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Exploring and developing 3D capture and AR visualization methods for subsurface utilities

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AUGMENTED REALITY FOR SUBSURFACE UTILITY ENGINEERING

EXPLORING AND DEVELOPING 3D CAPTURE AND AR VISUALIZATION METHODS FOR SUBSURFACE UTILITIES

BY
LASSE HEDEGAARD HANSEN

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AALBORG UNIVERSITY
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Augmented Reality for Subsurface Utility Engineering

Exploring and developing 3D capture and AR visualization methods for subsurface utilities

Ph.D. Dissertation

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English Abstract

On-site planning and excavation of underground infrastructure requires easy access to reliable and accurate subsurface utility records to ensure an informed decision-making foundation. Augmented Reality (AR) is a technology that enables displaying relevant information on site and provides comprehensible visualizations of complex data. Easy-to-use 3D capturing technology can be used for 3D documenting subsurface utilities generating 3D point clouds that delivers a far more informed data foundation when trying to locate the spatial placement of subsurface utilities than compared to conventional utility map data.

In this thesis new methods for combining both technologies were explored and developed to provide informed decision-making visualization for utility owners and contractors when planning and managing underground infrastructure projects. That included an AR visualization method for displaying 3D capture data of underground infrastructure for supporting subsurface utility engineering on site. The method was implemented in an outdoor AR prototype system capable of accurate and robust in-situ visualization of 3D capture data with close alignment to the real surroundings. Overall, the AR system and visualization method provided a comprehensible visualization that was greatly appreciated by the interviewed contractors and utility owners. Furthermore, the AR visualization provided a clear understanding of the positional placement of the utilities as well as providing enough realism and detail to identify the type of utilities and material properties.

Another AR visualization method was also developed, however, this time using conventional utility map data as visualization source as this data type is often the only available data source when planning for utility work. The method focused on visualizing the utility data as *virtual utility markings* providing close and seamless blending with the ground surface as well as adapt-

ing real utility marking design schemes from industry guidelines. The visualization method provided a clear overview of the map-based utility records as the virtual utility markings was easy to comprehend when visualized on the ground surface.

The AR visualization methods presented in this PhD thesis were evaluated on real industry end-users through hands-on demonstration and semi-structured interviewing. The overall response was that these AR visualizations methods would be extremely useful for avoiding excavation damage and generally also help ease the on-site planning process for underground infrastructure work. This was especially true since one of the major issues regarding excavation damages was caused by inaccurate and incomplete utility records according to the majority of the interviewed respondents.

Dansk Resumé

Planlægning og udførelse af underjordisk infrastruktur projekter kræver nem adgang til pålidelige og nøjagtige ledningsoplysninger for at sikre et informeret beslutningsgrundlag. Augmented Reality (AR) er en teknologi, der gør det muligt at vise relevant information på byggepladsen samt danne forståelige visualiseringer af komplekse data. Reality Capture-teknologi kan anvendes til at 3D-dokumentere underjordiske ledninger ved at generere detaljeret 3D-punktskyer, som især er nyttige til at bestemme den rumlige placering af underjordiske ledninger sammenlignet med traditionelle ledningskortdata.

I denne ph.d.-afhandling blev nye metoder til at kombinere begge teknologier udforsket og udviklet med målet om at levere en informeret visualisering til forsyningsejere og entreprenører, når de planlægger og udfører underjordiske infrastrukturprojekter. Det inkluderede en AR-visualiseringsmetode til visning af 3D-punktskyer af underjordisk infrastruktur. Metoden brugte et udendørs AR-prototype system, der muliggjorde nøjagtig og robust insitu visualisering af 3D-punktsky data med tæt placering til de virkelige omgivelser, hvilket samlet set gav en forståelig AR-visualisering. Ydermere gav AR-visualiseringen en klar forståelse af den rumlige placering af ledningerne samt leverede en tilstrækkelig realisme og detaljegrad til at identificere ledningstypen samt materialeegenskaber.

Der blev også udviklet en anden AR-visualiseringsmetode, denne gang ved at anvende traditionelle ledningskortdata som visualiseringsdata, da denne datatype ofte er den eneste tilgængelige datakilde, når man planlægger ledningsarbejde. Metoden fokuserede på at visualisere ledningsdataen som virtuelle ledningsafmærkninger ved at efterligne det samme visuelle udseende og stil som man kender fra virkelig ledningsafmærkning. Visualiseringsmetoden gav et klart overblik over de før flade ledningskortdata, da

de virtuelle ledningsafmærkninger var nemme at forstå, når de blev visualiseret direkte på jordoverfladen.

Begge AR-visualiseringsmetoder blev evalueret på industri slutbrugere fra anlægsbranchen gennem fremvisning og afprøvning af AR-prototypen samt efterfølgende semi-struktureret interview. Den overordnede respons var, at AR-prototypen ville være yderst nyttige til at undgå graveskader og generelt også være en stor hjælp under diverse planlægningsopgaver i forbindelse med ledningsarbejde.

Contents

Preface

The research presented in this thesis was carried out at the Department of the Built Environment at Aalborg University in the period from September 2018 to August 2021. The PhD project received funding in the first year as part of the research project *Virtual Reality in Design, Construction and Operation* granted by the COWI Foundation.

Thesis Outline

The core of this thesis consists of the following collection of papers:

Paper I: *Smartphone-based Reality Capture for Subsurface Utilities: Experiences from Water Utility Companies in Denmark. Int. Arch. of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 16th 3D GeoInfo Conference, 2021.*

Paper II: *Combining Reality Capture and Augmented Reality to Visualise Subsurface Utilities in the Field. Conference proceedings of the 37th ISARC, 2020*

Paper III: *Augmented Reality for Subsurface Utility Engineering, Revisited. IEEE Transactions on Visualization and Computer Graphics (TVCG) in special issue 2021 ISMAR, 2021.*

Paper IV: *Towards AR-enabled informed decision-making in subsurface utility projects through visualising 3D capture data of as-built utilities. Unpublished working paper, October 2021*

Paper V: *Addressing the Elephant in the Underground: An Argument for the Integration of Heterogeneous Data Sources for Reconciliation of Subsurface Utility Data. Int. Arch. of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* *16th 3D GeoInfo Conference, 2021.*

Paper VI: *Augmented Reality for Infrastructure Information: Challenges with information flow and interactions in outdoor environments especially on construction sites. Conference proceedings of the 37th eCAADe, 2019*

Even though this thesis is presented as a collection of papers, the structure resembles more that of a monograph. This means the presented papers are included throughout the thesis and are chosen for two reasons. Firstly, to avoid unnecessary repetitive reading (and writing) and, secondly, to guide the reader through the intended reading order while providing the necessary context to connect the papers. Papers I – V are included directly within the main body of the thesis while Paper VI is included in the Appendix.

Acknowledgment

This PhD thesis would not have been possible without the support from all my colleagues at AAU Build, my research collaborators from Graz University of Technology, my industry collaborators, my friends, and my family. A huge thanks to all those people who were involved in my research, but also those who supported me with their encouragement and understanding.

First of all, I would like to thank my PhD supervisor Erik Kjems for all the advises, brainstorming on ideas, and insights into the field of civil infrastructure, 3D geoinformation, Augmented Reality, and in research in general. I really appreciated all our valuable discussions especially those on utopianistic technology futures and how our research would affect it. Thanks for awakening my interest for research and providing me with the opportunity to pursue a PhD degree.

I want to thank Simon Wyke for being a great colleague and for all the time we have spent on writing research papers together. I really valued our great collaboration that was helpful especially during my stressful times. Thanks a lot, my friend. I also really appreciated our discussions on how to perform qualitative interview studies, in which I have learned so much that I to some extent consider you my unofficial second supervisor. I also want to thank Anders J. K. Jensen for expanding my research scope to beyond what typically is learned in an engineering research environment with your vivid conversations on discourse theory in organisations and management. Though sometimes a bit hard to grasp, still, thanks for the discussions, champ.

I would also like to give a huge thanks to Clemens Arth, Philipp Fleck, Marco

Stranner and Dieter Schmalstieg from Graz University of Technology that I visited as part of my PhD project. Thanks for all the valuable discussions on how to develop outdoor Augmented Reality systems, which has really helped progress this PhD project. Thanks for the time end effort spend on guidance during my AR visualisation development as well as on writing a fantastic research paper together.

I also want to give a thanks to all the individuals inside LE34, Novafos, and Aarhus Vand who have been engaged in my PhD project. A special mention to Torbjørn M. Pedersen, Michaela B. Eiris, Torben H. Petersen and Kim B. Kallestrup. Thank you for contributing with industry insight and access to technology services and utility data. This has been greatly appreciated and have helped shaped this PhD project.

Finally, I would like to thank my wife, Dansani. I know my PhD project sometimes has filled a lot in our daily life - especially in the last stages of my PhD project time. So thank you for always being supportive and patient even during stressful times. Love you.

Chapter 1

Introduction

Historically, tools for engineers and designers in the building and infrastructure industry have evolved from using pen and paper, to computers with a graphical user interface using CAD (computer aided design) software. Soon CAD became the *de facto* way of generating drawings to be used by other actors in a building project. 2D drawings progressed into 3D models with properties attached to the spatial geometry and, recently, the new norm was to make a digital representation of everything regarding the project: from documents to the physical assets themselves. The computer became the new information hub to store and manage all the data connected to a built asset. However, digitizing everything does not solve the problem of managing a complex project if the data cannot be accessed and visualized to better inform the decision-making process at the right time and in the correct context.

A technology that focuses on visualizing data in the right context is Augmented Reality (AR). AR can be described as a visualization technology that combines the virtual and real by superimposing virtual content directly in the user's observable surroundings allowing for interactions with the virtual content. AR has many definitions, however, this thesis agrees with the definition introduced by Azuma (1997). He stated that a true AR experience must include the following criteria:

- Combines real and virtual
- Interactive in real time
- Registered in 3D

Augmented Reality was not invented to specifically be used in the building and infrastructure domain, but is more related to fields like *Ubiquitous*

Computing and *Virtual Environments*, which contributes to a wide range of application domains. In the academic book (Schmalstieg & Hollerer, 2016) about Augmented Reality, the authors stated the following:

> "Augmented reality holds the promise of creating direct, automatic, and actionable links between the physical world and electronic information. It provides a simple and immediate user interface to an electronically enhanced physical world. The immense potential of augmented reality as a paradigm-shifting user interface metaphor becomes apparent when we review the most recent few milestones in human–computer interaction: the emergence of the World Wide Web, the social web, and the mobile device revolution."

Today, this bold promise is already starting to be realized as AR applications and features on smartphones have risen in popularity. Probably the most well-known example is the mobile game Pokémon GO, where virtual characters appear in cities displayed on a smartphone's video feed. A perhaps even more utilized AR feature is real-time face filters in social applications like SnapChat and Instagram, which are used by millions of users daily.

Returning to the building and infrastructure domain, AR has also been a popular area of showcasing its potential by targeting professional users. For example as an information tool for presenting architectural visualizations or aiding in managing construction projects by making building-related information directly accessible for on-site users. Probably the first significant example in research was the demonstration of the first outdoor AR system capable of visualizing 3D models of historical buildings in their correct geographical location (Höllerer, Feiner, Terauchi, Rashid, & Hallaway, 1999). More specific AR research targeting outdoor building architecture visualization was presented by Klinker, Stricker, and Reiners (2001) and for AR applications targeting underground infrastructure, Roberts et al. (2002) demonstrated the first AR system to visualize subsurface utility data. Continuing with examples of AR application for subsurface utilities, which this PhD project is about, Schall et al. (2009) demonstrated a *handheld* AR system for underground infrastructure visualization. A handheld AR system might not sound impressive considering today's powerful smartphones and tablets, however, this was quite a leap from the backpack-powered AR systems that came before it. The handheld AR system was further developed to demonstrate more advanced visualization methods with a focus on displaying underground utility data in a comprehensible manner (Schall, Zollmann, & Reitmayr, 2013; Zollmann, Schall, Junghanns, & Reitmayr, 2012). This included various visualization techniques, as shown in figure 1.1, aimed at achieving better depth perception of the displayed underground utilities which was greatly needed to deliver a more believable AR experience.

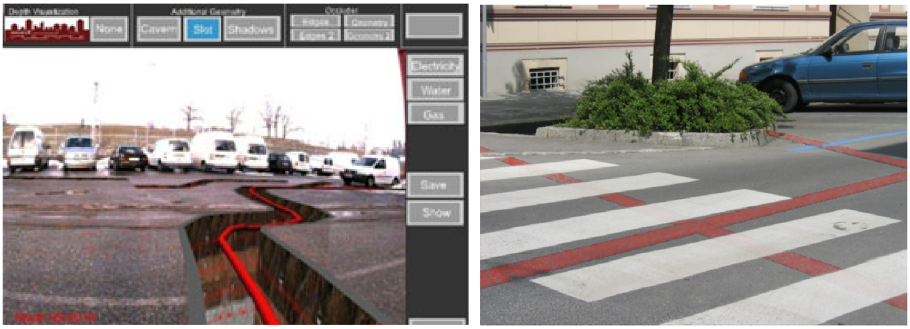

Fig. 1.1: Left: Virtual trench visualization demonstrated by Schall et al. (2013). Right: Image-based ghosting visualization demonstrated by Zollmann et al. (2014). Reprinted with permission from Schall et al. (2013) and Zollmann et al. (2014).

Schall et al. (2013) demonstrated how cut-away techniques could be applied for making a virtual trench along a displayed utility line as well as demonstrating vertical shadow projection displayed on a ground plane estimated from the ground surface. Whereas a user experiment conducted by Zollmann et al. (2014) showed how image-based ghosting techniques were significantly better for estimating depth perception compared to just a simple overlay rendering when visualizing subsurface utility data. Additionally, an evaluation study by Eren and Balcisoy (2018), also showed that cut-away techniques perform significantly better when compared against a careless visualization approach such as simple overlay.

Commercial AR solutions targeting the building and infrastructure domain have also emerged over time. As of 2021, the two must known industry players targeting underground infrastructure are probably vGIS[1] and Trimble[2]. Both companies offering a handheld system using off-the-shelf smartphones or tablets capable of visualizing subsurface utility data as shown in figure 1.2.

[1] https://www.vgis.io/
[2] https://sitevision.trimble.com/

Fig. 1.2: Commercial AR solutions for underground infrastructure as of 2021: On the left the Trimble SiteVision (picture by author) and on the right the vGIS solution (reprinted with permission from vGIS Inc. ©2021 vGIS Inc.)

Despite the availability of commercial all-in-one AR solutions, it is still evident that AR has not been widely adopted in the building and infrastructure industry when compared to other application domains such as entertainment and social media. While this might indicate a low technology readiness of AR, there are also promising signs for AR adoption gaining momentum in the construction industry, with systems such as vGIS, SiteVision, and AVUS[3] being active in development as well as being tried out by utility owners across many countries (Zeiss, 2020; Zeiss & Shinoaki, 2020).

1.1 Motivation

1.1.1 Comprehensible AR visualization

Throughout the PhD project, one of the main motivational factors has been to develop new comprehensible AR visualizations for subsurface utilities targeting the professional user on site. The state of commercial AR solutions has improved significantly in core AR technical areas such as tracking and outdoor localization, which have mainly been solved by the increased quality of native AR frameworks (ARKit and ARCore) and by the integration of compact and accurate GNSS-RTK antennas. However, when looking at AR visualizations techniques implemented in the same commercial solutions, it is clear that little to no improvements have been made or new novel visualization approaches put forward than already demonstrated by researchers in the past. This is very evident in the case of visualization technique for displaying 3D models of underground built assets, where AR visualization

[3] `https://www.avus.tech/`

approaches introduced by Schall et al. (2013) are largely the same as found in current commercial AR solutions (figure 1.3).

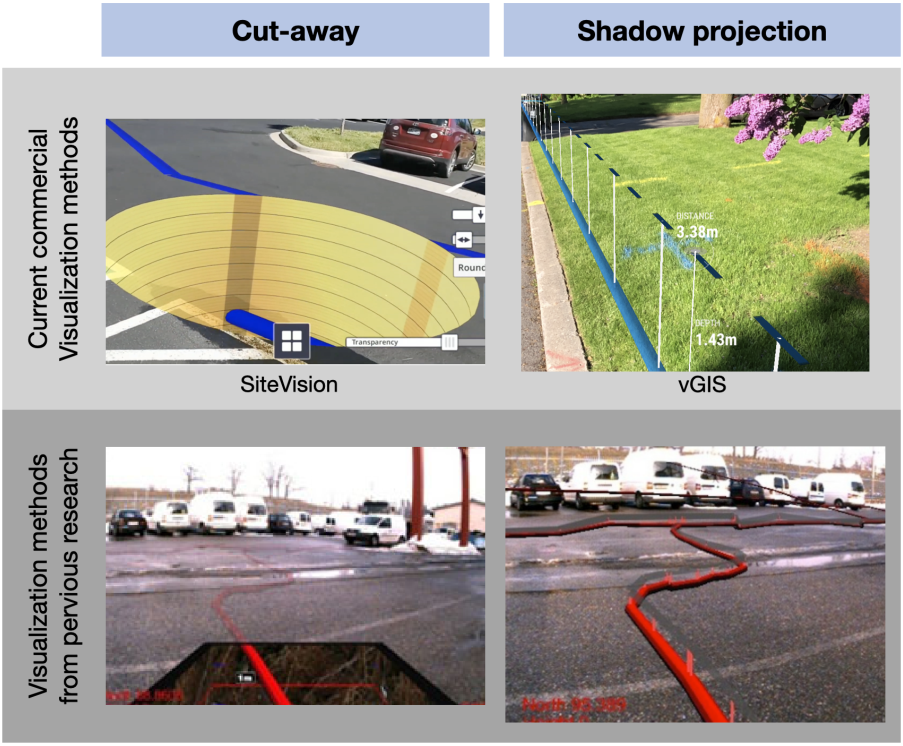

Fig. 1.3: Comparison between visualization methods for underground infrastructure. Top images are current approaches from SiteVision and vGIS. Bottom image are visualization techniques demonstrated by Schall et al. (2008); Schall et al. (2013). Top left image is reprinted with permission from Trimble Inc., ©2021 Trimble Inc. Top right image is reprinted with permission from vGIS Inc., ©2021 vGIS Inc. Bottom images reprinted with permission from Schall et al. (2013).

Therefore, to challenge the status quo and driven by a motivation to innovate, a novel visualization method was developed as a new approach for visualizing subsurface utility data with the design intended to be comprehensible for utility owners and contractors on site (figure 1.4).

Fig. 1.4: Our method: Subsurface utility data visualized as virtual utility markings for a comprehensible understanding

1.1.2 Preventing utility excavation damages

A second motivational factor was to find new solutions to prevent errors occurring on site when uncovering subsurface utilities with the use of AR. Utility damages during excavation is a global issue, many researchers have already put forward the idea of using AR to prevent such damages (Côté, Létourneau, & Marcoux-Ouellet, 2014; Schall et al., 2013; Stylianidis et al., 2016; S. A. Talmaki, Dong, & Kamat, 2010) by visualizing existing utility record data in AR to better inform the excavator on site. However, studies showed that the main cause behind excavation damages are due to inaccurate and unreliable utility records (Al-Bayati & Panzer, 2019; S. Talmaki & Kamat, 2014). Therefore, a solution that addresses both challenges has been explored; an AR approach relying on using accurate as-built 3D capture utility data as visualization source as shown in figure 1.5 (bottom). A smartphone-based Reality Capture solution (using photogrammetry) was used to generate geometrical detailed and precisely geo-referenced 3D point clouds of as-built utility work (Hansen, Pedersen, Kjems, & Wyke, 2021) that is then later visualized in AR to present a far more accurate and realistically looking visualization than otherwise seen in current AR solutions at the time Hansen, Fleck, Stranner, Schmalstieg, and Arth (2021); Hedegaard Hansen, Swanström Wyke, and Kjems (2020). Notice the intentional phrasing *at the time*, as some commercial AR solutions have now picked up on this AR use case. vGIS now supports visualization of 3D capture data as well (figure 1.5 top right), and a group of students at Aalborg University likewise developed a workflow for the Trimble SiteVision to demonstrate this visualization approach (figure 1.5 top left).

Fig. 1.5: As-built 3D capture data of exposed utilities displayed in AR demonstrated on SiteVision and vGIS (top images) and on our AR prototype system (bottom images) as demonstrated by Hansen, Fleck, et al. (2021). Top right image is reprinted with permission from vGIS Inc. ©2021 vGIS Inc.

AR as a technology to provide informed visualizations in subsurface utility construction projects lies at the core of this thesis. However, during the exploration of AR, it was recognized that AR as a technology is just one variable that has to interact with other variables affecting its overall usefulness. In other words, AR is just one puzzle piece that must fit into a larger puzzle consisting of interactions between technologies, information sources, actors, tasks, and requirements that are apparent during utility projects. Figure 1.6 shows the identified variables, where AR can be considered an information visualization tool alongside tablets and printed drawings. While this might not be a complete overview of all the variables affecting AR, it represents the most noticeable ones discovered throughout this thesis. These variables will later be addressed in this thesis, appearing as general themes throughout the presented papers.

