loop and the GeoSLAM was applied. Given the RMS of the Zeb Revo scan (2cm), it is not possible to say for sure that this deviation is due to drift.

The validity of these drift values depends partially on the RMS values of the point clouds. A table of the RMS for each point cloud can be found in **??** The georeferencing error using control points was around 2 cm for the Zeb Revo cloud used in this analysis, while the errors for co-registration between a georeferenced scan and another scan were in the 8-11cm range. One point cloud from each scanner



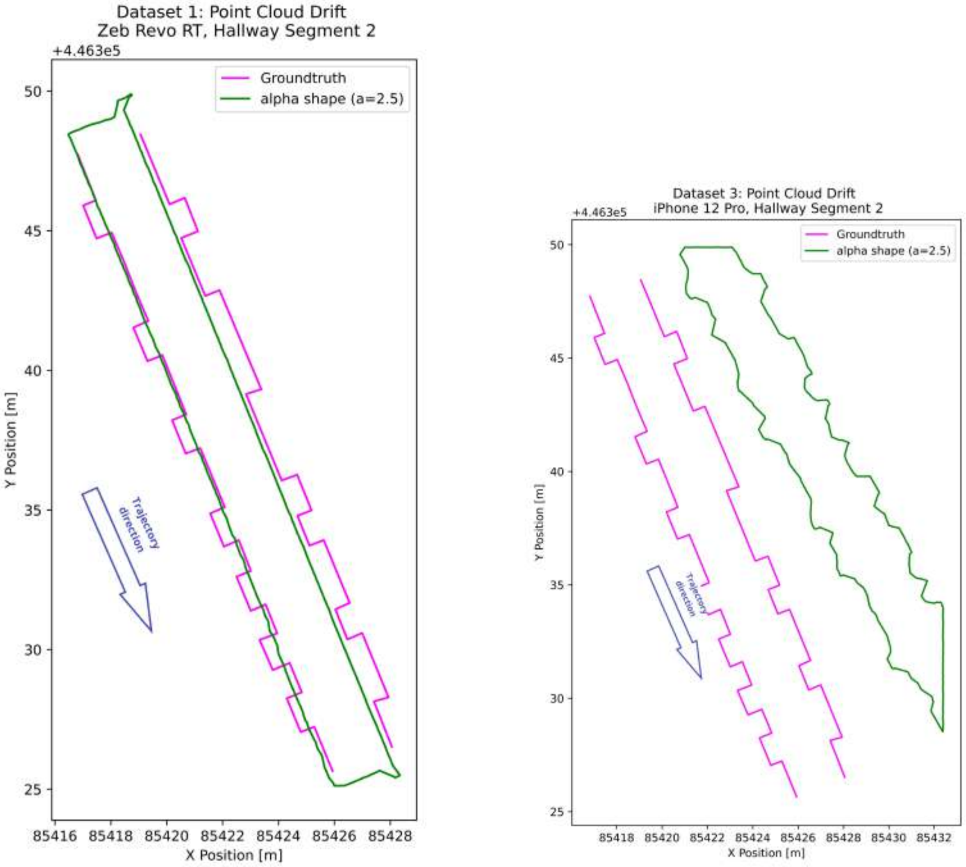
(a) Drift from the Zeb Revo RT scanner at along hallway segment 1.

(b) Drift from the iPhone 12 Pro scanner at along hallway segment 1.



(c) Drift from the iPhone 12 Pro scanner at along hallway segment 1.

Figure 9.3: Visualisation of point cloud drift occurring across hallway segment 1.



(a) Drift from the Zeb Revo RT scanner at along hallway segment 2.

(b) Drift from the iPhone 12 Pro scanner at along hallway segment 2.

Figure 9.4: Visualisation of point cloud drift occurring across hallway segment 2.

Scanner	Avg endpoint displacement (m)	Avg drift per meter (cm/m)
Zeb Revo RT	0.116	0.458
iPhone 12 Pro	5.563	20.225
Intel L515	0.698	2.604

Table 9.3: Table showing the average endpoint displacement and average horizontal drift per meter for each scanner.

Figure 9.5: Drift from the iPhone 12 Pro scanner along hallway segment 2.

was able to be georeferenced directly to the GCP, giving them a lower RMS. Co-registration errors could have been lessened, particularly with respect to the Intel L515 scans, if there had been more overlap between adjacent scans. This project was inhibited by the severely reduced range of the Intel L515 scanner during the data collection process.

The other limitation of these results is that they are based on very few point clouds. While the results from point clouds of the same scanner are consistent with one another (ie. the iPhone clouds show more drift at each segment than the other scanners), it is hard to generalize this behavior to all point clouds from the same scanner. Likewise, some segments were surveyed more than others (ie. segment 0 four times, and segment 3 only once). Applying this workflow to more data will strengthen these observations and conclusions. That said, the average drift per scanner metric is still useful for the analysis of scanner suitability conducted in part 3. Because the drift is also visible to the naked eye, it is safe to trust the assertion that iPhone clouds have the most drift and Zeb Revo clouds the least.

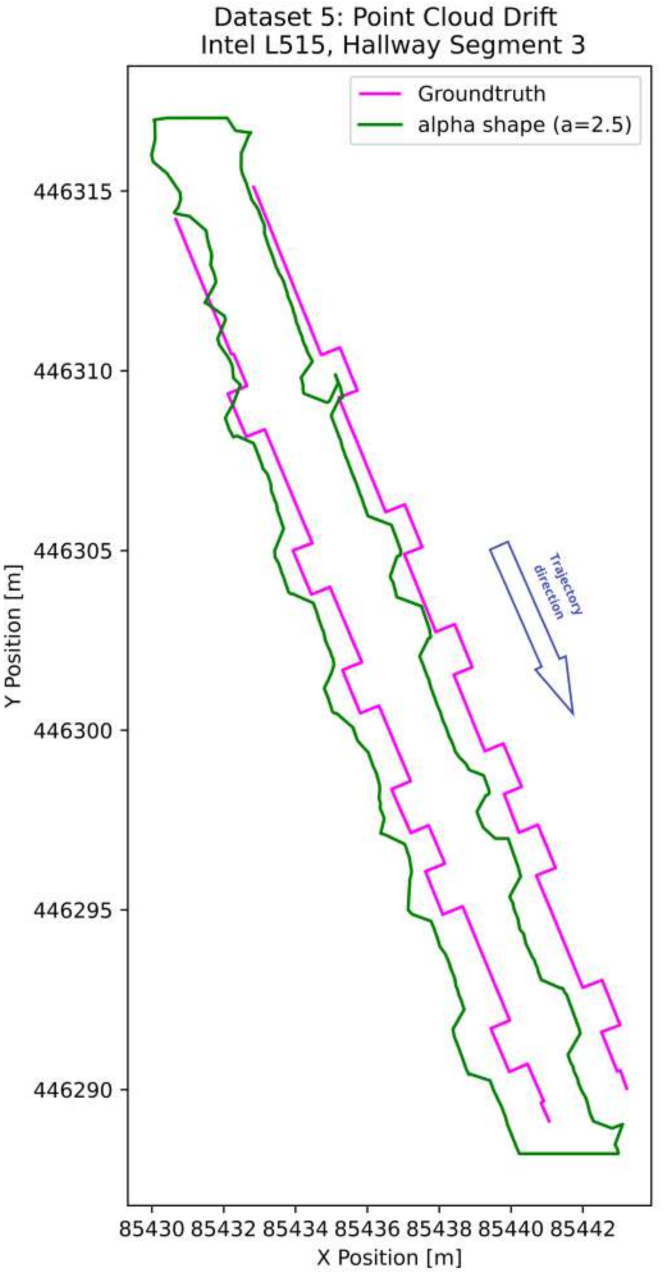


Figure 9.6: Drift from the Intel L515 scanner along hallway segment 3.

10

Discussion

This section comprises the first of two discussion sections relevant to the GRS committee. (The second one is Discussion.)

10.1. Drift Assessment Implementation Differences

Before producing the results, the drift assessment workflow was first developed using an iPhone point cloud. The drift assessment workflow was generalizable to the Zeb Revo RT and Intel L515 point clouds for the most part. It successfully produced the same output for clouds from each scanner. However, there were some differences in how the method worked.

Capturing Hallway Shape

Most noticeable was that the hallway nooks (see Figure B.9a) were captured differently by the alpha shape of each scanner, even at the same alpha value. Figure 10.1 shows an alpha shape of each scanner. In general, the Zeb Revo RT alpha shapes did not capture any of the geometric features of the hallway. The iPhone captured many of the nook shapes, but the Intel captured them most successfully.

Enlarged Bounding Box

Initially, the hallway segment bounding boxes were cropped close to the bounds of the hallway. However, the iPhone point clouds exhibited more drift than expected. Therefore a much larger bounding box was required to capture the point cloud data for comparison. Figure 10.2 shows the scenario.

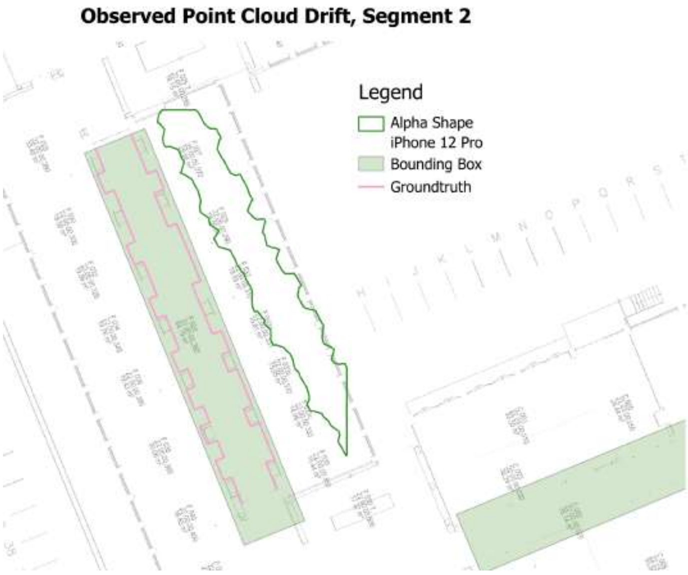


Figure 10.2: iPhone alpha shape (green line) lying outside the original bounding box (shaded green box).

Polygon Fragments

Lastly, the iPhone alpha shapes were more likely than the others to contain small data fragments (see Figure 10.3 after being converted from a point cloud into a polygon. These fragments caused issues with certain visualizations, although they did not interfere with drift measurements.

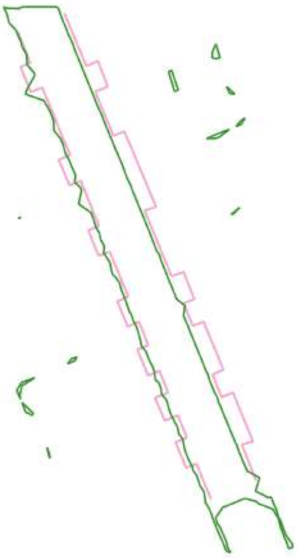
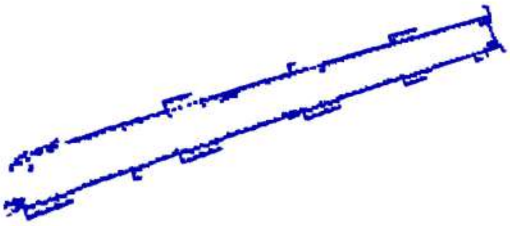


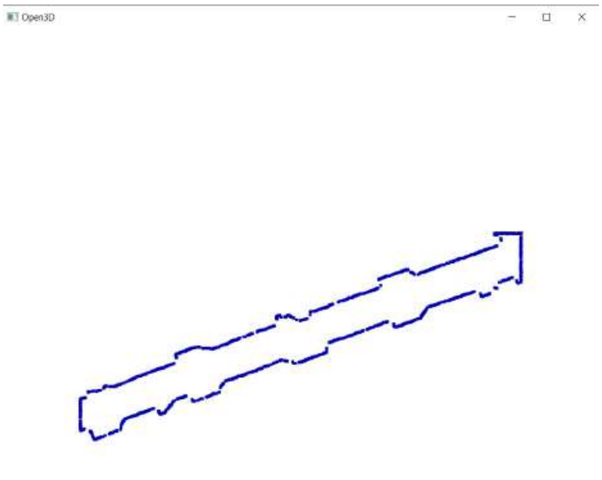
Figure 10.3: iPhone alpha shape (green line) lying outside the original bounding box (shaded green box).

10.2. Alternate Wall Extraction Method

Two different ways of extracting the walls from the point cloud were implemented, and the performance of each was assessed. It involved isolating the wall segments using point density and then using probabilistic Hough transform (PHT) for a finer-tuned approximation of the shape. See section B.10 section for more information about the implementation. A comparison of the two extracted wall point clouds can be seen in Figure 10.4.



(a) estimated with a threshold of 0.13



(b) estimated with an alpha parameter of $\alpha = 2.7$

Figure 10.4: Wall point cloud extracted two ways

While both methods produced a usable final wall output, the shape of the outputs differs somewhat. It is clear that the doorway nooks at the sides of the hallways are better captured in the alpha shape output because all of them (8, 4 on each side of the hallway) are present. However, the wall grid method captures the shape of the nooks much more accurately (see Figure 10.1b for an image of the nooks). Lastly, because the two methods approach the problem in different ways, there can be implications for the type of scenario it is implemented in. For example, the wall extraction and voxelization processes used in the wall grid extraction are relatively computationally heavy and take longer than retrieving the alpha shape. In a real-time scenario or one in which processing large amounts of data quickly is important, using an alpha shape might be better. In a scenario where capturing details of the structure's shape is very important, the wall grid + hough transform method might be better.

10.3. Scanner User Experience

The L515 is described as being optimized for indoor lighting ("Intel® RealSense (TM) LiDAR Camera L515", 2021), which is perhaps evidenced by the large number of points it was able to capture per unit area, as well as the good quality of the RGB data (especially given that the L515 data was captured at night, albeit with indoor lighting).

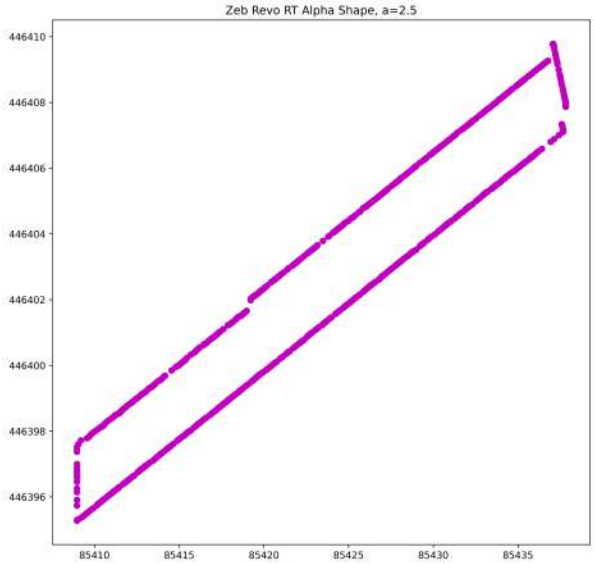
The decision of which interface or application to use for scanning can have an outsize effect on the experience of acquiring the point cloud data. For example, the Intel L515 was by far the worst of the three in terms of ease of use and ease of acquisition. However, had I known to try the Rtabmap interface instead of Dot3d pro and Intel's native RealSense Viewer, that may not have been the case.

10.4. Qualitative Drift Assessment Method

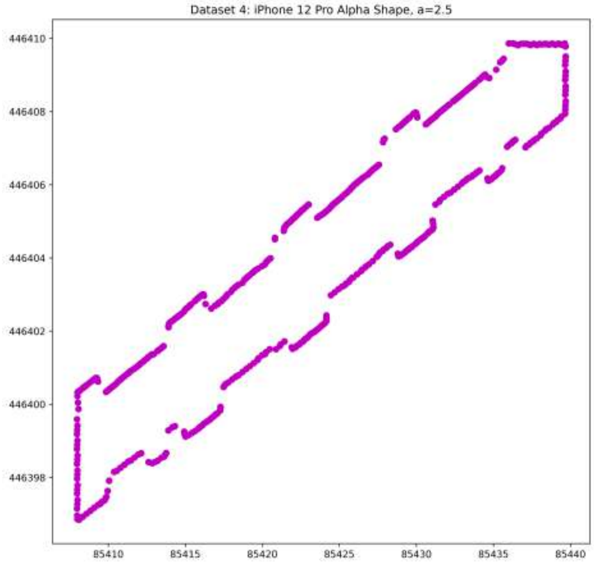
The qualitative workflow is meant to be accessible, so that personnel without much experience working with or collecting point cloud data would know how to make a first visual assessment of a point cloud's quality. Practically speaking, this assessment can only be applied to a sampling of locations in each point cloud. It would take far too much time to assess each point cloud comprehensively. So, the metrics were assessed at one or more locations within each point cloud, with an eye toward areas that appeared or had the potential to be of lesser quality. This approach minimizes the possibility that point clouds would be falsely assessed as being of higher quality than they actually were.

The inherent uncertainty and non-uniformity of qualitative assessment results is also the reason why it is important to conduct a quantitative assessment of point cloud drift. In this way, error metrics can be evaluated for each entire point cloud and afterward interpreted.

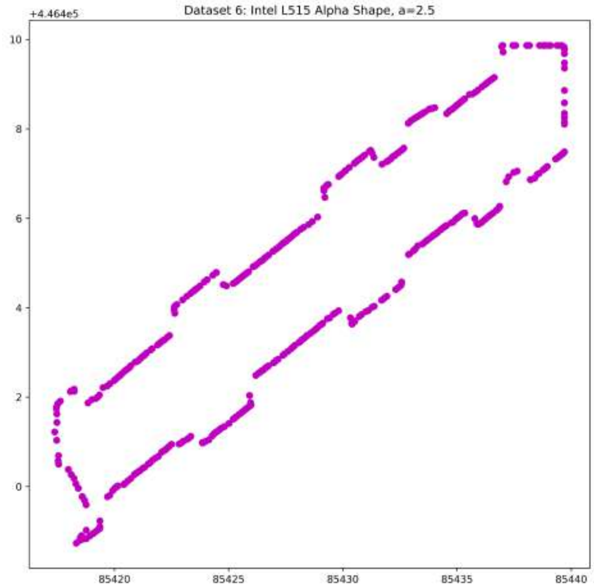
One benefit of this assessment is that it is simple and quick to execute. Knowing whether a mapped area is distorted or warped would be useful for first responders in a real-time scenario. The assessment is also useful as an input for the Value Matching Methodology in part 3. The qualitative assessment scores given in Table 9.1 are included as one of the scanner attributes used to gauge mobile laser scanner (MLS) performance.



(a) Zeb Revo RT



(b) iPhone 12 Pro



(c) Intel L515

Figure 10.1: Alpha shapes of hallway segment 0 with $\alpha = 2.5$

Part III

Linking LiDAR Technology to the First Responder Context

11

Introduction

Part 2 was focused solely on the technical capabilities of mobile lidar scanners and the outcome of analyzing their point cloud data. It focused on aspects of the MLS scanning experience related to indoor emergency response. We looked at how the scanners compare to one another with respect to data quality, data acquisition, and data processing. But just because we as researchers/developers are interested in these MLS properties doesn't mean that this is the smartest way to judge an MLS usefulness in emergency situations. So, for this third section of the report a new, evidence-based/design-based/research-based method was designed to do this evaluation. The method was developed based on the results of interactions with members of the target group, emergency first responders.

11.1. Problem Statement

Physical concepts can usually be measured objectively with the help of established measurement procedures (Kroes & van de Poel, 2015). However, measuring more abstract concepts such as values requires some thought. The objective of Part 3 of the project is to take the values expressed by first responders and devise a method of matching those values with different attributes of laser scanners. This allows us to make a judgment about how well-aligned each laser scanner is with the values of the first responders. Part III of the report brings together the CDI and GRS perspectives, using the results of their respective analyses to move to the next step in the project. The matching methodology described and applied in this chapter was created by bringing together concepts and analysis methods from value sensitive design, participatory design, and mechanical engineering to create a methodology that can be followed in order to achieve the desired objective. This methodology is henceforth called the ***Value Matching Methodology***.

11.2. Research Question

The research question that governs Part 3 is, *How do current mobile laser scanning capabilities measure up to first responder needs?*

The sub-questions are as follows:

1. Which scanner characteristics are relevant to assessing their suitability for first responder needs?
2. How do the capabilities of different MLS systems compare to one another?
3. Which MLS system(s) is the best recommendation for the different first responder use cases?

The research objectives are to

1. Construct a method to assess how different LiDAR scanners currently align with first responder needs
2. Assess how well each LiDAR scanner and its data aligns with first responder needs

The outcomes of this section are (1) a values - attributes matrix that developers or first responders can use to check the alignment between first responder values and scanner attributes, (2) a distillation of the methodology used to make create this matrix, and (3) an assessment of how well each LiDAR scanner and its data aligns with first responder needs.

12

Value Matching Methodology

In Part 3, value-sensitive design provides the foundation of the Value Matching Methodology. The matching is approached from the perspective of the values important to first responders. These values are used as metrics to evaluate the suitability of the different LiDAR scanners to first responder needs. The use cases defined in Use Cases could also have been used as metrics, but that limits the applicability of the assessment. Evaluating the suitability for first responders by way of the values creates a more broadly useful ranking system. Because it equates scanner *characteristics* to values, the assessment is applicable to any number of scanners. Likewise, by using values as metrics instead of specific use case scenarios, the assessment becomes applicable to any number of scenarios as long as the values relevant to the scenario are identified. This is approach to evaluation suits the dynamic context of first responder LiDAR use. The types of use case scenarios and the capabilities of the tools are ever-changing, so having a flexible evaluation method is a big benefit.

The methodology described in the following chapter, in combination with the LiDAR use context methodology described in Part I, comprises the full approach to identifying and considering why and how first responders use LiDAR, and how their current tools align with their needs. This methodology answers the research question, but it also serves as an example of how a developer could take steps to design, redesign, or improve upon technology used by a specific target group within a dynamic context.

12.1. Comparing Scanner Attributes

The first step in the process is putting together a comparison of the relevant attributes of the iPhone 12, Intel L515, and Zeb Revo RT LiDAR scanners. To build the scanner comparison chart, a list of relevant scanner attributes was assembled from a combination of scanner spec sheets and relevant literature. A few of the attributes (Point Density, Data Noise, Point Cloud Drift, Qualitative Assessment Score, Capture Coverage, and Ease of Acquisition) were obtained through additional analysis. We then grouped all of the attributes into seven self-defined categories.

Basic Attributes

These attributes relate to the most basic functionality of the laser scanner: the way in which it measures the surrounding environment. This information is given by the laser scanner manufacturers.

Sensing Method

For the purposes of this project, sensing method refers to the way in which the devices captures the point cloud data. In this case, the sensing method was either time of flight LiDAR, depth sensing, or both.

Wavelength

The wavelength on the electromagnetic spectrum at which the laser scanner operates. LiDAR systems typically operate at between 800nm and 1550nm wavelength, and using different parts of this spectrum result in differences with respect to how the light pulses reflect off of the observed surfaces(**J.-Angelo-Beraldin_FranÃğois-Blais_Uwe-Lohr_2011**).

Intensity

The representation of how well an object/scene has reflected the light used by the laser scanner(**NOAA-lidar**). Intensity refers to the strength of the laser's backscattered signal, converted and amplified into an indicator of the electronic signal strength. Intensity can be converted into reflectance values, which characterize the proportion of energy (from the laser beam) that is reflected back toward the sensor after hitting the surface (Sanchiz-Viel et al., 2021). This can be useful for distinguishing, for example, between materials like metal or brick and water or vegetation(El-Ashmawy, Shaker, & Yan, 2012).

RGB Capability

Whether or not the scanner can record the color (RGB) of the coordinate points as they appear to the naked eye.

Portability Attributes

Given that first responders may carry the MLS with them (and depending on the scenario, may be equipped with other gear as well), the dimensions and weight of the system are relevant metrics to consider (Rantakokko et al., 2010), and can be grouped together under the moniker of portability.

Scanner Dimensions

The length, width, and thickness or depth of the full laser scanning apparatus.

Scanner Weight

The weight of the full laser scanning apparatus.

Data Robustness Attributes

The number, density, and distribution of points within a point cloud influence both how the data looks when visualized, and how much time is needed to process the data for visualization and/or further analysis. In addition, qualities like noise and average error indicate how reliably the point cloud represents the real-world scene. We group these qualities together under the category of data robustness.

Resolution

The *spatial resolution* of the LiDAR scanner. Spatial resolution is a measure of how much detail a laser scanner is capable of capturing within a scene. For example, a scanner with a resolution of 5 centimeters creates a point cloud in which two same-sized objects can be distinguished from each other when they are at least 5 centimeters apart. A scanner with an angular resolution of 2° can produce a point cloud where objects at least 2° apart can be seen as separate.

Resolution is the minimum resolvable distance between two objects or features of the same size within the point cloud. The resolution can be expressed in multiple ways. The angular resolution is given in degrees, and represents the smallest possible angle resolvable between two features.

The scanner's field of view is "the angular extent of the observable world that is seen at any given moment" (Emery & Camps 2017, https://tinyurl.com/wfsxabe8)

The scanner resolution is given by the manufacturer in terms of the angular (degrees) or linear resolution (pixels), and the angular field of view (FOV) (degrees). If the scanner also includes a camera, the resolution of the camera is also given in megapixels (MPs).

Point Density

The number of points in the point cloud per unit area, in this case per square meter. The point density of each point cloud was calculated using the *Compute Volume Density* feature in Cloud Compare. A higher-density point cloud will contain point clouds spaced more closely together than a lower-density point cloud. A dense point cloud also creates a higher-resolution image, in which smaller details are visible within the point cloud. For example, a density of 0.5 - 1 point per square meter is suitable for creating a basic terrain model, while 5-10 points per square meter can capture the shapes of buildings for 3D city model and 20+ points per square meter is best for capturing the details of the building structures and surfaces (Rohrbach 2015).