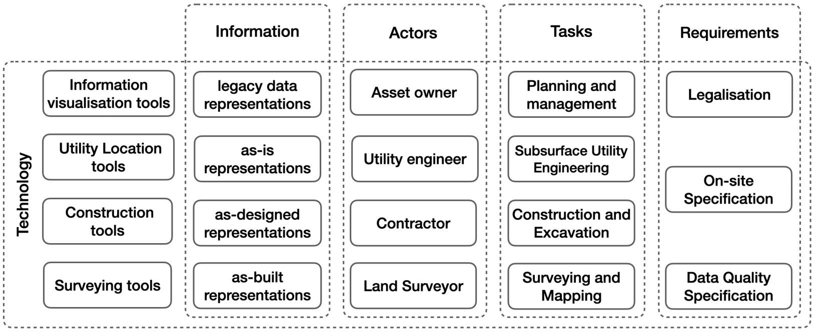

Fig. 1.6: The most noticeable variables in play during subsurface utility construction projects discovered in this PhD project

1.2 Preliminary Investigation: Challenges in Augmented Reality for Civil Infrastructure Projects

A preliminary investigation was carried out at the start of the PhD project in connection with a VR/AR research project (Aalborg University, 2017). The aim of the investigation was to explore and test (i) the current state of off-the-shelf AR devices and (ii) use cases of how CAD and BIM models of civil infrastructure projects could be *used for more* with the use of AR technology (Hansen & Kjems, 2019). Two AR prototype applications were developed with use cases located in Denmark and Norway as shown in figure 1.7.

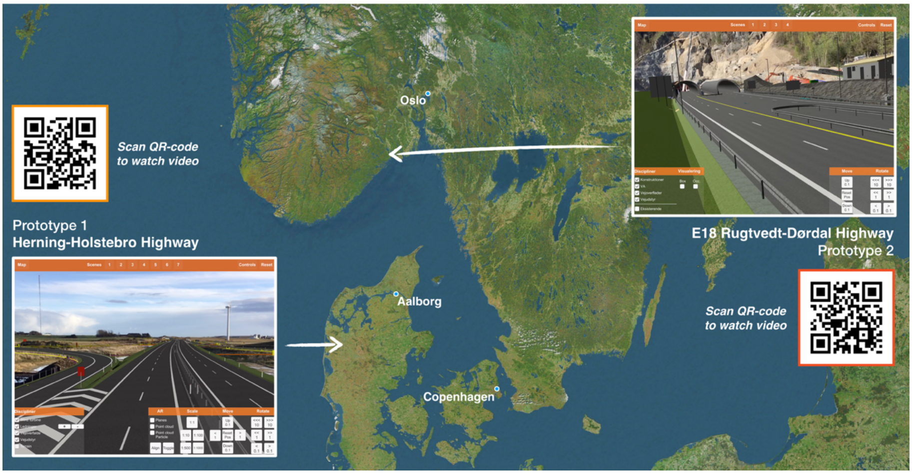

Fig. 1.7: Location of AR use cases in connection with civil infrastructure projects (Hansen & Kjems, 2019). Video link to use case 1 (`https://vimeo.com/276430462`) use case 2 (`https://vimeo.com/276431890`)

Application 1 focused on the planning and design phase, visualizing 3D as-designed representations of different design disciplines in a highway project, like road surfaces, traffic signs, and subsurface utilities. One of the imagined use cases was for site managers to easily communicate intended design models to non-technical people like politicians and citizens. While application 2 was also visualizing 3D design models of a highway project, it was, however, focused on the construction phase and how interactions could assist the contractor to report status progress directly in the augmented BIM model. The reader is encouraged to watch the linked videos of the two AR applications in action. Also, the interested reader can find a more detailed presentation of developed prototypes and use case results in Paper VI, titled: *Augmented Reality for Infrastructure Information: Challenges with information flow and interactions in outdoor environments especially on construction sites*, included in Appendix A. However, the more interesting part of the investigation, with respect to this thesis, was the identification of challenges regarding the development and use of the AR prototypes for displaying 3D models of civil infrastructure projects. The most noticeable challenges will be presented in the following subsections.

1.2.1 Device and display type

The first challenge was in choosing the most suitable hardware for which the AR prototype applications should be developed. The choice was either between handheld devices such as smartphones and tablets or head-worn devices such as the HoloLens (gen. 1) which in 2018 was the state-of-the-art AR headset for displaying 3D content. Both device types were tested and according to the on-site engineers and contractors, the handheld devices were the preferred choice as these were already a familiar form factor. Even though the HoloLens allows for hands-free interaction, which was a plus, it was still considered too intrusive as a work wear on the construction site. Another dislike about the HoloLens was the lack of ability to share the AR view with others resulting in a barrier of collaboration. For the same reason, tablets with large screen sizes were preferred over smartphones as they provided more screen area of the displayed AR content. From a display type point of view, mobile devices using video see-through display technology (figure 1.8 bottom) were clearly also preferred over optical see-through display technology (figure 1.8 top) when in the outdoors. The AR content visualized on the optical see-through displays was simple too transparent in bright daylight. On top of that, the field of view was not satisfying.

Based on the project participants, preference of using a tablet as device type, an iPad Pro 12.9 inch (gen. 2) was used as prototype hardware.

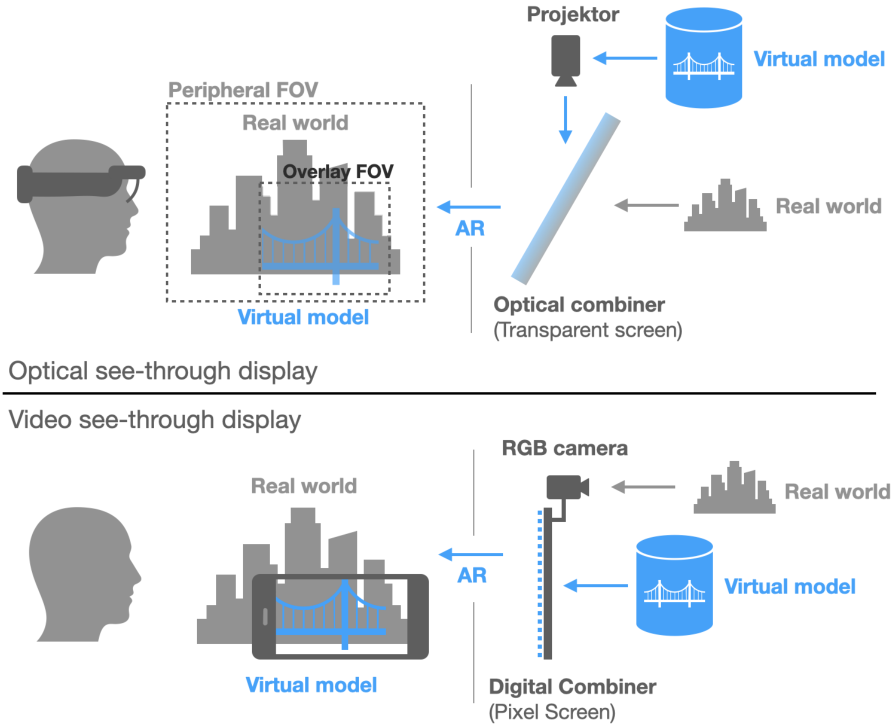

Fig. 1.8: Concept of optical see-through display technology and video see-through display technology.

1.2.2 Outdoor localization

The perhaps biggest challenge found in the study was to achieve accurate outdoor localization. Ideally, the goal was to have instant and automatic localization in the outdoors, however, the use of built-in GPS antennas in modern tablets (and smartphones) were quickly ruled out as these sensors deliver too inaccurate geographic coordinates to support a satisfying registration in AR. To briefly explain registration in AR, it refers to the alignment between virtual and real objects (Schmalstieg & Hollerer, 2016). In our case, that means the goal is for the coordinate system of the virtual 3D BIM model coordinate system to align with the real scenes coordinate system as seen from the user's perspective. To solve this alignment challenge, the AR prototype used a simple manual process by matching two known coordinate points. A more detailed description of this process can be found in Paper VI in Appendix A.

However, the struggle of solving this challenge showed that outdoor localization in AR was a barrier for developing an easy ready-to-use AR solution. Therefore, it is not surprisingly that research on AR in the construction industry (Asmar, Chalhoub, Ayer, & Abdallah, 2021; A. S. Fenais, Ariaratnam, Ayer, & Smilovsky, 2020) and in general (Arth, Wagner, Klopschitz, Irschara, & Schmalstieg, 2009; Kim, Billinghurst, Bruder, Been-Lirn Duh, & F. Welch, 2018) also finds it one of the most critical challenges to overcome.

1.2.3 Spatial tracking

After achieving a successful registration in AR, the next step is to maintain the alignment while moving the AR device. For this process, tracking methods are utilized, and the goal is to have a robust tracking without the AR content *drifting* away. Since our AR prototype was based on the iPad, we used the native ARKit[4] tracking framework introduced by Apple in 2017. The ARKit framework uses a technology called visual-inertial odometry (VIO) which can be categorized as an inside-out, model-free tracking technique or a form of Simulations Localisation and Mapping also called SLAM (Schmalstieg & Hollerer, 2016). Without going into too much detail, ARKit works by combining input from the inertial measurements units (IMU), that includes an accelerometer, a gyroscope, and a magnetometer, with the camera input to choose in real-time which input is the most favorable for keeping a robust tracking. Based on our experience, the ARKit framework delivered a satisfying tracking experience when the user only did minor movements, however, over longer walks drifts occurred with different level of magnitudes. The drifting problem relates back to the challenge of not having an continuously updating outdoor localization method implemented. Overall the use of ARKit was a major improvement compared to other non-native tracking framework which was also tested such as the Vuforia[5] tracking SDK.

1.2.4 Visual perception

Beside challenges regarding AR hardware and core technologies, the participants also reported challenges regarding the visual perception of the displayed BIM models. The issue was most noticeable when visualizing underground infrastructure assets such as drainage networks and wells. The issue is clearly visible in figure 1.9 whereas the simple overlay visualization of the underground 3D pipes are subject to perspective offset and thus appears as if they are floating above the ground.

[4] `https://developer.apple.com/documentation/arkit/`
[5] `https://developer.vuforia.com/`

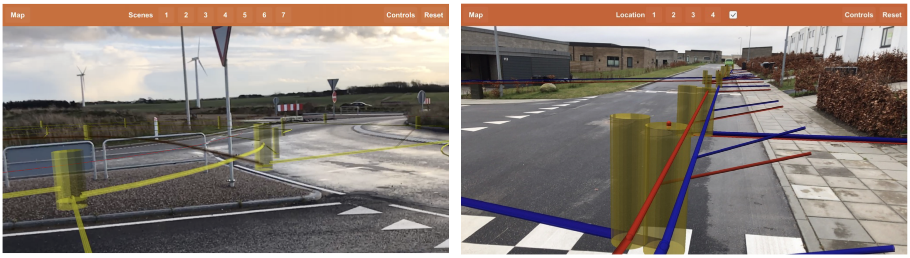

Fig. 1.9: Simple overlay visualization of underground 3D pipe networks leads to poor visual perception

The phenomena is also referred to as the parallax effect and is illustrated in figure 1.10.

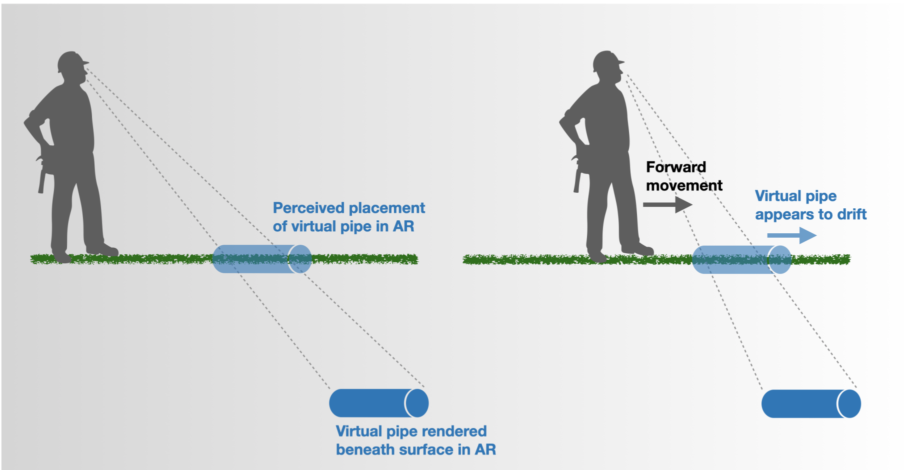

Fig. 1.10: When a virtual pipe is rendered beneath the surface while the AR user is moving it creates the effect of the virtual pipe (as perceived at surface level) is drifting.

Besides the simple overlay visualization technique delivering a poor AR experience, the project participants also noted how it was difficult to correctly estimate the depth distance from the displayed underground 3D pipe models to the ground surface. A clear perception of depth would otherwise have been useful information for the on-site engineer and contractor during maintenance work or planning of future utility work.

1.3 Research Objective

While a successful AR solution must consider all the challenges presented in the preliminary investigation, and arguably even more, in this PhD project the focus is on improving visualization methods for subsurface utilities. Commercial AR solutions for visualizing underground infrastructure are often using simple overlay visualization techniques, which have serious perception issues and ultimately lead to a less satisfying AR experience affecting the overall usefulness. This calls for exploration and development of new visualization approaches that mitigates these issues. Furthermore, the poor data quality of existing utility records (mostly related to accuracy) is the main cause of utility excavation damages. Driven by finding solutions for this data quality issue in order to prevent excavation damages, new approaches focused on better data capturing visualization of subsurface utilities will also be explored. Based on these reasons, the research question to be answered is the following:

How can the exploration and the development of new AR visualization and 3D capturing methods of subsurface utilities lead to informed decision-making for utility owners and contractors when planning and managing underground infrastructure projects?

To answer this research question, five papers are presented throughout the thesis from chapter 2-5. Before continuing with the papers, the remaining part of this chapter will present some overall considerations about the research approach, technical development, and key research methods that were used to shape the PhD project. Finally, a short description of the research contribution will be presented.

1.4 Research Approach

In general, research can be described as either basic research and applied research as shown in figure 1.11 (Faste & Faste, 2012). The figure implies that scientific areas, such as mathematics, physics, etc. are all methods to describe the behavior of science and the world. This is also referred to as basic research and is in general perceived to be more scientific and belongs in the left side of the figure. The right side of the figure is referred to as applied research and is where design research can be placed according to Faste and Faste (2012). The research in this PhD thesis also locates itself close to design research and applied engineering. For instance, the design and development of the AR visualization methods, resembles design related activities and is therefore more practice-based than scientific.

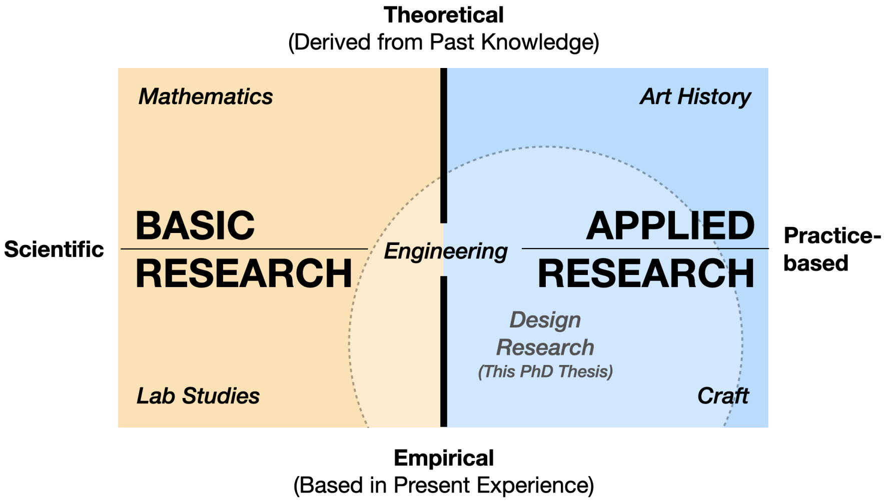

Fig. 1.11: Quadrant chart of research types and where Design Research is located. Chart is inspired by Faste and Faste (2012).

The y-axis in the chart in figure 1.11 represents research in the spectrum between theoretical (past knowledge) to empirical (present experience). Similarly, to design research, this PhD project locates itself near empirical-based research. However, this is not to say that knowledge derived from the past has not been used. For instance when developing the AR visualizations a lot of past knowledge from AR perception studies were used to guide the design and development part.

Faste and Faste (2012) continue by explaining how traditional research either follow two approaches: An inductive or deductive research approach. The inductive research approach aims to derive *what is so* from empirical observations while the deductive research approach aims to derive *what must be so* based on knowledge from the past. However, within design research a third kind of approach is often required for designing possible futures. That is, an abductive approach that can be explained as trying to figure out the *what might be so* by formulating "qualified guesses", which are later tested through case studies or experiments (Kolko, 2010). This PhD project also used an abductive research approach, as the development of the AR visualizations where influenced by experiences learned through hands-on demonstration and interviewing with industry experts. Later these insights from the interviews were converted into design inspirations to steer the design and development process of new AR visualizations methods. More on this in section 3.4.

The research carried out in this PhD project bears resemblance to the Faste and Faste (2012) explanation of design research. Therefore, the PhD project can be placed in the lower-right quadrant (with overlapping to other quadrants) in figure 1.11 alongside the field of design research. The approach taken in this PhD project can furthermore be described as being an empirical- and practice-based approach to explore, discover, and create knowledge.

1.5 Technical Development

1.5.1 AR system setup

In order to develop and explore new AR visualization methods for underground infrastructure, an AR prototype system setup was developed for outdoor use. Two versions of this AR system was developed using an iPad Pro as the hardware device.

Version 1: The iPad Pro (12.9 inch, gen. 2) used in the preliminary investigation continued to be the hardware device for the prototype setup as shown in figure 1.12. The main reason was that the targeted end-users (utility owners and contractors) had similar professions as the participants in the preliminary investigation and would therefore favor the tablet form factor as well. Another reason was because of the benefits that the video see-through display and the robust ARKit tracking framework provided in outdoor environments. The iPad was however missing accurate outdoor localization capabilities as the internal GPS module in the iPad was far from delivering a satisfying accuracy. The localization was handled through an initial geographic position and orientation (GeoPose) alignment process, which was done manually. A more detailed description of this can be found in Paper VI in Appendix A. However, as the focus of the AR prototype was on demonstrating new visualization methods, this setup was acceptable. Version 1 was used in Paper II.

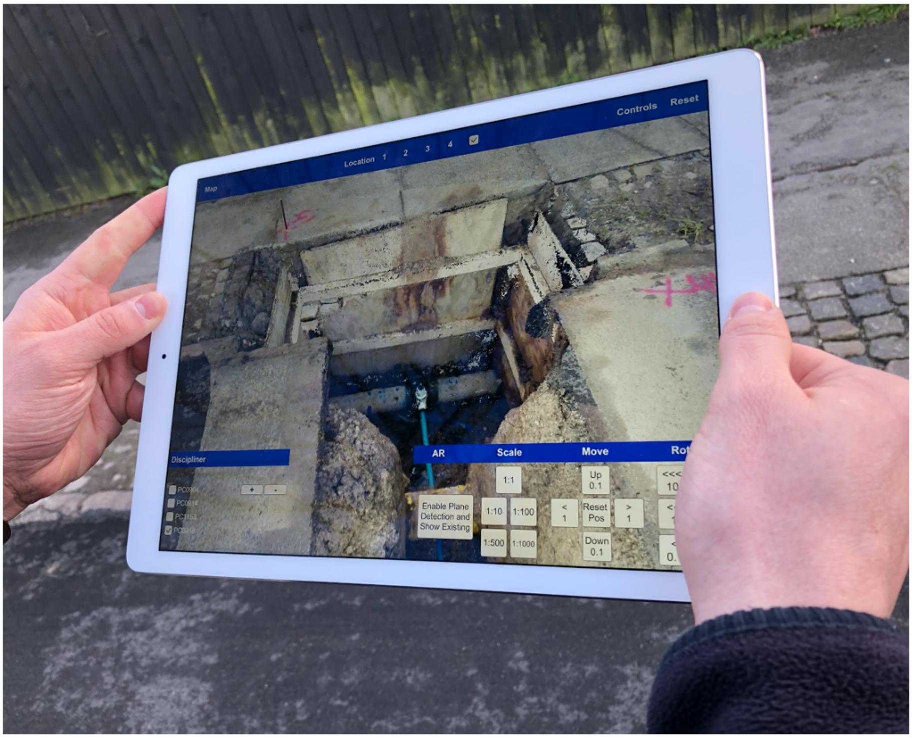

Fig. 1.12: Version 1 of the AR system using an iPad Pro (2. Gen 12.9 inch) as hardware

Version 2: The prototype setup was upgraded to use an iPad Pro (4. Gen 12.9 inch) as the hardware base. A significant change was that the new iPad Pro included a rear LiDAR sensor. This meant that the prototype was now capable of real-time 3D mesh reconstruction of the real environment, which allowed for AR content to interact with the surface of the real scene in a more believable way. For example, the unevenness on a ground surfaces can now be reconstructed in real-time as 3D mesh as shown in figure 1.13.