Data Noise

Data noise is a flaw or distortion in the point cloud that causes a misrepresentation of the true scanned object. Noisy data points can be caused by various factors such as sensor inaccuracies, environmental conditions, or data processing errors (Lin & Hsu, 2014). In the context of indoor laser scanning, noise can present as unwanted scattering due to the reflection of the laser from glass or other highly reflective surfaces. This is the definition used for this analysis. The scanners were ranked as having either high, medium, or low amounts of noise.

Average Error

The average difference detected between the true and measured positions of objects within in the point cloud data.

Capture Efficiency Attributes

Capture Speed

The number of points captured per second. This is influenced by how quickly the laser pulses are sent from and measured by the scanner (Degnan, 2016). The scanning speed can influence the density of the point cloud, as a higher scanning speed means that more points are collected per second.

Capture Range

The distance from the scanner at which signals can still be measured and the data can still be acquired.

Navigation-related Attributes

GNSS Capability

Whether or not the scanner has the ability to use GNSS positioning to geo-locate the point cloud data.

SLAM Capability

Whether or not the scanner uses a section 7.2 algorithm to correct the position of the acquired point cloud in space data after scanning.

Trajectory Capture

Whether or not the scanner produces a data file documenting the path that the scanner has taken during the scanning process.

Real-time Capability

Whether or not it is possible for the scanner to show an updated version of the acquired point cloud data while still scanning.

Point Cloud Drift Attributes

Point Cloud Drift

The amount of point cloud drift, as calculated and expressed in Part II of this report (see Quantitative Drift Assessment). Specifically, the point cloud drift is given in terms of centimeters of horizontal drift per meter of point cloud distance.

Qualitative Assessment Score

The qualitative assessment score calculated in Part II (Qualitative Assessment.) This score is an approximate representation of visible distortions within the point cloud.

Acquisition Attributes

Capture Coverage

Similar to the *surface coverage* metric introduced by (**diaz-vilarino_3d_2022**), capture coverage refers to how well the scanner captures a scene or object. For example, when walking at a "normal" pace, does the scanner achieve reasonable coverage of walls, ceilings, and floors? Can it capture an area in one sweep or does it require multiple passes with the scanner? Based on my personal experience during data acquisition, the scanners were ranked as having either high, medium, or low capture coverage.

Ease of Acquisition

This relates to how easy it is to start the scanner and get it ready for data acquisition. Additionally, once ready, how simple is it to operate the scanner? Based on my personal experience during data acquisition, the scanners were ranked as having either high, medium, or low capture coverage.

12.2. Defining First Responder Values

Before we can make any kind of assessment related to the values, they need to be defined. This value definition is a process of specification of values, which is an enhanced form of the conceptualization of values. Conceptualization requires defining or describing the values in order to clarify their meanings and possible applications. Specification goes a step further by introducing domain-specific (ie. relating to the technology in question) and/or context-specific (ie. relating to the social, user, or use context) into the definitions (van de Poel, 2013) in a way that makes subsequent decisions and analyses more tailored to the specific goals at hand. The specification element is part of what makes this methodology attractive for use in niche or otherwise lesser-explored contexts.

Basic Definition Method

Friedman$_K ahn_B orning_2$014$describeaphaseinthevaluesensitivedesignprocessinwhichthekeyvalueswithintheconte$

List the values that will be included in the analysis

Break the values down into separate dimensions, if necessary

Using insights from the interviews and focus groups, consider the different potential definitions of the values

Decide on a working definition for each value

To elaborate on the third item, it can be that the same value was given a different definition by different respondents. In order to show the nuances in the meanings of the values, we can use quotes, statements, and insights from the interview and focus group transcripts.

Reverse Engineering Too-Specific Values

In the world of value-sensitive design, values are the abstract layer at the top of the “values hierarchy" described by van$_d ep_P oel_2$013.$Alsocalledanintrinsic$ value$, thevaluesrepresentsomethingthatwestriveforforitsownsake.$
$normsarethemostrelevantandrefertoattributes, properties, orcapabilitiesthatthegiventechnicalitemshouldposse$
$normscanincludeobjectives, goals, orconstraintsthatfurtherelaborateonhowtheitemshouldbedesigned.Designre$
$normintoastandardthatcanbedirectlyfollowedinthedevelopment, design, orengineeringprocess.Thelowerlevelso$

Sometimes, respondents may name or describe a value in a way that is closer to a norm or design requirement in format than a value. For instance, they may use overly specific or overly technical terms, or even describe an actual potential feature. While this is valuable information, for the purposes of this value attribution methodology, it is ideal to decipher the value(s) underlying such terms whenever possible. This is important because, depending on the reason(s) why the term was named, multiple values could be relevant to it.

To identify the intrinsic value in such a situation, work backward from the term by considering this question:

> *“Why is first responder X interested in requirement Y? What is the underlying goal that this requirement contributes to?”*

van$_d ep_P oel_2$013$callsthisrelationshipa$*for the sake of*$relationbecauseitdemonstrateshowadesignrequirementisdesired$

Here is an example of how to identify an underlying or intrinsic value: The value "GPS reception," given by the fire department, is more specific than an intrinsic value and rather falls under the category of a norm or end-norm. Thinking about the sentiments expressed by respondents, one reason why GPS reception is important is for being able to accurately link the data being acquired to the correct location in space. Why is this important? One possible reason is so that others can use the data for navigation, which would point toward an intrinsic value of perhaps Accuracy or Navigability. It is important to note that there are many possible answers to these questions, so the project context and the opinions and experiences of the specific users/respondents become important guiding lights in this process.

12.3. Mapping Scanner Attributes onto Corresponding Values

Once the values have been defined, they can be linked to the scanner attributes. Friedman$_{K}ahn_{B}orning_{2}014describeaproce$
$al.$, 2014, p.16), $thevaluesofproductivity, physicalwelfare, andpsychologicalwelfarecanallbelinkedtothatbenefit.$

The mapping process progresses as follows:

1. List all known/gathered scanner attributes
2. For each value, consider, "Which scanner properties are related to the value as we have defined it?"
3. Draw lines between the value and any attributes that can be used to measure it. (can use evidence from the transcript and/or apply values coding)

13

Value Matching Results

This chapter starts with the results of the scanner attribute comparisons. Next, the values important to emergency first responders are defined based on the results of the Coding Analysis analysis that was applied to the interview and focus data from Part I. Lastly, connections are drawn between the first responder values and the scanner attributes and those links are briefly explained.

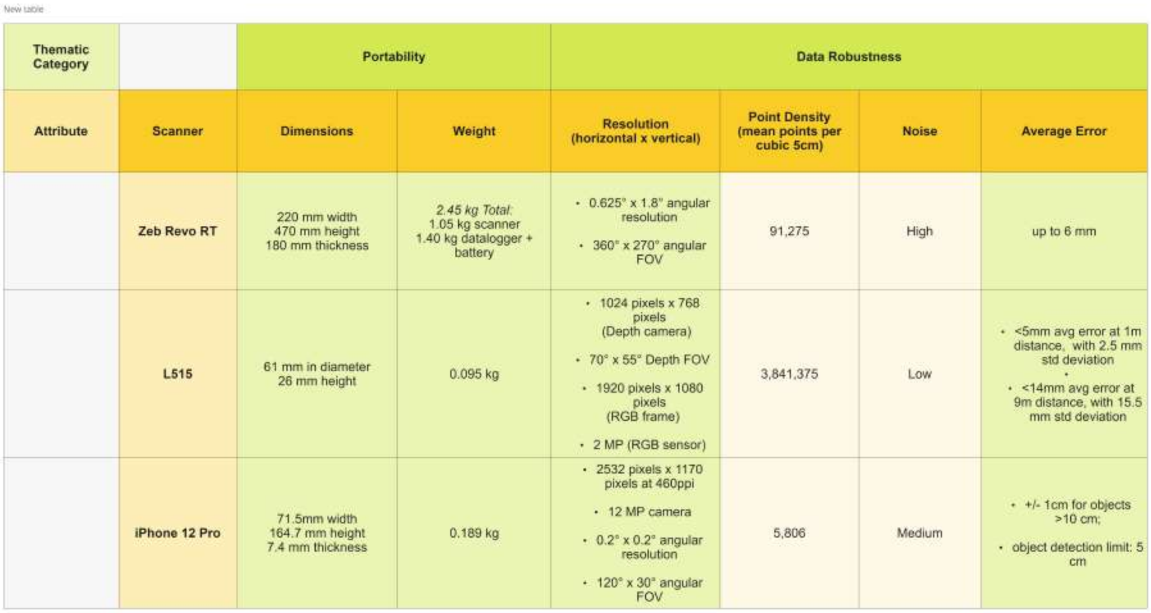
13.1. Scanner Attribute Comparisons

The following tables (Figure 13.1,Figure 13.2, Figure 13.3, and Figure 13.4) show a comparison of the Zeb Revo RT, Intel L515, and iPhone 12 Pro attributes, divided by category.

Thematic Category				**Basic**			
Attribute	**Scanner**	**Company**	**Cost**	**Sensing Method**	**Wavelength**	**Intensity**	**RGB**
	Zeb Revo RT	Geoslam	€26,000.00	ToF LiDAR	905 nm	no	no
	L515	Intel	€649.00	ToF Lidar, Depth Sensing	860 nm	yes	yes
	iPhone 12 Pro	Apple	€1,100.00	Direct ToF LiDAR	800s nm	no	yes

Figure 13.1: Table showing the Basic Attributes section of the scanner comparison chart. The scanner attributes are denoted by the yellow headings, and the comparison categories are denoted by the green headings. The light yellow boxes indicate values that are not scanner attributes, and the white boxes indicate the basic scanner attributes.

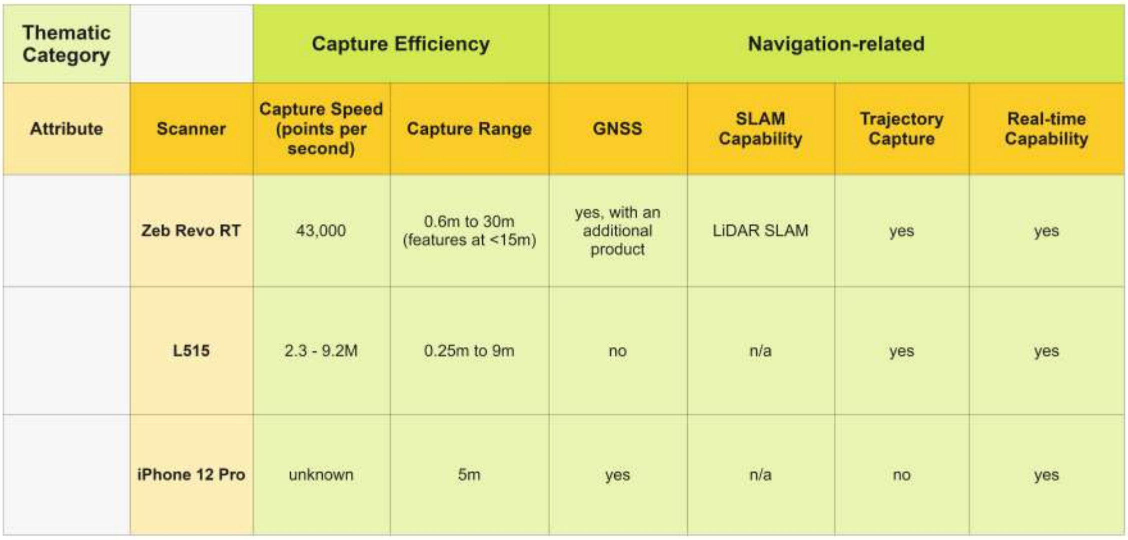
The most pronounced difference seen in Figure 13.1 is the cost of the scanners, with the Zeb Revo RT being by far the most expensive. The difference between the iPhone 12 pro and the Intel L515 is not too much.



New table

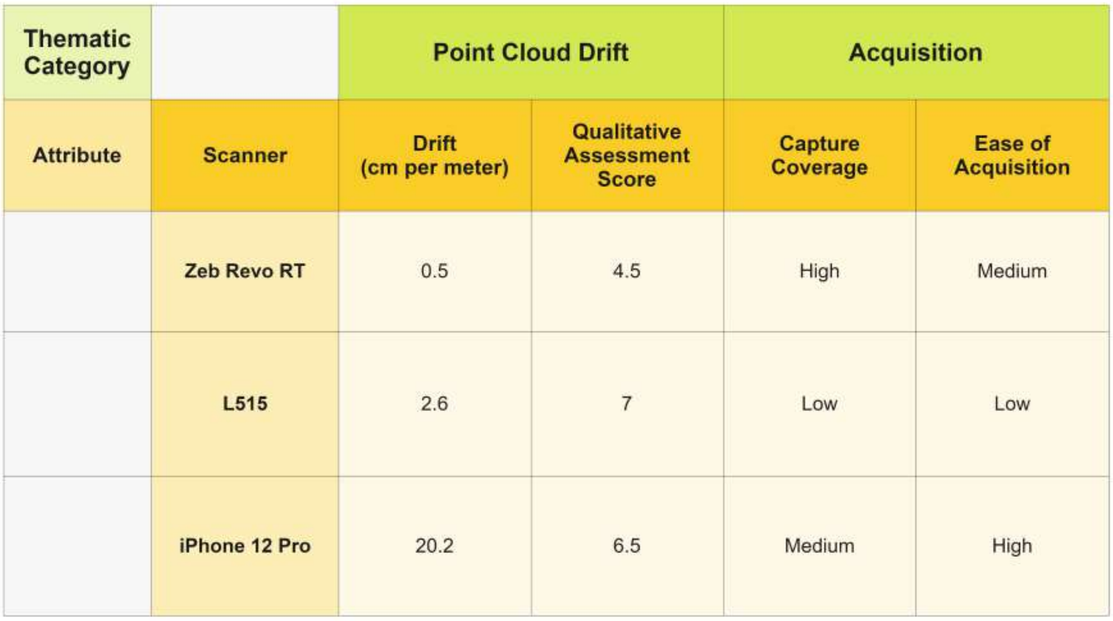
Thematic Category		Portability		Data Robustness			
Attribute	Scanner	Dimensions	Weight	Resolution (horizontal x vertical)	Point Density (mean points per cubic 5cm)	Noise	Average Error
	Zeb Revo RT	220 mm width 470 mm height 180 mm thickness	*2.45 kg Total:* 1.05 kg scanner 1.40 kg datalogger + battery	• 0.625° x 1.8" angular resolution • 360° x 270° angular FOV	91,275	High	up to 6 mm
	L515	61 mm in diameter 26 mm height	0.095 kg	• 1024 pixels x 768 pixels (Depth camera) • 70° x 55° Depth FOV • 1920 pixels x 1080 pixels (RGB frame) • 2 MP (RGB sensor)	3,841,375	Low	• <5mm avg error at 1m distance, with 2.5 mm std deviation • • <14mm avg error at 9m distance, with 15.5 mm std deviation
	iPhone 12 Pro	71.5mm width 164.7 mm height 7.4 mm thickness	0.189 kg	• 2532 pixels x 1170 pixels at 460ppi • 12 MP camera • 0.2° x 0.2° angular resolution • 120° x 30° angular FOV	5,806	Medium	• +/- 1cm for objects >10 cm; • object detection limit: 5 cm

Figure 13.2: Table showing the Basic Attributes section of the scanner comparison chart. The scanner attributes are denoted by the yellow headings, and the comparison categories are denoted by the green headings. White and green-colored boxes indicate values taken directly from literature or product documents, while beige boxes indicate values determined by the researcher.



Thematic Category		Capture Efficiency		Navigation-related			
Attribute	Scanner	Capture Speed (points per second)	Capture Range	GNSS	SLAM Capability	Trajectory Capture	Real-time Capability
	Zeb Revo RT	43,000	0.6m to 30m (features at <15m)	yes, with an additional product	LiDAR SLAM	yes	yes
	L515	2.3 - 9.2M	0.25m to 9m	no	n/a	yes	yes
	iPhone 12 Pro	unknown	5m	yes	n/a	no	yes

Figure 13.3: Table showing the Basic Attributes section of the scanner comparison chart. The scanner attributes are denoted by the yellow headings, and the comparison categories are denoted by the green headings. White and green-colored boxes indicate values taken directly from literature or product documents, while beige boxes indicate values determined by the researcher.



Thematic Category		Point Cloud Drift		Acquisition	
Attribute	Scanner	Drift (cm per meter)	Qualitative Assessment Score	Capture Coverage	Ease of Acquisition
	Zeb Revo RT	0.5	4.5	High	Medium
	L515	2.6	7	Low	Low
	iPhone 12 Pro	20.2	6.5	Medium	High

Figure 13.4: Table showing the Basic Attributes section of the scanner comparison chart. The scanner attributes are denoted by the yellow headings, and the comparison categories are denoted by the green headings. White and green-colored boxes indicate values taken directly from literature or product documents, while beige boxes indicate values determined by the researcher.

13.2. First Responder Value Definitions

The six top values for the police and the fire department are listed below in order from most to least important. Then the other named values for each agency are listed. Following the process described in Defining First Responder Values, potential definitions of each value are given and then the final working definition is confirmed.

13.2.1. Fire Department

The top six values for the fire department reported during the focus groups were safety, 3D Data, Maneuverability, Data Reliability, Data Consistency, and Data/Information Clarity.

1. Safety
The safety of the fire department personnel operating the devices. In situations with live victims, the safety of the victims in the situation. Broadly, the protection of a given party from harm during an incident.

2. 3D Data
Laser scanning data, also known as a 3D coordinate point, that allows one to visualize the X, Y, and Z dimensions of a scene or environment. Thereby creating a 3-dimensional dataset or image of the scene.

3. Maneuverability
The ability to comfortably move the LiDAR device throughout the incident environment in ways that facilitate data collection.

4. Reliability
Data reliability refers to whether you can trust the point cloud and/or image data as a true representation of the real-life scene. This includes both topologically, ie. related to the correct visualization and placement of objects or features within the scene; and metrically, ie. related to the actual recorded placement within the scene.

5. Consistency
Data consistency refers to whether you can expect a similar quality of results [in similar environments and/or across different uses of the scanner].

6. Clarity of Data / Information
Data clarity refers to whether objects, features, and other elements within the image recognizable are to a viewer. Another way to put it is, whether features can be distinguished/resolved within the image.

The other values for the fire department reported during the focus groups were Access, Effectiveness, Efficiency, Time, and GPS Reception:

Access
"Access is the platform you are using to enter the building."-focus group participant, fire department "The ability of fire department personnel to access the building"-accepted definition in the fire department focus group.

Effectiveness
This concept was not really discussed beyond the first mention. It will be loosely described as how well the scanner allows the team's objectives to be fulfilled.

Efficiency
This concept was also not much discussed beyond the first mention. It will be described as how well the scanner captures data with respect to the time it takes to do so. *"If it is efficient is not important. You can also put that one very low because it's not efficient [sp. important?] for that moment [during firefighting]" -Focus group participant, fire department.*

Time
Refers to the time it takes to deploy the LiDAR device at the scene and acquire the necessary data. In other words, response time.

(GPS) Reception
The ability to connect to GNSS, with the underlying purpose of being able to geolocate the point cloud data acquired by the scanner.

13.2.2. Police

The top six values for the police reported during the focus groups were safety, response time, user-friendliness, data transfer, visualization capabilities, and preparation/training.

1. Safety
The safety of the police operatives using the devices. In situations with live victims, the safety of the victims in the situation. Broadly, the protection of a given party from harm during an incident.

2. Response Time
Refers to the time it takes to deploy the LiDAR device at the scene and acquire the necessary data. In other words, Time (as defined by the fire department participants). *"Time is the enemy" - Focus group participant, police department.*

3. User-friendliness
The ease of working with the laser scanning device. This is specifically about the device interface, and not for example about its physical characteristics. *"It has to be foolproof...Everyone [emergency personnel of all levels of familiarity] has to be able to work with [the output of the scanning process]" - Focus group participant, police department.*

4. Data Transfer
Data Transfer relates to what happens to the point cloud data between scanning a scene and using some output based on the data. This includes sending the data to other parties, but it also concerns the processing and post-processing phases of the data acquisition process. An example of processing would be registering or georeferencing a point cloud. An example of post-processing would be conducting an

analysis such as identifying ground surfaces or extracting a slice of a scene. In a sense, data transfer is a proxy for processing time. *"[Processing the scanner data] takes very long. Because a mobile LiDAR scan is mostly combination of different central types that are combined afterwards, it's a linear process. If you have a walk of 10 minutes, you have at least 10 minutes processing time." – Interviewee A4*

5. Visualization Capabilities

Using the Reverse Engineering procedure uncovered the relevant intrinsic value of *Visual Comprehension of Data*. This is defined as the general visual display of the point cloud data, including how well a user or other observer is able to understand or interpret it. (So, similar to the fire department values of data clarity and consistency.)

6. User Preparation/training

- really about ease of use and how much training is necessary **Having personnel trained to use the LiDAR tools. Underlying value = Data Accuracy, Operational Efficiency**

The other values for the police reported during the focus groups were objectivity, information, data sharing, visual editability/modification, and overview/focus.

Overview / Focus

The Overview / Focus value refers to understanding the larger picture of what is going on during an incident. This means, for example, having a visual sense of the physical environment as well as knowledge of any additional factors such as victims, potential dangers or other people involved in the incident.

Information

This value can best be described as the acquired point cloud data plus any additional outputs created from further visualization, modeling, or analysis. Using the Reverse Engineering procedure uncovered the relevant intrinsic value of *Overview / Focus*.

Objectivity

This value was placed on the Miro board during the focus group, but was not discussed further. It most likely refers to how well the data represents the scene, ie. that there is a lack of distortion or obvious/large deviation in shape or location of features.

Data Sharing

Data sharing is similar to Data Transfer, but has to do specifically with the ability to make the point cloud data or LiDAR outputs available to the necessary parties handling an incident. *"If I push the data what I collected to an operator, he must he must [be able to] read it also." – Police focus group participant "Getting the data or the information to the user is always a problem." – Police focus group participants*

Visual Editability / Modification

This is defined as the ability to create images, models, and other visualizations from the acquired point cloud data. Often these modified visuals are then shared with members of the response team who are less familiar with LiDAR scanning and point cloud data.

13.3. Value-Attribute Relations

Here, the links between a value and its associated LiDAR scanner attributes are more thoroughly explained. Figure 13.5 (fire department) and Figure 13.6 (police) show the relationships between scanner attributes and each of the top first responder values.

13.3.1. Fire Department

Figure 13.5 shows the links between the values named by the fire department, and their related scanner attributes. What follows is a brief explanation of those links.

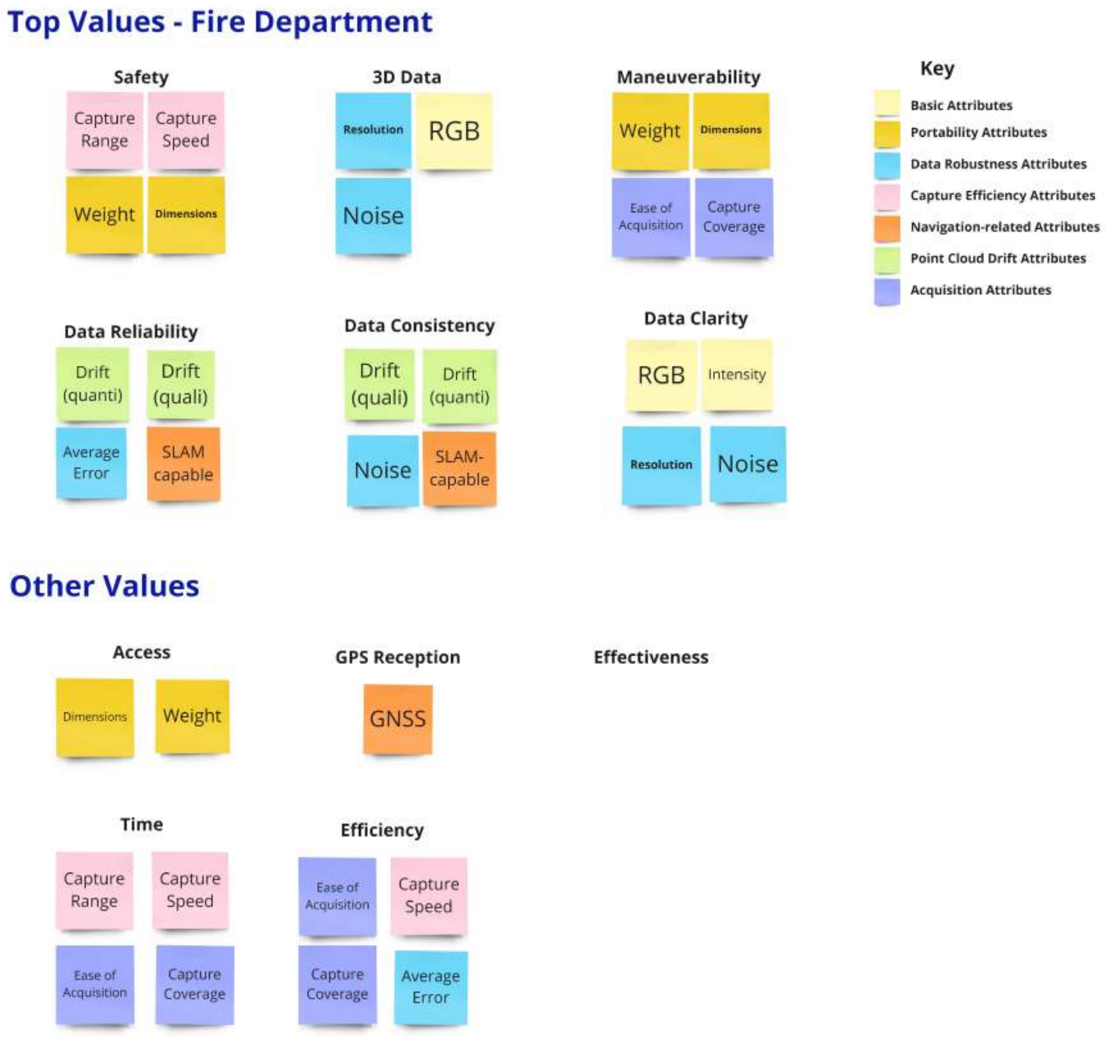


Figure 13.5: The six most important values to the fire department, and the scanner attributes related to each. The attributes are color-coded according to the category they fall into. *Note: there is no hierarchy of these values and attributes. The difference in text size is a function of the visualization software and could not be changed.*

Safety

The fire department uses a drone-mounted LiDAR scanner, so the safety of firefighters is usually not directly threatened. However, if the drone fails due to carrying too much weight or being in too-close proximity to the fire, it may be unsafe for firefighters to retrieve the item. Therefore, weight, dimensions, capture range, and capture speed are relevant.

3D Data

Straightforward; this refers to acquiring 3-dimensional data.

Maneuverability

Since the LiDAR is controlled remotely, weight and dimensions are relevant inasmuch a smaller scanner will be more easily maneuvered on a remote device. A scanner with more ease of acquisition and better capture coverage will likewise make data collection simpler as the scanner moves through the environment.

Data Reliability

Reliability refers to both qualitative and quantitative ways of representing a scene. Therefore, the average error and the qualitative and quantitative measures of drift are relevant. The use of SLAM influences (reduces) occurrence of drift, so that is also a relevant attribute.

Data Consistency
If a scanner exhibits a lot of noise, it makes it harder to know how a given set of results will turn out. Likewise with artifacts and distortion caused by point cloud drift. However, the use of SLAM reduces the incidence of drift.

Data Clarity
A higher resolution scanner allows smaller features to be resolved within the point cloud, and less noise means those features will be more clearly visible. The option to display the data's RGB and intensity values provides additional options for interpreting the image.

Access
Access is not intrinsically linked to the LiDAR devices themselves. As one focus group participant put it, "If we can't access, we create an access...I can always make holes or other things and to get in a building. So we can always go in." If anything, Access might be linked to Portability attributes because a more portable LiDAR device is more easily maneuvered inside once an entry point has been secured.

Efficiency
The scanner's efficiency is related to the capture coverage and ease of acquisition (related to operating the scanner); the average error (related to the data quality); and the capture speed (related to the time needed).

Time
The time it takes to acquire data is directly influenced by the capture speed and capture range of the device, as well as how easy it is to use the scanner and how good the capture coverage is.

GPS Reception
The only relevant scanner attribute here is GNSS capability.

Effectiveness

13.3.2. Police

Figure 13.6 shows the links between the values named by the police, and their related scanner attributes. What follows is a brief explanation of those links.

Safety
Sometimes the police use remotely-operated LiDAR scanners, in which case officer safety may be impacted if information flow stops due to instability in the device. If the scanner is being used on the ground by an officer, smaller scanner weight and dimensions make it easier for the officer to maneuver. Having a higher capture range allows officers to acquire data at more of a distance if necessary, and along with capture speed will allow them to complete the scanning and exit the situation more quickly.

Response Time
Response time is most related to the capture speed and capture coverage of the scanner, as these attributes influence how quickly data can be recorded. A scanner with a larger capture range is also able to scan an environment more more quickly than with a shorter range. Lastly, real-time capability allows the user to see what has been scanned instantaneously, making it easier to catch missed spots and to see when sufficient data has been acquired.

User-friendliness
User-friendliness of the scanner is related to the ease of acquisition. In addition, a scanner with better capture coverage is more forgiving to a user with less experience or who is working under difficult conditions.

Data Transfer
Data transfer and processing abilities are especially influenced by the size of the point cloud. High resolution data, colorized data, and data with high point density all result in larger datasets which take more time to process and more space to store. Implementing a SLAM algorithm also adds to the processing time

Figure 13.6: The six most important values to the police, and the scanner attributes related to each. The attributes are color-coded according to the category they fall into. *Note: there is no hierarchy of these values and attributes. The difference in text size is a function of the visualization software and could not be changed.*

Visual Comprehension of Data

How well a user is able to comprehend the data is influenced by many visualization-related attributes. RGB and Intensity, data resolution, noise, and drift (quantitative, but especially qualitative distortion) all affect the way the data will look to the user. Real-time point cloud and trajectory visualization can both help the user or other observer to more fully understand the situation.

User Preparation / Training

Having a well-trained operator using the LiDAR equipment. ***"I think the operator needs to be certified and that's indirectly related to how accurate you're working."– Police focus group participant*** This value is not included in the analysis because as it was described during the sessions, it does not directly relate to a particular LiDAR scanner attribute.

Overview / Focus

Obtaining RGB and Intensity values can both help to interpret a point cloud image. GNSS capability allows for geo-location, while high point density and resolution can make it easier to capture detail in a scene. Trajectory capture and real-time capability both contribute to situational awareness, especially in a dynamic scenario.

Information

While keeping in mind that an incident does not always require as much information as possible, the attributes relevant to this value are those that relate to the different types of data that can be collected: RGB, trajectory capture, capture range, point density, GNSS capability, and resolution.

Objectivity

Having a low average error and noise indicate that point cloud data has higher objectivity. Additionally, less drift means that the scene is represented more objectively.

Data Sharing

The ability to quickly share the data with other parties is mainly influenced by the size of the point cloud. High resolution data, colorized data, and data with high point density all result in larger datasets which take more time to process and more space to store.

Visual Editability / Modification

In many police use cases, the acquired LiDAR data is transformed into different forms to be used by non-specialists. For instance, a point cloud of an indoor crime scene might be transformed into a 3D mesh model that a viewer can virtually “walk through." Being able to create such outputs requires good-quality data, which is reliant on such attributes as resolution, point density, noise, and average error. Often, documenting the color in the scene is also important, so RGB is relevant as well.

14

LiDAR Use Case Evaluations

This chapter builds upon the results shown in Value Matching Results by extending the analysis a step further. Given (1) the relationships identified between first responder values and the different scanners, and (2) the relationships identified between LiDAR use cases and relevant values, it is possible to draw conclusions about how well each of the three scanners is suited to a given LiDAR use case.

14.1. Use Cases

One of the results of the interviews conducted with first responders was gaining insight into the ways in which they use or consider using LiDAR scanning. What follows is a set of use cases. These use cases represent different types of scenarios in which first responders, specifically police operatives and firefighters, are likely to use LiDAR scanning. The use cases were initially derived from a combination of the interview data and information gathered during the observational visit. These were then validated directly and indirectly during the focus group sessions. They do not represent the full range of use case possibilities expressed by study participants, nor necessarily the most frequent use cases. Rather, they were chosen in order to showcase some of the disparate scenarios in which LiDAR is used.

It is important to note that performing LiDAR analyses that address the use case scenarios is outside the scope of this project, and is not the point of the use cases. Rather, the use cases are a tangible way to comment on the usefulness of the scanners and their point cloud data. Rather than just arbitrarily assessing the data quality on the basis of metrics, we can go a step further by considering how a given dataset or scanner might perform in a particular use case. There are two use cases each for the fire brigade and the police, described below.

Some important characteristics of each use case are mapped out in Figure 14.1. These characteristics can then be assessed against the different categories in the scanner comparison chart.

14.1.1. Fire Department: MLS Use Case 1

Real-time assessment of the extent of a fire, when the fire is in an interior location. The assessment might include the presence and/or location of safe entry points in and out of the building, whether there are any victims inside and where they are, and whether first responders can be sent inside. If possible, the scanning is done in the part of the area not yet on fire.

14.1.2. Fire Department: MLS Use Case 2

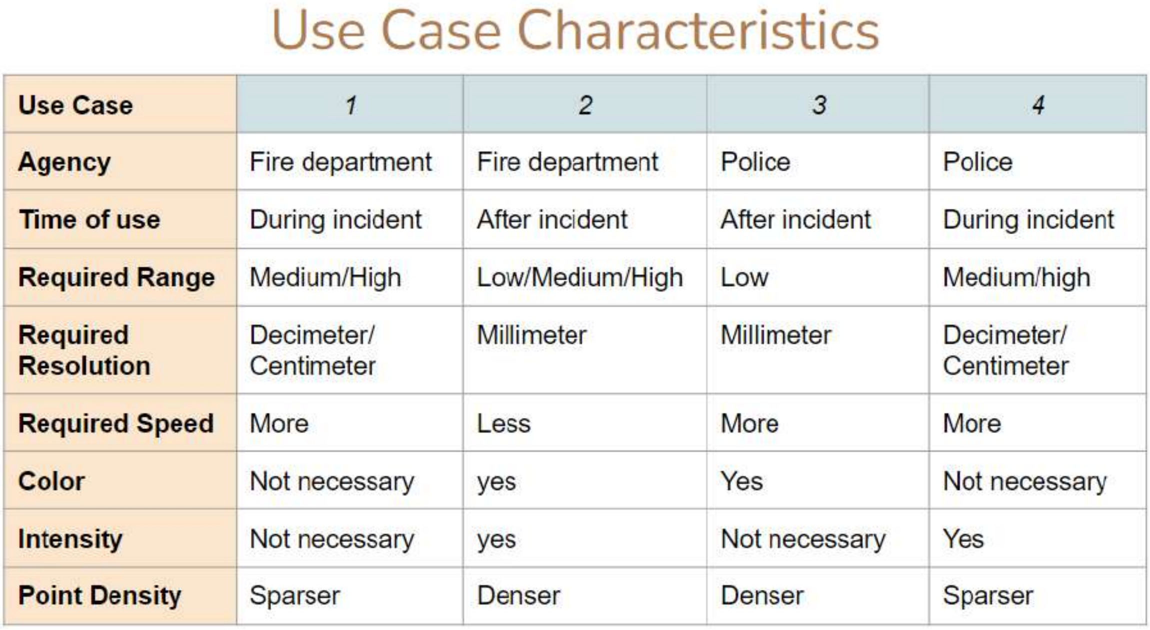
Post-incident investigation of a house or other interior or partially-interior location. The investigation usually includes finding out how the fire started, documenting the layout of the house, and assessing the extent of the fire damage.

14.1.3. Police Department: MLS Use Case 1

Post-incident modeling or assessment of an indoor crime scene, like an apartment. This involves closely documenting the location of the crime for continued analysis and detective work. For example, the positions of objects and furniture, potential vantage points of the attacker or involved people, and/or the orientation of the body.

14.1.4. Police Department: MLS Use Case 2

Real-time scanning of a location during a raid, for example to search for a drug laboratory hidden in a warehouse or industrial space. In this type of scenario, officers are sent inside the location to retrieve point cloud data and may be at risk of confrontation with the people using the space. The officers are likely communicating remotely with members of the crisis response team who are on the outside.



Use Case Characteristics

Use Case	1	2	3	4
Agency	Fire department	Fire department	Police	Police
Time of use	During incident	After incident	After incident	During incident
Required Range	Medium/High	Low/Medium/High	Low	Medium/high
Required Resolution	Decimeter/ Centimeter	Millimeter	Millimeter	Decimeter/ Centimeter
Required Speed	More	Less	More	More
Color	Not necessary	yes	Yes	Not necessary
Intensity	Not necessary	yes	Not necessary	Yes
Point Density	Sparser	Denser	Denser	Sparser

Figure 14.1: Table showing the characteristics of each use case

14.2. Evaluation Methodology

This part of the discussion takes the scanner-value outputs from the Value Matching Methodology, and extrapolates a step further to consider how the different scanners match up to the use case scenarios introduced in section 4.1. This is possible because in the focus group sessions, participants wrote down which values they considered most relevant to the different use case scenarios they named. The following figures show these associations.

Use Case Values

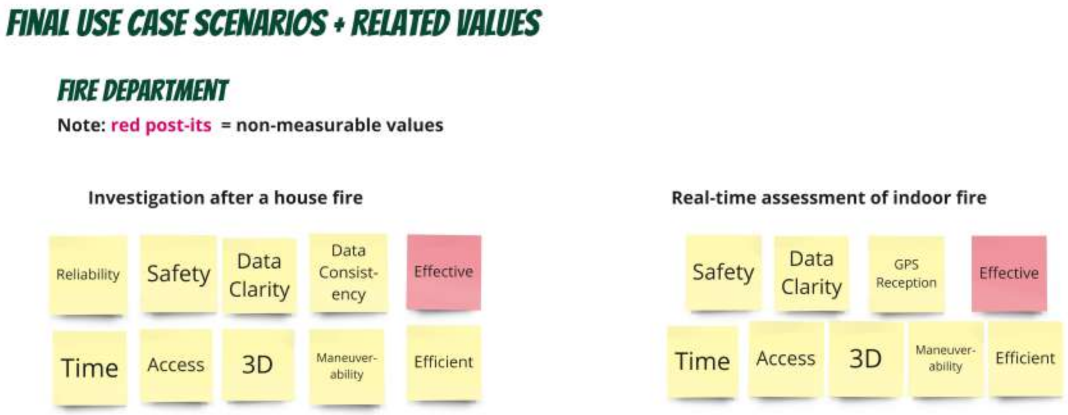


Figure 14.2: The values associated with each fire department use case

Figure 14.2 shows the values associated with each of the two fire department use cases mentioned above. Both scenarios contain safety, data clarity, time, access, 3D data, maneuverability, efficiency, and effectiveness. The first scenario, investigation after a house fire, also contains reliability and data consistency. The second scenario, real-time assessment of an indoor fire, also contains GPS reception. One of the values, effective(ness), was included by first responders in the fire department focus group but cannot adequately be measured because there was no clear definition determined.

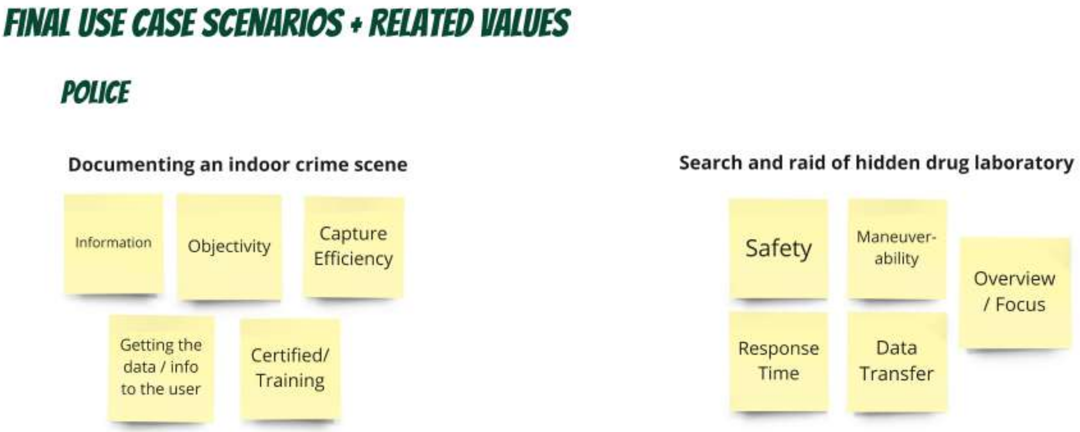


Figure 14.3: The values associated with each police use case

Figure 14.3 shows the values associated with each of the two police use cases. In this case, both scenarios contain Data transfer. The first scenario, documenting an indoor crime scene, also contains objectivity, capture efficiency, information, and certification/training. The second scenario, search and raid of a hidden drug laboratory, also contains safety, maneuverability, response time, data transfer, and overview/focus.

14.2.1. Comparing Scanner Suitability

Once it is clear which attributes can serve as metrics for each value, the scanners can be compared to one another. In order to make a comparison between the three scanners, the values were subjected to a Pugh Matrix Analysis to determine how each scanner ranks against the others with respect to the different characteristics. A Pugh Matrix Analysis, sometimes known as a decision matrix analysis, is a multi-criteria decision making (MCDM) method well-suited to evaluating multiple ideas or alternatives against a set of criteria(Olabanji & Mpofu, 2020). Pugh analysis allows the user to evaluate a set of options based on criteria with different units, ranges, and importance levels, leading to an evidence-based decision made in a systematic way(Mahboubkhah, Aliakbari, & Burvill, 2018). It is often used by mechanical, electrical, systems, and industrial design engineers to determine which alternative is the most suited to a particular process or product based on the criteria (Frey et al., 2009; Mahboubkhah et al., 2018). We applied this method to the first responder value data to see which scanner is most aligned with a given value based on its attributes.

Figure 14.4 shows the Pugh matrix for a fire department use case. The rows (value criteria) are the scanner attributes and the columns are the different scanners, with an additional column for weight. Each of the four Use Cases has its own chart to reflect the relevant values and attributes. Most attributes are related to more than one value, so each attribute is weighted according to how many values are linked to it. For example, the Noise attribute has a weight of 3 because it is related to three of the values important to the use case (3D Data, Data Clarity, and Data Consistency). On the other hand, GNSS has a weight of 1 because it is only related to GPS reception.

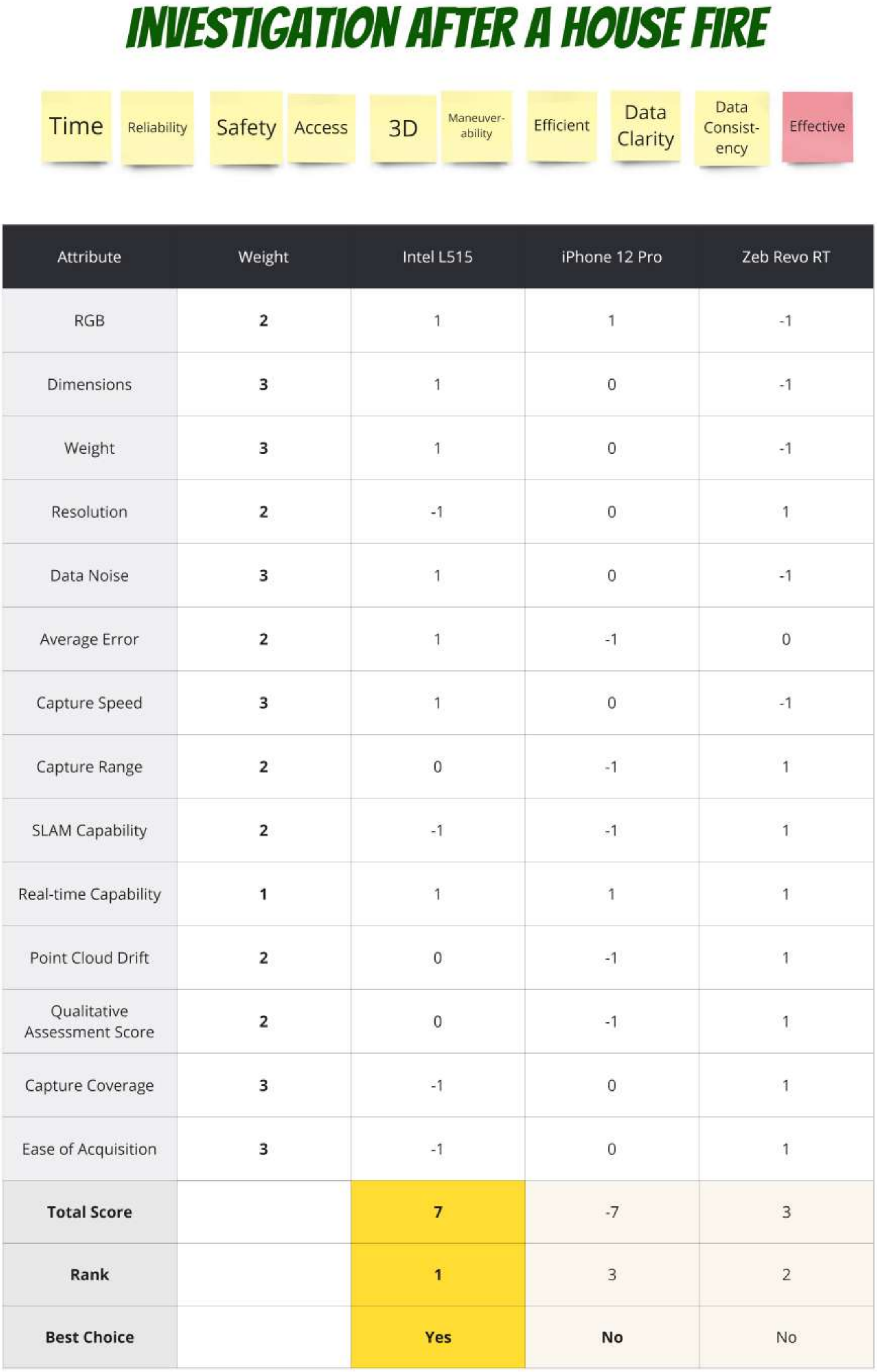
The Pugh method usually also requires choosing a datum, the standard against which the other options in the chart are compared (Frey et al., 2009). The datum is often the current leader in the market, but it can also be one of the alternatives being compared in the chart. Instead of a datum for comparison, the attribute values of the scanners were compared to one another. The lowest value of the three will receive a -1, the middle value a 0, and the highest value a 1. For categories where they are all equal, each entry gets a 1. For yes/no categories such as SLAM Capabilities, yes gets a 1 and no gets a -1. The total weighted points in each column gives a final score, which is ranked between 1 and 3.

14.3. Scanner Suitability Results

What follows are the results of the Pugh matrix analysis.

14.3.1. Fire Department Use Cases

Figure 14.4 shows the Pugh chart for case study 1, investigation after a house fire. It shows that the Intel L515 is the most suitable scanner with a score of 7, followed by the Zeb Revo RT with a score of 3, and lastly the iPhone 12 Pro with a score of -7.



INVESTIGATION AFTER A HOUSE FIRE

Attribute	Weight	Intel L515	iPhone 12 Pro	Zeb Revo RT
RGB	**2**	1	1	-1
Dimensions	**3**	1	0	-1
Weight	**3**	1	0	-1
Resolution	**2**	-1	0	1
Data Noise	**3**	1	0	-1
Average Error	**2**	1	-1	0
Capture Speed	**3**	1	0	-1
Capture Range	**2**	0	-1	1
SLAM Capability	**2**	-1	-1	1
Real-time Capability	**1**	1	1	1
Point Cloud Drift	**2**	0	-1	1
Qualitative Assessment Score	**2**	0	-1	1
Capture Coverage	**3**	-1	0	1
Ease of Acquisition	**3**	-1	0	1
Total Score		**7**	-7	3
Rank		**1**	3	2
Best Choice		**Yes**	**No**	No

Figure 14.4: Pugh Matrix showing scanner comparisons for fire department use case 1, investigation after a house fire.

Figure C.1 (in the appendix) shows the Pugh chart for case study 2, a real-time assessment of an indoor fire. It shows that the Intel L515 is the most suitable scanner with a score of 5, followed by the iPhone Pro 12 with a score of 0 and lastly, the Zeb Revo RT with a score of -2.

14.3.2. Police Department Use Cases

Figure 14.5 shows the Pugh chart for case study 2, documenting an indoor crime scene. It shows that the Zeb Revo RT is the most suitable scanner with a score of 6, followed by the Intel L515 with a score of 5 and lastly the iPhone Pro 12 with a score of -6.

Figure C.2 (in the appendix) shows the Pugh chart for case study 2, searching for a hidden drug lab during a raid. It shows that the Zeb Revo RT and Intel L515 are both the most suitable scanners, with a score of 5, followed by the iPhone Pro 12, with a much lower score of -3.

Figure 14.6 shows the most suitable scanner for each use case scenario. The Intel L515 was found most suitable for both fire department use cases, while the Zeb Revo RT was found most suitable for both police use cases as well as the first fire department use case.

Figure 14.7 shows the most suitable scanner per use case alongside the Pugh Matrix scores for each individual scanner. The matrix scores show how decisive the choice of most suitable scanner was.

14.4. Discussion

14.4.1. Comments on the "best" Scanner

Based on this Pugh assessment method, the Zeb Revo RT is the most suitable scanner for the two police use cases. However, based on my experience using the three scanners, I would not necessarily choose the Zeb Revo RT. Although on paper it greatly surpasses the Intel and iPhone scanners in terms of the final Pugh analysis score, in reality, some of the Zeb Revo RT's qualities seem to make it less of a good choice. For example, the extremely long capture range can cause noise and distortion in environments with reflective surfaces. The fact that it is SLAM-capable does not necessarily translate well to a real-time scenario, especially if the scan cannot be ended in the same place it starts. Lastly, the Zeb Revo RT is the most unwieldy of the three scanners and the heaviest. There are solutions for some of these things: it is possible to buy an open-loop software add-on and a backpack carrying case for the Zen Revo RT.

Similarly, the Intel L515 has by far the highest scores for the fire department use cases. However, the gap in scores (7 or 5 vs. -7 or -2) makes the choice seem very clear when it may not be.

At face value, the two fire department use cases have almost exactly the same Value requirements (the only difference being that one requires Data Consistency while the other does not) and, thus, the same "most suitable" laser scanner. However in practice, based on my experience using the scanners, I would say that the *Intel L515* is best for a post-fire investigation scenario while the *iPhone Pro 12* is better for a real-time fire assessment or search-and-rescue scenario.

With respect to Capture Range, technically the iPhone (5m) is lowest, because the Intel has a range between 2m and 9m. However, based on my own experiences, the iPhone gives the impression of having a better capture range because the overall scanning experience is smoother and more pleasant. Specifically, the iPhone has better capture coverage and more successfully captured the ceilings and upper wall areas while walking.