Fig. 1.13: Uneven ground surface in the process of being reconstructed as a 3D mesh as the iPad user moves around

Compared to the iPad used in version 1, which was only capable of generating plane surfaces estimated of the ground, this new iPad version was a significant improvement with regard to spatial scene understanding. Furthermore, this mesh reconstruction was directly utilized in the virtual utility marking visualization method presented in Paper III.

Version 2 also integrated a GNSS-RTK sensor box used to provide high-precision outdoor localization (Stranner, Fleck, Schmalstieg, & Arth, 2019). The sensor box combines a differential GNSS receiver, an inertial measurement unit (IMU), an altimeter, and a WiFi component in a compact box. The integration was made possible through collaboration with Graz University of Technology and the Austrian-based AR4 GmbH company and their on-going development of the mentioned sensor box. The Austrian team has carried out further iteration of the sensor box and the newest version is now called Vizario.CapsLoc[6], and is shown in figure 1.14. The sensor box was used in Paper III as well as evaluated with an accuracy test. While it was not a goal in this PhD project to have accurate outdoor localization capabilities, it surely helped in making the prototype a more complete outdoor AR system.

[6] https://www.ar4.io/vizario-capsloc/

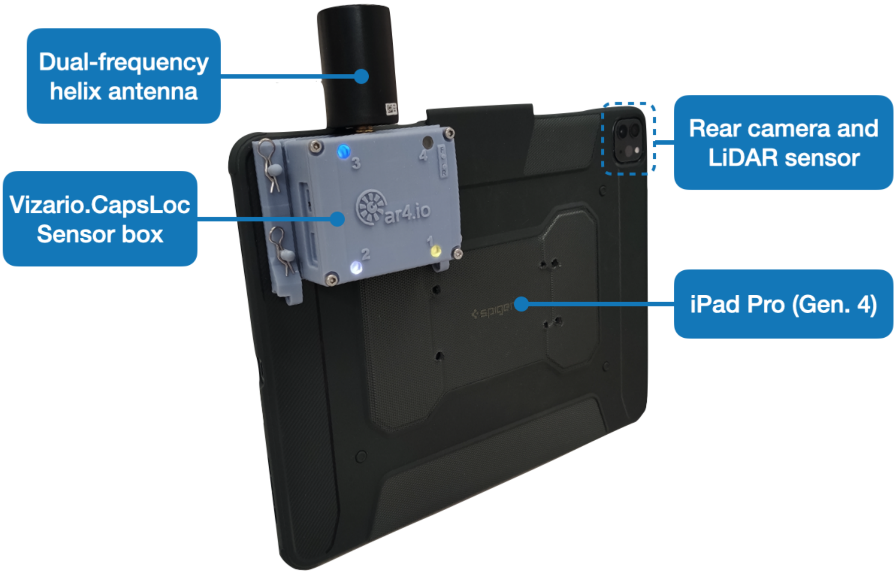

Fig. 1.14: Version 2 of the AR system using an iPad Pro (Gen. 4) with rear LiDAR sensor and sensor box with a dual-frequency helix antenna

1.5.2 Software development

The Unity3D game engine software[7] was used as the render engine in the AR system. The Unity editor and C Sharp scripting in Visual Studio Code were used as development tools for developing the prototype software application that mainly included (i) integrating the ARKit framework by using the AR Foundation Unity Package provided by Unity, (ii) designing the user interface to control and interact with the AR content, and (iii) developing the visualization methods which included the virtual utility daylighting and virtual utility marking methods. A detailed description and demonstration of the visualization methods can be found in Paper III. However, the remaining part of this section will elaborate on some further details related to the two main AR visualizations methods as well as some insight into the development process in general.

Virtual utility daylighting: To achieve a performant way of rendering large and dense point clouds on the iPad, an octree structure made by Fraiss (2017) was utilized and is available on Github[8] as a Unity project. Fraiss' point cloud rendering optimization in Unity is based on the nested octree structure found

[7]https://unity.com
[8]https://github.com/SFraissTU/BA_PointCloud/

in Potree (Schuetz, 2016). Therefore, for common point cloud formats such as LAS files to be read, a conversion into the Potree data structure is necessary. The Potree converter used in this project was also developed by Schuetz (2016) and can be found on Github[9] as well.

Figure 1.15 shows a dense point cloud rendered in Unity and segmented in different level of detail (LoD) volumes by the octree structure. A fork of Fraiss' GitHub project has since been made and can be found on Github[10] which integrates the AR Foundation framework to demonstrate how point clouds can be visualized in AR. Since Fraiss' project was not necessarily intended to work on mobile devices and for AR use, some modifications needed to be added. The most noticeable change was the reprogramming of shaders to work with Apple's Metal graphic framework, which is used across iOS devices and does not support geometry shaders. The unity project has only been tested on ARKit supported iOS devices, but should also work with ARCore supported Android devices.

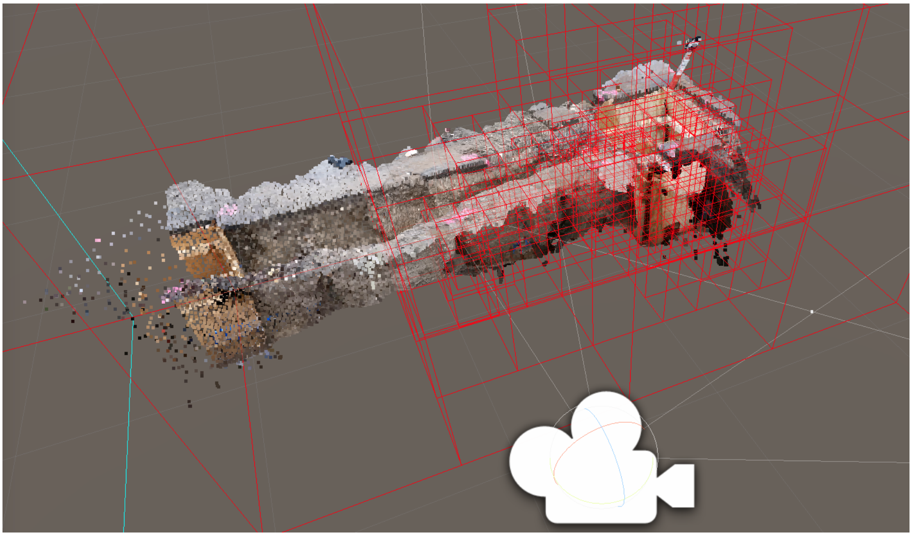

Fig. 1.15: Point cloud rendered in Unity editor using octree integration by Fraiss (2017). The octree structure divides the point cloud into LoD volumes in order to focus on rendering what is visible for the camera's field of view. The number of points allowed to render are limited by a total point cloud budget. 3 million were found to be a satisfying number of points.

Virtual utility marking: As explained in Paper III, the virtual utility marking method consists of three elements (i) the close alignment to the ground

[9]`https://github.com/potree/PotreeConverter`
[10]`https://github.com/lassehh92/PointCloud_Vis_AR`

surface, (ii) the texture blending with real scene ground texture, and (iii) the adaption of marking schemes, colors, and styles. A close look of how the virtual markings are placed on the ground surface is shown in figure 1.16. The surface in this case is a static 3D mesh of a real street surface reconstructed with photogrammetry. This was then imported into Unity for developing and testing purposes to simulate the scenario of having a real-time mesh reconstruction available. The virtual marking line consists of densely placed quad-shaped sprites representing a spray dot that follows a horizontal orthogonal-projected path of imported utility poly-line data.

Fig. 1.16: The virtual markings follow the ground mesh closely as shown on the left image, and a closer look on the right image reveals how the virtual marking line consists of densely placed quad-shaped sprites representing a spray dot that aligns with the ground mesh with regard to position and rotation.

User interface and interaction: The user interface (UI) was not created with the end-user in mind, but with the purpose to control and adjust the displayed AR content as well as the visualization methods. This included controls such as:

- Turning AR content on/off
- Adjusting the position and orientation of the AR content
- Adjusting the size of particles in point clouds
- Manipulating the line style of the virtual utility markings. This was especially useful when experimenting with getting the *right* visual appearance.

The controls and interactions were developed by using basic UI elements in Unity such as buttons, toggles, and sliders. Figure 1.17 shows a screen capture of the UI controls from the AR system (version 2) displaying virtual utility markings.

Fig. 1.17: UI controls available in the AR system (version 2) when displaying virtual utility markings

1.6 Key Research Methods

1.6.1 Evaluation methods

Two types of systems were evaluated in this thesis. The first was a smartphone-based Reality Capture (RC) solution that was evaluated on end-users in Paper I. The second product was the developed AR prototype system, which focused on the designed visualization methods (Papers II and III). To some extent, the applied evaluation methods were based on techniques in usability evaluation studies and to some extent based on experiences from literature evaluating AR systems.

According to Albert and Tullis (2013), two types of usability studies are often distinguished. That is, formative and summative. Summative studies aim to benchmark a system or product, by taking a quantifiable *how much* approach. For instance, by evaluating how well a user can perform by using a likert-scale for performance measure or by measuring how fast a task can be completed. Formative studies, on the other hand, are more about investigating the *why is it* or *how is it* and, therefore, often tends to be more qualitative in nature. Here the focus is more on interaction, identifying shortcomings, finding errors, exploration of alternatives, and making recommendations.

Swan II and Gabbard (2005) found that user studies evaluating AR systems often were divided into three types. Those types are, studies evaluating (i) perception, (ii) performance/interaction, and (iii) collaboration. Out of the three, perceptual studies were of special interest in this PhD project as it investigates how users perceive the AR content blending with the real world. This type of study was interesting, as one of the main AR challenges identified in the preliminary was the lack of depth perception when visualizing underground utilities in AR. Therefore, when evaluating the AR visualization methods developed, the focus has been on perception and related to that the comprehensibleness and understandability.

Motivated by the Swan II and Gabbard (2005) literature review on AR evaluation studies, Dünser, Grasset, and Billinghurst (2008) conducted a more comprehensive literature review. Here, the authors also mapped the much commonly used methods for AR user evaluations. They divided it into five categories:

- Objective measurements. Includes measurements such as accuracy testing, number of actions, and time measurements for completing tasks. The measured variables were often statistically analyzed afterwards for summative results.
- Subjective measurements: For instance, judgements, questionnaires, ratings, and rankings relying on user's subjective experience. Also, the measured variables were often statistically analyzed afterwards for summative results.
- Qualitative analysis: data is for instance gathered through structured observations (e.g., video analysis) or by conducting structured, semi-structured, or unstructured interviews (formal). Here the results are often presented in a formative way.
- Usability evolution techniques: For instance, cognitive walk-throughs, task analysis, thinking aloud, or heuristic evaluations.

- Informal evaluation: For instance, user observations or interviews gathered during demonstration.

In this thesis, the insight-seeking formative evaluation approach was favored over the summative approach when evaluating the RC solution and the AR prototype systems. The formative approach was primarily chosen to try and address the *how can* aspect in the thesis's research question. It was primarily done through on-site demonstration allowing for hands-on experience from industry end-users and, secondly, by conducting formal semi-structured interviews leading to a qualitative analysis afterwards. When a formative approach is chosen, Albert and Tullis (2013) recommends that participants must be representative of the target group. Hence which is why the participants for the hands-on demo and interviews were land surveyors, contractors, and utility owners.

The qualitative formative approach was favored in this thesis, however, accuracy testing (objective measurements) of both the RC system and the AR system was carried out providing summative results.

1.6.2 Semi-structured interviews

Semi-structured interviewing was another key research method used in this PhD project. It was, as previously mentioned, directly used in the evaluation of RC and AR systems, but also in a broader scope to gather insight from industry end-users (land surveyors, contractors, utility owners, etc.) about current work practices, excavation damages, data quality requirements, etc.

Several semi-structured interviews were carried out following the recommendation by Brinkmann and Kvale (2015). Although each interview study had slight variations, in general they all followed the same two-part structure. Firstly, an empirical data collection process i.e., the semi-structured interviews and, secondly, a thematic data analysis, revealing commonalities and discrepancies between the statements made by the interview respondents. Furthermore, all interviews were also sound recorded and transcribed.

1.7 Contribution

The research conducted within this thesis mainly contributes to the field of Reality Capture and Augmented Reality applications for underground infrastructure with a focus on subsurface utilities. On a more general level, the research also contributes to the field of AR visualization techniques in outdoor environments including perception and realism in AR. The 3D capturing and AR visualization methods put forward in this thesis work towards more clearly communicating subsurface utility information for utility owners and contractors working in the field. It does this by demonstrating easy-to-use 3D capturing workflows and new approaches to comprehensible AR visualization. The main contributions are as follows:

- Methods and workflow description of a simple and easy-to-use smartphone-based Reality Capture solutions for documenting as-built subsurface utilities in open excavation as dense 3D point clouds.
- Demonstrating how the Reality Capture solution and 3D point clouds are adding value and improving workflows for utility owners and contractors compared to using conventional surveying.
- AR visualization method description for visualizing dense point cloud data of as-built subsurface utilities in a performant and comprehensible way.
- AR visualization method description for visualizing GIS data of subsurface utilities by blending in with the ground surface in a seamless and comprehensible way that mimics real utility marking design schemes and visual appearance.
- Demonstrating how these AR visualizations methods are supporting informed decision-making for utility owners and contractors during planning and excavation of underground infrastructure projects.
- Presenting a conceptual data reconciliation framework for updating our inaccurate and incomplete subsurface utility records by integrating heterogeneous data sources from data capture opportunities during underground-related projects. For instance by using as-built 3D capture data sources.

Chapter 2

3D capturing of as-built subsurface utilities

This chapter focuses on investigating Reality Capture (RC) technology as a method for surveying subsurface utilities. As the following paper will present, two water utility companies in Denmark have been proactive in trying out this technology to capture as-built 3D point clouds of newly installed water utilities during open excavation. The paper is a fitting start to this thesis, as the activities carried out by these utility companies can to some extent be considered the initiator of this PhD project. The reason for this being the case will be discussed afterwards in section 2.2.

2.1 Paper I: Smartphone-based Reality Capturing for Subsurface Utilities

The following paper, referenced as Paper I, is titled: *Smartphone-based Reality Capture for Subsurface Utilities: Experiences from Water Utility Companies in Denmark.* The paper has been published in *Int. Arch. of the Photogrammetry, Remote Sensing and Spatial Information Sciences, October 2021.* as an open access paper under the *CC BY 4.0 License*.

SMARTPHONE-BASED REALITY CAPTURE FOR SUBSURFACE UTILITIES: EXPERIENCES FROM WATER UTILITY COMPANIES IN DENMARK

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KEY WORDS: Reality Capture, point clouds, photogrammetry, subsurface utilities, as-built documentation, water pipes

ABSTRACT:

Inaccurate and inconsistent documentation of subsurface utilities is a reoccurring problem in the construction industry affecting not only the end-users, but all actors involved in designing, constructing, and maintaining pipes, cables and other utilities hidden underground. In this study, a new method for 3D capturing of subsurface utilities, based on a newly developed Smartphone-based Reality Capture (RC) solution is explored. The research was divided into two parts. Firstly a testing of the method accuracy and secondly, an investigation of the usability of the method. The research results firstly showed that the RC solution is a feasible surveying method, that facilitate capturing of as-built utility assets, which can be used as a supporting tool to conventional surveying methods or alone, as the testing showed an accuracy of ±5 cm for the generated point clouds. Secondly the usability testing revealed that the RC solution benefited the utility owners by allowing time-savings on construction projects, as well as generating visual-realistic 3D models of exposed subsurface utilities to be used for quality assurance and planning of future utility work.

1. INTRODUTION

Lack of accurate and reliable subsurface utility documentation is a real issue in the construction industry making it difficult for planners, excavators, and utility owners to manage underground utility and construction projects. Several research and development projects such as Mapping the Underworld in England (Metje et al., 2007), City Digital in Chicago (UI Labs, 2016) and Digital Underground in Singapore (Van Son et al., 2018) have been and are still investigating how to create more accurate and reliable utility information. The most recent project, Digital Underground, sought to improve the understanding of Singapore's underground infrastructure by developing and implementing a common utility data model (Yan et al., 2021) as well as exploring best-practice methods to capture and generate more reliable underground 3D maps (Van Son et al., 2018) with the goal of creating an underground digital twin (Yan et al., 2019). To achieve this, a case study investigating the use of ground penetrating radar (GPR) equipment, to detect and map buried utility lines was carried out (Van Son et al., 2019). The study showed that the use of GPR has clear advantages compared to conventional surveying techniques, as it is a non-destructive method i.e., no need to remove top surface to locate the buried utilities. The study additionally showed that scanned radar data are laborious to manually process and analyse, which is often not feasible when construction projects are challenged on time and economy – especially on smaller projects. The idea of a city-wide GPR survey approach to 3D map all subsurface utilities was furthermore not recommended. Instead, the study recommended to capitalise on data capturing opportunities of subsurface utilities whenever visible during open excavation using conventional and alternative surveying techniques (Van Son et al., 2019).

Examples of alternative surveying techniques to GPR, are point cloud-based methods, which use data capture from laser scanners or RGB-cameras (photogrammetry) to generate a visual-realistic 3D model of real objects or environments (Van Son et al., 2018). The method is also known as Reality Capture in the construction industry and is used to capture detailed as-built 3D models of built assets. Reality Capture is not yet commonly used for surveying of exposed subsurface utilities in Denmark where conventional surveying techniques are used almost exclusively. Similar tendencies were also observed in Singapore (Van Son et al., 2019).

However, this is not the case for two Danish water utility companies, which are currently exploring the use of a smartphone-based Reality Capture (RC) solution to generate as-built point cloud documentation of their water pipe installments during open excavation (Hansen et al., 2020a). The utility companies' primary motivation for testing Reality Capture is to raise the level of documentation quality of their as-built water pipes, in such a way that it can support work processes including quality assurance of as-built utilities, operation and maintenance tasks, and future planning of new construction projects. As of 2021, the two water utility companies have already 3D captured more than 3.500 excavation holes containing water pipes as well as other nearby subsurface infrastructure. This paper thusly investigates the experiences gathered by the utility companies, to develop the use and adoption of Reality Capture as an alternative surveying method for capturing subsurface utility documentation.

The contribution of this paper is divided into three parts. Firstly, in section 2, presenting the workflow behind the RC solution for generating and geolocating as-built point clouds of subsurface utility excavation holes as well as how the utility companies are using conventional surveying. Secondly, an evaluation of the geospatial accuracy of the point clouds generated from water pipes, whereas the methodology behind is presented in section 3. The results are then presented and discussed in section 4. Thirdly, the RC solution is evaluated in terms of usefulness focusing on which added value it facilitates compared to conventional surveying. This was done by conducting and analyzing semi-structured interviews, as described in section 3. Challenges and limitations identified in the RC solution and evaluations methods are furthermore described in section 5.

This contribution has been peer-reviewed.
https://doi.org/10.5194/isprs-archives-XLVI-4-W4-2021-25-2021

2. SURVEYING OF SUBSURFACE UTILITIES

This section presents a description of how the conventional surveying and the smartphone-based Reality Capture solution are used in two water utility companies for surveying and documenting as-built water pipes.

2.1 Conventional surveying

Water pipes are often placed in open excavations making them visible after installment. The utility companies, therefore, make sure to survey the water pipes when the excavation holes are still open, as it provides them with the the best opportunity to collect accurate information of their built assets.

Equipment used for conventional surveying includes GNSS real time kinematic (RTK) and a total station to measure points along the visible water pipes as shown in figure 1. These tools generate a trajectory of sparse geographically coordinated points, which are afterwards processed into digital vector lines representing the installed water pipes. Informative attribute values are also added to the vector lines, such as depth, thickness, material, time-of-installment, etc. The mapped and documented utility lines are then stored and managed in GIS. This is common survey practice for most water utility companies in Denmark, as well as other utility company types, dealing with gas, sewage, electricity, tele-com etc. whenever installed during open excavation.

Figure 1. Surveyor using conventional GNSS-RTK equipment to survey a newly placed water pipe.

The utility companies have their own requirement specifications for surveying of installed water pipes. In terms of horizontal and vertical accuracy, a tolerance of ±5 cm is acceptable. This is easily achievable with survey-grade GNSS-RTK equipment, as this equipment has an accuracy threshold of ±1.5 cm. The accuracy requirements set by the utility companies are also well within the new and forthcoming Danish nation-wide legislation describing accuracy requirements for exchange of utility information between utility owner and excavator (KEFM, 2019). The requirements are ±50 cm in both the horizontal and vertical direction and will be mandatory from medio 2023 for all utility owners surveying newly installed or repaired surface utilities in public areas. However, "soft" cables such as electricity and tele-com, are not obligated to document vertical information, having to only provide indicative depth documentation.