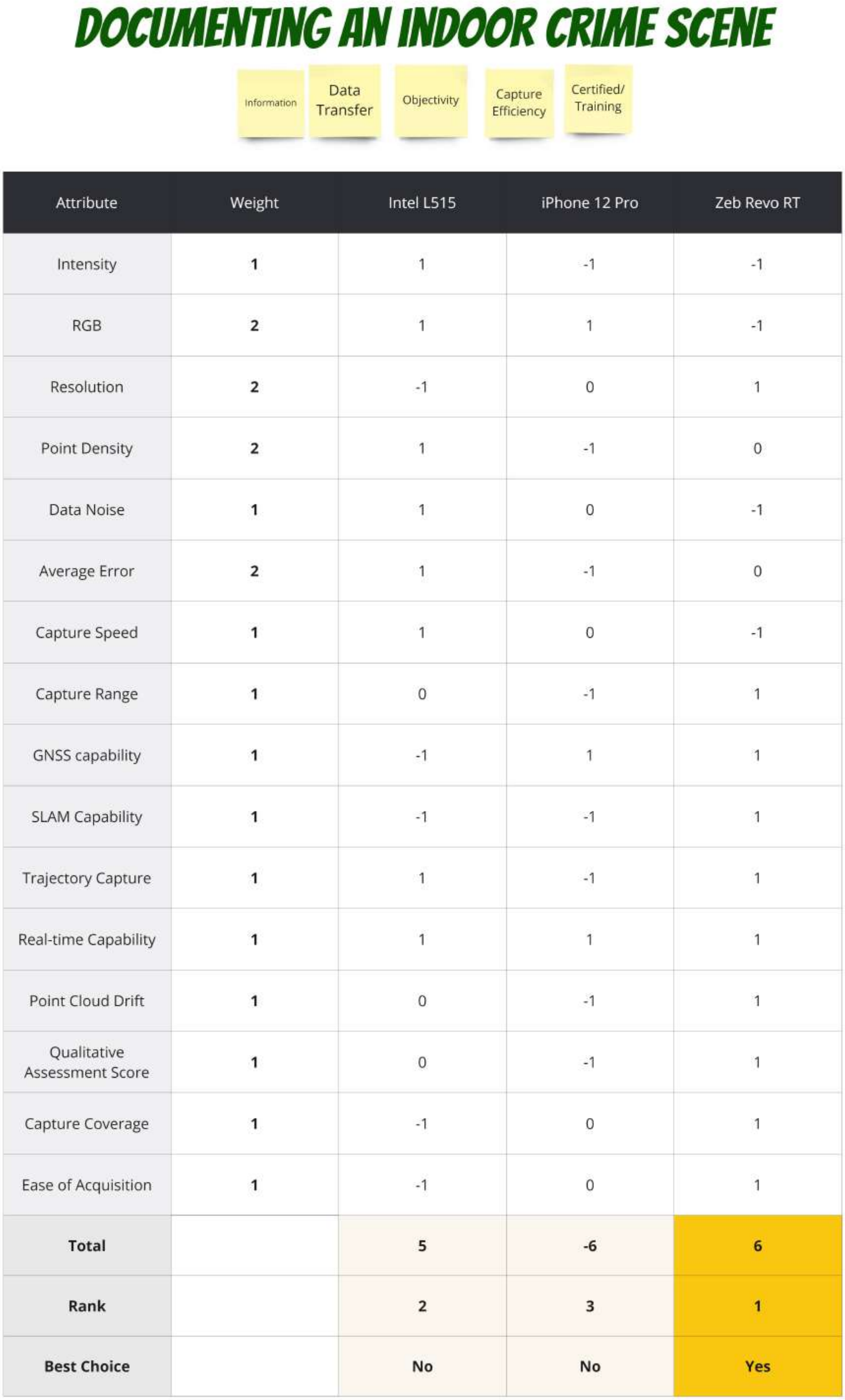
14.4.2. Comments on the Evaluation Method

The scanner characteristics included in the Scanner Attribute Comparisons represent the attributes considered relevant at this time and for this particular context. However, the links drawn are subjective and based on the researcher's knowledge, so some variation is likely based on who is doing the analysis. It would also be interesting to consider if different scanner attributes would be useful in evaluating laser scanner suitability for different scenarios. This is one of the appealing things about the methodology outlined in this paper: it is modular and flexible enough to allow for different values, attributes, and scenarios to be highlighted, evaluated, and/or considered.

One thing about the comparison process that could be refined for the future is better conveying the difference between attribute values. Sometimes two scanners do not differ significantly in an attribute, but the difference in scoring does not reflect that. For example, the iPhone is only 96 grams heavier than the Intel L515. In some cases, it would be useful to know that their weights are quite similar so that such a small difference does not become the deciding factor between the two scanners in a scenario where that would not make a difference.

Ranking the attribute values is not a direct correlation to how well-suited to a task they are. It is more of a proxy, so sometimes the resulting assumption may not be completely correct. For example, a comparison of Capture Speed says that the Intel (2.3-9.2 million points/sec) is best, iPhone (unknown) is second best, and Zeb Revo (43,000 points/sec) is worst. However, it is very possible that the actual, noticeable difference in capture speed is negligible, and that any of the three options would be equally suitable with respect to that attribute.

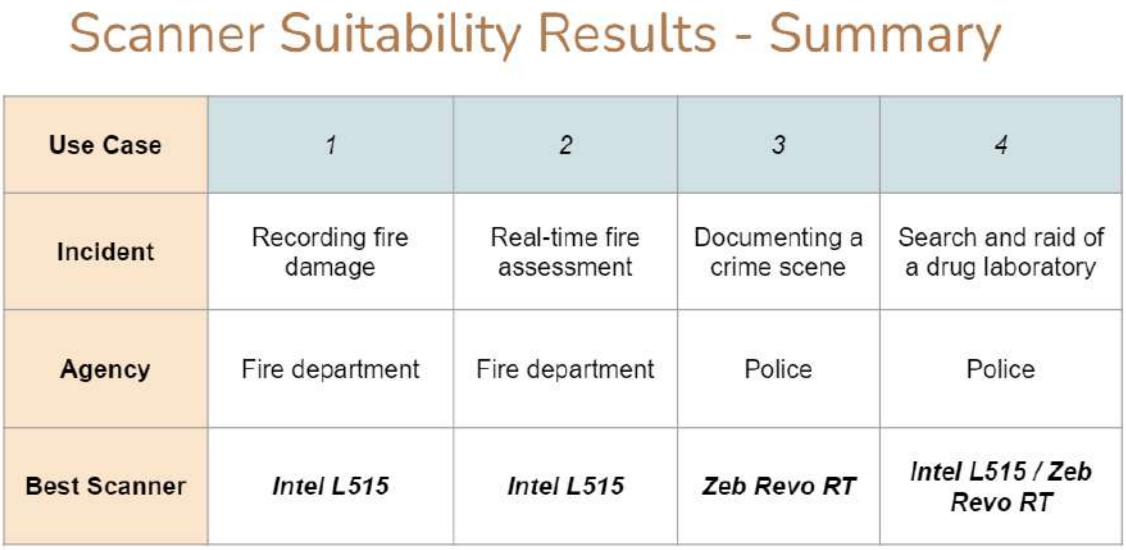
The two fire department use cases were evaluated solely using fire department values. However, the police use cases each used one fire department value that was not originally mentioned as a police value. Documenting an indoor crime scene includes the value capture efficiency, and search and raid of a hidden drug lab includes the value Maneuverability.



DOCUMENTING AN INDOOR CRIME SCENE

Attribute	Weight	Intel L515	iPhone 12 Pro	Zeb Revo RT
Intensity	**1**	1	-1	-1
RGB	**2**	1	1	-1
Resolution	**2**	-1	0	1
Point Density	**2**	1	-1	0
Data Noise	**1**	1	0	-1
Average Error	**2**	1	-1	0
Capture Speed	**1**	1	0	-1
Capture Range	**1**	0	-1	1
GNSS capability	**1**	-1	1	1
SLAM Capability	**1**	-1	-1	1
Trajectory Capture	**1**	1	-1	1
Real-time Capability	**1**	1	1	1
Point Cloud Drift	**1**	0	-1	1
Qualitative Assessment Score	**1**	0	-1	1
Capture Coverage	**1**	-1	0	1
Ease of Acquisition	**1**	-1	0	1
Total		**5**	**-6**	**6**
Rank		**2**	**3**	**1**
Best Choice		**No**	**No**	**Yes**

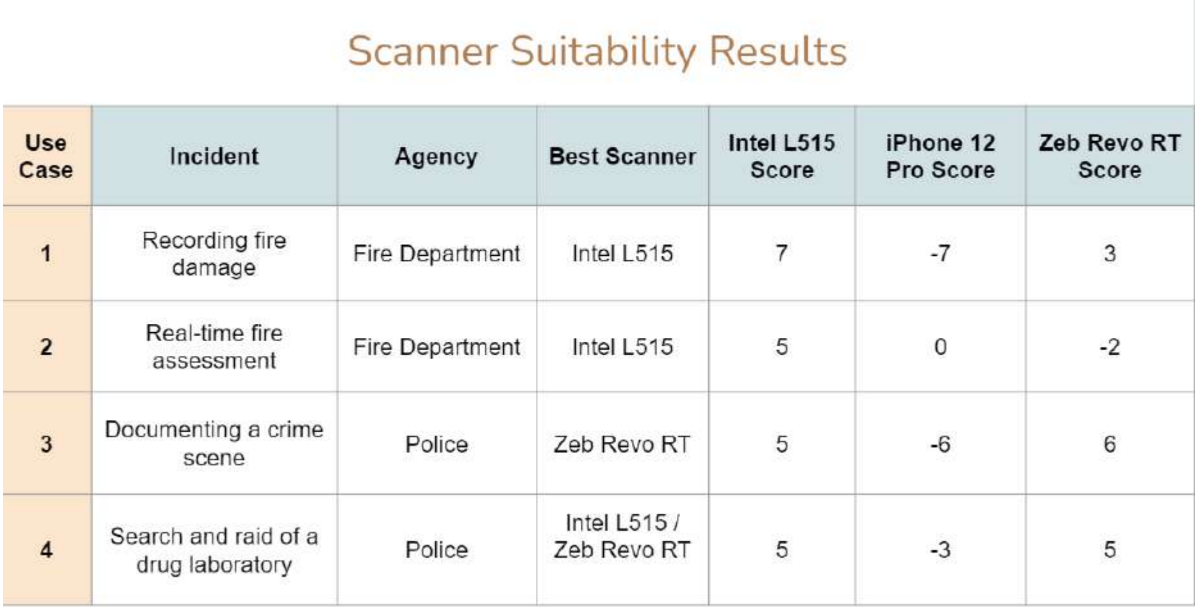
Figure 14.5: Pugh Matrix showing scanner comparisons for police use case 1, documenting an indoor crime scene



Scanner Suitability Results - Summary

Use Case	*1*	*2*	*3*	*4*
Incident	Recording fire damage	Real-time fire assessment	Documenting a crime scene	Search and raid of a drug laboratory
Agency	Fire department	Fire department	Police	Police
Best Scanner	***Intel L515***	***Intel L515***	***Zeb Revo RT***	***Intel L515 / Zeb Revo RT***

Figure 14.6: Table showing the most suitable scanner for each use case



Scanner Suitability Results

Use Case	Incident	Agency	Best Scanner	Intel L515 Score	iPhone 12 Pro Score	Zeb Revo RT Score
1	Recording fire damage	Fire Department	Intel L515	7	-7	3
2	Real-time fire assessment	Fire Department	Intel L515	5	0	-2
3	Documenting a crime scene	Police	Zeb Revo RT	5	-6	6
4	Search and raid of a drug laboratory	Police	Intel L515 / Zeb Revo RT	5	-3	5

Figure 14.7: Table showing the most suitable scanner for each use case and the Pugh Matrix scores used to determine this

Part IV

Designing Future LiDAR Applications

15

Introduction

Problem Statement

Part 4 of this thesis describes how developers can use the output of the design methodology developed in prior parts of the thesis to create an improved LiDAR tool. The previous chapters of this report have led to a deeper understanding of the needs of first responders in emergency scenarios as well as the current state of LiDAR scanner capabilities. Therefore, it is more clear what aspects of LiDAR for emergency response are currently going well. However it is also clear that there is room for improvements to be made. So the question is, what do developers need to do to design a better LiDAR tool for first responders?

Research Goal

The goal of this final part of the report is to show how implementing the results of the design methodology constructed in Part I and Part III would look in practice. What do developers need to do to design a better LiDAR tool? How would this improved tool influence first responder communication in the field?

Research Question

The research question that governs Part 4 is, *How can developers improve mobile LiDAR scanners to better support first responder operations during emergencies?*

The research objectives are to

1. Use the results of the valuematching methodology to create design requirements for an improved mobile LiDAR scanner
2. Provide a guide developers can use to (re)design mobile LiDAR scanners

The outcomes of this section are (1) an elaborated example of how developers could redesign a mobile LiDAR scanner to better support first responders in a particular use scenario; (2) a more general guide developers can use to implement these changes; and (3) a demonstration of how the design methodology created in this thesis can be used to improve upon LiDAR technology given the particular needs of a first responder group.

Chapter 15 focuses on what the improved tool would look like and how the improvements relate to / impact first responder communication. Chapter 16 discusses what actions developers need to take to actually create that tool.

16

Case Study Scenario

To answer the question of how developers can create an improved mobile LiDAR scanner, we will show an example of the **design methodology** applied to a new use case scenario that has not already been discussed in Part III. This chapter takes the results of the conceptual, empirical, and technical investigations conducted in the previous three parts of the report, and applies them to a new scenario. In Part I, first responders named use case scenarios in which they do or would use mobile LiDAR. In this chapter, one particular use scenario serves as a test case for the Value Matching Design Methodology developed in Part III. First the scenario is described. Then, using the insights generated from the interviews and focus groups (see Values, Methodology: Understanding the LiDAR Use Context) and theoretical relationships developed in Value-Attribute Relations, the values and scanner attributes most relevant to the scenario are identified. Next, a combination of literature and insights from the interviews and focus group sessions conducted in Part I are used to propose some improvements to the current mobile LiDAR scanner offerings. Lastly, the implications of this improved LiDAR scanner are discussed.

16.1. Scenario Description

The dienst speciale interventies (special interventions team) (DSI) is a specialized unit of the National Police that handles a variety of extreme situations (Defensie.nl). The unit consists of a mix of military and national police personnel, and is divided into four different special units. The units respond to large-scale terrorist attacks, hostage situations, and situations involving explosives, dangerous substances, and large firearms among other things (Defensie.nl). The common denominator is that each team handles life-threatening scenarios while operating in a dynamic environment.

In a 2023 edition of the Ministry of Defense's KMar Magazine, a lieutenant in the DSI describes a manhunt situation that unfolded in the center of Utrecht: "In het begin was het chaos, maar met sturing vanuit de meldkamer, werd de verdachte door verschillende teams in de stad steeds meer ingesloten. Zo kwamen we uiteindelijk bij hem terecht. [In the beginning it was chaos, but with guidance from the control room, the suspect became increasingly contained by different teams in the city. That is how we eventually captured him.]" Later, he describes intervention situations more generally: "Tijdens een interventie wordt er veelal gebruik gemaakt van technische hulpmiddelen zoals robots of drones [During an intervention, technical aids such as robots or drones are often used]" (Defensie Magazine). These quotes illustrate two important components of a DSI intervention scenario: a ***command center*** that coordinates communication among different responder parties, and the use of ***robots or drones***. While the description above refers to an outdoor scenario, these basic components would not differ much in an indoor emergency.

Let us consider an indoor scenario that could be faced by the marine intervention unit, which handles "large-scale, offensive, and complex terrorist actions" (Defensie.nl): *the police received emergency calls from workers in a large industrial complex on the outskirts of Rotterdam, where at least two people are armed with guns and possibly explosives. DSI operatives are preparing to enter the complex to find and apprehend the suspects and evacuate the people sheltering inside.*

In a crisis scenario, emergency first responders use two types of information to mount a response: static and dynamic (**dilo2011data**). Static information is reference data such as building plans, topographic maps, and administrative data and has been gathered beforehand. Dynamic information is collected during the incident itself and gives the users a better understanding of the incident and its effects (**dilo2011data**). For example, the number of people trapped, the detection of dangerous substances, and the obstruction of an interior pathway in a building are all pieces of dynamic information.

As the DSI operative mentioned in section 16.1, it is common for operatives in an intervention-based scenario to rely on a central command center (or control room) to coordinate the overall plan and the necessary actions. In a scenario like this one, which involves multiple threats (armed suspects, trapped civilians, possibility of explosives), it is likely that several different departments within and outside of DSI have been notified and are working together (**dilo2011data**). This means that the command center plays an even more crucial role.

16.2. Important Elements

Based on the value-attribute links, the most important values for police LiDAR usage are safety, data transfer, visual comprehension of data, response time, user-friendliness, and user training/preparation. During the focus group, overview/focus and user-friendliness were also specifically named as values relevant to DSI operations. I also add maneuverability to the list given the large-scale and dynamic nature of many of the DSI scenarios.

Based on the value-attribute links, the most important technical attributes related these values are:

- Capture range
- Capture speed
- Scanner dimensions
- Resolution
- Point density
- Noise
- RGB
- Intensity
- Point cloud drift
- SLAM capability
- Real-time capability
- Trajectory capture

They are not necessarily all equally important, so as a developer, it is worth prioritizing these further as you consider what kinds of improvements might make the most impact.

Some relevant pain points discussed by interviewees and participants of the police focus group include

1. Lack of real-time processing, which would allow the user to see the data they have already scanned
2. Long wait to access the data after scanning due to slow processing time
3. High reflectance and/or obstructive objects in the laser scanning path
4. Very little pre-written software to automate point cloud analyses
5. Difficulty transmitting or sharing large volumes of data
6. LiDAR scanner interfaces are not always user-friendly

The pain points, in combination with the relevant scanner attributes, are a good starting point for considering new features or scanner elements to (re)develop.

We know from the data collected in chapter 4 that the ability to make measurements from a distance, the ability to quickly acquire data, and the high level of data detail are all valued by police first responders in their current devices.

In that same dataset, three features in particular are relevant to this scenario:

1. Augmented reality vision with measurement capabilities
2. 3D data viewer functionality
3. More data viewing capacity

Alongside the ideas generated by first responders, literature points to some other suggestions for useful LiDAR features for this scenario:

1. Real time sharing/streaming of dynamic spatial information from incident scene (Bart-Peter Smit, 2020)
2. Connect indoor and outdoor navigation capabilities (Yan, Diakité, & Zlatanova, 2019)
3. Generate and visualize 3D model of a building given a floor plan or other 2D spatial information (Okorn et al., 2010; Pouraghdam et al., 2019)
4. Extract and share floor plans from a 3D point cloud in real time (Okorn et al., 2010; Pouraghdam et al., 2019)
5. Implement open-loop SLAM in real time

Typically, the real barriers to cooperation between different emergency service units are not lack of data or appropriate technical abilities (Zlatanova et al., 2004). Rather it is a lack of interoperability and alignment between the various information and data sources acquired, compiled, and accessed by the individual agencies. Twenty years later, this still dovetails on some level with the complaints of first responders expressed in this research: namely that the processing, post-processing, and sharing of point cloud data are areas of the LiDAR experience that beg improvement.

As one participant from the fire department put it, *"Heel veel [data] bestaat er al. Het is niet zozeer de techniek dat een probleem is; over het algemeen is het de social innovvation dat nog plaats moet vinden. Heel veel data is er, maar...iedereen werkt in silos. De grootste crux van mij, de grootste bedoeling voor mij is deze silos te voorkomen, zodat we met elkaar echt data kunnen delen."*

"There is already a lot of data. It's not really the technology that's a problem; in general it's the social innovation that still needs to catch up. There is a lot of data, but...everyone works in silos. The crux, the biggest goal for me, is to prevent these silos, so that we can really share data with one another."

16.3. Suggested LiDAR Features

Desired Features provides relevant inputs which are based on the aforementioned values. This, along with existing literature, Plus Points, and Pain Points provides a basis for the potential LiDAR features discussed here.

16.3.1. Real-time Processing

Situation Awareness theory, coined by Mica Endsley, describes situation awareness as a "constantly evolving picture of the state of the environment" Endsley, Bolte, and Jones (2003, p.12). In a dynamic scenario like the one described in this chapter, situation awareness is very important for supporting decision-making and coordinating multiple response parties. Real-time processing is the development that will make the most difference in such a scenario. As one police focus group participant said, *"Sometimes we have to be very quick and then it's, yeah, it would be useful to have near real-time Intel."* There are a few different recommended features that fall under the umbrella of real-time processing.

Scanning Overview

A scanning overview shows the operator(s) what has already been scanned and updates this image in real time. It also allows the operator(s) to see their position in the environment and those of any other operatives. This overview can also be made available to those in the command center. Having a continuously-updating overview of the acquired data supports situation awareness and allows the LiDAR operator and/or commander to direct their movements accordingly.

Streaming of Dynamic Spatial Data
In a real-time intervention scenario, the purpose of sharing data is to include other parties (agencies, first responders, decision-makers) in the situation as it unfolds so that they can contribute to the response actions. Information being scanned should be shared near-instantaneously with remote viewers such as the command center. Ideally, an actual data transfer occurs so that remote members of the team can also manipulate the data if need be. However, even view-along is helpful. This streaming of spatial data supports decision-making also better facilitates collaboration between members of the operation. It also avoids the problem of long gaps in time between acquiring data and acting on it.

Automated Analyses
Processing LiDAR data in real time can aid navigation, decision-making, and overall situation awareness; both for the officer(s) doing the scanning and any other operatives on the ground. There are a number of analyses that would be relevant to implement, including automatic segmentation, wall and floor classification, and extracting a floor plan or cross-section of an area. There should be an option to turn these analysis features on or off depending on what the situation calls for. Implementing automated analyses allows the team to build an interactive, 3D model of the building on the go. This shapes other facets of the response such as plans for officer movement inside the building and the placement and number of officers needed for backup.

16.3.2. Integration of Multiple Sensing Modes

Recording data at multiple wavelengths (say, RGB, Infrared, and Intensity) would give officers options for visualizing and understanding the environment. For example, it could reduce the severity of capturing highly reflective or absorptive objects within the point cloud. This would result in a clearer acquired image, and possibly the ability to distinguish more features and objects within the image. It is also possible that operatives fulfilling different tasks use different data streams. For example, operatives on the ground could use Infrared data to detect where people might be hiding, while the command center focuses on intensity and RGB data to get an overview of the building's layout and structure.

16.3.3. Intuitive Dashboard

While related to the real-time processing overview mentioned above, the intuitive dashboard is more concerned with the actual design of the platform/screen/canvas showing the overview. The person scanning and the people observing have different tasks, and may want or need to access and visualize the LiDAR data differently in the moment. In a scenario like this one time is of the essence, and so it is also important to cut down on any potential sources of confusion. Offering a set of customizable, intuitive dashboards built into the LiDAR scanning apparatus/workflow would help reduce information overflow in such a scenario.

There is research in the field of situation awareness that can shed light on developing information displays (Endsley, 2015; Endsley et al., 2003). In fact, situation awareness is linked to user-centered design and encourages using good system design to help make the right information available to users (Endsley et al., 2003). The important note for designers is that it will be helpful to find out from their target group what kind of information they want and need to see on such a dashboard.

16.3.4. Warning: Avoid Information Overflow

One thing that the proposed features all have in common is that they introduce additional data streams or potential for visualizations. While it is certainly useful for first responders to have access to more spatial information about the surrounding environment during an operation, it also brings the risk of overwhelming the users. Providing too much data and/or providing data without the proper context and filtering or pre-processing steps can lead to information overflow (**smit_creating_2021**)(Endsley, 2016). This overflow can especially occur in situations where first responders are not deeply familiar with using spatial data (**dilo2011data**) and/or need to apply the information "under pressure and within stressful conditions" (**smit_creating_2021**; **dilo2011data**). Something as simple as a poorly-designed display can lead the observer or operator to expend extra time and mental space sifting through all the available information to determine what is relevant and immediately necessary (Endsley et al., 2003)).

To avoid this, developers should build different levels of detail into the visualization and sharing options(**smit_creating_2021**). For example, in a scenario with multiple laser scanners, perhaps the ones navigating the laser scanner only see their own capture trajectory and position on the screen, while the commander can see the full picture to aid in decision-making. Along with this, they should consider which information is important to visualize in real time for the command center and the data collector and what simply needs to be transmitted for processing and analysis.

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A Developer's Guide to Design Methodology

As we saw in the previous chapter, developers can use the results gathered from Part 1, Part 2, and Part 3 of this project to (re)design mobile LiDAR scanners with features and attributes that better support first responder communication needs. In the previous chapter an example use scenario was sketched out for developers. The design methodology was applied to this scenario, and then recommendations for LiDAR improvements were made based on the resulting information. But in addition to using the recommendations set forth in this report, a developer team may want or need to gather additional or different information from their own target group. So in this chapter, we take a closer look at the actual method that developers can use to create the improved LiDAR scanners. For example, what kind of additional questions would be useful or necessary to ask in order to implement some of the suggested features? What are the core considerations, steps, and questions that developers need to keep in mind in using this design methodology to design improved first responder LiDAR?

17.1. Guide for Developers

While Value Matching Methodology introduces the Value Matching Methodology and applies it to the data collected in First Responder LiDAR Use in Emergency Situations, this section packages the methodology in a way that makes it simple for developers to apply it to the mobile LiDAR first responder context and beyond.

Main Steps

The basic design methodology from Part I and Part III can be distilled into five main steps. The following is a simplified description of the design methodology that a developer could use as a reference for their own work.

1. Gather information about the *user* and *use contexts* Possible ways to do this include
2. Gather information about what *values* are important
3. Assess quality of technical tool
    - qualitative metrics
    - quantitative analysis
    - gather data on relevant attributes
4. Define important concepts: technical attributes and user values
    - refer to literature
    - refer to user data (transcripts, visits, etc)
5. Match the technical attributes to the values

- Give a short, simple explanation / reasoning for each link you draw

There are many different ways to gather the relevant information. A few possibilities include interviews, focus groups, literature reviews, and site or observational visits with target group members. Some may work better than others depending on your specific circumstances. The outcome of this process is a large quantity of user data, a technical assessment of the tool type in question (LiDAR), and relationships between user values and different aspects of the tool.

Guiding Questions

Because every design scenario is different, following the steps as given above may not be the right fit for every developer team. Therefore, developers can use the following questions to guide their research during the design process.

1. How many people within the group are trained to use LiDAR scanners in the field?
2. In an emergency response scenario, how many people are using the scanners? Are they all based at a single location, or are they spread between on-site and remote / off-site?
3. Does the target agency typically respond to such incidents in teams? Of how many people? Does everyone have a different task? Are they trained to do multiple tasks?
4. What kind of information is needed by the first responders? Do different teams and/or roles need different information? Who is in charge?
5. What information is needed in real-time and what can be received later? What information is urgent and what is less urgent?
6. What are the goals of the user(s) when using this technology? What does this say about the data that they need to be aware of?
7. What tasks do the on-the-ground (ie. LiDAR scanner user) and remote observers (ie. command center) tend to do in a dynamic scenario? What are their respective informational needs?
8. With respect to the scanner's visual display, does each element or piece of information serve some purpose?
9. With respect to the design of digital interfaces, have you considered including toggle and customization options to allow the users more control over what they see?

These questions were distilled from my own experience in conducting this research. The last four questions on the list also incorporate some of the situation awareness design methodology discussed in (Endsley et al., 2003).

Ways to Use It

This form of the methodology has been distilled to its essential steps so that developers can adapt it to their process in multiple ways. The following are different ways that the above method could be used.

- Use it to consider relevant starting points in other scenarios
- Use it to see how development ideas may mesh with first responder needs
- More broadly, you can redo some of the steps to create new value-attribute relationships (or even consider different use contexts or target groups)

17.2. Comment on Deriving Design Requirements

This might not be relevant anymore, I'm not sure.

Deriving design requirements from values is very context-dependent (van de Poel, 2013). This is why we chose to not only show the results of linking first responder values to the specific attributes of this scanner, but to show the reasoning behind the choices made and the working definitions of the values and attributes. Demonstrating the process of defining these constraints is part of what makes this methodology replicable and useful to other developers. It means that they can follow the methodology and adapt it to their specific target group, range of laser scanners, or even a different technology altogether. There is flexibility in the types of technical attributes to be looked at, depending on the overall goals of the project or product (re)design. Furthermore, even in a case where someone wants to apply this methodology to the exact same technical and social context, it is possible that the target group has different values (or a different set of most-important values) in mind, or that they define certain values in a slightly different way. This might mean that the technical attributes should be matched or weighted differently, or that certain attributes should be included or removed altogether.

Deriving values from the transcripts provides an additional perspective about the values important to first responders. In addition to what they explicitly mention, you can infer information and viewpoints from the participant responses that they may not have thought to mention explicitly.

Part V

Conclusions and General Discussion

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Conclusions

In the following chapter, conclusions are presented in the form of brief answers to each research question. Although some parts of this report have been designated as belonging to one discipline or the other (or both) for the purposes of the committees' evaluation plans, this project was developed as an integration of the two disciplines. Therefore, the conclusions cannot be easily separated into one discipline or the other and I ask everyone to simply read the full conclusions chapter.

Question 1: Why and how do first responder organizations currently use mobile laser scanning in their operations?

The majority of first responder LiDAR use falls into two categories: searching and documenting. Searching encompasses active, time-sensitive actions that usually take place during an incident. The purpose is to find a particular target or targets. Documenting encompasses actions whose purpose is to capture the details of a scene either before or after an incident.

As a type of device, mobile laser scanners have many characteristics that are valuable to first responders: an MLS is portable, can document a scene far more quickly than most terrestrial scanners without losing too much detail, and requires fewer passes/sweeps/swathes than a method such as photogrammetry. The point cloud data produced by an MLS is interactive, interoperable among many different file types, and can be visualized and analyzed in a myriad of ways that can provide further value to first responder operations.

Question 2: How can LiDAR sensor, data processing, and data acquisition capabilities be evaluated for indoor emergency response?

Used as a proxy for data quality, the presence of point cloud drift gives information about a LiDAR scanner's sensing and data acquisition capabilities in an emergency situation. Methods to assess point cloud drift are discussed in Qualitative Assessment and Quantitative Assessment.

From a qualitative perspective, the presence of distortions in the orientation of permanent structural features such as walls, floors, and ceilings (as shown in **??**) might signify the presence of drift. From a quantitative perspective, section 8.3 and **??** describe a suitable workflow for quantifying the drift error present within an interior point cloud. First, the data must be georeferenced at the site of entry. Then, the point cloud is cropped to the proper bounded area. The floor plane is extracted using the RANSAC algorithm, and the walls are subsequently approximated using the Alpha shape algorithm. The outline of the interior walls can then compared against the groundtruth data to determine the point cloud drift.

However, many scanner attributes besides point cloud drift are relevant when evaluating LiDAR capabilities for indoor emergency response. In section 12.1 and section 13.3, the sensor and data acquisition capabilities of the different laser scanners are categorized. Then they are compared based on their relevance to the values most important to emergency responders using the value sensitive design-based Value Matching Methodology framework.

Question 3: How do current mobile laser scanning capabilities measure up to first responder needs?

In chapter 14, the Zeb Revo RT, the iPhone 12 Pro, and the Intel L515 scanners were evaluated based on suitability for different emergency responder use cases. For real-time scenarios, the Intel L515 was found most suitable. For pre-and post-incident use cases where precisely documenting the scene is important, the Zeb Revo RT is the best choice for police department needs, while the Intel L515 is most suitable for the fire department. The iPhone was found to be less suitable for first responder scenarios than the other scanners.

As explored in section 4.3, emergency first responders consider many values important during their operations, including Safety, Response Time, and Data Visualization Capabilities. Some of the scanner attributes associated with these values include maneuverability, capture speed, point density, and scanner resolution. (For the full list of relevant attributes, see section 13.3.)

Question 4: How can developers improve mobile LiDAR scanners to better support first responder operations during emergencies?

Developers should focus on the software and data processing aspects of mobile laser scanning features. The concepts of dynamic environments and situational awareness explain the gap between the current capabilities of the LiDAR systems reviewed in this thesis and the type of LiDAR systems that would better support the work first responders are doing. The primary improvements first responders would like to see in their LiDAR devices are real-time processing, fast data sharing / data transfer capabilities, and the ability to quickly and easily modify the data and/or create new data products for other members of the response teams. Enhancements like these would serve to increase first responders' situational awareness and generally facilitate collaboration between the various operatives/involved parties in a given emergency scenario.

Furthermore, developers can use the guidance given in A Developer's Guide to Design Methodology to gather additional information from members of their target group that would help tailor the LiDAR product more to their needs.

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GRS Recommendations and Future Work

In terms of this project, there are a few items that would enhance the value of the results.

1. See how the evaluation changes if you evaluate the whole room/region as one polygon instead of going hallway by hallway.
2. Apply the workflow to more point clouds from each scanner, and across more segments of the building.
3. Implement an analysis for quantifying vertical drift.

Looking further into the future, there are two extensions of this project that would be useful to work towards. Both of them would improve the working conditions of first responders using LiDAR in emergency scenarios.

1. **Implement the drift assessment workflow in real time.** Interview and focus group data revealed that police have up-to-date plans for many existing (public, important, government) buildings. So, determining drift on the fly would actually possible in those cases where the existing floor plan or BIM model can be accessed.
2. **Implement a drift correction algorithm.** Although precision to a centimeter level was shown not to be necessary in most real-time scenarios, if a correction for point cloud drift was produced first responders would benefit from the added accuracy.

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General CDI Discussion

20.1. Project Relevance

In the past, design was considered a value-neutral and purely technical process in which the engineers creating the product were completely separate from the moral or societal concerns of the clients and users(van den Hoven, Vermaas, & van de Poel, 2015). However, the perspective of how design can and should take into account the values of different stakeholders is increasingly changing (Kroes & van de Poel, 2015; van den Hoven et al., 2015). Designers are increasingly considering moral, social, and personal values in design requirements and the development process for products, buildings, and utilities (van den Hoven et al., 2015).

The communication design methodology developed and applied in this project, especially in First Responder LiDAR Use in Emergency Situations and Linking LiDAR Technology to the First Responder Context, is a prime example of how such an attitude shift can manifest in practice. In a societal sense, there is value in better considering the needs of first responders when developing technology that they use to respond to emergencies. One could consider first responders a consumer group like any other, and indeed they are one tasked with responding to incidents that have the potential to negatively impact individuals and groups throughout the Netherlands. Conversations with members of these departments seem to indicate that units from different regions are increasingly looking to laser scanning technology as a potential operational aid. As regional fire and police departments begin to investigate how laser scanning can be of use to them, research relating to the quality of laser scanning data and the differences between different instruments will be increasingly relevant.

In a scientific sense, this methodology adds to the body of literature concerning design approaches that incorporate values into the technical design process.

20.2. Reliability of the Methods

In terms of data collection, there is an inherent unreliability in interview and focus group data because unstructured and semi-structured responses are not necessarily predictable or replicable. However, the same or very similar interview protocols were used for each interviewee, and the same focus group protocol and Miro board setup were used for each group. The questions and focus group activities were designed to elicit specific information about a subject the participants were familiar with. In addition, the conclusions (about values, pain points, desired features, etc) drawn from these data are reliable. Because these elements were usually explicitly named in the data, it did not require much interpretation to draw the conclusions. Taken together, these facts indicate that the data collection methods are fairly reliable.

While there were different trends in the data from the fire department vs. the police department, there was still some overlap in the answers with respect to how they described their use of and experiences with LiDAR. Furthermore, data from respondents within the same agency had even more overlap in the answers. Together, these two facts indicate that the resulting data is relatively credible and that the methods were reliable.

In terms of coding, the explicit coding process described in **??** is quite reliable. This method was used to identify important values and understanding why and how first responders use LiDAR. although some inference was required, much of the relevant material was easy to identify in the transcripts. So it is likely that a different coder would produce many of the same codes if using the same coding approaches.

That said, there is something that calls the internal and external reliability, and perhaps also external validity, of the methods into question: there was no pre-defined definition for the values expressed by first responders. In order not to influence potential responses from respondents, values were not suggested ahead of time except for the use of a singular example of an unrelated scenario, value identification, and related feature. But this also meant that there was no definition list given for the meaning of values, so although all participants may have listed "safety" as their most important value, the explicit definition and/or conceptualization of "safety" might be different for each person. This mainly has an impact on the matching methodology developed in part 3, where the values are conceptualized in terms of specific scanner characteristics. I made this determination myself, on the basis of the way I chose to define the values. However, this process leaves doubt about whether my chosen definition and subsequent conceptualization of the values aligns completely with those of the first responder respondents. Therefore, a validation of the outcome of the matching process would be ideal, to confirm that the respondents' initial inputs were properly understood and interpreted in the next step of the design process.

20.3. Generalizability of the Results

The results from Part I are generalizable, likely even to other police and fire departments around the world who use mobile laser scanners. The results about how and why LiDAR is used are specific to organizations who are already familiar with LiDAR, but not especially unique to the location and environment of the Netherlands. The results about use cases, plain and plus points, and important values may differ more from country to country as the emergency response structure might be organized differently and the types of emergencies and environments will be different. Some of those results might also not generalize well to other safety regions within the Netherlands, because not every fire department uses LiDAR. However, the police results should generalize well as they came from the national police.

The concept of the Value-Attribute Relations from Part 3 is very generalizable, because the same method could be used to make links between different values and/or different attributes. It could also be adapted to a different technological context entirely. In addition, the value-attribute links from part 3 could also be used to assess the suitability of different laser scanners than the ones profiled in this thesis. So, that is another type of generalizabilty of those results. The Suggested LiDAR Features are not so generalizable, because they represent the intersection of a specific set of values and a specific set of scanner attributes applied to a specific scenario.

20.4. Validity of the design

There are two designs in question: the Value Matching Methodology developed in Part III, and the A Developer's Guide to Design Methodology shown in part 4. The design methodology implemented in Part I and Part III draws from well-established design for values methods including value sensitive design and participatory design, which which lends some credibility to the value matching methodology. The case study scenario in Designing Future LiDAR Applications serves as an example of how the value matching methodology looks when applied in practice. As such, it serves as a first validation of the method. That said, because the method is newly developed, it would also benefit from an external evaluation to assess its validity. Ideally, someone with a background related to VSD and an understanding of LiDAR technology could evaluate the method. That person or the first responder participants could also validate the values - attributes links.

The developer's guide is meant to be a distillation of everything learned during this process, presented as a tool for developer's to use. Considering this, it would be ideal to validate the guide by showing it to one or two developers and conducting a short interview-feedback session. This session would primarily focus on whether the respondent understood the material presented in the guide, whether they found the presented methodology valuable (useful), whether they would consider using it, and whether they would make any changes to it.

20.5. Value Matching Methodology Discussion (CDI)

20.5.1. Presenting the Value Matching Methodology as a Design

I designed and followed a process that uses the values of a target group as metrics to evaluate how suitable a technical tool is for the target group's needs. Being grounded in value-sensitive design, this process identifies and defines values that are important to the target group and relevant to the context.

Identifying these values at the start of the design process can mean that a developer team has less freedom to create or experiment with features and functions later on in the process. However, this design process assumes that this more limited freedom is a worthy trade-off in situations where the goal is to design with the user in mind. Identifying the starting values still leaves freedom to design other parts of the tool.

However, if you wanted to use this method to design a specific product, you could use this process and take it all the way to the point of defining the ideal role of the tool, the features it should have, how it should be used in practice, etc. Besides gathering data about relevant values, pain points, and plus points, you might want to create a list of more specific design requirements as the interim outcome. From there you could move into the product development phases of the design process.

20.5.2. Reflections on the Methodology

The design methodology implemented in Part I and Part III draws from design for values methods including value sensitive design and participatory design. It is not a perfect inspiration, because this project's methodology does not focus only on moral and ethical values. It would have been interesting and beneficial to engage first responder participants, especially focus group participants, a bit more extensively in the design process. While the focus group session resembled the future workshop (Jungk & Mullert, 1981; Kensing & Munk-Madsen, 1993; van der Velden & Mörtberg, 2015), and participatory prototyping (Brodersen, Dindler, & Iversen, 2008; Hillgren, Seravalli, & Emilson, 2011; Lim, Cortina, & Magley, 2008)methods from participatory design, time constraints and the fact that there was only one session per group limited the amount that could be done in the session. It would have been great to go one step further than the final focus group activity described in subsection 3.3.5, and work with focus group participants to further develop their ideas about possible LiDAR features. This could have resulted in a more concrete set of design requirements, an action plan for creating these desired features, or a more thorough translation between values and design features, as envisioned by and created with the first responders.

Another thing to note is that the number of steps makes it seem like a complicated methodology. Perhaps it is possible to achieve a similar result with fewer intermediate steps, but that would be a different methodology serving a different aim. The focus on values as the basis for the evaluation of the technology and (re)development of its features or functionality is the key factor of this methodology. This is a good strategy because using values, which are very broad compared to norms or design requirements, leaves the developers room to consider what design elements would be well-suited to their target device or target population. There are many possible ways to design and implement additional functions, features, and/or tools in a way that channels particular values. The value acts as a constraint on the developers' actions, but is a loose enough constraint to still allow for their creativity and technical domain knowledge to flourish.

Choosing attributes

Because the values were clearly derived from respondents via a particular methodology. But from the attributes side, it's a bit circular. I started out by gathering the standard scanner specs. Then I added a few categories based on the feeling or experience of actually using the scanner. And lastly, I added a few categories based on point cloud drift. The point cloud drift categories are a vestige of the original project's focus on drift but would not necessarily be applicable in other scenarios (or even in the context of this project once understanding that drift doesn't matter much to the first responders). The attributes were originally chosen because I thought they somewhat related to the point cloud quality and the scanner's suitability to a first responder context. This approach doesn't work if you want to standardize it, though, so you need to guide the process of choosing the attribute list a bit better.

Things to do differently
(Friedman et al., 2014) suggest conceptualizing, or clearly defining the boundaries of, the values that respondents are asked about. This is good advice that should also be undertaken in this methodology.

In the case of this project, the focus on values was not fully decided upon until after the first three out of the four interviews had been completed. This meant that while values could explicitly be asked about in the last interview and in the subsequent focus groups, they would need to be implicitly determined from the first three interview transcripts.

There are a couple of parts of the focus group results that lack thorough explanations (see bullet points below). These are places where the answers given by first responders on the board are either unclear or hard for me to expand on fully without having more information. It helps to have the transcripts of the focus groups because I can look at the parts of the transcript from around the time of those activities and try to get more context. However, I wish I had asked for clarification on the definitions of the values the respondents named, the relationship of those values to the use case scenarios, and the relationship of those values to the desired features.

Time constraints on the focus group made that difficult, but maybe there is an alternate activity type I can suggest for the developer's guide. In any case, I can definitely emphasize that getting information about the reasoning behind their answers is also important for successfully executing the method and getting the most personalized results possible.

20.6. Other Points of Discussion

This part of the discussion contains some critical comments about other parts of the research and results. Not included here is the Discussion from Part 3 about the value matching methodology.

First Responders are knowledgeable

One thing I noticed throughout this process is that the first responders I spoke to were largely very knowledgeable: about how to use the LiDAR scanners they work with, the intricacies of the data, the problems they do or might face based on limitations of the LiDAR tools they work with, and about what technical features they would like to see. This was in contrast with literature about emergency responder use of spatial data, which sometimes paints first responders as unfamiliar with spatial data and LiDAR technology, and even with the expectations of stakeholders who are more familiar with the technical aspects covered in this project and less familiar with the specific first responder context. This contrast is partly due to the fact that I sought out the people from the first responder community who had the most relevant experience with LiDAR. For example, it was clear that one respondent had less experience with it than others, although even he had a fairly thorough understanding of what LiDAR scanners are capable of doing. I also got the impression that Regio Rotterdam-Rijnmond is very much at the forefront of innovation within the Dutch fire department community. So it would be interesting to see whether the level of familiarity is indeed different in different safety regions or among different departments. On the flip side, everyone I spoke to was at the national police, and they have apparently been working with LiDAR for over 2 decades. However, I don't think that there is this same level of knowledge at the regional/local police department level. I spoke to two people from the regio Haaglanden police office, and they had some understanding of laser scanning (and expressed interest or excitement in incorporating it more into their operations), but not as much understanding of how it actually works and what is possible.

The target group may be smaller than you think

Reflecting on the above, for a developer who wants to consider their target group in the design process, a useful takeaway might be that the target group is smaller than you think. It is not the entire Dutch police force, nor is it every firefighter across the country. Rather, it is the members of specific, specialized digital exploration teams in each agency. The members of these teams are either specially trained in the use of laser scanners and the handling and/or interpretation of LiDAR data, have prior knowledge and experience working with this data and technology, or both. Likewise, the target group is also relatively knowledgeable about LiDAR possibilities and, in many cases, quite able to express what goes wrong and what they would like to see improved. In some cases they already have experience working with researchers (including TU Delft students) to develop new features, and in some cases even have dedicated staff (or contracts with professional developers) working on technical innovation related to using spatial data and geodata. All of this to say, developers can and should take advantage of this knowledge of the target groups when possible. (I also realize that public agencies have rules about when and how they are able to work with individual companies, so this may not be immediately applicable for a developer team. But the underlying findings of this research and the general recommendation mentioned here still stand.) Certainly, at the moment that a contract with first responders has been established, it could be useful to follow this type of methodology.

20.7. Future Work

Some possibilities for improving this methodology in the future include:

1. Improving the reasoning behind the links between values and scanner attributes.
2. Validation of the design criteria with a different, larger group of first responders.
3. Include a consideration of tensions between competing values in the way that the methodology is applied.
4. Crystallizing the design methodology into a tool /guide / approach that can be readily applied to a different technology, different context /target group, or both.
5. Create a way to evaluate the suitability of a single scanner for a task (instead of always comparing multiple to one another)
6. Expand the analysis to all MLS use scenarios, not just indoor.

20.8. Combination of the two masters

Approaching this project through a combination of Communication Design for Innovation and Geoscience-Remote Sensing methods had a wide-reaching impact on the research process and on the eventual results. By definition, the research carried out in CDI and the methods approaches typically used in that discipline are iterative. While the starting point and the objectives may be known and relatively clear, the methodology and results may not be. In my case, my journey through the communication parts of the thesis consisted of many iterations (see section A.5). Each loop resulted in a refinement of even foundational project aspects such as the relevant context and stakeholders, the specific research goals, and/or the specific methods needed to achieve the results. But through it all, some things stayed constant: the focus on an emergency response context, the use of value-sensitive design as a guiding theory, the focus on evaluating laser scanner use and capabilities within the first responder context. While the GRS methodology and research process was relatively linear, the CDI process was necessarily non-linear. Each iteration incorporated new information gained from literature, data collection from and interactions with respondents, and even from the methods and results of the GRS research process. This is in contrast to the GRS process, where the deviations and questions mainly fell within the bounds of what analytical methods to employ to arrive at the different results.

One of my favorite parts of this project and research process has been seeing the way that CDI influenced the GRS aspects of the project and vice versa. The combination of these two programs led to a different research focus and outcome than there otherwise would have been. The CDI perspective was especially instrumental in shaping the overall focus and themes of the project. It allowed the scope to expand past solving a singular technical problem in the field of indoor emergency response, and instead to consider more deeply how the technical tool inhabits that context.

For example, the initial project focus was on identifying and correcting point cloud drift. The justification for point cloud drift was that correcting this issue would support first responders in emergency scenarios. While there is sone truth to this statement, after conducting interviews with first responders from the police and fire department I found out that point cloud drift was less of a concern than initially thought. This discovery led me to eventually broaden the research scope to compare the different scanners to one another and to assess how suitable each one was to the different scenarios undertaken by the first responders. It also led to the addition of a qualitative point cloud quality assessment process alongside the quantitative analysis of the point cloud drift.

In the reverse direction, it is harder to point to specific moments where the technical research process influenced the CDI process. But, it is abundantly clear to me that developing this methodology would have been very difficult, if not impossible, without having knowledge of LiDAR principles and experience working with LiDAR technology. Having this background informed the types of questions I included in the interview protocols, gave me a common knowledge base with respondents and participants when it came to discussing their experiences with LiDAR and using laser scanners, and allowed me to better interpret the data I collected from respondents. Understanding how laser scanners work and having used them myself to collect data also made it possible to consider how to define the different values and scanner attributes and how to identify the connections between the two.

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Part VI

Appendices

A

Part 1: Appendix

A.1. Informed Consent Forms

A.1.1. Interviews

Example of an informed consent form used for interview participants

Consent Form for “Thesis Project: *Laser Scanning for Emergency Response”*

Please tick the appropriate boxes	**Yes**	**No**
Taking part in the study		
I have read and understood the study information dated [30/06/2023], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw at any time, without having to give a reason.	☐	☐
I understand that the interview will be audio-recorded. The recording will be transcribed as text, and then kept as a primary source document for potential future reference within a research context.	☐	☐
I understand that the content discussed during the interview will also be documented in real time via handwritten notes.	☐	☐
Risks associated with participating in the study		
I understand that taking part in the study involves the following risks: - In the case of a data breach, some or all of my identifying information may be compromised/leaked.	☐	☐
Use of the information in the study		
I understand that information I provide will be used for reports written by the researcher for their University programme.	☐	☐
I understand that personal information collected about me that can identify me, such as full name or place of residence, will be considered confidential and will not be shared beyond the study team.	☐	☐
I agree that the information, thoughts, and experiences I discuss during the interview can be quoted anonymously in research outputs.	☐	☐
Future use and reuse of the information by others		
I give permission for the confidential interview transcript data that I provide to be archived in a repository held by the Delft University of Technology (TU Delft) so it can be used for future research and learning.	☐	☐
I give permission for the audio recording data that I provide to be archived in a repository held by the Delft University of Technology (TU Delft) so it can be used for future research and learning.	☐	☐

Signatures

_______________________ _______________________ _________

Name of participant Signature Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands what they are freely consenting to.

__________________________ ____________________ _________

Researcher name Signature Date

Study contact details for further information: Camera Ford, c.a.ford@student.tudelft.nl

A.1.2. Focus Groups

Example of an informed consent form used for focus group participants

Consent Form for “Thesis Project: Indoor *Laser Scanning for Emergency Response”*

Study Information

You are being invited to participate in a research study titled “Indoor Laser Scanning for Emergency Response.” This focus group is conducted for the purposes of a thesis project collaboration between the IT consulting firm CGI, under the supervision of Robert Voute, and the TU Delft, under the joint supervision of Roderik Lindenbergh (GRS-remote sensing) and Caroline Wehrmann (Science Communication). The project concerns the use of mobile laser scanners in indoor built environments in an emergency response context. Emergency response is for us limited to the police and the fire department.

The purpose of this focus group is to understand the current uses of mobile LiDAR technology in the fire department, the values governing these use cases, and potentially useful LiDAR features related to these values. During this focus group, you will participate in activities and discussions about these topics with other group members. The session will last approximately one and a half hours.

The entire session will be video recorded and then transcribed, and your contributions will be used to inform the development of prototypes for mobile laser scanning functionalities which might be of interest to the study’s target groups. The transcript will be used for the purposes of writing the MSc thesis report and related publication materials such as presentations, poster boards, and project summaries/briefs. It may also be used by CGI in the future for product development purposes related to Lidar scanning technology.

To the best of our ability, your focus group data will remain confidential. Collected personal data includes your job title and the department you work in. This data will be pseudonymized before data analysis in order to protect your identity. Your personal data will not be shared with anyone outside of the research team. The full interview transcripts will not be shared outside of the research team. However, the risk of a breach is always possible when storing data digitally. We will minimize these risks by storing the information on a secure server.

Your participation in this study is entirely voluntary and you are also free to decline to answer any questions I will ask. If you would like to remove/recant some of your answers after the fact, you can contact me within one week of the focus group session to discuss removing the information from the session data.

For further information, you can contact primary researcher Camera Ford at c.a.ford@student.tudelft.nl or +31 (0)6 51 71 56 74; or research supervisor Caroline Wehrmann at C.Wehrmann@tudelft.nl.