2.2 Smartphone-based Reality Capture

The smartphone-based Reality Capture (RC) solution used by the two water utility companies was originally co-developed under an innovation partnership between one of the water utility companies and their collaborating contractors and a surveying company. The purpose of the partnership was to co-innovate new work processes and solutions dealing with planning and constructions of underground water pipes. The surveying company within this partnership has further developed the RC solutions since its first prototype was developed two years ago and is now publicly available as a service called SmartSurvey[1]. The two utility companies which participated in the study, have prior to the public release tested the RC solution as an alternatively as-built 3D documentation method. The RC solution has not yet been fully adopted by the companies but has seen a gradually increase in use during the two-year test period.

At its core, the smartphone-based RC solution is a simple and easy-to-use smartphone app/service that is geared towards generating 3D as-built geolocated point clouds of subsurface utilities during open excavation. The RC solution is based on close-range photogrammetry using video recordings captured from a camera-equipped smartphone. Metashape by (Agisoft, 2021) is used for the photogrammetry process and is automatically handled on a server managed by the surveying company. Accurate Ground Control Point (GCP) markings must, however, be marked around the excavation hole and surveyed to geolocate the generated point clouds. A minimum of four GCP markings has currently been found to be sufficient by the developers of the system. It is, furthermore, important that the user in the field capture the markings within the view frame during the video recording to ensure that the geolocation process can be completed.

As part of the RC solution the point clouds are made accessible in a 3D web platform, called PointView[2], also developed by the surveying company. The 3D web platform uses Potree, a free open-source WebGL-based point cloud renderer (Schuetz, 2016), as its 3D rendering framework. A multi-window view setup of the 3D web platform is shown in figure 2, rendering a point cloud (left 3D view), which location is shown on a map (right 2D view).

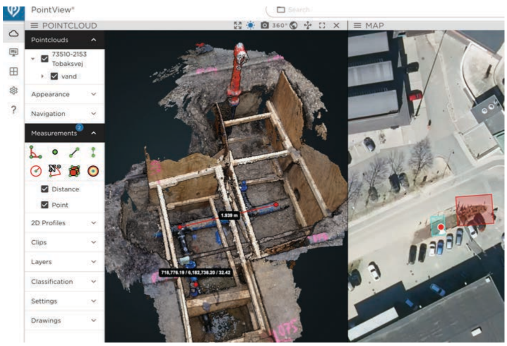

Figure 2. Point cloud model of as-built water pipes viewed in the 3D web platform.

The whole process from capturing to viewing point clouds follows a semi-automated workflow that is depicted in figure 3. It is noticeable that the user in the field i.e. utility owners or contractors only need to be equipped with a marker and a

[1] https://it34.com/en/services/smartsurvey-app-en/#le34

[2] https://it34.com/en/services/pointview-it34/#le34

This contribution has been peer-reviewed.
https://doi.org/10.5194/isprs-archives-XLVI-4-W4-2021-25-2021 | © Author(s) 2021. CC BY 4.0 License.

smartphone to complete their part of the RC process. The process includes three easy steps: (I) creating GCP markings around the excavation hole, for instance with a spray marker, (II) video recording the excavation hole from all angles by circling around while pointing towards the hole, and (III) uploading the video via the RC solution app. The captured image material is then sent to a server managed by the surveying company. After the first step is completed, a surveyor then needs to measure the coordinates of the GCP markings with GNSS-RTK equipment and upload it to the same server. It is noticeable that the surveying of GCP markings can be done without the presence of the user in the field as long as the user has left the markings untouched. This also means that the user, for instance the contractor, can proceed to fill in the excavation hole still leaving the markings untouched after the second step is completed i.e., the video recording.

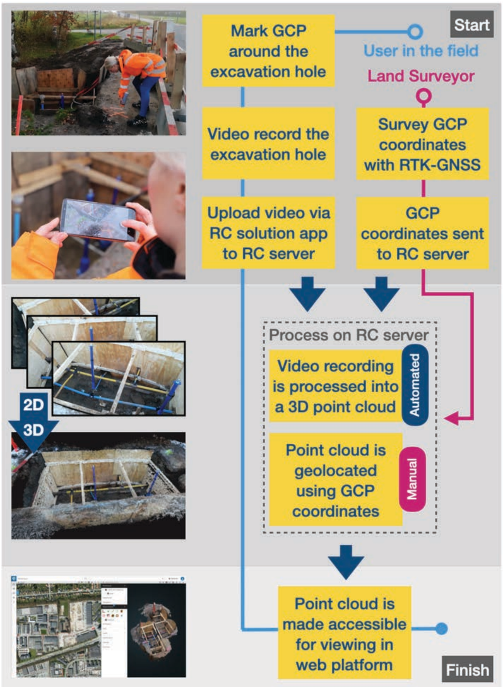

Figure 3. Process diagram of the RC solution

Using photogrammetry and GCP are well-known techniques to generate and geolocate 3D models and is not in itself a novel approach in the industry. However, combining these approaches in a complete, simple and easy-to-use solution designed for documentation of subsurface utilities that requires minimum equipment and actions from the user's perspective is what makes this solution unique.

3. METHODOLOGY

Evaluation of the smartphone-based Reality Capture (RC) solution was divided into two parts. Firstly, evaluating the geospatial accuracy of the generated point clouds and secondly, interviewing respondents regarding the usability of the RC solution.

3.1 Accuracy evaluation

A total of 41 point clouds were selected for an accuracy assessment, measuring the horizontal (XY) and vertical (Z) displacement in 52 Check Points (CPs). The point clouds where selected so it represented a variety of different sizes of excavations ranging from 1-20 m^2 in hole aera. CPs were marked onto the installed water pipes and surveyed with survey-grade GNSS-RTK equipment similar used in conventional surveying with an accuracy of ±1.5 cm. Most of the point clouds contained one CP with some of the larger excavation holes including up to 4 CPs. The CPs were identified in the point clouds, as shown in figure 4, and the extracted XYZ-coordinates were compared to the surveyed CP coordinates through calculating of an error distance represented as the Root Mean Square Error (RMSE). The horizontal ($RMSE_{XY}$) and the vertical ($RMSE_Z$) accuracy error measurement were calculated as shown in Eqn. 1 and Eqn. 2. The calculations were done following the guidelines of the Geospatial Positioning Accuracy Standard (FGDC, 1998) .

$$RMSE_{XY} = \sqrt{\frac{\sum_{i=1}^{n}\left[(X_{PC,i}-X_{GPS,i})^2+(Y_{PC,i}-Y_{GPS,i})^2\right]}{n}}, \quad (1)$$

$$RMSE_{Z} = \sqrt{\frac{\sum_{i=1}^{n}(Z_{PC,i}-Z_{GPS,i})^2}{n}}, \quad (2)$$

where $X_{PC,i}$, $Y_{PC,i}$, $Z_{PC,i}$ are the XYZ-coordinates of the ith Check Point (CP) in the point cloud dataset

$X_{GPS,i}$, $Y_{GPS,i}$, $Z_{GPS,i}$ are the XYZ-coordinates of the ith CP in the surveyed CP dataset

n is the number of CPs tested

Figure 4. Check Points (CPs) marked as white crosses, which coordinates has been identified in the point cloud.

3.2 Usability evaluation

Interviews were conducted in two sessions, with a total of four respondents participating. This included employees from the two utility companies and a single respondent from an excavation company.

Each of the respondents were chosen based on her/his involvement and experience using the RC solution. Information about the participating respondents is shown in Table 1. Respondents 1 and 2 participated in the first interview session and respondents 3 and 4 in the second.

No.	Company type	Role in company	Gender
1	Utility Company A	GIS team manager	Female
2	Utility Company A	Maintenance team manager	Male
3	Utility Company B	Senior project manager Geodata specialist	Male
4	Contractor (working for company B)	Excavation team manager	Male

Table 1. List of respondents participating in the interviews.

The semi-structured interviews were conducted, following the guidelines by Tangaard & Brinkmann (2015). Semi-structured interviews were utilised to provide the interviewer the ability to ask both pre-determined questions as well as potential follow-up questions that could occur during the interview session.

The interviews were sound-recorded and transcribed, in order to facilitate the analysis of the interview data. An initial reading of the transcribed data revealed re-occurring themes, which were then used to structure the main data-analysis. In all two main themes were identified: (I) surveying and excavation workflow and (II) added value of 3D point clouds.

4. RESULTS AND DISCUSSION

4.1 Accuracy evaluation

Out of the identified 41 point clouds, 52 check points (CPs) located on the installed water pipes were surveyed and compared to their corresponding CPs in the point clouds. The combined horizontal ($RMSE_{XY}$) and vertical ($RMSE_Z$) accuracy error measurement and standard deviation of the CPs are shown in table 2.

	Horizontal Error (XY) [cm]	Vertical Error (Z) [cm]
RMSE	3.04	3.26
St. Dev.	1.60	2.21

Table 2. Horizontal ($RMSE_{XY}$) and vertical ($RMSE_Z$) accuracy error measure and standard deviation calculated on 52 CPs.

It is important to note that the horizontal and vertical accuracy measurements of 3.04 ±1.60 cm and 3.26 ±2.21 cm mean error and standard deviation values, are within the accuracy threshold mandated by the two utility companies, set at ±5 cm. Looking at the upcoming Danish national accuracy requirements, it is also well within the accuracy requirements set at ±50 cm (KEFM, 2019).

The calculated horizontal (XY) and vertical (Z) accuracy errors are presented in a frequency histogram as shown in figure 5 and figure 6 respectively. Both calculated accuracy error datasets shown in the histograms shared similarities. Noticeably for both are that around 2/3 of the error measurements are within the 0-3 cm range. However, the vertical errors have two larger error outliers within the 8-12 cm error range, compared to the horizontal errors, which is the main reason for $RMSE_Z$ being higher than $RMSE_{XY}$. This is because the accuracy error is calculated by using RMSE, which penalizes large errors more compared to using for instance Mean Absolute Error (MAE) that equally weights all averaged error values. Furthermore, it can be assumed that factors contributing to a large RMS error is related to the accuracy and deviation of the physical measured XYZ coordinates in the (i) GCPs, (ii) CPs and (iii) in the selection of GCPs in the captured image material as well as selection of CPs in the point cloud. This is especially true for measuring Z-coordinates with GNSS-RTK equipment which are well-known to differ under challenging outdoor conditions. Moving forward it is clear, that eliminating those larger errors would help achieving an even more accurate level for the RC solution.

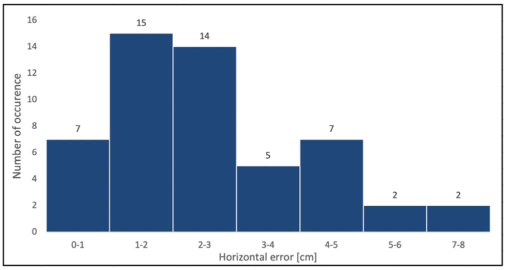

Figure 5. Frequency histogram of horizontal (XY) accuracy error measurements.

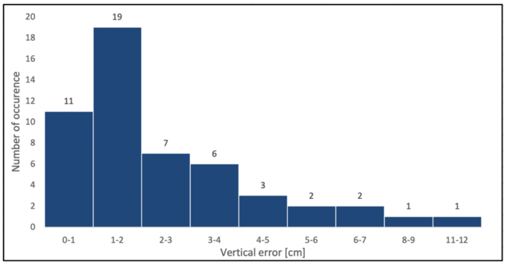

Figure 6. Frequency histogram of vertical (Z) accuracy error measurements in absolute values.

4.2 Usability evaluation

Results from the semi-structured interviews evaluating the usability of the RC solution are divided by two themes, (I) surveying and excavation workflow and (II) added value of 3D point clouds.

Generally, when questioning the utility companies during the interviews the conversation naturally gravitated towards comparing the RC solution with conventional surveying. Thus, the following presented results and discussions of the interview data will reflect this.

4.2.1 Surveying and excavation workflow: Some of the respondents noted that the RC solution enabled an improved workflow for the digging contractor by removing most of the waiting time for a scheduled surveyor to survey the exposed as-built utilities and thus resulting in time savings for the entire construction project. This was especially pointed out by respondent 2, 3 and 4. Respondent 4 further elaborated from an excavator's perspective, that being able to finish and move onto the next digging site is a huge benefit and something generally new the RC solution offers compared to how a traditional digging and pipe instalment job is carried out. Often contractors need to return to the dig site the following day as a surveyor is rarely available at the time as when the water pipe instalment is ready for surveying.

However, for this improved workflow to function, respondent 4, who has carried out most of the GCP markings and video recordings for utility company B, noted that placing the GCP markings need careful consideration, as they must stay untouched and visible after filling up the excavation hole. This is something that can be considered as a new practice the RC user needs to learn. An example of badly placed GCP marking is shown in figure 7, where a GCP is marked on an iron plate, which would likely be moved during the excavation hole closing process.

Figure 7. Point cloud capture of an excavation hole containing as-built water pipes (blue pipe in bottom) with other types of utilities crossing over.

In discussions about how to improve the workflow further, all respondents mentioned wanting to survey the GCP markings on their own, or give the task to the contractor, to eliminate the need of a land surveyor in the field. It was also discussed if the geolocation process done by measuring GCP markings could be replaced by GPS data retrieved from the same smartphones used for video recording. It was, nonetheless, made clear by respondent 3, that this would, at best, result in a 1-5 m accurate point cloud, which would not be sufficient for documentation purposes. Respondent 1, 2 and 3 however, noted that based on their current needs, the point clouds generated by the RC solution had a satisfying accuracy level. Thus, underscoring that geographic accuracy is key with respect to the generated point clouds as it is the only way to compare it with other geospatial data.

Respondent 3 also brought up the idea of integrating a high-accuracy GNSS-RTK antenna on the smartphone used for the RC solution to do the geolocation process automatically. Thus, entirely skipping the GCP marking and surveying process. This solution was also explored by Geosystems France[3]. However, the overall opinion from the respondents was that they appreciate the simple approach and minimum equipment needed for the RC solution. Even though a more advance setup could potentially be more efficient it might also become more complex, and more equipment dependent. As the setup is now, needing only a smartphone and a spray marker, it is an easy and simple approach that is very accessible and usable in the field.

4.2.2 Added value of 3D point clouds: The interviews showed that the point clouds benefited the utility companies in a wide range of usages. Respondent 1 described the GIS team's current testing of using the generated point clouds as an input source for creating vector lines of installed water pipes in their GIS utility management system. Having the visual-realistic point clouds available in the 3D web platform furthermore helped to complete the registration process as certain attributes values, like component type, can easier be identified.

Respondent 2 noted that point clouds could be used as an excellent tool for quality assurance of the agreed as-built instalments. With respect to the same type of inspection process, respondent 2 also mentioned that the point clouds could be used as documentation to prove that other types of closely located utilities (as seen in figure 7) have not been damaged during the excavation and instalment work.

Another usage, expected by the respondents are for future utility projects planned on the same location, where previously captured point clouds are available. They expect that the visual-realistic view of underground infrastructure will make the design and planning process more efficient. It is, furthermore, beneficial on locations where installed water pipes are crossing under other types of utilities (as shown in figure 7), because by the respondent's experience, other utility map records, often lack accuracy and completeness. It was further noted, that this is especially true for "soft" cables such as electricity and tele-com, which is coherent with research by Hansen et al. (2020b).The research, furthermore, showed that using Augmented Reality for visualising as-built point cloud models in the field would be a valuable tool for utility work planning, in order to potentially prevent damage of subsurface utilities during excavation.

On the same note, the respondents also hoped, that other utility owners will start to capture their excavation holes and then exchange 3D capture data with each other. This is an interesting observation, as the continued use of the RC solution or similar solutions could potentially serve as an as-is documentation source for the entire body of underground utility networks, delivering high spatial accuracy and completeness. This falls in line with the Singapore study (Van Son et al., 2019) which suggested that every open excavation is an opportunity to update existing utility records instead of solely relaying on GPR methods. However, the idea of exchanging 3D capture data in Denmark has some challenges. Firstly, other utility owners must start using 3D capturing solutions and secondly that there are no common platform or programme pushed by the Danish geospatial authority that supports or incentivises exchange of such 3D capture data or 3D GIS data in general. Currently the Danish utility information exchange model is undergoing an implementation to use a newly developed GML-based utility data model, which will only support regular 2D GIS data (KEFM, 2019).

5. CHALLENGES AND LIMITATIONS

During the testing and evaluation of the RC solution some challenges and limitations were observed. These are presented below and will serve as future work to further developing and researching the RC solution.

5.1 Challenges

Documenting large and deep excavation holes. Excavation holes for water pipe instalments and repairments are often small compared to holes excavated for sewage projects. General dimension for water pipe excavations is ranging from 1-20 m^2 in area and a depth of 1 m. On sewage projects the excavation area is often considerably larger and deeper, sometimes including an entire road section, thus making 3D capturing challenging as

[3] https://f3d.geosystems.fr

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more GCP markings are needed as well as more area to video record at a greater distance.

Messy and incomplete generated point clouds. A final aspect challenging the RC solution is that the responsibility of capturing image material is given to the users in the field instead of surveying professionals that has expertise in photogrammetry. Even though this challenge is accommodated through illustrative guides and an instant calculated blur and error factor to filter poorly captured video material out, this sometimes has consequences, as shown in figure 8, in which the water pipe appears incomplete and messy. Poorly generated point clouds are likely caused by random and shaking camera movement or lack of angle range capturing the water pipe. In some circumstances, the RC user was met with challenging terrain conditions making it difficult to walk around the excavation hole whilst video recording.

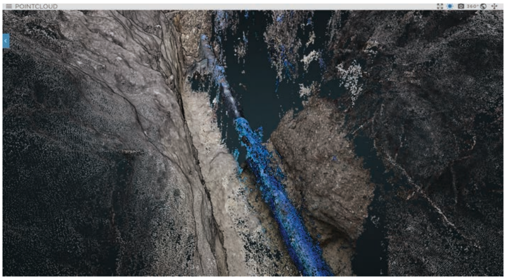

Figure 8. Incomplete and messy point cloud of a water pipe.

5.2 Limitations

The accuracy evaluation does include a lot of parameters such as the selected point clouds for testing has different amounts of GCPs and different sizing in excavation hole area ranging from 1-20 m^2. A different accuracy testing design is further needed to evaluate the accuracy impact of the numbers of GCP necessary as well as the impact of distance from GCP (located around the dig hole) to CP (located on the water pipes). Thus, resulting in a more wholesome accuracy testing of the RC solution.

The interview data, used to evaluate the usability of the RC solutions was only collected from two of Denmark's largest water utility companies. The study would have benefited from interviewing other utility companies using RC to achieve a better understanding of how point cloud-based capture methods are utilised across smaller-sized utility companies as well as utility companies managing other types of utilities. The generalisability of the study is additionally limited by the small number of respondents.

6. CONCLUSION

This paper presents a smartphone-based Reality Capture (RC) solution geared towards documenting subsurface utilities in open excavation holes. Through semi-interviews with respondents from companies having utilized RC for two years, it was revealed that the RC solution has an easy and simple workflow and a low equipment dependency, which makes the solution very accessible in the field. The interviews showed that benefits such as, better quality assurance of as-built work and a better-informed decision-making process when planning new excavation work at the same location, can be achieved using the solution.

To compare the accuracy levels of the RC solution with conventional surveying methods, an accuracy assessment was carried out on 52 check points marked on the captured water pipes. It showed a horizontal and vertical accuracy of 3.04 ±1.60 cm and 3.26 ±2.21 cm mean error and standard deviation values, respectively. Which conservatively speaking, can be estimated to an overall accuracy of ±5 cm. Noticeably, this was within the accuracy requirements of ±5 cm, set by the utility companies and therefore acceptable. It was additionally well within the future accuracy threshold of ±50 cm, soon to be implemented in the Danish construction industry.

Overall, the RC solution was concluded as a useful surveying method, which captures unique and comprehensible 3D documentation of as-built utility assets, compared to a traditional outcome of conventional surveying. The evaluation of this study finally showed that the use of RC is feasible solution, which was also reflected through the continued use of the RC solution by the utility companies.

Looking forward, one clear advantage of the RC solution is that it automatically captures other exposed utilities within the same excavation hole. The collected 3D capture data, has the potential to serve as an as-is data source update to reconciliate legacy utility information which is known to lack spatial accuracy and completeness. An investigation on how to approach this is further needed, as the Danish utility data exchange model does not support 3D capture data.

DISCLAIMER

The authors would like to disclose a possible conflict of interest as the second author is also shareholder in the commercialization of the RC solution presented in this paper. We do however not believe that the results have been affected by this.