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information dated [*5/1/2024*], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves: a video-recorded focus group session. The recording will be transcribed as text, and the content discussed during the focus group will also be documented in real time via notes taken by the interviewer and by participants on Miro.com. The recording will be destroyed after the project is finished, but the primary source materials on Miro.com will be kept.	☐	☐
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
7. I understand that taking part in the study also involves collecting specific personally identifiable information (PII), namely my job title and the organization that I work for. This brings the potential risk of my identity being revealed and my comments being traceable back to me and my organization.	☐	☐
9. I understand that the following steps will be taken to minimize the threat of a data breach, and protect my identity in the event of such a breach: my focus group data will be pseudonymized, and only the transcripts will be kept beyond the duration of the project.	☐	☐
10. I understand that personal information collected about me that can identify me, such as my name and job title, will not be shared beyond the study team.	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
12. I understand that after the research study the de-identified information I provide may be used for research outputs such the thesis manuscript, thesis presentations, research publications, and product development.	☐	☐
13. I agree that my responses, views or other input can be quoted anonymously in research outputs	☐	☐
D: (LONGTERM) DATA STORAGE, ACCESS AND REUSE	☐	☐
16. I give permission for the de-identified transcript data that I provide to be archived in the TU Delft student research repository so it can be used for future research and learning.	☐	☐

Signatures

____________________________ ___________________________ ________
Name of participant [printed] Signature Date

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

__________________________ ___________________ ________
Researcher name [printed] Signature Date

Study contact details for further information: Camera Ford, c.a.ford@student.tudelft.nl

A.2. Question Motivations

A.3. Notes from Observational Visit

These are the notes from the observational visit with the Fire Department Digital Exploration Team, Thursday 31 August 2024.

Ride-along with Rotterdam fire department digital exploration team
Thursday, 31 August 2023 @ 6:30-9pm

Present: A2, some(?) members of the team

Context: The digital exploration team is 32 members from the VRR, with the primary goals of making the work of firefighters less dangerous and their job more efficient.

The team practices weekly on Thursday evenings, at an industrial park in Rotterdam. The team is trained in the use of different drones, including the Elios3 (which is used for indoor laser scanning). A2, a fire captain and head of the team, invited me to look along and said they could show me the Elios3.

I'll introduce myself and the project to the team, either on the drive over or before/during the training.

Goal:

1. To get a sense of how the fire department uses LiDAR technology (in this case on a drone) in the field ← *could bijv lead to design constraints for brandweer list*
2. To hear from different team members (ideally those who use the Lidar drone) about what information and interface elements/software features they miss and/or would find useful in their work
3. To look at the Elios3's user interface
4. To determine whether this group is a good candidate for a focus group

Missing info/things I'm curious about:

- What do they practice?
- Do the exercises/practice contents ever change? Based on what criteria?

Some questions:
General

1. About the team

6 teams, this one has waterborne (sonar), land, and flying drones, only ones to LiDAR

One person on duty at all times. Mobile command center in this van, can see on screen what's being scan. Can operate smaller one on his own to see what's going on. Pilot. He notifies the other van w 3 ppl (other pilot, observer and payload operator) and they come to the scene. Payload operator can look from command center.

Fire: what are the hotspots? What's the extent of the fire? Most likely position drones to get imgs of the whole scene. Translation happens bc officers usually can't tell what they're seeing in the img. Imgs usually LiDAR or thermal. That requires training. Only 8/32 team members can do the translation (2 of those are unveiled). Don't need prior experience, most helpful if you're fireman.

Sometimes helps Police respond to missing persons things. Have 16 pilots vs police's 4. Diff tactics: tooling like laser range finder can help find missing ppl. Can point laser, get coords and measure distance to drone. Can search for specific temp. AI would help to recognize ppl in thermal imgs when it's only heads and hands. That's being developed. (What other similar things?) simulated warehouse fire, would be nice to be able to ID person vs object (obj class). Sometimes need 3D img of situation. Then LiDAR isn't that useful. Can't make a model with surfaces. Photogrammetry was better

Meeting @gezamelijke station:
10 ppl + me + meekijker
Uitdrukking
Some updates (to which drone/what?):

- Automatic photo upload
- Can draw on controller —> coords
-
- 2 others

Last wk did test to determine temp in cups using scanner
Grouping ppl for specific scanners

2. What are everyone's positions within the team?

3. What is everyone's professional/relevant background or experience with respect to drones and lidar scanning?

4. ***What do you see as the most important part of the digital exploration team's function? How important a part of the team's tasks/operations is Lidar scanning?***

5. Which drone operator team member do you see as the most important part of the operation?

Lidar Scanning

6. Have you operated different types of Lidar equipment before?/How many members of the team have done so? ← can gauge experience level, also for design reqs

A.4. Focus Group Planning Document

section A.4 is the document used to plan the focus groups. The first section shows the schedule and the guiding questions relevant to each part of the focus group session (3 parts in total). *"Planning thoughts"* contains brainstormed notes about what content to include in the focus group; *"Re: Facilitation"* contains notes about how best to facilitate the focus group sessions; *"Re: Board Design"* contains notes about how to best design the Miro board for the sessions; and *"Differences per target group"* contains notes about the differences I expected between the two session groups.

Schedule / Order of operations

1. Intros / icebreaker (15 min)
    a. Intro slides
    b. Intro to Miro (5 min)
        i. Explain the codenames
        ii. Show an overview of the board and show each individual part of the board
    c. Icebreaker / Participant intros
        i. Team, job title/position, maybe [in 2 sentences or fewer] responsibilities & experience wrt LiDAR
        ii. What do you like most about your job?
        iii. Maybe I can note this down on their boards (or elsewhere, for myself)

2. Part 1: Use Cases (25 min)
    a. Use case / LiDAR scenario definition (7 min)
        i. Generate their own use case scenarios
            1. generate 3 w/ accompanying pain points
        ii. For pain points, think:
            1. What would you change about the way you currently use LiDAR in your work?
            2. What's missing from the current abilities of your LiDAR tools?
        iii. Can use text and/or images

    b. Discuss the use cases (7 min)
        i. Each participant shares 1 (possibly 2 depending on number and time)

    c. Commentary on my use cases (7 min)
        i. Thermometer for do they seem accurate?
        ii. Option to verbally comment and/or write on sticky notes

3. Part 2: Value prioritizing/ranking (20 –30 min)
    a. Generate their own (10 min)
    b. Discuss everyone's values (7-10 min)
        i. How/do the values you named come back in your work?
    c. Commentary on my values (7-10 min)
        i. Use thermometers to react (3 min)
        ii. Group re-rank (5-8 min)
        iii. Discuss the re-rank / record any discussion happening during the process

4. Part 3: Tool building (20-30 min)
   Guiding question: "If I wanted to design the perfect tool (based on/keeping in mind these values), what would it look like?"
        i. Values either from our collective list or from your personal list
    b. How would you link the values to a specific LiDAR function / design?

    c. Commentary on my own design requirements
        i. What do you think of the design requirements / scanner functions that I have come up with myself? [as a group]

Planning Thoughts

- Relevant themes + questions
    - Prioritize/rank the values I've come up with
    - Define for yourself the most important values
    - How/do the values you named come back in your work?
    - Question / activity to link the values to specific design requirements
    - "If I wanted to design the perfect tool based on these values, what should I design?"
    - Introduce themselves [maybe via stickies / images]: team, job title/position, maybe responsibilities & experience wrt LiDAR
    - Ranking the values in order of importance: will be good to have them do this together, to basically have to agree on a ranking and record / observe the discussion about that. But does it make sense to ask them to first take 30 sec or 1 min to rank them for themselves?
        - Is there value in seeing peoples' individual rankings too?
        - If they've mentioned multiple use case scenarios then probably they will be considering & ranking values relating only to one. So maybe useful to see their personal rankings for a use case of their choosing, and then have them choose one use case as a group to do a group ranking with
    - "What would you change about the way you currently use LiDAR in your work?"
    - What's missing from the current abilities of your LiDAR tools?
    - ***Look at the interview qs from the end that I usually didn't get to–maybe these are exactly the right qs for the focus group***

- Have a specific goal per focus group round
- Make sure that each question / activity is doable for all participants, ie. regardless of their specific background and LiDAR experience
- Ask the target group to think with you about the design goals/outcomes I want to produce

Re: Facilitation

- What order will I ask questions in?
- If you ask about values vs. use cases, make sure to disentangle if there is a difference between the values they ranked and their own personal opinion
    - Is there a difference between the values they've listed and their own personal values for the situation?
    - What would you change about your stated values / the value rankings?

- Make sure to bring everyone into the conversation

    - Start with a positive icebreaker ie. what do you like most about your job?

- When doing discussions or communal rankings, show the relevant part of the Miro board on the shared screen in Teams

- Encourage them to write any thoughts down on sticky notes that come to them throughout the process, especially if they don't get a chance to share it verbally.

- Mention they can continue to access the board through this link, but don't share with others without consent (?)

Re: Board Design

- Each person assigned a codename with specific color and icon. They use that color post-its throughout the miro board, and that icon to react to the thermometers.

- Personal boards arranged around the communal board where they will do the common rankings

- Each person has their own board to work from w/ values, pain points, & ideal features. Then we come together and they discuss what they've written. Maybe they together come up with a set of agreed upon vals/pps/ideals & things that are not agreed upon, in a new board. Then I can introduce mine and they post their comments. Lastly, commentary on the use cases I came up with. Maybe to ask, "how would you modify these to better match reality (ie.current LiDAR use)? How would you modify these to represent how you expect to use LiDAR in the future?" ← **as of 4 January this is more outdated; have newer order/plan now**

Differences per target group

- Fire department
    - Group of 3
    - Two people are direct colleagues and I think the 3rd is also on the same team
    - Could invite A1 as well: I think he'd have some great insights but not sure if/how that would throw off the dynamic. Especially because he knows A1, but I don't know that they are close or work together often. I don't think Ais directly above/below the others in a hierarchy, but it could be that for example he interacts with them more in a distant or unfamiliar way.
        - Could also call A2 to ask about their working relationship / whether he would feel comfortable discussing things related to work goals / his view of the most important values, etc in a group that includes A1.

- Police department
    - Likely a group of 5
    - People from different units/departments → will likely have different use cases, values, and design reqs

A.5. Project Iterations

The following figures show the three iterations of the CDI portion of project pursued prior to arriving at the more fully integrated version presented in this report. Each figure shows the general focus of the communication research, the general communication context relevant to the research, and the workflow needed to complete the research. Figure A.1 shows the first iteration of the project, in which the focus was data reliability and how to visualize it. The governing question was how reliable and trustworthy the LiDAR data is and how to visualize that. In this case the research design consisted of using interview data and literature to compile design requirements for LiDAR headset features, coming up with three to four prototypes based on this information, getting feedback on these prototypes via a focus group, and then producing one further-developed prototype based on the feedback.

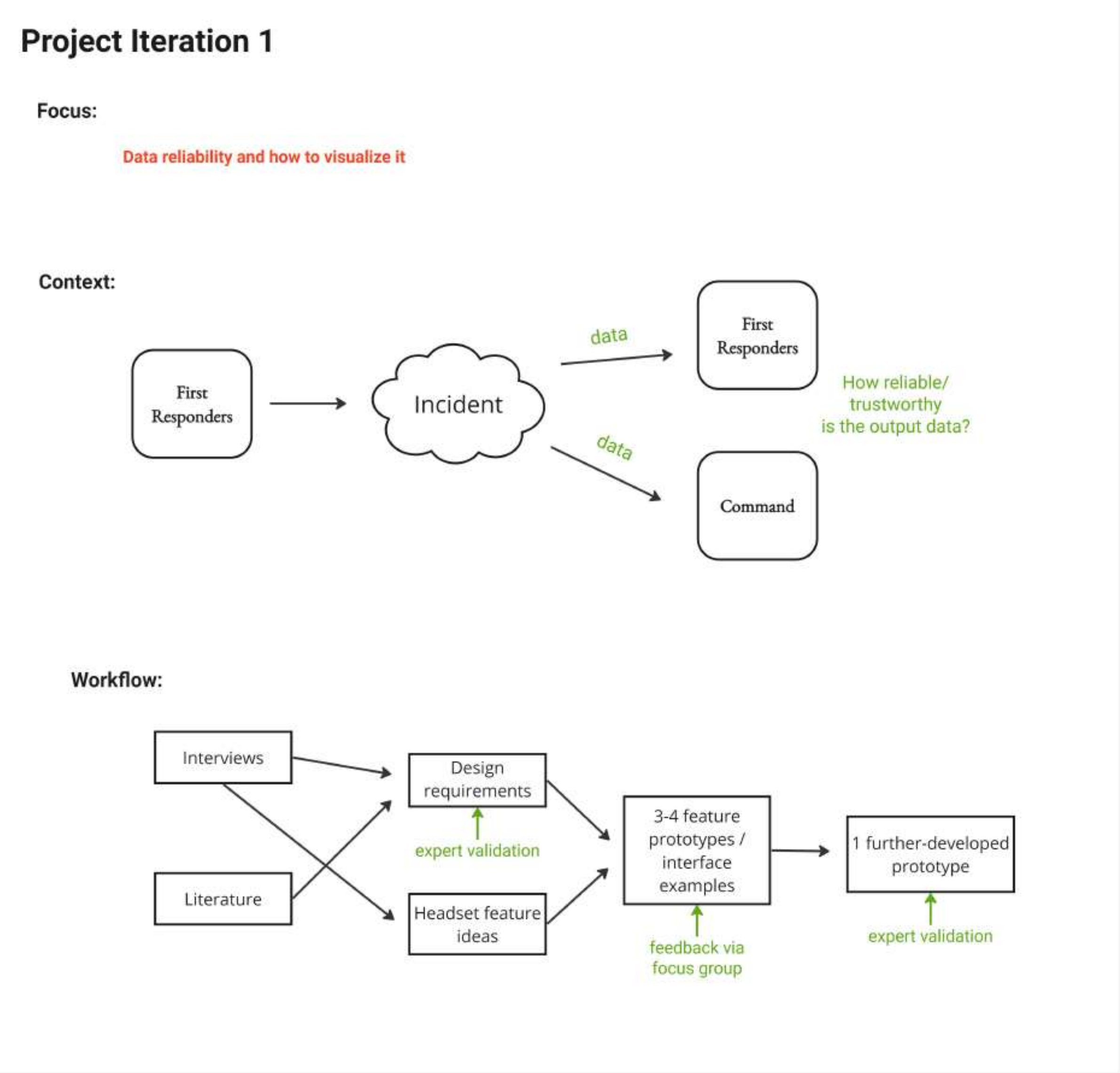


Figure A.1: Schematic representation of the first iteration of the CDI project.

The second iteration shifted focus slightly to the desired LiDAR headset features per focus group and associated prototypes. Here, the question was not specifically how to visualize the reliability of LiDAR data, but more broadly to determine which data outputs were most important to the target groups in the first place. Figure A.2 shows a slightly refined workflow that only includes headset feature ideas, getting rid of the design requirements step. The workflow still included getting feedback on a few feature prototypes (in the form of wireframes) before producing one further-developed prototype as a final output.

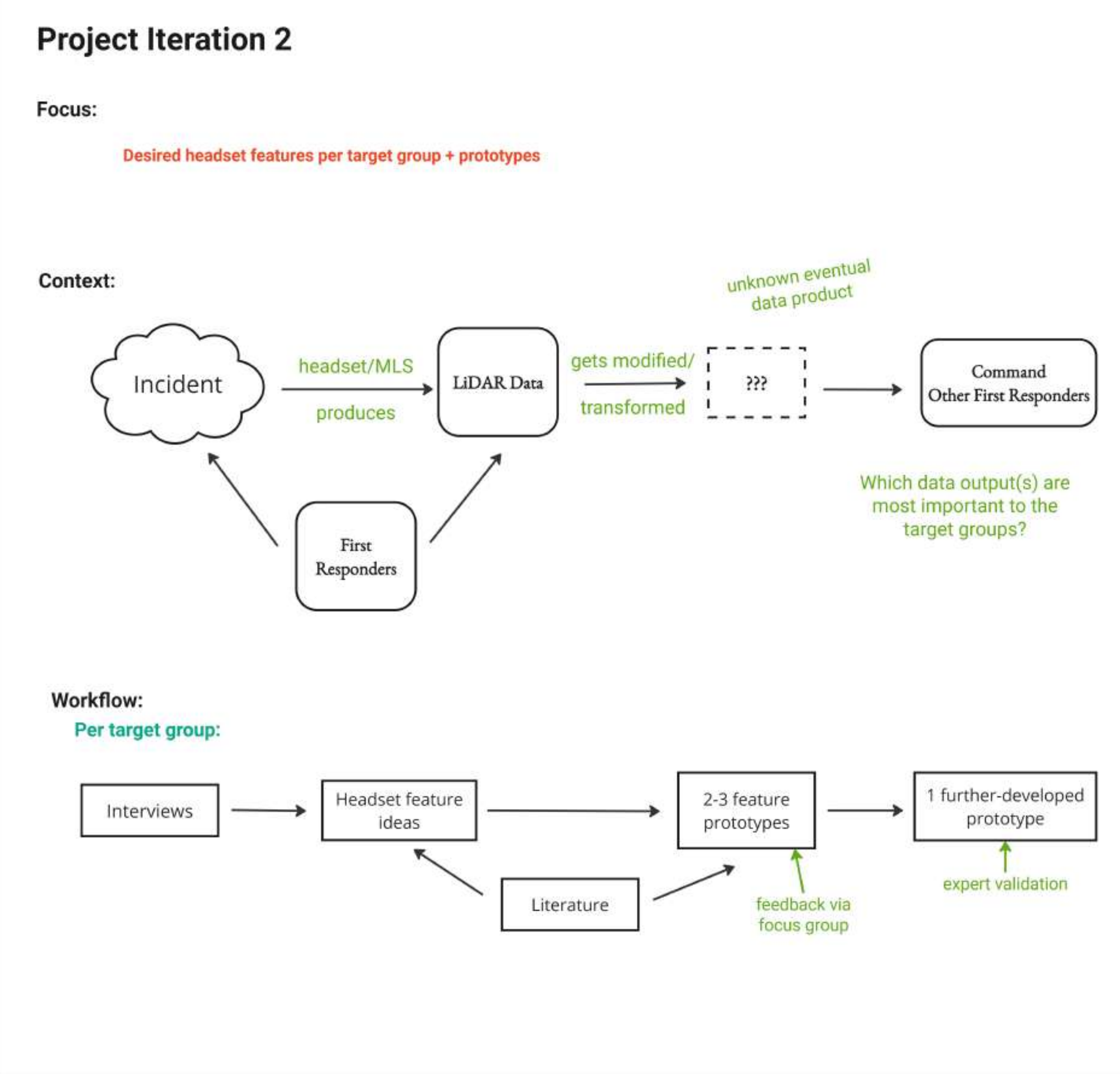
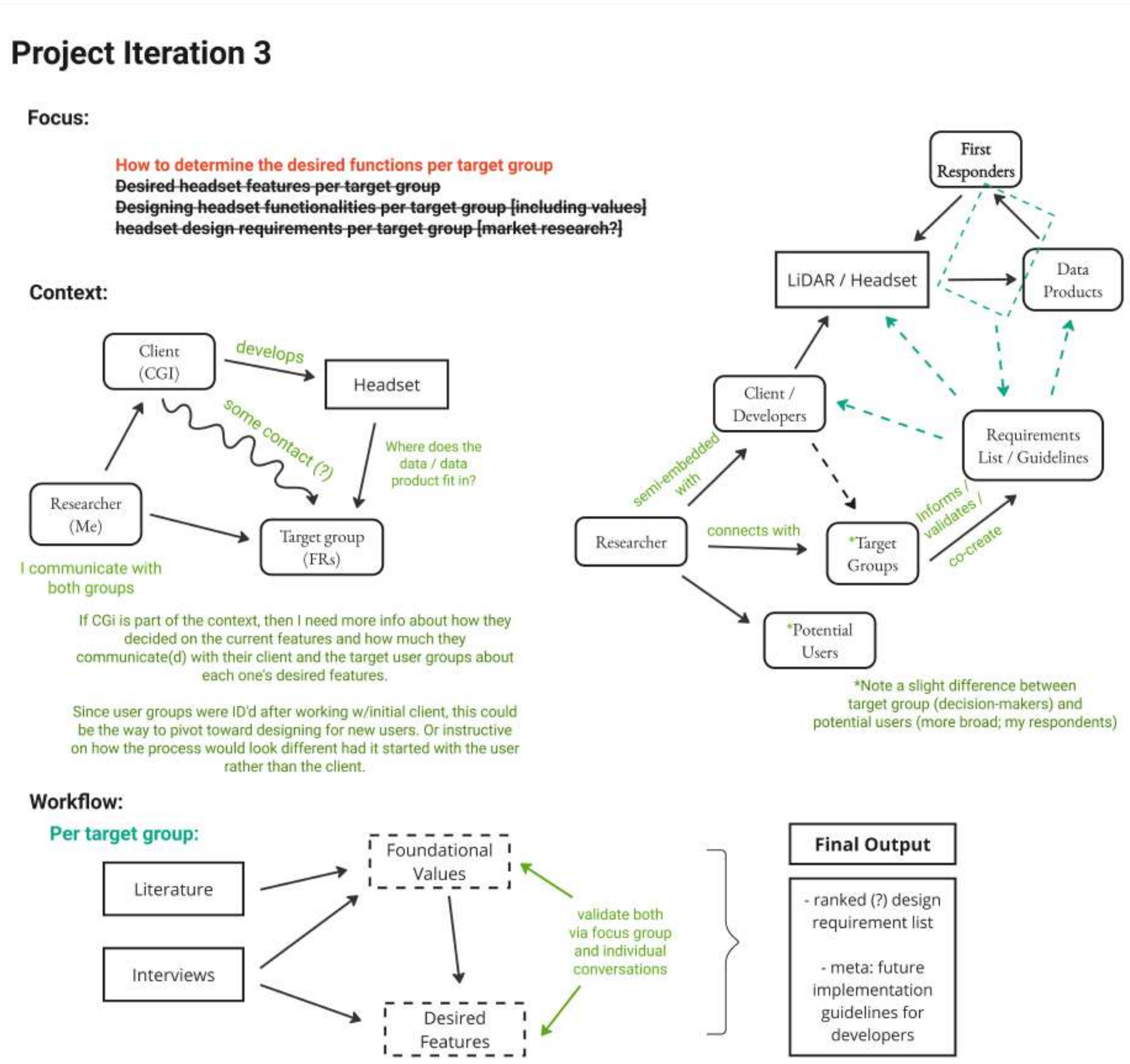


Figure A.2: Schematic representation of the second iteration of the CDI project.



If CGi is part of the context, then I need more info about how they decided on the current features and how much they communicate(d) with their client and the target user groups about each one's desired features.

Since user groups were ID'd after working w/initial client, this could be the way to pivot toward designing for new users. Or instructive on how the process would look different had it started with the user rather than the client.

*Note a slight difference between target group (decision-makers) and potential users (more broad; my respondents)

Figure A.3: Schematic representation of the third and final iteration of the CDI project.

The third project iteration most closely describes the current version of the project. Here, the context includes me, the researcher, as an independent entity, headset developers (in this case specifically from CGI) as one stakeholder group, and two additional first responder-related stakeholders. As shown in Figure A.3, the "target groups" stakeholder group refers to members of the police and fire departments who use LiDAR, but specifically the decision-makers within those organizations. They are the ones supplying information about and/or co-creating the list of design requirements for a more suitable LiDAR headset, and who might later validate a final version of that list. The other stakeholder group, "potential users," is described as more broad and consisting of my respondents. They are first responders in general who would use LiDAR and for whom the design requirements would be used to make a better LiDAR tool. In the end, the relationship between the researcher and these two groups was a bit different. The presence and status of decision-makers within the organizations was not explored, and so as a researcher I connected with the "potential users" group and they are the ones who provided the information needed to create a requirements list. Some of these potential users might also be descision-makers, but that was outside the scope of the research.

The other significant thing shows in Figure A.3 is that the workflow includes values, derived from literature and from interviews, as an input for creating a list of desired LiDAR features. This represents the introduction of value sensitive design into the methodology. Both the values and the list of desired features would then be validated by interview and focus group respondents before leading to two final outputs: a design requirement list and a future implementation guideline for developers. This workflow remained largely the same.

A.6. Coding Tree

This is the coding tree used during data analysis in Part 1.

Figure A.4: Coding Tree representing the codes used during data analysis in Part 1

B

Part 2: Appendix

B.1. Candidate Scanning Locations

In the search for a study location, potential options were chosen with the intention of considering multiple types of building facades and internal configurations. For example, some buildings had facades that included large glass windows or paneling, while others were mainly concrete. Some buildings possessed varied interior layouts with large open spaces, while others had uniform, repetitive, and more closed layouts. The CGI office building in Rotterdam and the following three academic buildings on the TU Delft campus were considered for data collection:

1. The Echo Building
2. The new Faculty of Computer Science, Math, and Electrical Engineering (EEMCS) Building
3. The old Faculty of Applied Sciences (TNW) Building

B.1.1. Echo (building 29), Van Mourik Broekmanweg 5, 2628 XE


(a) (b)

(c)

Figure B.1: The (a) exterior and (b,c) interior of the Echo Building on TU Delft campus.

Echo's exterior is relatively simple, comprised mainly of planes and straight lines. The building has front and back entrances, and is connected to the new EEMCS building on one side via a tunnel. There are no curved elements in the building's facade, but the structure is complicated by the presence of many small ridges and by a roof slab/segment on the top level that protrudes out over the sides of the building. Scanning this facade might also prove tricky because the walls are more or less entirely window glass; however this would be a good test case for scanning a building where the method cannot rely on the window panes being unique elements in the structure. Ideally any emergency scanning method/protocol put in place would be applicable to this type of facade and facade material as well. Overall this building would make a decent choice of locations, but the scans would likely need to be made either early in the morning or later in the day when there are not too many cars parked in front of the building, and when the window reflection would pose less of a problem to the quality of the scans.