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Supplementary material about the error measurements from the accuracy evaluation can be found in Appendix B as well as the mentioned illustrative guide describing how the Reality Capture user should properly video record the utility asset of interest.

2.2 Additional discussion

A noticeable insight found in the paper, was that using the Reality Capture (RC) solutions to 3D capture as-built subsurface utilities provided a data source that was radically different compared to data sources outputted from conventional surveying methods. The primary data source outputted from the RC solution, i.e. colored dense 3D point clouds, is a realistic looking visual representation as it literally can be interpreted as a “3D picture”. On the other hand, the primary data source from conventional surveying, which is typically a sparse point trajectory transformed into a vector line, is a quite abstract visual representation in comparison to the realistic looking point clouds.

Another noticeable insight was that the utility companies have captured more than 3,500 point clouds during the two years they have tested the RC solution and continue to use it. In some areas, this have accumulated to a lot of point clouds as for instance shown in figure 2.1. Therefore, if the trend of using Reality Capture for surveying as-built utilities among other utility owners becomes more common, we can expect that 3D capture data as a subsurface utility data source will be more accessible. Looking outside of Denmark, the trend of using RC technology to capture as-built subsurface utilities is also emerging in other countries such as France, Canada, and the UK (Zeiss & Shinoaki, 2020).

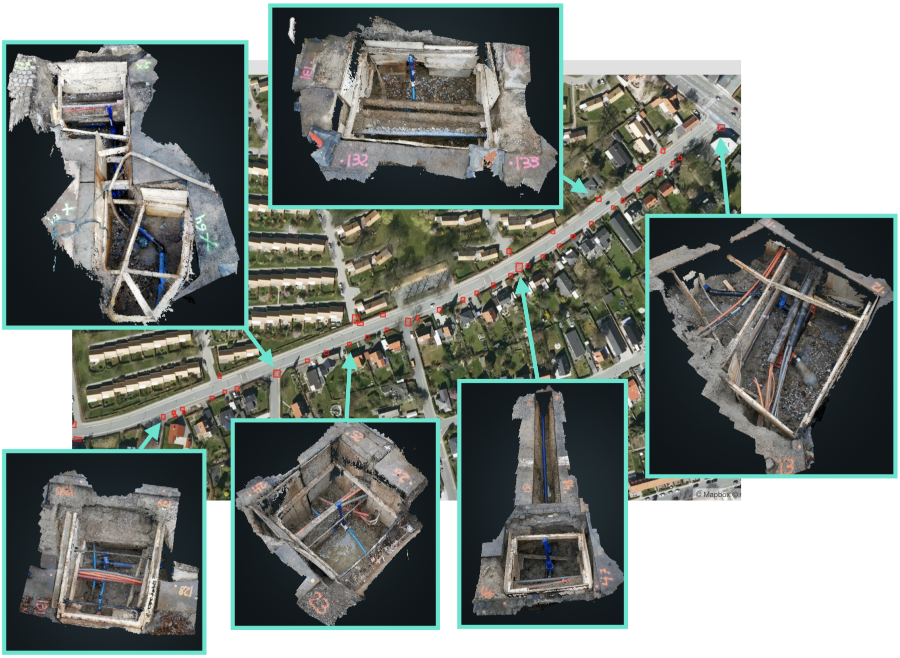

Fig. 2.1: Map overview of an area showing locations (red rectangles) of 3D point clouds of as-built utilities

Moving forward with this thesis's research agenda, which included the exploration and development of new AR visualization methods of subsurface utility information, the two mentioned noticeable insights were of direct impact. The reasons were that (i) it recognized 3D capture data of subsurface utilities as an emerging and available data source in at least some organizations and (ii) the 3D capture data was a far more visually comprehensible representation than traditional GIS-based utility record data. For those reasons an opportunity emerged to visualize these as-built 3D capture models in Augmented Reality, which will be investigated in the next chapter.

Chapter 3

Augmented Reality for Subsurface Utility Engineering

This chapter covers the main contribution of this thesis. It elaborates on how the development and design process of the AR visualizations methods were developed. The interview results from the AR visualizations methods are presented providing insights into how this can lead to value-creation and informed decision-making for utility owners and contractors managing underground infrastructure projects. Insights not directly linked to the AR visualizations including current work practice, excavation damage, data quality requirements, etc. are also presented.

3.1 Exploring as-built 3D capture data in Augmented Reality

The chapter begins directly as a reaction to the opportunity presented in the follow up discussion from Paper I. Here the opportunity to visualize the as-built 3D capture data in AR presented itself and will be explored in Paper II. Before introducing Paper II, let us just elaborate on why this opportunity was interesting to explore. It can be divided into three main reasons.

Firstly, we can achieve better depth perception compared to carelessly rendering 3D model data in AR. One of the most popular ways to mitigate the depth perception issue is by using the cut-away visualization method, also called *virtual excavation* by Schall et al. (2009) and was the first to use it for subsurface utility lines represented as 3D tubes (See figure 1.3 in chapter 1).

The use of the as-built 3D capture data is interesting as the 3D point cloud model naturally forms a virtual excavation, thereby removes the need to generate an artificially cut-away hole around the subsurface utility lines. It can therefore be assumed that the 3D point cloud models, if they are positioned and orientated correctly in AR, will lead to great depth perception.

Secondly, we can use it as an approach to help prevent utility damage during planning and excavation of underground infrastructure projects. Many studies (Al-Bayati & Panzer, 2019; Makana, Metje, Jefferson, Sackey, & Rogers, 2018; S. Talmaki & Kamat, 2014; Zeiss & Shinoaki, 2020) points towards inaccurate and incomplete utility records as the main cause of excavation damage. Furthermore, S. Talmaki and Kamat (2014) and Al-Bayati and Panzer (2019) specified that missing depth information is the main issues. The as-built 3D capture data are geometrically detailed and highly accurate down to ±5 cm and thereby also includes accurate depth information of the utility lines. The assumption is then that visualizing 3D capture data in AR will potentially prevent excavation damage if made available for planners and excavators in the field. The condition is of course that 3D capture data are available for the given project location.

Thirdly, no literature was found that had tried to visualize subsurface utility 3D capture data in AR nor evaluated it on users. Previously, literature on AR for underground infrastructure had only focused on visualizing GIS or CAD data (A. Fenais, Ariaratnam, Ayer, & Smilovsky, 2019; Schall et al., 2008; Stylianidis et al., 2016; S. A. Talmaki et al., 2010; Zhang, Han, Hao, & Lv, 2016; Zollmann et al., 2014). Likewise, a similar focus on 3D data sourced from GIS or CAD was found in commercial AR systems, like vGIS or Trimble SiteVision. This called for a demonstration and evaluation on industry end-users to explore the use of visualizing 3D capture data in AR.

3.2 Paper II: Combining Reality Capture and Augmented Reality to Visualise Subsurface Utilities in the Field

The following paper, referenced as Paper II, is titled: *Combining Reality Capture and Augmented Reality to Visualise Subsurface Utilities in the Field.* The paper has been published in *Proceedings of the 37th ISARC, 2020.* as an open access paper under the *ISARC 2020 Copyright Transfer Agreement*. The reader is encouraged to watch this video[1] of the AR visualization in action. The video was recorded with the version 1 AR prototype system.

[1] `https://youtu.be/joJek6BwaV0`

Combining Reality Capture and Augmented Reality to Visualise Subsurface Utilities in the Field

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Abstract -

In this paper, Reality Capture technologies are used to reconstruct 3D models of utility excavation holes which can later be visualised in the field, allowing for a more reliable, comprehensive and perceptible documentation and viewing of utilities before excavating to potentially reduce subsurface utility damages. An Augmented Reality (AR) prototype solution was developed and demonstrated for a group of respondents, concluding that visualising reality capturing models in AR would benefit fieldwork before, during and after excavation.

Keywords -

Augmented Reality; Reality Capture; Point Clouds; Underground Infrastructure; Subsurface utilities; Damage Prevention; Utility strike;

1 Introduction

Most streets in industrial countries are filled with hidden infrastructure beneath ground creating risk of striking underground utilities during excavation work. In the UK the direct cost is estimated at £3600 per utility strike which led to a total cost of approx. £7 Million in 2017-2018 [1]. However, this does not take the indirect cost of strike damages into account, which include project overrun, downtime and social cost such as traffic delays and loss of productivity in businesses. By adding these indirect costs the total cost is significantly higher and has an estimated average ratio between direct and indirect cost of 1:29 [2], thereby increasing cost of each utility strike to approx. £100,000. Similarly, in Denmark it is estimated that the Danish society has lost 2.8 billion DKK over a 10-year period due to underground utilities being damage during excavating [3]. Clearly there is a need for new tools and work processes, preventing underground utility damage.

Poor documentation in terms of quality, accuracy, and access to utility data is often the cause of utility strikes [4] [3]. In best case scenarios utility data is documented in GIS as straight poly-lines with attributes such as elevation and thickness, allowing qualified estimation of where utilities are located. In worst case scenarios the documentation is missing, incomplete or out-of-date and often represent as-planned data instead of as-built data [5]. This form of documentation is, therefore, more a schematic representation of where the utility is placed rather than a representation of its accurate shape where twists and turns can occur along the path [6]. As a consequence, issues often arise when trying to locate utilities before and during excavation. In Al-Bayati and Panzer's survey, (2019) [5], completed by 477 contractors, the most contributing cause for hitting underground utilities was a) the lack of depth information, b) painted markings placed to far from the utilities either because of inaccurate data or the surveyor being rushed or untrained, and c) the temporary state of the marking, i.e. the marking disappears when the top-layer surface is removed or is washed away by weathering. Locating equipment to measure the depth of utilities is, nonetheless available, such as Ground Penetrating Radar, which is often rejected because of the added cost for the utility owner and the limited benefits it provides [5]. Using locating equipment and following good-practice Subsurface Utility Engineering (SUE) is another solution that can be applied to prevent utility strikes [7], it can, however, be very expensive and time consuming. Often this solution does not harmonize with the contractor and utility owner being on a tight schedule and budget [5]. It is clear that more complete and accurate utility data are needed in today's construction industry and also, if not just as important, a more reliable way to display utility information before and during excavation work.

In this paper we showcase a potential solution to reduce utility damage that combines two emerging technologies to deliver a more informed, comprehensible and perceptible visualisation for utility professionals by combining Augmented Reality and Reality Capture. The aim is to visualise point cloud models of previous captured utility excavation holes informing the next person in the field to come.

1.1 AR visualisation of underground infrastructure

One popular solution used to display underground utility information in the field is Augmented Reality (AR). The method was first demonstrated by Roberts et al. (2002) [8] who visualised a 2D projection of underground utility lines on the surface area. The AR prototype was a rather clumsy setup, compared with today's standards, consisting of a backpack powering a wired and handheld binocular-formed viewing device. Later Schall et al. (2009) [9] improved the concept with a smaller handheld device resembling nowadays handheld mobile devices in form factor. Besides visualising utility lines on the surface the handheld device could generate a geospatial 3D model from GIS utility data and display it at a given elevation value. To aid the users depth perception of the underground placed 3D model, the AR system used a cut-away visualisation technique resembling a virtual excavation. The 3D model was then only visible inside the virtual excavation cut-away volume. According to the authors in later studies this visualisation technique as well as the ability to change between other "x-ray" visualisation techniques, like Ghosting [10] and Shadow Projecting onto the surface, was very useful [11]. The studies further recommended to use comprehensible visualisation techniques to avoid depth perception issues instead of having the user trying to imagining the depth distance between utility pipe and surface [12]. A user study done by Eren Balcisoy (2018) [13] evaluated the vertical depth judgement performance on different x-ray visualisation techniques. It showed that users were performing better in estimating depth of 3D pipelines when using a cut-away excavation box technique compared to a careless overlay and edge-based ghosting technique. A survey by Ortega et al. (2019) [14] similarly showed that the virtual cut-away excavation technique also performed best when compared to other visualisation techniques for viewing of underground infrastructure in virtual environments.

As previously mentioned, other scientific work has primarily focused on visualising 2D GIS data superimposed to the surface or 3D models generated from the existing GIS data and occasionally as-planned 3D models. The latter being more common for large infrastructure projects, such as highway projects [15]. However, not much focus has been directed at using 3D models generated from Reality Capture. In fact to the best of our knowledge this has not before been attempted as a way of visualising underground utility information in the field.

1.2 Documentation of utility assets with Reality Capture

Reality capture is a technology that is used in a wide range of industries and is often used by surveyors to 3D scan constructions such as cultural heritage sites [16], bridges [17] and underground utilities [18].

One popular Reality Capture technique is Close-range Photogrammetry because of the widely available hardware in form of mobile cameras in smartphones and amateur drones as well as a wide range of reliable software. The 3D data output of Reality Capture is most often represented as either point clouds or 3D textured meshes. In this paper we use dense point clouds of underground utilities as our reality capturing data. The point clouds are provided by a Danish utility company and originates from an on-going pilot test made in cooperation with another Danish surveying company to use their Reality Capture technology for documenting underground utilities [19]. Using a smartphone app, workers in the field video-recorded the exposed utilities located in the excavation holes. A dense point cloud was then generated using close-range photogrammetry of the captured video recording. The point clouds were also geo-referenced, ensuring that location and scale were aligned with the existing surroundings. The point clouds serves as improved documentation and can be revisited by the utility company if needed in future activities. The interface view of how point clouds are managed by the utility company is shown in figure 1.

In this paper the mentioned Danish utility company provided access to point clouds from a water distribution renovation project from 2019, in which 14 utility excavations were captured and documented with Reality Capture.

1.3 Research goals

This paper is a preliminary attempt to utilise Augmented Reality as a planning tool allowing both surveyors, inspection engineers and contractors to attain a perceptible visualisations of where utilities are located below ground, based on documentation of previous excavations registered using Reality Capture.

The research presented in this paper consist of the development of an AR prototype and a showcase session for the utility owners and the surveying company, participating in the study. The study demonstrate how captured point clouds can be visualised to inform workers in the field before a new utility excavation project is carried out in the area of a previously captured location.

The aim is to highlight the usefulness of visualising point cloud captures in AR for field workers to prevent damage when excavating as well as assist in other general asset managing tasks in the utility industry. Using Reality Capture in combination with AR has yet to be studied in-depth with regards to obtaining better interaction and visualisations techniques for underground infrastructure in this study.

This paper additionally presents incentives for utility companies to document utility assets with Reality Capture technologies as well as share these 3D captures with other utility owners in the industry.

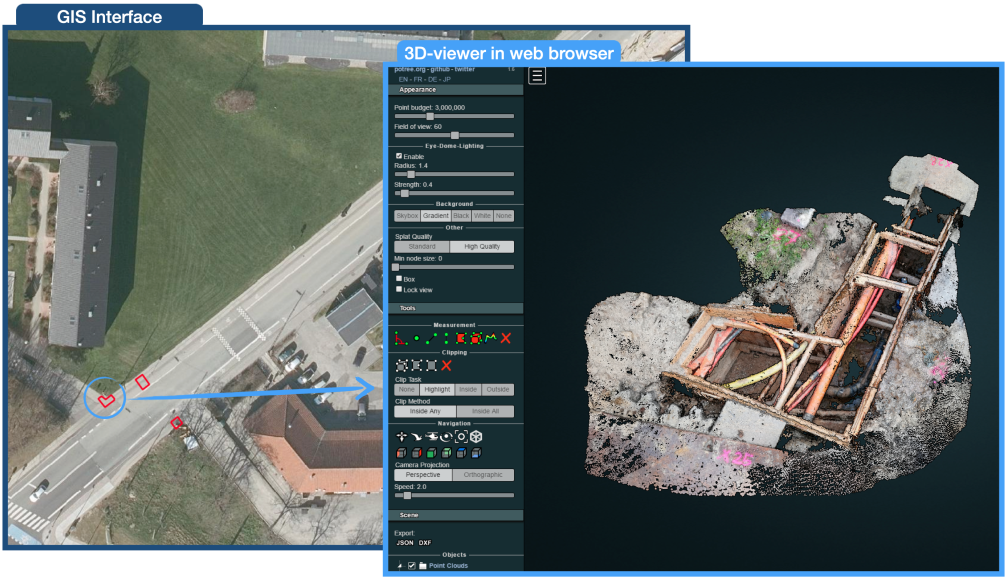

Figure 1. Right: Polygons boundaries in a GIS interface indicating the location of utility excavation point clouds. Left: A dense point cloud capture of an utility excavation displayed in an interactive 3D web-viewer using Potree

2 Methodology

2.1 Empirical method

Empirical data was acquired through a series of informal interviews with stakeholders from the utility industry over the span of six months.

Interviews were conducted in two parts. The first part included phone-calls with two stakeholders to attain background information with respect to current practises and experiences with excavation, strike-damages and planning of underground utility work. The second interview partly consisted of a demonstration of the AR prototype developed as part of this research, and partly of an informal group interview evaluating said AR prototype demonstration. The participating respondents were all employees in the already mentioned utility company and surveying company. In all, seven respondents participated, five male and two female with various years of experience in the utility industry.

Empirical data acquisition was based on semi-structured interviews, as described by Brinkman and Tangaard (2015) [20], documented through sound-recordings. A selection of predefined questions were directed to the respondents guiding the interview session whilst follow-up questions were added to the discussion by the interviewer in reaction to the comments given by the respondents, allowing elaboration on comments as well as getting spontaneously occurring questions relevant to the prototype demonstration answered. The questions guiding the interviews were divided into two categories, 1) AR for informed decision-making in the field and 2) AR to prevent utility excavation damage.

Data collected in the interview-session additionally include comments from the respondents from conversations happening during the demonstration of the AR prototype. After empirical data were collected it was analysed and structured through a brainstorming process harmonizing the interview-data gathered with the scope of this paper.

2.2 Prototype development

The AR prototype was developed using Unity3D and ARKit as AR framework running on a 2nd Gen. 12,9" iPad Pro. The dense point cloud models of the utility excavations were managed using Potree created by Schuetz (2016) [21]. By leveraging the octree structure implemented in Potree the rendering process was made efficient to visualise the relative large point clouds (avg. 1-2 million points), for the prototype hardware to handle with a satisfying frame-rate while shown in the AR view. The implementation of Potree in Unity3D was made possible by using a Unity-package developed by Fraiss (2017) [22].

Prior to the demonstration of the prototype tool, markers

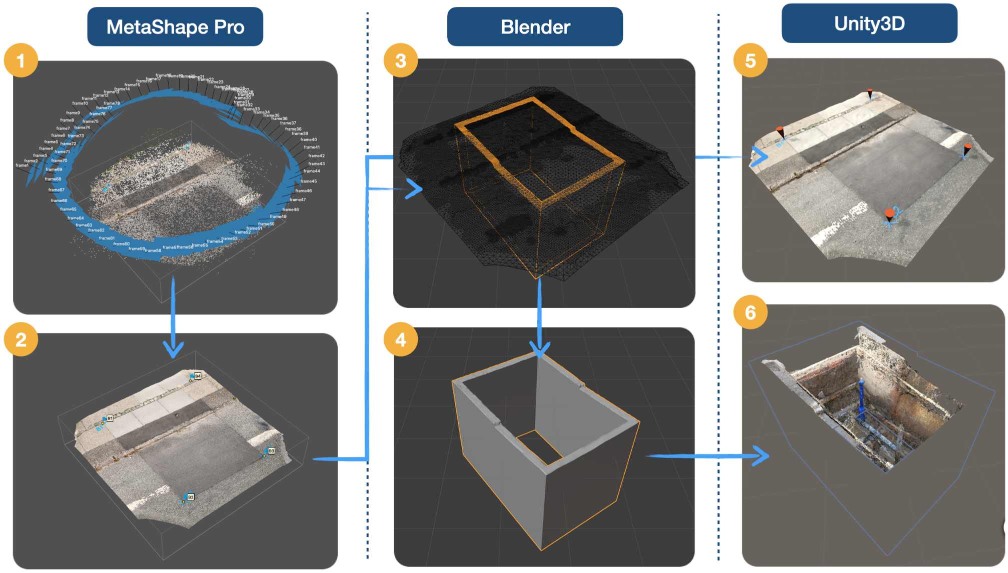

Figure 2. The overall workflow for creating occlusion box

was painted around the ground surface of the previously reality captured utility excavations. By video recording the surface area and surveying the painted markers on the test-site a 3D mesh was generated by using close-range photogrammetry in Metashape Pro. This process is illustrated in figure 2 in step 1 and 2. The surface mesh was aligned with its corresponding utility excavation point cloud. This was done for two reasons.

Firstly, to create an occlusion box around the utility excavation point cloud to keep the illusion of how a physical utility excavation hole would look, i.e. it is not possible to see the outer sidewalls of the excavation as the ground surface occludes it. This was done by modelling a box-shaped 3D model around the utility excavation point cloud using Blender as illustrated in step 3 and 4 in figure 2. The 3D model box was then imported to Unity3D and an occlusion shader was applied as illustrated in the last steps (5 and 6) in figure 2.

Secondly, to manually positioning and orientating the utility excavation point clouds at the correct geo-position in AR. By manually place the point clouds on top of the known markers by utilising ARKits horizontal plane detection and model-free tracking capabilities a stable and robust Six Degrees of Freedom (6DoF) tracking was achieved. This approach was used to obtain a simple and yet reliable AR geo-positioning and tracking solution, satisfying for demonstration purposes.

3 Results

The seven employees from the Utility Company (UC) and the Surveying Company (SC) participating in the demonstration as respondents were given a hands-on demonstration of the AR prototype, as seen in figure 3, before the semi-structured interview was conducted. The participant's roles in the company were primarily team leaders and department managers, all responsible for people with field work, such as planning, inspection and management on site as well as collaborating with contractors responsible for excavation.

In the following section the results from the demonstration and interview are presented, following the structure of the questioning categories presented in section 2. An important aspect to have in mind is that the use of Reality Capture for documentation of utility assets is, a new work process for the UC, as mentioned in section 1, and therefore they are still exploring what value-creation Reality Capture can add to their work routines.

To start the interview the UC first described what current value-gain they have achieved from using Reality Capture. Besides being an additional form of documentation that can be accessed through GIS, as seen in figure 1, the UC also use the point clouds to quality inspect the utility installation work done by the contractors. At the moment only larger water distribution construction projects are documented with Reality Capture, but the UC is confident that

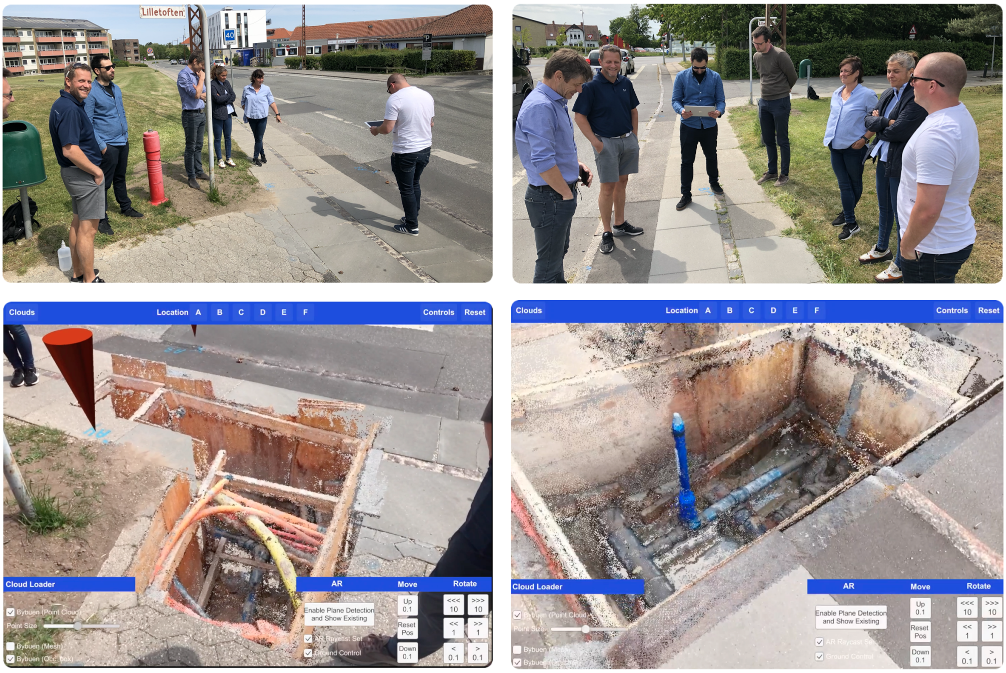

Figure 3. AR prototype in use during the hands-on demonstration seen from AR device view (bottom) and 3rd-person view (top).

it is to be utilised in other types of excavation projects, such as district heating, waste and storm water, in the future. Looking further ahead they believe these point clouds can be useful in the planning phase of new excavation projects near locations of previously reality captured utility assets. In fact, this was one the reasons why the UC was interested to see what their 3D point cloud models would look like when visualised in the field using AR.

3.1 AR for informed decision-making in the field

None of the respondents from the UC has experience working with AR solutions for displaying GIS data to aid fieldwork. The SC, however, is a seller of professional industry AR solutions (currently AugView and Trimble SiteVision) but has not seen Reality Capture 3D models visualised with these systems.

The respondents were asked to discuss what kind of value-creation it would add to their work routines based on their hands-on experience with the AR prototype. All respondents agreed that the ability to view the point cloud models in AR during fieldwork would greatly help planning and coordination with other professionals and non-professionals e.g. in communicating with citizens. The most impressive aspect for the respondents was how perceptibly and comprehensible the virtual utility excavation was visualised in the AR prototype, making it suitable for communicating technical details. For example, to help visualise where a water supply utility is located in relation to cadastre boundary for a house-owner. Another example, could be in case of a water leakage. In such case the UC might have a rough estimation of where the leakage is located based on sensor data. However, entering the field with the ability to look through the surface and see the underground utility pipes with high visual detail, and in context with the physical surroundings, might lead to a faster localisation of the leakage. Ultimately the respondents felt motivated to include the AR prototype in their fieldwork as they agreed it would support a more informed decision-making.

During and after the demonstration the respondents from the UC got so inspired when interacting with the AR prototype that they started to suggest new functionalities. The most requested functionality was distance measuring in the two primary directions: 1) vertical depth from utility to surface level and 2) horizontal distance from utility pipe snapping to horizontal road cross-section features such as center line, drive lane, curbs, bicycle-path, sidewalk, shoulder and road boundary limit. They also would like to have their own 2D GIS utility data visible together with the utility excavation point cloud. When asked about visualising 2D GIS utility data from other utility owners like tele-com and power, they where more hesitant.

3.2 AR to prevent utility excavation damage

When asked if the demonstrated AR prototype could help prevent utility damage during excavation work, all respondents agreed that it would be helpful for the contractor. Again, the main reason is the ability for the contractor to get a perceptible view of what underground utility assets are hidden beneath the surface. This information can then easily be understood by the contractor to plan the digging activity before breaking ground, and reassess during excavation. A particular useful scenario is when multiple underground utilities are buried in the same place, as shown in the utility excavation seen in the bottom left picture in figure 3. In the utility excavation, the flexible and smaller orange and yellow cables are clearly visible, even though the purpose of Reality Capture was only to document the blue water supply pipe laying below. When experiences with utility damages occurring during excavation work was discussed further the respondents agreed that the main cause for utility damages are inaccurate and out-of-date utility data - especially data from tele-com companies. Technical drawings of tele-com cables are often only schematic representation. This can lead to a lot of guesswork for the contractor, when locations of underground cables on the drawings does not correspond to locations in reality. The presented AR prototype solution has great potential to reduce utility strikes, however, as commented by the respondents, this is only useful if previous captured point clouds located beneath or close around the excavation site exist and can be accessed.

4 Discussion

4.1 Reality Capture and AR to incentivise data sharing

The presented AR solution in this paper uses point cloud models of previous reality captured utility excavation to deliver a more informed, comprehensible and perceptible visualisation for utility professionals in the field. Using Reality Capture models as the only data source of visualisation, however, creates the obvious limitation, that the coverage is only as adequate as the number of utility excavations which have been excavated, reality captured and transferred into the AR device. Even though this approach has a weakness in terms of coverage area, it ensures that only accurate utility information is presented for the user. Compared to other AR solutions that use traditionally 2D GIS utility data which are prone to be inaccurate as told by the respondents and others [5]. One could argue that the approach, presented in this paper, is actually a strength by only visualising utility information that are accurate and thus trustworthy for the professionals in the field. Nevertheless, it is clear that the more point clouds the UC can capture, the more relevant the AR solution will become, as the likelihood of revisiting a previous reality captured location increases.

In the future the UC hopes that its neighbouring utility owners will also begin documenting utility assets with Reality Capture. This, they hope, will lead to data sharing between them, which they can all leverage from. For example it is clearly visible from figure 3 that other types of utilities are present in the excavated hole. It is certainly possible that other utility owners have plans to revisit these utilities before the utility owner that originally captured it. It seams only logical to share Reality Capture models. This type of sharing is already a known practice in Denmark as it is mandatory to ask for underground utility information before a contractor starts excavating. However, the utility data is at best only regular 2D GIS utility data and is prone to be inaccurate for some utility types. When documenting utility assets with Reality Capture it automatically documents other utilities appearing in the excavation. This could lead to updating out-of-date data of utilities and cables, benefiting the next contractor to excavate at a previously captured location. Especially if the contractor is able to visualise these virtual utility excavations in the field as demonstrated in the AR prototype presented in this paper. Such sharing of utility data through an AR platform has been proven as an attractive solution for utility owners to engage in as demonstrated by Fenais et al. (2019), although the AR platform was only using regular 2D GIS utility data [23].

4.2 Visualisation of Reality Capture models in AR

The AR prototype used dense point cloud models of utility excavations provided from the utility company. The reason was to demonstrate for the utility company what is possible to visualise in AR with data they already possess. However, that is not to say the point clouds were the optimal Reality Capture model datatype to visualise in AR. In fact it might be more suitable to use 3D textured mesh representations. One of the benefits 3D meshes is that it consist of triangulated faces and therefor occludes the surrounding background when viewed in AR. Contrary, when using point clouds it is possible to see-through where the points are not dense enough which can sometimes break the illusion of AR. In either case, it is interesting to have both point clouds and 3D meshes being optimized for AR visualisation to be suitable for as many Reality Capture techniques as possible.

5 Conclusion

The aim of this paper was to identify potential value-creation using Reality Capture models of utility excavations, visualised in Augmented Reality for utility professionals in the field. Based on the responses collected in a prototype demonstration and interviews with respondents from a Utility Company and a Surveying Company, it is possible to conclude that visualising Reality Capture models in AR can be useful for field workers for planning of subsurface work, and also during excavations. All participating respondents, furthermore, noted that they wanted to implement a finished version of the prototype-tool demonstrated in this study, in the future.

Many of the respondents had not previously tried AR in an outdoor professional context and was quite overwhelmed with how much sense and value it added. Although visualising Reality Capture models in AR was concluded useful the respondents further noted that more interaction features in the AR prototype, with respect to specific fieldwork tasks and needs. Future work will investigating and develop prototypes to study what value-creation such interaction features can facilitate for utility construction professionals in planning and executing excavation work.

6 Disclaimer

The interview results presented in this paper was collected with participation of the surveying company that provided point cloud models of the utility excavations to the utility company using the survey company's own developed Reality Capture app. The solution and the conclusion of advocating the use of Reality Capture as a way of documentation could therefore be in the surveying company's own interest.

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3.3 Additional discussion

The additional discussion begins with addressing the assumption made from section 3.1. This was that, the 3D capture models, if placed correctly in AR, would lead to great depth perception. The assumption matched the respondents' experience of the AR visualization as they found it very comprehensible. The subsurface utilities were clearly visualized beneath the ground surface because they were surrounded by the virtual excavation hole. Here, the pre-modelled occlusion boxes used to prevent backside rendering of point clouds had an effect of mitigating the parallax effect and thus achieving a clear depth perception. However, a more automated approach to achieve occlusions instead of the manual modeling approach would surely have been desired.

When further asked why the AR visualizations were so comprehensible, it was clear that the high realism and almost tangible-looking visual representation was a major contributing factor. The high realism were a direct cause of the capability to render the dense and colored 3D point clouds in a performant way. Therefore, the effort of implementing Potree (Fraiss, 2017; Schuetz, 2016) for handling of large point clouds was concluded a working solution.

On a more critical note, a noticeable limitation concerning the interview study was that no digging contractor was present during the AR demonstration nor the afterward interview sessions. This limitation was noticeable as one of the objectives was to investigate in which way AR visualizations of 3D capture data could help prevent excavation damage. However, the respondents' opinions on the matter of excavation damages were deemed valid as many had on-site experience working with subcontractors in utility projects. Still, the study could have benefited from interviewing contractors.

Another obvious limitation, this time regarding the AR visualizations applicability, was the fact that 3D capture data had to be previously collected before it could be visualized in AR. Or simply put, no data capture, no data visualization. In the long run, the hope is that using Reality Capture for documenting as-built utility assets becomes more widespread, however, in the present most utility records are 2D vector line representations stored in GIS or CAD. This called for an approach to also visualize existing utility records in AR to fill in the space where 3D capture data was missing. Because of that need, an AR visualization method was later developed and presented in Paper III, which is the next paper to be introduced. However, before that, the following will explain the incentive behind developing the method.

One incentive was found in the remarks by the respondents (mainly from the utility company) pointing at having their own GIS utility data visualized in AR. They were, however, more hesitant about visualizing data records from other types of utilities such as communication lines and electricity cables. The argument was that in their experience other utility records were often inaccurate and incomplete. Especially the lack of depth information is very evident. Hence the hesitations of visualizing such data in AR as it could lead to poorly informed decision-making. In Paper I the issue of poor data quality of existing utility records was also discussed by the interviewed respondents with similar remarks as in this study and will be addressed again in Paper III-V.

Another remark by some of the respondents was that, in their opinion the current AR solutions delivered a poor visualization experience in terms of perception. The respondents hinted that the careless visualization approach of 3D model data resulted in a poor depth perception. Also, this approach of visualizing utility data as 3D models (3D tubes) placed below the ground surface becomes meaningless if depth information is unknown.

The remarks from the respondents further incentivized the exploration of new ways of visualizing existing utility records in AR. The challenge became, to develop a visualization method for subsurface utility information with unknown depth information while still being perceptual and to consider mitigating the parallax effect.

3.4 Design-thinking of AR visualization methods

Before introducing Paper III, the design and development of the AR visualization methods are elaborated. This is worth noting, as it only briefly has been addressed in the presented papers. The hope is, that a more detailed elaboration would contribute to design ideas when developing AR visualization methods both inside and outside the scope of subsurface utility engineering.

The start of the design-thinking process begins after reexamining the interview results, which were conducted after the hands-on demonstration from visualizing as-built 3D capture data in AR (Paper II). Here, a connection was discovered to Orlikowski's (1992) work on interactions between technology and organizations, named *the duality of technology*. To understand the connection, a brief explanation of the relevant aspects from duality of technology concept follows. Orlikowski suggested that, for analytical examination of human interaction with technology, the interaction should be recognized as having two iterative modes. Those modes are, (i) the design of technology and (ii) the use of technology. She argued that often organizations (and researchers) fail to recognize this when examining technology. Especially in the case of information technology (IT). She argued that one reason is that the development of technology and use of technology are often carried out in different organizations. For instance, a CAD software product is developed by software vendors while being used by engineering companies. She further argued that because of this separation in time and space between technology development and technology use, the value gained from using a given technology often decreased over time in organizations. Mainly because the implemented technology was shaped around institutional properties and work practices that were present during development and thus failed to meet the expectations of end-users that now worked in a different environment, with different institutional properties and practices. Thus, the implementation of technology may ultimately end up shaping the work practices of end-users instead of adapting or building upon them.

The important insight attained from Orlikowski's (1992) work was that the technology designer (in this case, me) could consider the technology end-user's current work practice into technology design to mitigate the difference for required practice needed to use the technology effectively. In the case of developing AR technology an argument can be made that the use of technology also includes AR visualizations perception and comprehensiveness. This was where the connection to Orlikowski's work became influential to the design-thinking process of the developed AR visualizations. When reexamining the interview data from Paper II as well as reactions from industry users outside the study, the response was often that the augmented as-built 3D capture models of the virtual utility excavations felt very life-like and almost tangible looking and thus was perceived highly useful and understandable. This was not a surprisingly response, as the as-built 3D capture models are very realistic looking as they literally represent a "3D picture" of open excavation holes.

While it can be argued that the perceived usefulness can be explained by the realism of 3D capture data, which I do not disagree with, I would also argue that this can be explained by the similarity in visual appearance to their current work practice thus making it more relatable. In this case, the work practice would be the excavation of underground utilities, which is also called utility daylighting according to subsurface utility engineering (SUE) work guidelines (Vine, 2014) by means of exposing utilities through carefully digging to locate their position. Hence the reason why the AR visualization method was named *virtual utility daylighting* in Paper III, as it has resemblance to the real work practice of locating subsurface utilities through daylighting.

Finally, based on the connection to Orlikowski's concept of technology ultimately led to the emerging of a design assumption (DA) that shaped the design and development of the next AR visualization method.

DA: Recreating the visual appearance of subsurface utility engineering work practices into AR visualization methods for displaying subsurface utility information leads to comprehensible and relatable visualizations for contractors and utility owners, and thereby a more successful adaption of AR technology.

While not all aspects of SUE work practices make sense to recreate into AR visualizations, it suddenly was the case when developing the second AR visualization method named *virtual utility marking* which will be presented in Paper III. The method aimed at recreating the visual appearance and style of real utility markings as shown in figure 3.1 and how these marking designs are used to communicate subsurface utility data by means of spray marking the street surface.

Fig. 3.1: Utility markings on a street surface

To summarize: the connection between Orlikowski's concept of technology and the AR visualization of 3D capture data was found through an inductive research approach. Later this connection inspired an abductive research approach when developing the *virtual utility marking* method presented in Paper III. The empirical exploration of the respondents current work practices became the first step of the design and development process, while the result thereof became the design-thinking behind the AR visualization. During this abductive process, the objective now also became to test the aforementioned design assumption.

3.5 Paper III: Augmented Reality for Subsurface Utility Engineering, Revisited

The following paper, referenced as Paper II, is titled: *Augmented Reality for Subsurface Utility Engineering, Revisited.* The paper has been published in *IEEE Transactions on Visualization and Computer Graphics (TVCG) in special issue 2021 ISMAR, August 2021.*

The incentives for this paper were presented in subsection 3.2 primarily based on the shortcomings from Paper II and the new insight gained through interviewing respondents with on-site utility project experience. The following paper covers a lot by presenting solutions to those shortcomings and insights as well as presenting other technical solutions for making a more complete outdoor handheld AR system. The paper presents a new AR visualization method called *virtual utility marking* as well as improvements of the AR visualization method presented in Paper II which is now called *virtual utility daylighting*.

In comparisons to most research on AR visualization for underground infrastructure (Li et al., 2018; Schall et al., 2009; Stylianidis et al., 2016; Zhang et al., 2016), the *virtual utility marking* method stands out, by not necessarily relying on GIS data converted into 3D primitives such as 3D tubes or by directly relying on using 3D CAD models. Instead, the aim was to develop an AR visualization method that works with utility data records that have unknown information about depth. Thereby focusing on visualizing the utility information on the street surface. Thus revisiting the idea of using shadow projections as demonstrated by Schall et al. (2013) and since then also applied in other AR systems for subsurface utilities (Côté & Mercier, 2018; A. Fenais et al., 2019; Stylianidis et al., 2020). However, this does not mean that AR visualization approaches relying on 3D model data are not relevant as this can provide depth information about underground assets to the AR user. This is why the *virtual utility daylighting* method is also presented, that similarly relies on using 3D model data, although 3D point cloud data is a different type of 3D data. However, we believe that enough incentives exist to also focus on improving AR visualization methods that favor utility data with missing depth information as this is often the only available data source for utility workers.

On a final note, the reader is again encouraged to watch this video[2] that was included with the submission of the paper and presents the improved AR prototype system (version 2) in action including the developed visualiza-

[2] https://youtu.be/fRpniWVhMZA

tion methods. Additionally, a follow-up version of the video was made with some other screen recordings displaying the *virtual utility marking* method. The video is available here[3].

[3] https://youtu.be/0dMIBJBFf1Y

Augmented Reality for Subsurface Utility Engineering, Revisited

Lasse H. Hansen, Philipp Fleck, Marco Stranner, Dieter Schmalstieg and Clemens Arth

Fig. 1. Virtual utility marking and daylighting in comparison to physical counterparts: (left) physical spray markings on the street surface, (mid left) virtual utility marking of similar information in AR, (mid right) worker examining a virtual excavation in Aalborg (Denmark), (right) AR view with embedded 3D reconstruction of said excavation.

Abstract— Civil engineering is a primary domain for new augmented reality technologies. In this work, the area of subsurface utility engineering is revisited, and new methods tackling well-known, yet unsolved problems are presented. We describe our solution to the outdoor localization problem, which is deemed one of the most critical issues in outdoor augmented reality, proposing a novel, lightweight hardware platform to generate highly accurate position and orientation estimates in a global context. Furthermore, we present new approaches to drastically improve realism of outdoor data visualizations. First, a novel method to replace physical spray markings by indistinguishable virtual counterparts is described. Second, the visualization of 3D reconstructions of real excavations is presented, fusing seamlessly with the view onto the real environment. We demonstrate the power of these new methods on a set of different outdoor scenarios.

Index Terms—Augmented Reality, Infrastructure, Computer Graphics, Localization

1 Introduction

In civil engineering, knowing the exact type and location of subsurface utilities, both old and new, is extremely important. This knowledge is required to efficiently plan construction activities, to avoid accidental damage during excavations, to communicate with other stakeholders in the construction process, and to document the assets for long-time archival purposes.