There are some freestanding structures within Echo's interior (freestanding meaning, unattached to the exterior walls). The structures are large, which in theory would increase the amount of data included in an interior scan. That said, the building's interior has lofty ceilings, a lot of open space, and is relatively uncluttered by interior structural elements relative to some of the other buildings on the list. These qualities could make it a good scanning option because it should be easier to distinguish rooms and structures in the scan. The interior connection between the EEMCS building and the echo building (visible in Figure B.2a) means that it would be possible to walk a loop from the entrance of the EEMCS building entrance, inside the echo building and past its front entrance, and through the cafe around to the back entrance. However, the aforementioned curved and sometimes complex interior elements of the Echo building might make producing a high-quality scan more difficult than in the EEMCS building.

B.1.2. EEMCS Faculty (building 28), Van Mourik Broekmanweg 6, 2628 XE

(a) (b)

Figure B.2: The (a) exterior and (b) interior of the new mathematics/computer science building on TU Delft campus.

The EEMCS building has a simpler structure than the Echo building – it is cubic and only has one non-uniform protruding element at the front, plus a staircase leading up to the front entrance. The windows are small and square with grates next to or in front of each pane, which could probably be used for identification within a scanned point cloud. One downside of the structure is that the part of the façade where the panels are attached to each other appears to be a tin-like material, which might make it harder to scan. There is a front and a back entrance, and an above-ground tunnel that connects the side of the building directly to the Echo building next door.

The building's interior is relatively small and compact, with a more open area on the ground floor than the floors above. From any given room on the ground floor, it is possible to see at least one window (although perhaps not from every single vantage point). This is similar from first and upper floors of the building as well. Each floor's layout of study space, meeting rooms, and open hallway space is built around the center column of the building, which contains both an elevator shaft and a staircase. The ceilings are low and there are chairs and tables in the open spaces outside of rooms which give the building a more cluttered feeling than the other buildings. This compactness might be an advantage during the scanning process, but it could also result in a relatively cluttered scan due to the high prevalence of furniture in a relatively small space.

B.1.3. CGI Rotterdam Office: George Hintzenweg 89, 3068 AX

(a) (b)

Figure B.3: The (a) exterior and (b) interior of the CGI office in Rotterdam.

The CGI office building is much taller than the other considered locations, having eleven floors. CGI occupies a number of these floors, but not all. Much of the exterior walls are comprised of square windows arranged in a uniform pattern, with the rest being a red brick facade. The interior floors are structured very similarly. Each has a short hallway leading from the elevator to an open common area, and one office wing branching off from each side of the common area. The office wings are open-plan, filled primarily with rows of desks and then four to six conference rooms and offices built with interior walls. The main issue with choosing the CGI office as a location is that there are very few options for different scanning trajectories. Each office wing has only one entrance (aside from the emergency staircase exit in the back), and because there is only one way in and out of the adjoining common area, it would be impossible to make an open-loop scan.

B.2. Scanning Protocol

B.3. Scanning Protocol

Goal:
Open-loop scans of a multi-floor path through the TNW faculty building, made with 2-4 different scanners (Apple iphone 12 Pro, Zeb revo rt, and maybe Intel L515 and Leica BLK2GO)

Location:
TNW building 22 (between CiTG and the Aula)
Lorentzweg 1, 2628 CJ Delft

B.4. Scanning Target Inventory

B.5. Scanning Target Inventory

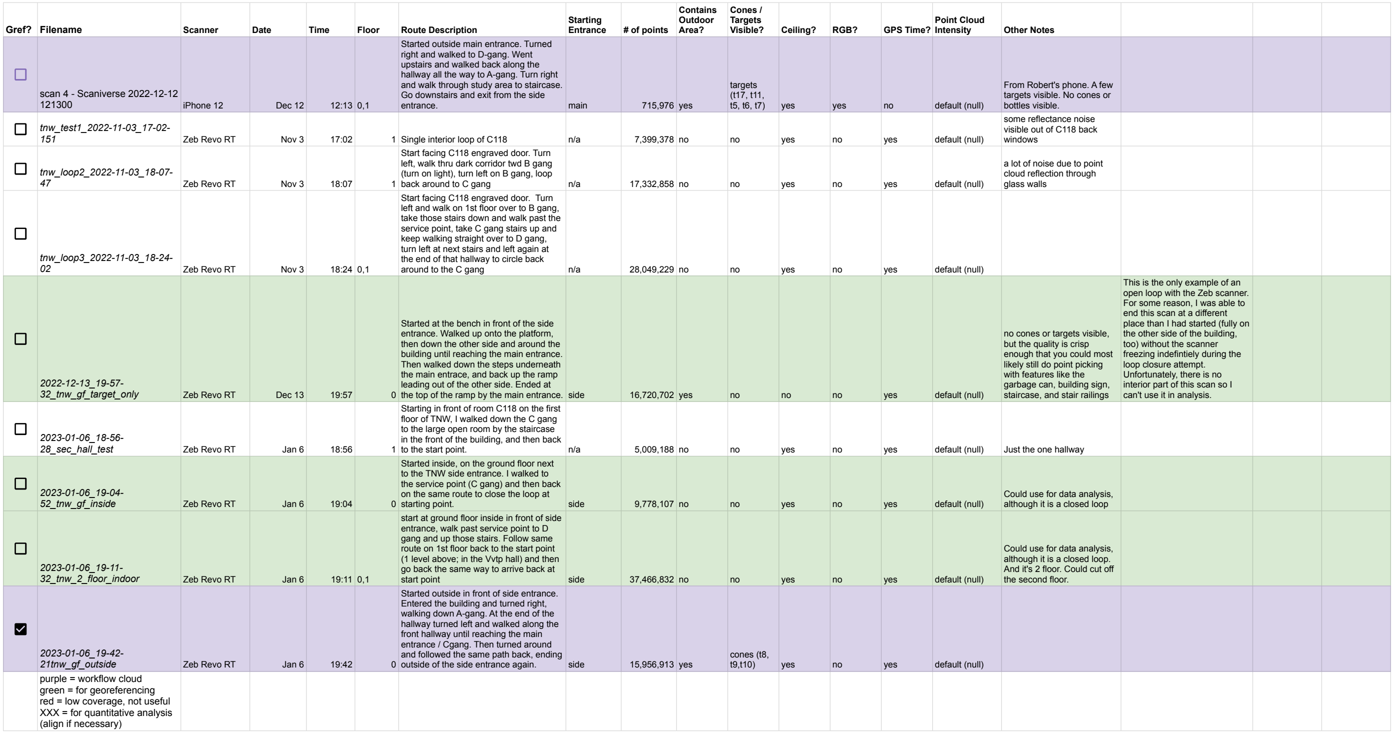
Goal:
Open-loop scans of a multi-floor path through the TNW faculty building, made with 2-4 different scanners (Apple iphone 12 Pro, Zeb revo rt, and maybe Intel L515 and Leica BLK2GO)

Location:
TNW building 22 (between CiTG and the Aula)
Lorentzweg 1, 2628 CJ Delft

B.6. Point Cloud Dataset Inventory

B.7. Scanning Target Inventory

Gref?	Filename	Scanner	Date	Time	Floor	Route Description	Starting Entrance	# of points	Contains Outdoor Area?	Cones / Targets Visible?	Ceiling?	RGB?	GPS Time?	Point Cloud Intensity	Other Notes
☑	*2023_01_18__19_16_17_cones_outside_non-opt*	Intel L515	Jan 18	19:16	0	Street and plaza outside the building's side entrance.	side	36,725,295	Yes	cones (t8, t9,t10)	no	Yes	no	Yes	Captured after dark, so the RGB coloring reflects that. Slightly more points when you don't remove the no color points. may be helpful with aligning other clouds to this one.
☑	*2023_01_18__19_16_17_cones_outside_removenocolorpts*	Intel L515	Jan 18	19:16	0	Street and plaza outside the building's side entrance.	side	36,174,509	Yes	cones (t8, t9,t10)	no	Yes	no	Yes	cones visible, no targets. Columns appear to possibly be a bit distorted, like wider than reality. they stick out farther than both scan 1 - Scaniverse 2022-12-12 113604 and 2023-01-06_19-42-21tnw_gf_outside
✗	*2023_01_18__19_35_10_non-opt*	Intel L515	Jan 18	19:35	0	printer from open room at end of A-gang (aka small room fragment)	side	628,682	no	no	no	yes	no	yes	tiny fragmen
✗	*2023_01_18__19_36_14_non-opt*	Intel L515	Jan 18	19:36	0	area inside of side entrance + first part of A-gang	side	8,681,433	no	no	no	yes	no	yes	Very dark because hallway lights were out. Not enough of A gang to be worth it
✗	*2023_01_18__19_40_13-opt*	Intel L515	Jan 18	19:40	0	Shows fragment of the open room at the front corner of A-gang.	side	3,609,721	no	no	no	yes	no	yes	fragment
✗	*2023_01_24__18_27_37_non-opt*	Intel L515	Jan 24	18:27	0	Shows a small part of the raised terrace/plaza outside of the side entrance	side	11,943,277	yes	no	no	yes	no	yes	No targets or bottles visible. Very small area, so probably not useful.
☐	*2023_01_24__18_36_46_non-opt*	Intel L515	Jan 24	18:36	0	Start inside in front of side entrance door. Turn right and walk down A-gang, ending in the large open space at the end of the hallway.	side	57,877,272	no	no	no	yes	no	yes	only the A gang, so would need to be an additional analysis cloud. Also maybe hard to do point picking / interior alignment
✗	2023_01_24__18_59_40_non-opt	Intel L515	Jan 24	18:59	0	Shows part of the open room at the front corner of A-gang.	side	21,024,062	no	no	yes	yes	no	yes	patchy coverage of one interior room
☐	2023_01_24__19_40_41_non-opt	Intel L515	Jan 24	19:40	0	Front hallway including open area of B-gang (?)	side	65,434,972	no	no	no	no	no	yes	
✗	2023_01_26__17_29_01_non-opt	Intel L515	Jan 26	17:29	0	Shows part of the open room at the front corner of A-gang.	side	12,194,664	no	no	yes	yes	no	yes	room fragment
	2023_01_27__18_25_54_non-opt	Intel L515	Jan 27	18:25	0	Front hallway including open area of B-gang	side	44,835,556	no	no	yes	yes	no	yes	probably difficult to georeference. Maybe possible with internal point picking
	2023_01_27__19_09_27_non-opt	Intel L515	Jan 27	19:09	0	Outside of main entrance + part of the interior entryway	main	35,292,173	yes	cones (t2, t3,t4)	no	yes	no	yes	could use as reference cloud for main entrance side
	2023_01_27__19_31_30_non-opt	Intel L515	Jan 27	19:31	0	Started outside main entrance. Turns to the right and walks down front hallway to D-gang. Ends in the open room at the beginning of D-gang	main	59,771,098	yes	cones (t2, t3,t4)	no	yes	no	yes	could use as reference cloud for main entrance side // quite high alignment error compared to other reference Intel scan, so I won't use it
	2023_01_27__19_47_31_non-opt	Intel L515	Jan 27	19:47	0,1	Started right before entrance to D-gang. Scan the open room, walk up the stairs, and turn right to walk down the hallway toward C-gang. Ends about halfway down that hallway	main	58,379,156	no	no	yes	yes	no	yes	probably too difficult to georeference. Maybe possible with internal point picking. would be good for vertical drift
☐	*Scaniverse 2022-12-13 182726*	iPhone 12	Dec 13	18:27	0	Started outside, in front of side entrance. Entered building and turned right. Walked to the front of the building and continued along the front hallway until reaching the main entrance. Exited and scanned the area in front of the main entrance.	side	518,414	yes	bottles (t8, t9, t10, t2) targets (t7, t17)	yes	yes	no	default (null)	From Adhi''s phone. Captured after dark, so the RGB coloring reflects that. targets (somewhat) visible. Could georef on the aula side, but would need to make a new GPS layer with the bottle height offset
☑	*scan 1 - Scaniverse 2022-12-12 113604*	iPhone 12	Dec 12	11:36	0	Started outside, in front of side entrance. Entered building and turned right. Walked to the front of the building and continued along the front hallway until reaching the main entrance. Exited and scanned the area in front of the main entrance.	side	775,466	yes	targets (t11, t5, t6, t7)	yes	yes	no	default (null)	From Robert's phone. Targets (somewhat) visible. No bottles or cones visible.
☐	*scan 2 - Scaniverse 2022-12-12 115635*	iPhone 12	Dec 12	11:56	0,1	Started outside the main entrance. Turn right down the front hallway and walk until the D-gang. Walk up the stairs to 1st floor and walk back along the front hallway in the other direction, all the way to A-gang. There turn right, walk to the staircase and go back downstairs to the ground floor. End outside of the side entrance.	main	603,226	yes	targets (t5, t6, t17)	yes	yes	no	default (null)	From Robert's phone. Targets barely visible. No bottles or cones visible.
☐	*scan 3 - Scaniverse 2022-12-12 120339 -* ***MESH***	iPhone 12	Dec 12	12:03	0	Started outside side entrance. Entered building and turned right down A-gang. Walked to front of the building and continued along the front hallway until reaching the main entrance. Exited and scanned the area in front of the main entrance.	side	n/a (627,727 faces)	yes	targets (t5, t6, t12,t15)	yes	yes	no	n/a	From Robert's phone. This is actually a mesh; the corresponding point cloud turned out to be an accidental copy of scan 2



Gref?	Filename	Scanner	Date	Time	Floor	Route Description	Starting Entrance	# of points	Contains Outdoor Area?	Cones / Targets Visible?	Ceiling?	RGB?	GPS Time?	Point Cloud Intensity	Other Notes			
☐	scan 4 - Scaniverse 2022-12-12 121300	iPhone 12	Dec 12	12:13	0,1	Started outside main entrance. Turned right and walked to D-gang. Went upstairs and walked back along the hallway all the way to A-gang. Turn right and walk through study area to staircase. Go downstairs and exit from the side entrance.	main	715,976	yes	targets (t17, t11, t5, t6, t7)	yes	yes	no	default (null)	From Robert's phone. A few targets visible. No cones or bottles visible.			
☐	*tnw_test1_2022-11-03_17-02-151*	Zeb Revo RT	Nov 3	17:02	1	Single interior loop of C118	n/a	7,399,378	no	no	yes	no	yes	default (null)	some reflectance noise visible out of C118 back windows			
☐	*tnw_loop2_2022-11-03_18-07-47*	Zeb Revo RT	Nov 3	18:07	1	Start facing C118 engraved door. Turn left, walk thru dark corridor twd B gang (turn on light), turn left on B gang, loop back around to C gang	n/a	17,332,858	no	no	yes	no	yes	default (null)	a lot of noise due to point cloud reflection through glass walls			
☐	*tnw_loop3_2022-11-03_18-24-02*	Zeb Revo RT	Nov 3	18:24	0,1	Start facing C118 engraved door. Turn left and walk on 1st floor over to B gang, take those stairs down and walk past the service point, take C gang stairs up and keep walking straight over to D gang, turn left at next stairs and left again at the end of that hallway to circle back around to the C gang	n/a	28,049,229	no	no	yes	no	yes	default (null)				
☐	*2022-12-13_19-57-32_tnw_gf_target_only*	Zeb Revo RT	Dec 13	19:57	0	Started at the bench in front of the side entrance. Walked up onto the platform, then down the other side and around the building until reaching the main entrance. Then walked down the steps underneath the main entrace, and back up the ramp leading out of the other side. Ended at the top of the ramp by the main entrance.	side	16,720,702	yes	no	no	no	yes	default (null)	no cones or targets visible, but the quality is crisp enough that you could most likely still do point picking with features like the garbage can, building sign, staircase, and stair railings	This is the only example of an open loop with the Zeb scanner. For some reason, I was able to end this scan at a different place than I had started (fully on the other side of the building, too) without the scanner freezing indefintiely during the loop closure attempt. Unfortunately, there is no interior part of this scan so I can't use it in analysis.		
☐	*2023-01-06_18-56-28_sec_hall_test*	Zeb Revo RT	Jan 6	18:56	1	Starting in front of room C118 on the first floor of TNW, I walked down the C gang to the large open room by the staircase in the front of the building, and then back to the start point.	n/a	5,009,188	no	no	yes	no	yes	default (null)	Just the one hallway			
☐	*2023-01-06_19-04-52_tnw_gf_inside*	Zeb Revo RT	Jan 6	19:04	0	Started inside, on the ground floor next to the TNW side entrance. I walked to the service point (C gang) and then back on the same route to close the loop at starting point.	side	9,778,107	no	no	yes	no	yes	default (null)	Could use for data analysis, although it is a closed loop			
☐	*2023-01-06_19-11-32_tnw_2_floor_indoor*	Zeb Revo RT	Jan 6	19:11	0,1	start at ground floor inside in front of side entrance, walk past service point to D gang and up those stairs. Follow same route on 1st floor back to the start point (1 level above; in the Vvtp hall) and then go back the same way to arrive back at start point	side	37,466,832	no	no	yes	no	yes	default (null)	Could use for data analysis, although it is a closed loop. And it's 2 floor. Could cut off the second floor.			
☑	*2023-01-06_19-42-21tnw_gf_outside*	Zeb Revo RT	Jan 6	19:42	0	Started outside in front of side entrance. Entered the building and turned right, walking down A-gang. At the end of the hallway turned left and walked along the front hallway until reaching the main entrance / Cgang. Then turned around and followed the same path back, ending outside of the side entrance again.	side	15,956,913	yes	cones (t8, t9,t10)	yes	no	yes	default (null)				
	purple = workflow cloud green = for georeferencing red = low coverage, not useful XXX = for quantitative analysis (align if necessary)																	

B.8. Georeferencing

B.8.1. Preparing the GPS Data

Before beginning any analysis, the collected point cloud data needed to be georeferenced to ensure that it was properly located in geographical space with respect to the ground truth data. To do this, the GNSS image points and ground control points (GCPs) measured with the Leica GS18i were used to georeference the data to the **RD-New (EPSG:28992)** reference frame. The Leica GS18i recorded the GPS points in both orthometric and ellipsoidal heights. The point clouds were georeferenced using the orthometric height, because we are interested in each point's distance from the geoid rather than from the reference ellipsoid. *This will also allow the changes in (orthometric) height with respect to the geoid to possibly be teased out.*

Raw data output from the Leica Infinity processing software included 1 averaged and 2 'GNSS Phase measured RTK" entries per point, with 43 total points. (Includes 3 duplicate measurements at most control points).

In QGIS, each of the 15 control points and Lidar target measurements was considered a feature. First, k-means clustering was used to identify the multiple GPS measurements taken at each feature as well as any outlier measurements. The result was 31 measurements spread across 8 clusters. Next, the coordinates of the points in each cluster were averaged using coordinate averaging from the QGIS vector analysis toolbox. Resulting in 8 coordinate measurements. Then, the other attribute fields for each of these 8 averaged points were averaged and assigned to each point. Lastly, these averaged coordinates were assigned to a new layer and combined with the other control point measurements to create a final GPS layer with 15 points and 20 attribute fields.

With the correct GPS coordinates together in one file, the height values were adjusted to compensate for the height of the traffic cones and the wine bottles used to mark the location of the control points in some of the LiDAR point clouds. The adjusted height field for the cones was calculated by applying an offset of 46cm to the orthometric height, and for the wine bottles the offset was 32.5cm.

B.8.2. Method

The targets are primarily visible in the iphone scans taken in December. The bottles initially placed on top of the ground control points during the December data collection period appear in some iPhone and Zeb Revo RT point clouds, but are typically difficult to distinguish from the background. The cones are only present in the Intel scans made in January, as that is when they were able to be secured. However in those scans no targets are present. Because the cones are more easily visible in the point clouds than the targets, the Intel scenes containing the cones were first georeferenced to the ground control points in Cloud Compare. Then, these newly-georeferenced scans were used to align other scans to them, thereby georeferencing the scans that contained no cones and/or targets **parent2022classifying** [elaborate for reference].

In CloudCompare, use the "Align by point picking" tool with the GPS points as the reference point cloud. The tool requires at least three corresponding pairs to be marked on the set of point clouds, in this case three point pairs were used, one for each GCP covered by a traffic cone. Because some scans differ in scale from one another, the 'adjustable scale' option was used. Figure B.4 shows the alignment between three ground control points (t8, t9, t10) and one of Intel L515 point clouds which contained visible ground control points.

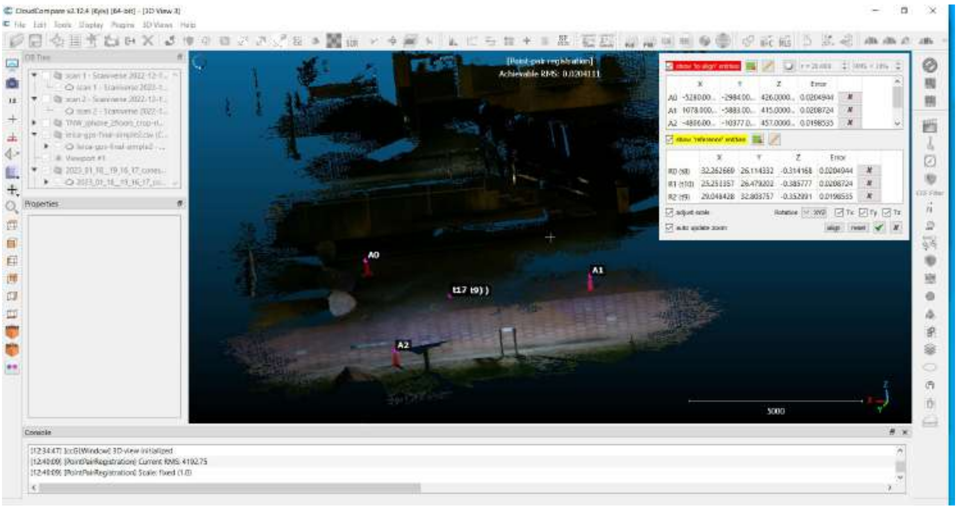
B.8.3. RMS

B.9. Quantitative Drift Assessment Table

Table B.2 shows the full table of quantitative drift results: the hallway length, the displacement of each hallway endpoint, and the average drift per meter.

B.10. Alternate Wall Extraction Method

As discussed in Alternate Wall Extraction Method, a second method for wall extraction was implemented. After extracting the floor plane with RANSAC, instead of using alpha shapes to approximate the shapes of the walls,



	X	Y	Z	Error
A0	-5280.00...	-2984.00...	426.0000...	0.0204944
A1	1078.000...	-5883.00...	415.0000...	0.0208724
A2	-4806.00...	-10377.0...	457.0000...	0.0198535

	X	Y	Z	Error
R0 (t8)	32.262669	26.114332	-0.314168	0.0204944
R1 (t10)	25.251357	26.479202	-0.385777	0.0208724
R2 (t9)	29.048428	32.803757	-0.352991	0.0198535

```
[12:34:47] [ccGLWindow] 3D-view initialized
[12:40:09] [PointPairRegistration] Current RMS: 4102.75
[12:40:09] [PointPairRegistration] Scale: fixed (1.0)
```

Figure B.4: Alignment between three ground control points (t8, t9, t10) and an Intel scan (control point locations are marked by the traffic cones)

Dataset Number	Scanner	**Initial RMS [m]**(point picking)	**Secondary RMS [m]**(ICP)	Combined Error [cm]
1	Zeb Revo RT	0.0214276		2.143
2	Zeb Revo RT	0.0269999	0.0864292	9.055
3	iPhone 12	0.0280741	0.0989126	10.282
4	iPhone 12	0.0575391		5.754
5	Intel L515	0.00650387		0.65
6	Intel L515	0.0416713	0.114395	12.175

Table B.1: appx:georeferencing-method-RMS

Voxelization

With the wall point cloud obtained, it needs to be put into a form that can be used by the Hough Transform algorithm. The Hough Transform takes an image as input, so the wall cloud needs to be transformed into a binary image that shows at which coordinate locations there is part of a wall, and at which there is not. The solution is to voxelize the data.

To preserve the distances between point locations while downsizing from a float64 number format to a binary one, the coordinate values were transformed by subtracting the minimum value from each (ie. translating range down to zero). Then a grid full of zeros was constructed with a voxel size of 1cm. This voxel size was chosen because it is small enough to register any possible variation in the shape of the hallway, while remaining large enough to maintain some computational efficiency.

Dataset	Segment	Hallway Length (m)	Left Endpoint displacement (m)	Right Endpoint displacement (m)	Avg drift per meter (cm / m)
1-Zeb	0	30.779	0	-0.084	0.136
	1	26.337	0	-0.222	0.421
	2	23.95	-0.168	0.224	0.818
3-iPhone	0	30.779	0	0.336	0.546
	1	26.337	3.71	3.32	13.346
	2	23.95	7.082		14.785
4-iPhone	0	30.779	-2.4	-2.55	8.041
	1	26.337	7.012	6.953	26.512
	2	23.95	-13.864	-13.976	58.121
5-Intel	3	26.115	-1.085	-1.225	4.423
6-Intel	0	30.779	-0.211	-0.272	0.785

Table B.2: Table showing the average drift detected per hallway segment

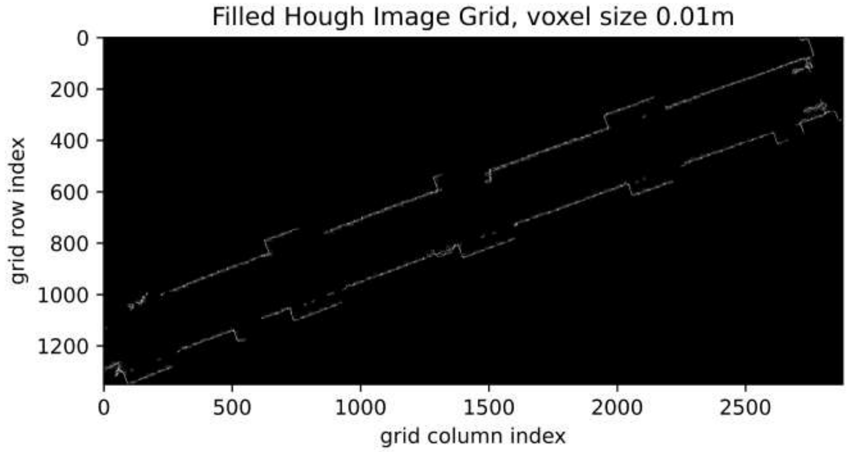


Figure B.5: Voxelized wall point cloud with 1cm cell size

Figure B.5 shows the final voxel grid, with a grid size of 1cm and the walls marked in white in the image.