Excavation damage to underground infrastructure in particular is causing huge financial losses. Reports speak of GBP 270 million in the UK [6, 22] and USD 30 billion in the US [9] annually. Of course, *subsurface utility engineering* (SUE) does everything to prevent damages by following established procedures. Current best practices include:

1. Applying spray markings to annotate utility locations on the ground surface, based on information extracted from paper maps or geographic information services (GIS) running on handhelds
2. Using ground penetrating radar to scan for subsurface assets
3. So-called *daylighting*, *i.e.*, slow and careful excavation work until the underground assets are exposed to daylight

Obviously, all these best practices incur additional cost, and measures such as radar scans or daylighting are only pursued if deemed necessary. Consequently, much reliance is placed on SUE documentation. According to a recent survey [1] questioning 477 excavation contractors, poor or outdated documentation of subsurface utilities is one of the main causes of damages. Ordered by significance, the damages resulted from (1) lack of depth measurements in the documentation (*i.e.*, no information about the level below surface where a utility is located), (2) street-level markings painted too far from the utilities (*i.e.*, inaccurate surveying data created by rushed or unskilled surveyors), and (3) missing markings (which may have become eroded by weathering, or been removed along with the top-layer surface during construction).

Clearly, human error contributes most to damages and other problems in SUE. This is a clear indicator to consider *augmented reality* (AR) to improve upon traditional paper-based inspection, planning or maintenance procedures. Indeed, using AR for infrastructure visualization in SUE has already been proposed over 20 years ago by Spohrer [34]. At this time, it seemed plausible that emerging AR devices would soon deliver mobile 3D visualization of GIS data. Yet, to date, development and commercialization of such efforts has been modestly successful at best, as we will point out in the related work.

There are several technical, but also social reasons for this curb. In general, civil engineers operating under time pressure and with a tight budget tend to be very conservative and are reluctant to trade existing tools for technology considered immature. When it comes to AR, contemporary devices, be they handhelds (*e.g.*, using ARKit/ARCore) or headsets (*e.g.*, Hololens), lack the ability for city-scale localization with the surveying-level accuracy expected by civil engineers. Even if accurate localization is solved, measurements in GIS databases are still ambiguous, since they are expressed *relative to the surface at site without recording the absolute height* of the actual surface.

Besides, while methods for creating high-quality 3D models exist (*e.g.*, laser scanning after daylighting), there is no straight forward way to exploit them for on-site underground infrastructure visualization, other than through (non-AR) GIS viewers on handhelds.

In this paper, we *revisit previous approaches to using AR for SUE, concentrating on lifting the aforementioned limitations*. We feel that contemporary technologies, which were not feasible 10 or 20 years ago, warrant such a re-evaluation. We present the following contributions:

Wide-area localization. We describe a custom highly accurate sensor module, which enhances a tablet computer with wide-area lo-

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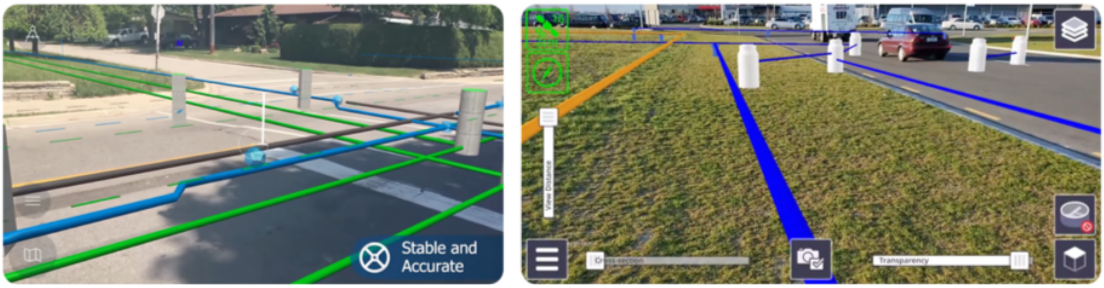

Fig. 2. Examples for commercial data visualization systems: (left) screenshot of vGIS, (right) screenshot of Trimble SiteVision. The usual visualization methods sufficiently convey basic location information for subsurface utilities; however, they fail to deliver on matching known and well-established marking schemes or plausible visual realism.

calization. We describe the hardware, which is currently in its second generation, and give details on a user-friendly procedure for accurate sensor-to-camera calibration. By fusing wide-area localization with SLAM, we can recover the surface elevation, which is necessary when interpreting measurements from GIS databases that lack explicit height.

Virtual utility marking. Based on accurate localization and an instant 3D scan of the user's immediate surroundings (using a tablet with LIDAR sensor), we give the user the ability to place annotations in the form of virtual spray markings on the street surface. Not only does this approach resemble established work practices and is easy to understand, the visual appearance of simulated spray paint also ensures high contrast over arbitrary backgrounds. The latter is important when looking at a video-see through display with limited dynamic range in an outdoor setting (Fig. 1 left, mid left).

Virtual utility daylighting. In our experience, GIS data quality is often insufficient to synthesize a useful 3D model for AR visualization. However, it is becoming common to acquire 3D reconstructions (usually colored point clouds) of excavations created on site, before the excavation hole is covered up, and store them in a GIS. We show how these datasets can be prepared for on-site visualization with an AR system, for instance, as a prerequisite for planning or on-surface marking (Fig. 1 mid right, right).

The resulting AR application supports SUE at a previously unseen level of quality, as we will demonstrate with several selected use cases.

2 Related work

Previous work on AR for SUE has been conducted by different interest groups. The AR research community has primarily focused on technical problems, such as outdoor localization and X-ray visualization techniques. Meanwhile, the civil engineering application investigated system integration and data management. Yet another relevant category are recent AR-like extensions of commercial surveying systems. This section gives an overview of these developments.

2.1 Outdoor localization

While early outdoor AR used bulky GPS sensors [12,25], the *Going Out* system was the first to introduce visual-inertial fusion for localization in a mobile form factor [27]. Around the same time, PTAM [19] showed how simultaneous localization and mapping (SLAM) can have practical use, paving the way for a huge wave of visual tracking for AR. Some of these works investigated outdoor localization [20,41]. Wide-area localization may either leverage large-scale 3D reconstructions [3,5] or models synthesized from GIS-like maps of above-surface structures [4]. However, the issue remains that all these works remain dependent on maps or other data sources, which may be scarce or non-existent.

Meanwhile, the performance and versatility of GPS has increased silently, but significantly, since the 2010s. Most users frustrated by the underwhelming accuracy of GPS in their smartphones do not realize that centimeter-level localization via GPS not only exists, but is actually a reasonably inexpensive commodity. The main factor precluding the deployment of enhanced GPS in smartphones is that a slightly larger GPS chip and a significantly larger antenna cannot be comfortably fitted into a smartphone case. We will pick up on this observation in our hybrid tracking system, which combines RTK-GPS, LIDAR and a camera in a low cost platform.

2.2 Infrastructure visualization

Soon after the first outdoor AR systems for navigation [12] and urban modeling [25] were introduced in the late 1990s, AR was adopted for SUE, first, using a 2D projection of utilities onto the street-level surface [28]. In the late 2000s, handhelds became available, and more complex SUE scenarios were addressed with X-ray visualization techniques [29–31]. This line of work considered more advanced forms of location sensing and combined them with 3D infrastructure visualizations generated from GIS data using a cut-away technique resembling a virtual excavation. We revisit this idea in our daylighting application.

Later work contributed enhanced X-Ray visualisation techniques, ghosting and shadow projections [44, 45]. The studies reported in these papers demonstrated that synthetic depth cues are essential for observers of SUE visualization techniques and that plain overlays alone are insufficient for understanding spatial relationships. A recent approach [7] for using AR in road-side maintenance has a focus on aligning worker motion and laser-range data.

Probably closest related to our work on virtual markings is the one of Cote and Mercier [8], who propose the use of elevation data for proper on-surface marking of subsurface utilities. Their approach uses an offline 3D reconstruction of a predetermined site, together with a manual registration procedure in order to recover the elevation changes of the street surface. Obviously, their approach has two significant restrictions: First, without a prior 3D reconstruction, their method cannot be used at unseen sites. Second, the current appearance of the surface at the given location cannot be incorporated. Our approach overcomes both restrictions by incorporating a live reconstruction obtained by SLAM. Moreover, our method not only considers surface geometry, but also surface *appearance* on site, ensuring the proper visual fusion of virtual and real parts of the scene.

2.3 Civil engineering applications

In the 2010s, AR applications have caught the interest of the civil engineering community, while the AR community seemed to loose interest in SUE. This new wave of implementations focused on general system design and data management [13,21,33,36–38,43]. Some more recent works in this continuity also investigated perceptual issues using contemporary AR technology. A recent study evaluated the vertical depth judgement performance on different X-Ray visualisation techniques [10], revealing that users perform better in estimating depth of pipes when using a cut-away technique compared to a simple overlay and edge-based ghosting technique. A similar survey on virtual environments confirmed that cut-away performed best for understanding the spatial placement of underground infrastructure [40]. A study based on informal interviews concluded that visualizing 3D reconstructions of previously captured utility excavation holes potentially benefits utility owners' planning activities [17].

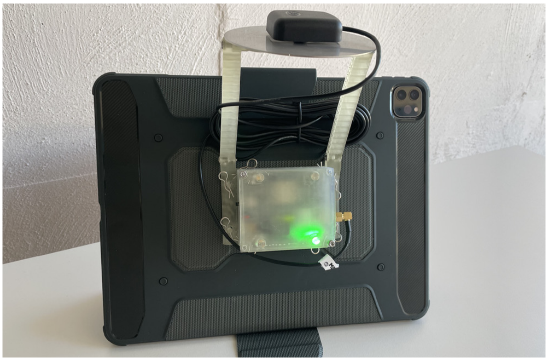

Fig. 3. Prototypical handheld visualization setup: We use a 12.9" Apple iPad Pro (4th gen.) equipped with a built-in rear-view LIDAR sensor. The center box contains the sensor platform used for accurate outdoor registration. The antenna is separately mounted on an adjustable bracket.

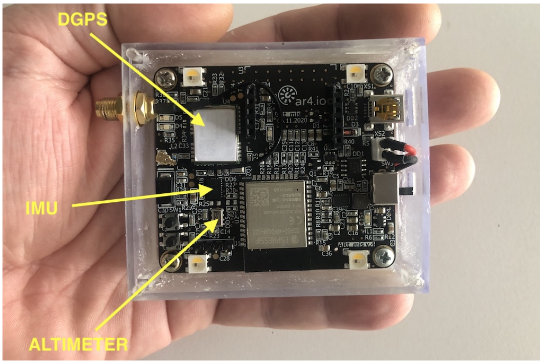

Fig. 4. Sensor board in transparent 3D-printed case: An optional GSM module can be mounted for fully autonomous operation.

2.4 Commercial approaches

Several companies involved in construction and GIS data management developed commercial AR applications for SUE. *AugView*[1] were the first to deploy a commercial AR solution explicitly targeting underground infrastructure. More recently, *vGIS*[2] (Fig. 2, left) and *AVUS*[3] started selling systems for "reality captures", *i.e.*, 3D reconstructions.

Common to these solutions is that they provide only software for bridging GIS with a visualization engine, while relying on third-party surveying equipment, such as laser theodolites, for localization. The only exception to this is *Trimble SiteVision*, an all-in-one solution for outdoor GIS data visualization (Fig. 2, right). All these commercial solutions follow a similar workflow, consisting of (i) GIS data import, (ii) localization using free-standing hardware (theodolite on a tripod) or other bulky hardware, (iii) visualization of simple 3D models using transparent overlays. With these capabilities, current commercial solutions improve upon traditional surveying or inspection work by presenting GIS data in a situated context, but without the interactivity or mobility typically associated with AR. Features such as "virtual spray paint" are not feasible with current commercial approaches.

3 Platform

Both head-worn and handheld form factors are suitable for outdoor AR. We favored a handheld (tablet computer) form factor for several reasons. First, premium tablet computers can now compete with notebook computers in terms of performance, while AR headsets remain more constrained with respect to computational resources. Second, ruggedized tablet computers are widely used by civil engineers as mobile appliances, while headsets are considered too brittle. Third, compared to optical see-through headsets, presenting video-see through AR on a tablet computers can more easily achieve sufficient contrast in bright outdoor conditions. Fourth, tablet computers can be spontaneously shared by multiple users by jointly looking at the screen. Therefore, the relative benefits of AR headsets (primarily the hands-free operation) are diminished compared to handheld devices in the foreseeable future.

Consequently, we chose a tablet computer (Apple iPad Pro, 4th generation, Fig. 3) as our AR platform. Because of its built-in LIDAR sensor, it currently provides the best 3D scanning and SLAM performance for outdoor use. Our software framework runs as a Unity application and interfaces to the SLAM system through Unity ARFoundation: The framework can also run on other platforms, such as Android/ARCore or Microsoft HoloLens/MRTK. However, all results reported here were obtained with our preferred platform, the iPad.

[1] `https://www.augview.net/`
[2] `https://www.vgis.io/`
[3] `https://www.avus.tech/`

3.1 Outdoor location sensing

SLAM systems using visual-inertial sensing provide 6DOF poses with high precision, but only relative to a starting point or, in vendor jargon, a *world anchor*. To present world-referenced content for SUE, it is necessary to place the world anchor in a global coordinate system. Establishing this global coordinate system is most easily done using GPS. However, consumer-grade GPS, as found in smartphones, is only accurate to tens of meters and not considered useful in civil engineering.

High quality GPS is available in surveying equipment, such as theodolites and total stations, but at a high cost and poor mobility. The actual sensor components are relatively inexpensive, but not ready for plug and play on mobile computers. Moreover, certain components, such as magnetometers and antennae, are susceptible to electromagnetic interference and must be placed at a minimum distance from other electronic components.

For these reasons, we designed a self-contained sensor box in order to solve the outdoor localization problem. This platform is an evolution of the work of Stranner *et al*. [35] on integrating all required components on a single board with a small form factor. The commercially available[4] device version (Fig. 4) contains exactly the same electrical components with the same accuracy and precision. Its main components include (i) a differential GPS-RTK sensor, (ii) a highly accurate smart IMU with integrated sensor fusion, and (iii) a performance pressure sensor with altimetry. The board is powered over USB with an integrated charging circuit, which optionally enables wireless operation on battery. The board is equipped with a low-power, dual-core 32-bit SoC microcontroller, which controls sensors over I2C and manages communication to external devices over Wifi or Bluetooth using the MQTT protocol [18]. A multi-color LED array is used to signal the current status of the sensor platform.

During regular operation, the host is put into Wifi hotspot mode to enable direct communication with the sensor box. While using an external Wifi network is also possible, the Wifi hotspot is simpler and alleviates additional latency in sensor data transport incurred from Wifi contention with other devices on the same network. Moreover, it establishes a tight connection between the host and the sensor box, allowing the latter to directly leverage the host's Internet up-link to retrieve differential GPS correction data from an NTRIP server. The sensor box streams absolute position and rotation measurements (*i.e.*, GPS coordinates and north-aligned quaternions) to a predefined MQTT broker, which is usually residing on the host. Any visualization software (AR or non-AR) can connect to the MQTT broker to consume the actual sensor data at high frame rates.

3.2 Runtime operation

For good rendering precision, the outdoor AR application operates in local coordinates. Due to the limited numeric precision of datatypes used by rendering engines, any content (SUE data in our case) needs to

[4] AR4 GmbH: `https://www.ar4.io`

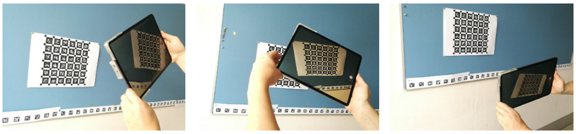

Fig. 5. Procedure to acquire calibration data: After assembling a rigid sensor setup, the user acquires the dataset. It is essential to perform a set of rotational and translational movements, as well as displacements of the sensors with respect to a calibration pattern in order to capture enough variation for the calibration method to perform properly.

Fig. 6. Importance of IMU-to-camera calibration: (left) The building model is rendered with a proper calibration. (right) Through using an inaccurate calibration, the rotational error around all axes accumulates to about 6°, which leads to a clear displacement of the virtual model from reality.

be transformed into this local coordinate frame before rendering. For tracking position and orientation of a user, two options are available:

1. On devices with on-board SLAM features, the local frame is automatically created and maintained by SLAM. To establish a global reference, we require only a single 6-DOF position and orientation measurement right at the beginning, *i.e.*, a GPS measurement and a north-aligned orientation measurement from the IMU. During further operation, we assume that re-localization and map refinement of the SLAM system ensure drift-free operation.
2. If no SLAM is available on the host computer (*e.g.*, when using a tablet running Windows), the sensor box can be used at full frame rate as the sole source of tracking. In other words, the application resorts to purely non-visual tracking served by the sensor box, performing global pose estimation and registration on a frame-to-frame basis.

In both cases, the IMU-to-camera calibration plays a crucial role to properly align the coordinate frame in terms of global rotation. On the one hand, in SLAM-enabled systems, the gravity vector is usually known, but alignment to north is needed at least once at the beginning. On the other hand, when using pure inertial tracking, the need for proper mapping of the full 6-DOF pose estimate from the sensor box to the camera at frame rate is apparent. Even small errors accumulate and lead to a clear misregistration of virtual data (see Fig. 6 for example).

3.3 IMU-to-camera calibration

Because the overall tracking quality strongly depends on it, we must ensure proper IMU-to-camera calibration. We need a proper mapping of axes between the IMU and the camera, such that an axial rotation measured by the IMU is transformed into a proper rotation matrix matching the motion perceived by the camera. The underlying problem is a very common and extensively studied topic in robotics [23], as it is fundamental in visual-inertial SLAM [26]. We use Kalibr[5] to perform the required computations. The algorithms of Kalibr [15, 24] were not modified; our contribution is a framework that actually makes it easy for untrained users to perform the required calibration quickly without requiring special knowledge.

Ease of use is essential for our application area, as devices cannot be calibrated ahead of time. In contrast to rigid sensor arrangements, e.g., in drones, which are calibrated at design time or during manufacturing, the calibration of our external sensor box to the host device's camera is only possible after assembly and must be performed by the user. Calibration depends on the form factor of the device used, the available mounting options, or may even vary with the application. The proper transformation matrix between the IMU and the camera as delivered by the server will remain valid for any number of runs or applications, as long as the rigid configuration is not changed. If the configuration is modified, the recording and the calibration have to be repeated.

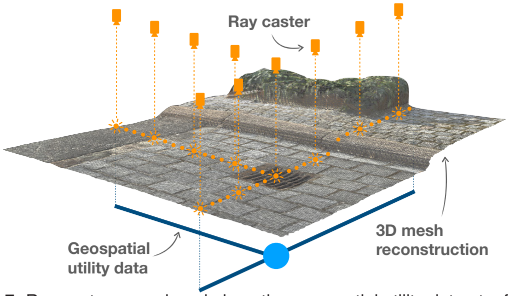

Fig. 7. Ray casters are placed along the geo-spatial utility data at a fixed height, shooting rays downwards to check for collisions with a 3D mesh reconstruction of the ground surface.

Fig. 8. Example of overlay blend mode used to blend the spray paint texture on the top layer with different surface textures on the base layer

We propose a method comprised of two stages: A client component collects all relevant information on a device paired with the sensor box, and a server component in the cloud runs the computationally expensive part of the algorithm. The client component records a video file and stores timestamps for individual frames in a local database. At the same time, sensor information (*i.e.*, the absolute rotation and acceleration of the IMU recorded at 120 Hz) is retrieved through MQTT and stored in the database as well. Upon finishing the recording, the database and video file are uploaded to a cloud server (hosted on Amazon Web Services), which exposes an API to Kalibr via Node-RED[6]. Upon finishing a calibration run, the user is automatically notified by email of the intrinsic camera matrix and the extrinsic transformation describing the relative position and orientation between IMU and camera center.

A regular camera calibration typically requires 50-100 frames, but the timing of these frames is not important, provided the scene does not change. In contrast, calibrating the IMU to the camera requires accurate timestamps for both data sources (the IMU and the camera frames) with thousands of samples in order to infer the proper geometric constellation between the two entities. It is therefore important to capture sufficient translational and rotational motion during the recording of the calibration dataset in a time-synchronized fashion (Fig. 5).

In a typical calibration run, the user captures a dataset with respect to a calibration target with known properties for a length of 2-3 minutes, properly stimulating the IMU gyroscope and accelerometer along and around all axes through alternating slow and fast motion.

Our method calibrates only IMU to camera and does not recover the geometric relationship of the GPS antenna to the rest of the setup. Calibrating the GPS antenna position directly with respect to the camera center would be extremely challenging and is better resolved by relying on real physical measurements taken from the antenna mount.