Then the modulo operation was used to determine for each point, which grid cell (row, col) it falls in. Each cell containing a point was given a value of 1, which results in the white-on-black image seen in Figure B.5. This grid is the input for the Hough transform.

Hough Transform

To apply the Hough Transform to the data, the coordinates are transformed to integers by first rounding to the fourth decimal point (which provides precision to the micrometer level, more than satisfying the project needs) and then multiplying by 104. Due to the fact that the hallway has nooks in the walls, the Hough Line Transform cannot adequately approximate the walls. Therefore, the Probabilistic Hough Transform (PHT) was used. Figure B.6 shows the output of the PHT.

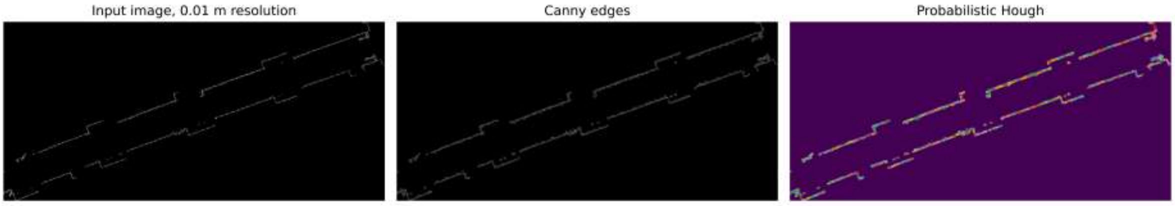


Figure B.6: Probabilistic Hough Transform at a 1cm resolution

Wall Grid Method The wall grid method starts with the cropped point cloud, and then builds a grid with a pre-determined cell size. After some experimentation, the default cell size of 0.15m was chosen. Details about this choice can be found either in the discussion or in Appendix B. Each point in the point cloud treated as a 2D point (the z coordinate is dropped) is then assigned to the grid cell in which its coordinate location falls. After matching every coordinate point to a grid cell, the grid cells are sorted by the number of points contained in each one. The assumption is made that cells containing the most points are likely to be part of a wall, because in the 2D plane, all of the points measured at any given height at a set of (x,y) coordinates would fall in the same grid cell. Thus, the more points in a grid cell, the more likely it is to be a wall. A threshold has to be chosen, in order to determine what percentage of points will be used to approximate the wall.

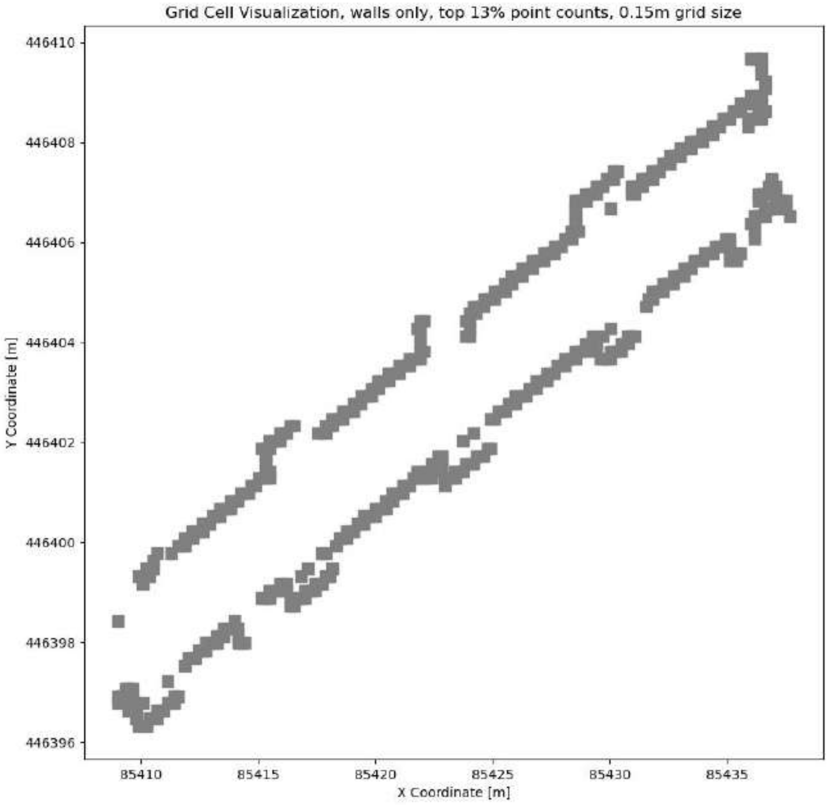


Figure B.7: The 15% of grid cells with the most points contained within them

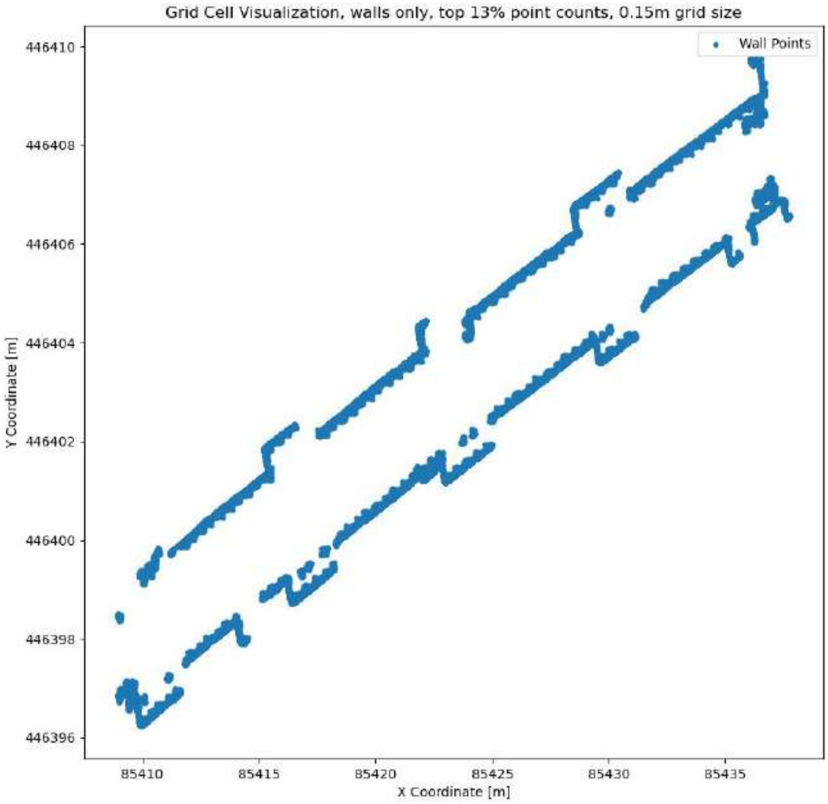


Figure B.8: The points contained by the top 13% of grid cells

In the case of this hallway layout, 13% proved to be a great threshold value. This means taking the top 13% fullest grid cells–in other words, taking the 13% of grid cells containing the most points. The points contained in those grid cells become the wall point cloud. Figure B.7 shows these top 13% of grid cells, and Figure B.8 shows the points contained within them.

Note that in a location with straight hallways, the threshold percentage can be reduced to as low as 1% or 2% because there is less detail to capture.

B.10.1. Alpha shape vs. Grid cell method

Is the alpha shape method compatible with the hough transform analysis in the same way? Is one method more precise and/or accurate than the other? Is one method computationally faster than the other? [could express in terms of Big O Notation]

B.10.2. Choosing a threshold for hallway edge points

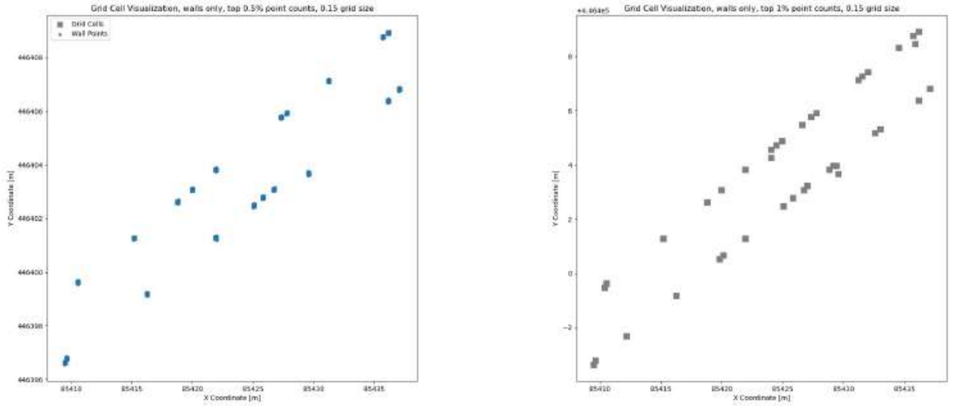
(a) The doorway "nooks" (inset in circles) present in the hallways

(b) Example transect (blue center line) of the full hallway with nooks visible

Figure B.9: The doorway "nooks" and their length relative to the full length of the hallway.

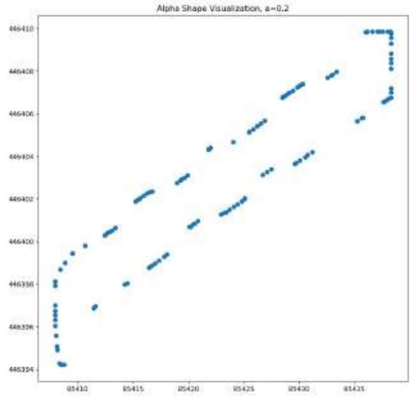
When choosing a threshold for the hallway edge points, in both methods there was a clear point at which important detail in the shape of the hallway was lost. Figure B.9 shows the feature in question, 'nooks' containing doorways and set about half a meter back into the main hallway wall. To preserve the presence of the doorway nooks in the final representation of the hallway walls, when using the grid cell method the top **5%** of the densest cells (and the points contained within) were chosen to represent the hallway edge points. In the alpha shape method, the shape created with a value of $\alpha = 0.8$ was chosen to represent the hallway edge points. However, it is worth noting that when this workflow is applied to a location with straight hallways, the thresholds can definitely be increased (for example, maybe to the top 0.5% (Figure B.10a) or 1% (Figure B.10b) densest cells or to a value of $\alpha = 0.2$ (Figure B.10c) because there is less detail and variation in the shape to capture.

Increasing these thresholds would result in a faster processing time and less active memory usage **[citation needed?]**. For example, in a point cloud with 132,454 points, there are 37,101 points contained in the top 5% of cells and 4,773 contained in the top 0.5% of cells–a difference of 32,328 points. Of course, the difference depends partially on the overall distribution of points in the original point cloud. It is possible that in a cloud with many non-wall floor-to-ceiling structures (large pillars, for example), the difference between the number of points in the top 5% and top 0.5% of cells would be smaller. **[Not sure if this is mathematically true; maybe taking the top few percentages of densest cells would still be accessing the data from the peak of the overall distribution, however high that peak is compared to the mean.] [Can I somehow describe the difference in size/memory-usage of the different alpha shapes? If there is not one or not a big one, maybe that is the sign that the alpha shape method is better adapted to this project/future use/real-time use.]**



(a) Hallway edge points identified by considering the top 0.5% of densest cells

(b) Hallway edge points identified by considering the top 1% of densest cells



(c) Hallway edge points identified using a value of $\alpha = 0.2$

Figure B.10: Examples of alternate thresholds which could be used to identify the hallway edge points using the alpha shape **(a)** and grid cell **(b,c)** methods.

B.11. Hough Transform

B.11.1. Voxelization

One of the things to consider when implementing the Hough Line Transform is at which resolution to construct the voxel grid that ultimately becomes the input image for the Hough Transform. The lower the resolution, the less computational resources and processing time it will take to iterate through the identified wall points and fill the grid accordingly.

A 1mm grid resolution is not necessary for actually creating the hough line transform unless you want to capture variations in the input image at a scale of 1mm. At first 1cm seemed most appropriate, but after double-checking the approximate distance between the straight part of the hallway wall and the little nooks, it became clear that even a decimeter (10cm) voxel grid size should be sufficient. (The nooks are set about 55cm back into the wall, and are about 2.5m from one end to the other, in a hallway 29m long.) The change from 1mm to 10cm, 1cm, or even 5mm drastically reduces the needed size of the numpy grid and therefore also the processing time it takes to fill it with the input image. The table below is for an iphone scan with 775,466 total points and 37,101 identified wall points, and shows the different dimensions of the voxelized hough input grid depending on the grid resolution:

The 5mm row is highlighted because that was the resolution ultimately chosen for the analyses. The table makes it clear the huge jump in variable size when moving from a 5cm resolution to a 1cm

Voxel Grid Resolution	# Rows (y direction)	# Columns (x direction)	Total Grid Cells	# Filled Cells
1 m	13	29	377	77
0.1 m	128	281	35,968	715
0.05 m	255	561	143,055	1,720
0.01 m	1,275	2,804	3,575,100	9,854
0.005 m	2,700	5,757	15,543,900	33,106
0.001 m	13,500	28,782	388,557,000	65,022

Table B.3: Table showing the dimensions of the voxelization grid at different resolutions, as well as the number of "filled" cells, containing a piece of wall segment, at each resolution. The highlighted row shows the characteristics for 5mm voxel resolution, which was ultimately used in the creation of subsequent results.

resolution, and from 1cm to 5mm or 1mm.

B.11.2. Non-linear hallways: Hough Line Transform vs. Probabalistic Hough Transform

The Hough Line Transform is a fine implementation for straight line hallways, but for this project's location it is not helpful. Because it is built to recognize straight lines within the given input image space, the HLT will not capture the doorway nooks shown in Figure B.9a. Figure B.11 shows the input grid in the left plot, and in the right plot, the resulting Hough Line estimates overlaid on top. For non-straight or unknown geometries, the Probabilistic Hough Transform is a better choice.

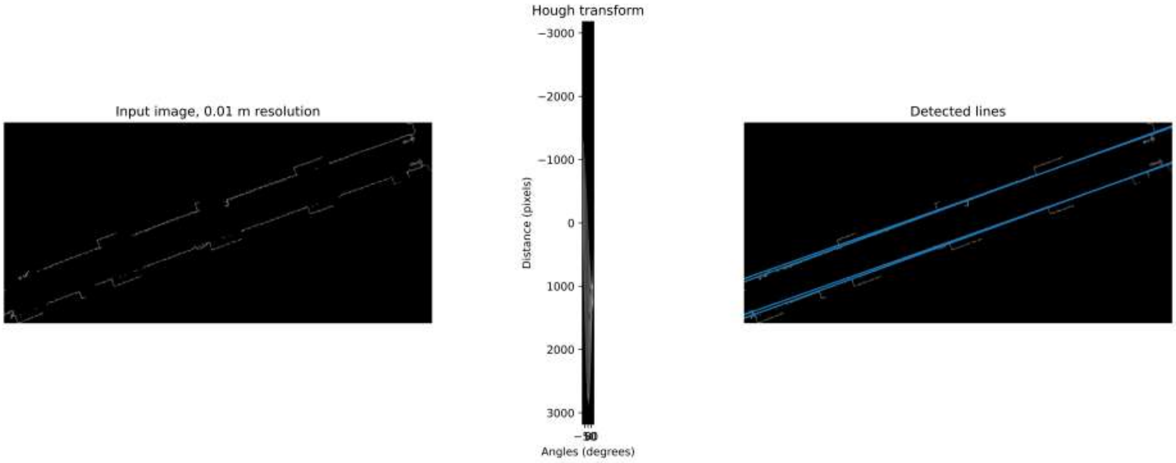


Figure B.11: Hough Line Transform applied to an input image with 1cm grid size.

If implementing this for a real time scenario, you would want the program to be able to implement either HLT or PHT depending on the relevant geometry in the moment. One way to address this could be to implement some sort of test based on nearby/visible points within the field of view to determine whether the walls are straight. Based on whether they are straight or not, choose which method to implement.

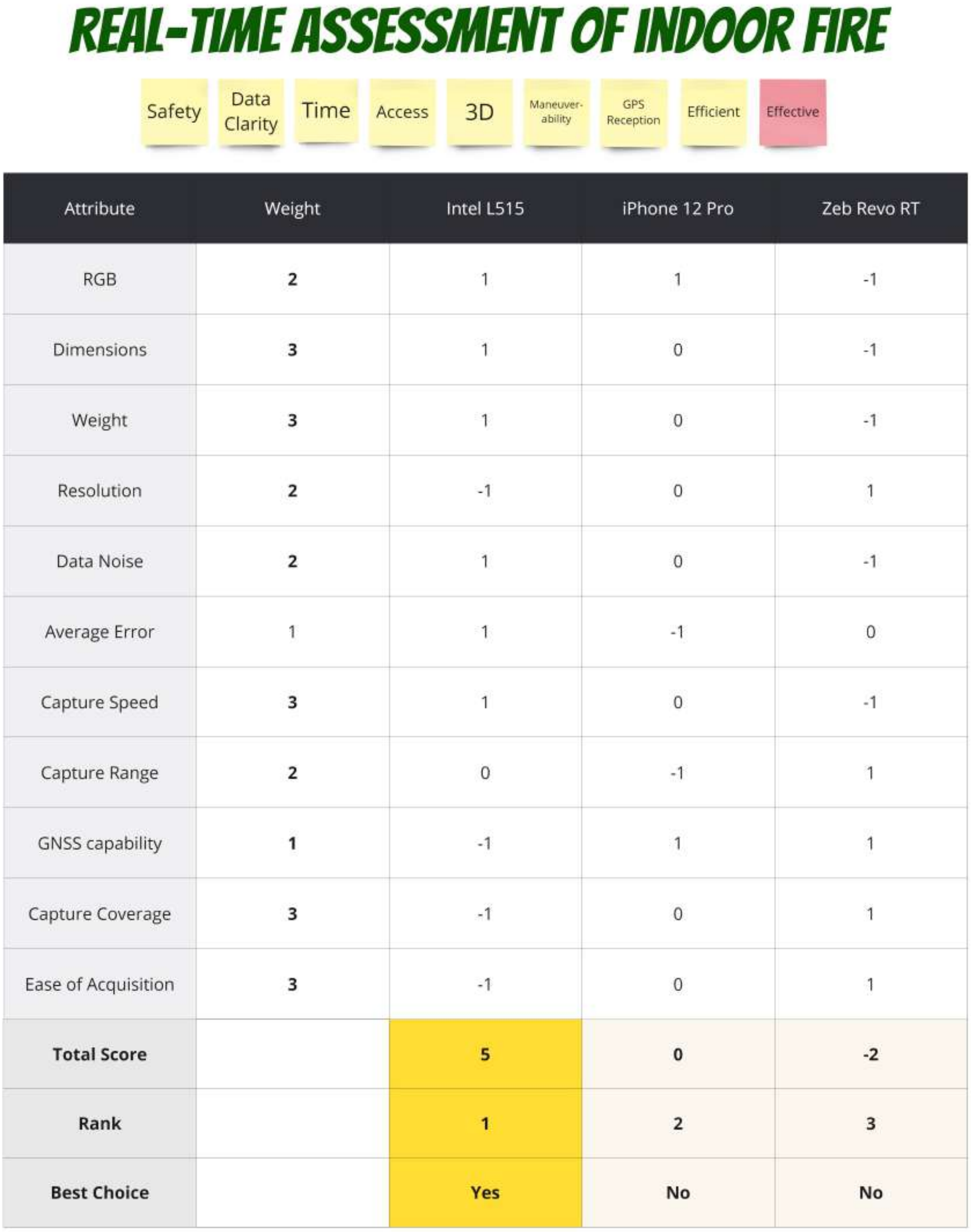
Another implication of the HLT - PHT split is that in a hallway or other room with distinctive, non-linear geometry, the sparse wall extraction method discussed in **??** will not work. You need to make sure the entire shape is visible in the input image in order for the PHT to work, which means that depending on the shape you will want to choose an alpha coefficient or a wall extraction threshold that is relatively robust. This in turn takes away from the computational efficiency.

C

Part 3: Appendix

C.1. Pugh Charts for Use Case Evaluation

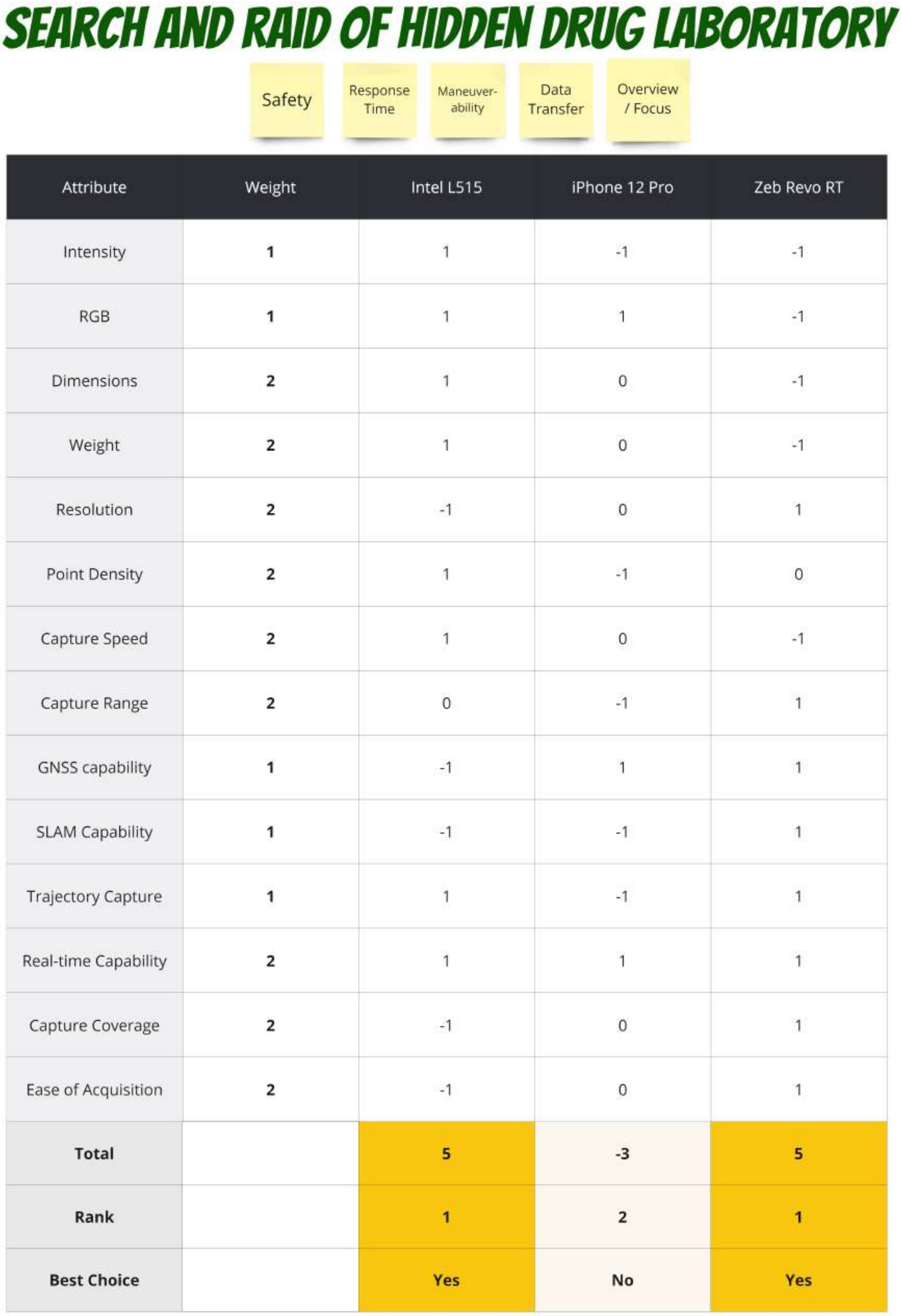
The following tables show the decision-making matrices for the use case evaluations conducted in part 3 of the report. The results are discussed in LiDAR Use Case Evaluations.



REAL-TIME ASSESSMENT OF INDOOR FIRE

Attribute	Weight	Intel L515	iPhone 12 Pro	Zeb Revo RT
RGB	**2**	1	1	-1
Dimensions	**3**	1	0	-1
Weight	**3**	1	0	-1
Resolution	**2**	-1	0	1
Data Noise	**2**	1	0	-1
Average Error	1	1	-1	0
Capture Speed	**3**	1	0	-1
Capture Range	**2**	0	-1	1
GNSS capability	**1**	-1	1	1
Capture Coverage	**3**	-1	0	1
Ease of Acquisition	**3**	-1	0	1
Total Score		**5**	**0**	**-2**
Rank		**1**	**2**	**3**
Best Choice		**Yes**	**No**	**No**

Figure C.1: Pugh Matrix showing scanner comparisons for fire department use case 2, real-time assessment of an indoor fire



SEARCH AND RAID OF HIDDEN DRUG LABORATORY

Safety
Response Time
Maneuver-ability
Data Transfer
Overview / Focus

Attribute	Weight	Intel L515	iPhone 12 Pro	Zeb Revo RT
Intensity	**1**	1	-1	-1
RGB	**1**	1	1	-1
Dimensions	**2**	1	0	-1
Weight	**2**	1	0	-1
Resolution	**2**	-1	0	1
Point Density	**2**	1	-1	0
Capture Speed	**2**	1	0	-1
Capture Range	**2**	0	-1	1
GNSS capability	**1**	-1	1	1
SLAM Capability	**1**	-1	-1	1
Trajectory Capture	**1**	1	-1	1
Real-time Capability	**2**	1	1	1
Capture Coverage	**2**	-1	0	1
Ease of Acquisition	**2**	-1	0	1
Total		**5**	**-3**	**5**
Rank		**1**	**2**	**1**
Best Choice		**Yes**	**No**	**Yes**

Figure C.2: Pugh Matrix showing scanner comparisons for police use case 2, making a dynamic overview of a building area during a raid