4 Virtual Utility Marking

Civil engineers and construction workers use spray paint marking on the ground surface to indicate the type and location of underground infrastructure. These markings stand out from the environment because of their bright colors and, simultaneously, use conventions and visual encodings (*e.g.*, glyph shapes) familiar to the stakeholders on location. Commercial solutions display markings by simple overlay of renderings created from the respective CAD model, which lack realism and do not match the appearance of the site. Plausible display of virtual spray paint requires that

1. the placement of markings follows the ground surface;

[5] `https://github.com/ethz-asl/kalibr`

[6] `https://nodered.org/`

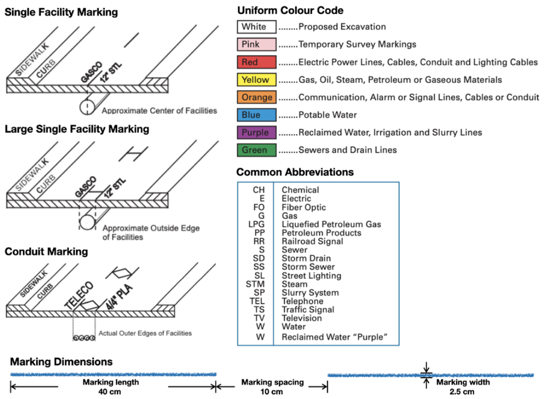

Fig. 9. Examples of common utility marking designs, colors, abbreviations and dimensions sourced from uniform marking guidelines.

2. the markings blend into the ground surface;
3. the design of the markings follows the styles, symbols and colors set forth in industry guidelines.

These requirements have only been partly addressed in previous work, which used simplistic marking placement and texture (Fig. 2). In this section, we describe our visualisation technique, *virtual utility markings*, which aims to address these requirements in full. As a prerequisite, we assume that SUE data is already imported and has been converted to *marking primitives*, *i.e.*, 2D or 3D graphical primitives, such as poly-lines or tubes. Moreover, we assume the AR system provides a *ground mesh*, *i.e.*, a 3D mesh reconstruction of the ground surface or, at least, a ground plane estimate, in real-time.

4.1 On-surface placement

To obtain the on-surface effect, we place ray casters along and above the marking primitives to check at which location the vertical rays intersect with the ground mesh. This is illustrated in Fig. 7. The ray origins are placed at fixed height above the utility line with a downwards casting direction. We use the farthest intersection of a ray with the reconstructed mesh, *i.e.*, the lowest surface point, for placing the markings. In case any physical objects above the ground surface are captured by the mesh reconstruction process, for example, the arm of an excavator or other construction site equipment, this strategy ensures that the visualizations are always placed on the ground surface.

From the position and orientation of the surface point hit by the ray, "paint" particles, *i.e.*, semi-transparent billboards with a size of 16×16 pixels, are instanced. We use a resolution of 30 particles per meter to ensure that they appear as a complete line. Placing dense particles mimics the way real spray paint behaves, making the marking follow the curvature of the ground surface closely.

4.2 Spray paint texture

We use an *overlay blend mode* as known from image editing software to create a realistic appearance of semi-transparent paint. We derive a blended color by combining per-pixels luminance values of the ground layer, denoted by $g \in [0,1]$, and the top layer, denoted by $t \in [0,1]$, using the formula

$$f(g,t) = \begin{cases} 2gt, & \text{if } t < 0.5 \\ 1-2(1-g)(1-t), & \text{otherwise,} \end{cases} \quad (1)$$

where f is computed in a pixel shader, g is obtained by projecting the video texture of the AR device to the ground mesh, and t is obtained by rendering the particles into an off-screen framebuffer (Fig. 8).

4.3 Standardized marking templates

To facilitate clear and consistent communication, SUE professionals have developed industry guidelines for marking, standardizing symbols, styles, abbreviations, colors and dimensions. Inspired by these guidelines, we have implemented procedural visualization templates of some common marking designs (Fig. 9). The type of marking is determined from the attributes of the SUE data, and the appropriate template is chosen. The templates can include plain outlines, simple glyphs of vectorized outlines, *e.g.*, a diamond-shaped conduit, and text. Thereby, the virtual spray paint is not only applied to indicate simple lines following real utility tracks, but also to place such signs and glyphs at locations indicated by the SUE data attributes.

5 Virtual Daylighting

While on-surface markings can quickly convey standard SUE information, virtual daylighting allows a detailed view of subsurface infrastructure, which may be important in ambiguous or dangerous situations. Automatically acquired laser scans of excavation sites are often large, in the order of 1-10 million points per site, which is challenging for a mobile GPU. Since we want to support ad-hoc work practices where timely preprocessing (*e.g.*, geometric simplification) is not really an option, an alternative strategy is required to cope with the significant amount of data.

Our rendering solution is based on Potree[7], an open-source point cloud renderer for the web [32]. We have integrated the renderer directly into Unity using the method of Fraiss [14], such that it can run entirely on the device without involving cloud rendering and inducing communication latency. The cloud service is therefore only responsible for preprocessing, to serve the point cloud data, and to create occlusion information created, as described below.

As demonstrated by Zollmann *et al.* [45], contradictions within the virtual and the real world are confusing to users. Unfortunately, since we rely on 3D point clouds without explicit surface information, occlusion cannot be resolved by simple backface culling. To tackle this small but important problem, we developed a method to automatically create occluders from scanned data sets, which tightly fit the excavation holes, enabling ad-hoc use of the scanned models in AR. Our goal is to find the contour of the excavation hole at street level. We assume that all walls of the excavation hole are vertical, so that a polygonal extrusion of the street-level contour downwards to the lowest point of the scan delimits the excavation in a way that is suitable for occlusion rendering. The challenge is to find the street-level contour without knowing the exact street level elevation in the scanned data.

Our method accepts as input either unstructured point clouds (as acquired with LIDAR) or 3D reconstructions created from photo sets via photogrammetry. First, we compute point normals for each point using a disk-based Poisson distribution. The normals will be used to vote for the street level: While points inside the hole belong to the walls and tend to have horizontal normal, the points on and above street level tend to have vertical normals.

Starting at the lowest point of the excavation, we sweep a horizontal plane upwards and statistically evaluate all scanned points inside slices with a depth 2ε, where ε was empirically set to $0.2mm$ as a compromise between the number of slices and the average number of points per slice. When we observe a sudden switch from horizontal to vertical normals, the sweep stops, and the points just below the street level are selected to form the contour of the excavation hole.

The result is applied as a stencil drawn on a plane at ground level, which is served alongside the actual point cloud to the end-user application, masking the area outside the contour during rendering of the scanned model. The result are realistic-looking occlusions of a virtual excavation hole (Fig. 10).

6 Experiments

In order to show the impact of our work over existing approaches, we conducted several experiments. We first show some results for the proposed calibration method, followed by some use cases in outdoor AR applications and an expert study to assess the plausibility of our new visualization methods.

[7] https://github.com/potree/potree

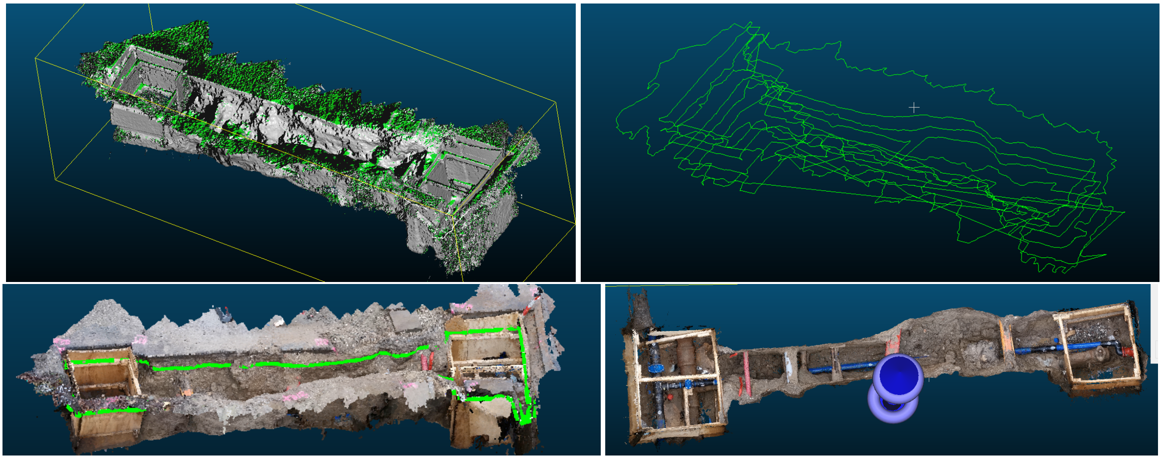

Fig. 10. Plane-sweeping algorithm applied to excavation data: (top left) estimated normals of points, where green denotes orthogonality to street level, (top right) individual contours estimated from bottom to top, (bottom left) intermediate contour overlaid on colorized point cloud, (bottom right) top-down view of final occluder applied on colorized point cloud

Rotation [°]			Translation [mm]		
	mean	std. dev.		mean	std. dev.
r_x	-2.5391	0.9908	t_x	51.9249	4.6588
r_y	0.6609	0.3704	t_y	207.9650	7.6064
r_z	-178.7168	0.4641	t_z	35.7136	7.8353

Table 1. Results for our 11 calibration runs. Both rotation and translation estimates are plausible as compared to the setup shown in Fig. 11.

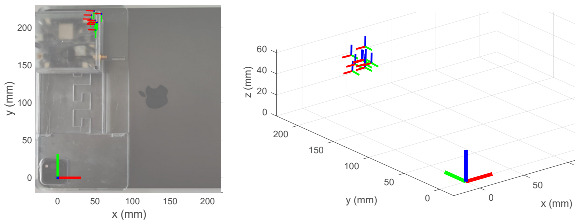

Fig. 11. Calibration results for a prototypical sample configuration: (left) camera coordinate system and individual coordinate systems overlaid on a top-view of the calibration setup. The individual IMU estimates cluster around the real IMU location (axes color coded as x=red, y=green, z=blue), (right) side-view revealing the offset in z-dimension.

6.1 Calibration results

The accuracy of the differential GPS-RTK sensor in our sensor box falls into the range of $2-4cm$ for position measurements. For the IMU, the error in orientation measurements is well below $1°$. Thus, the global pose estimates delivered by the sensor box already reach the required accuracy for geodesy applications. For more detailed evaluation results, the reader is referred to Stranner *et al*. [35]. In the following experiment, we are concerned with the accuracy of our calibration method, which maps the global pose estimates into the camera coordinate system, ultimately solving the misalignment problem depicted in Fig. 6.

Based on our distributed setup, we performed a total of 11 calibration runs with a rigid configuration of the iPad and our sensor box in the sample configuration shown in Figure 11, together with the camera coordinate system and the estimated IMU coordinate systems for said runs. The data points clusters consistently around the real position of the IMU. On the right of Fig. 11, a side view is shown, revealing the offset in z-direction. In Tab. 1, the mean and standard deviation of rotation and translation is shown. The results are accurate, coming at the ease of an almost fully automatic approach.

During our developments, we had two insights that were not immediately apparent from the documentation and literature of Kalibr. First, it is crucial to consider the accuracy of the manual measurements (*i.e.*, the size and spacing of individual tags) taken from the physical calibration target. This information needs to be provided to the application before uploading recordings in order to introduce metric scale. Even an error of less than $1mm$ in the target causes the calibration to deviate by $1cm$ or more in translation. Second, in order to arrive at an accurate result, the calibration run needs to incorporate significant translational and rotational (spontaneous) motion (Fig. 5). Insufficient motion results in inaccurate and useless transformation estimates. It is of utmost importance that the calibration recordings are taken with due diligence.

6.2 Accuracy and repeatability of virtual utility markings

We performed an evaluation of initial accuracy and repeatability of the localization delivered by the fusion of our sensor box with SLAM. We omit a dedicated evaluation of pure sensor-based tracking (*i.e.* when

Fig. 12. Setup for our marking repeatability and accuracy test: (left) A tape measure is placed perpendicular to measure displacements of virtual spray marks. We measure (middle) the offset at the reference point and (right) the displacement at the $1m$, $2m$ and $3m$ marking.

SLAM is not available), as it can be reduced to the raw sensor accuracy. Consequently, results only depend on the quality of the GPS fix, *i.e.* if a fixed-integer fix is reached, the accuracy is always $< 2cm$ at that particular point.

We sprayed four virtual concentric circles around a geodesically verified reference point (RP) near our laboratory at a radius of $10cm$, $1m$, $2m$ and $3m$ with a tape measure laid out for reference (see Fig. 12). We collected measurements using the following procedure: (i) The user starts at a random position within $4m$ of the RP. (ii) The user walks around the RP to obtain a SLAM map. (iii) The user takes screen snapshots along the tape measure at distances of $10cm$, $1m$, $2m$, and $3m$. Snapshots are automatically annotated with timestamp, initial GPS position and snapshot position. This procedure was repeated on three different days, obtaining a total of 15 measurements.

In the snapshots, we can read the displacement of the virtual markings on the tape measure and calculate the initial distance Δ of the device to the RP, the displacement from the center (ε) and the deviation from meter markings (ε_{1m}, ε_{2m}, ε_{3m}), which are summarized in Tab. 2.

Date	RTK	Δ	ε	ε_{1m}	ε_{2m}	ε_{3m}
31/5/21, 12:35	float	47	12	3	1	1
31/5/21, 12:50	fixed	85	10	11	8	10
31/5/21, 12:45	fixed	287	2	8	10	11
31/5/21, 12:38	fixed	291	1	1	3	9
31/5/21, 12:53	fixed	207	1	1	4	5
1/6/21, 15:54	float	91	30	23	21	19
1/6/21, 15:27	float	365	25	13	16	20
1/6/21, 15:34	fixed	199	9	6	10	12
2/6/21, 11:28	float	122	17	20	27	35
2/6/21, 11:24	float	264	15	21	30	33
2/6/21, 11:31	float	157	15	10	5	2
2/6/21, 11:34	fixed	59	10	11	9	7
2/6/21, 11:18	fixed	66	10	2	2	2
2/6/21, 11:14	fixed	281	6	2	2	4
2/6/21, 11:07	fixed	165	1	3	3	4

Mean (μ) fixed only	**5.56**	**5.00**	**5.67**	**7.11**
Std ev (*std*) fixed only	**4.28**	**4.12**	**3.50**	**3.55**
Mean (μ) float only	19.0	15.0	16.67	18.33
StdDev (*std*) float only	6.96	7.72	11.71	14.58
Mean (μ) fixed and float combined	10.93	9.0	10.07	11.6
StdDev (*std*) fixed and float combined	8.61	7.53	9.33	10.75

Table 2. Virtual utility marking evaluation results: All measurements are taken in centimeters. Δ refers to the initial GPS distance to the reference point. ε is the measured virtual marking error at $0m$, $1m$, $2m$ and $3m$.

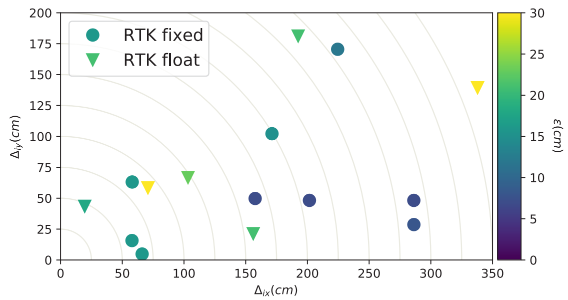

Fig. 13. Position specific initialization error: The origin depicts the reference point (RP), and the position of the mark shows absolute distance from the RP. The color encodes the displacement error between the virtual spray mark center and the RP. Lower is better. A less accurate GPS-RTK signal ("RTK float", triangles) results in worse results.

The use of SLAM accumulates drift with increasing tracking distance. With GPS in "floating" mode (DGPS, *i.e.*, only corrections, but no phase information), we expect at least an initialization error of $30cm$, while, in "fixed" mode (RTK-GPS), of at least $2cm$, as shown by the evaluation data. For the intended use case, namely running "fixed" mode GPS while being within $3m$ distance of the RP, the errors are within a margin of $10cm$.

A closer look into the expected precision of hardware components reveals the following characteristics: (i) GPS-RTK gives $< 2cm$ of error, (ii) errors concerning compass based heading strongly depend on the environment and fall within a range of $1^\circ - 5^\circ$, and (iii) local tracking drift [42] over a $4m$ distance is $\leq 9cm$ on tarmac. The measurements taken in our evaluation, as shown in Figure 13, confirm this behavior and initialization errors from up to $10cm$. We observed higher SLAM drifting when facing strong direct sunlight, as it causes more interference at the test location. Overall, the results deliver the precision required for SUE applications.

In general, the number of observed satellites is neither directly related to the quality of the GPS fix, nor is it reported by our sensor. In contrast, the quality of the receiving antenna has the largest impact on the fix. However, depending on the satellite constellation at a particular site, a cheap antenna can also deliver the same results at the cost of a longer initialization time. The reader is referred to reports on GNSS antennae [39] and receiver performance [16].

6.3 SUE information and datasets

SUE data generally refers to all kinds of information about buried or hardly accessible subsurface infrastructure, with a considerably varying degree of accuracy, completeness and, more importantly, availability.

A SUE database usually contains information about cable or pipe specifications, purpose, owner, and location. The latter is represented in 2D only, *e.g.*, 2D points or line strips, while 3D information about the sub-surface depth or utility width is scarce, often based on manual measurements and subject to regional documentation practices. The location accuracy may vary significantly in the centimeter range, notwithstanding additional sources of error induced through the conversion between coordinate systems (*e.g.*, Gauss-Krüger to UTM) during documentation and later remapping to reality. While these circumstances make it difficult or impossible to specify a single ground truth for localization accuracy of geo-referenced data, it is accepted practice that the utility should be discoverable within $\pm 30cm$ from the spot where it is marked in the GIS data.

For our experiments, we used two datasets. The first dataset includes geo-spatial subsurface utility data from a suburban area in Copenhagen, Denmark. The dataset consists of points and poly-lines representing underground facilities like manholes, wells, pipes and cables. The geo-spatial data is further divided into utility supply types such as electricity, gas, water, telecom, *etc.* The geo-spatial data also has attributes such as material type, thickness, cross-section shape, accuracy tolerance zone, *etc.* The dataset is provided by the *Danish register of underground cable owners* as a test dataset to educate others on how geo-spatial utility data should be structured following their GML data model. For productive use, the same information can be directly retrieved from a live GIS database using proper credentials.

The second dataset consists of geo-located 3D reconstructions of utility excavation holes gathered from a nearby area. The 3D reconstructions are represented as point clouds and are captured by the local water utility company. The company uses these 3D reconstructions as a supplementary as-built documentation for their water utility facilities. Using 3D reconstructions techniques as a means of documentation during excavation work was introduced in 2019. Currently the goal is to explore which value creation and benefits these new technologies have in practice.

6.4 Outdoor virtual utility marking and daylighting

In order to demonstrate the visual appeal of our spray paint effect, we present selected results from multiple scenarios, including showcases illustrating virtual daylighting.

Fig. 14 (top left) shows a surface reconstruction obtained with LIDAR, which is used to draw the markings directly onto the surface. Because the reconstruction closely follows the real surface, the markings align neatly across the curb (see top mid of Fig. 14). Fig. 14 (top right) shows two examples of multiple lines with different colors, demonstrating the impact of real-world shadows on the appearance of the lines. The shadows do not harm the visual effects at all, and the spray markings appear coherently, because the spray effect directly incorporates the real surface appearance captured by the camera. In Fig. 14 (bottom left), two results are shown comparing our approach to a traditional shadow-projection visualisation, which only targets planar surfaces that are estimated at a fixed height. Because the surfaces (sink and curb) violate the planarity assumption, the shadow projections deviate from the real location of the subsurface utilities. Leveraging real data from GIS, Fig. 14 (bottom mid) depicts the results of our spray paint visualization. The markings look very realistic and are placed at their correct location. This is especially noticeable at surfaces with darker-colors and rich textures, for instance, on a wet pavement. In case the surface has been reconstructed properly, temporary occlusions can be resolved [2] (see Fig. 14 bottom right).

The previous examples show the use of our system on closed road surfaces. To demonstrate the accuracy with respect to real buried infrastructure, Fig. 15 shows an overlay of virtual utility markings on top of an actual excavation. As can be seen, the overlays deviate from the uncovered assets by an offset of a few centimeters. Nonetheless, finding and identifying the assets during excavations is successfully guided by the overlays.

Fig. 14. Outdoor virtual utility marking using real GIS data: (top left) The mesh generation from LIDAR closely follows the real surface. (top mid) Virtual spray markings showing glyphs which respect the elevation change. (top right) Rendering with dynamic illumination. As the spray effect directly incorporates the shadows as seen by the camera, the spray markings fuse with reality in an indistinguishable way. (bottom left and inset) The orange dashed lines are showing the location of the subsurface utility as a naive overlay on the video, while the blue lines show the spray following the reconstructed surface. (bottom mid) Real subsurface utility data overlaid on wet surfaces. (bottom right) Using a feature to detect people, dynamic occlusion is correctly resolved.

In analogy to GIS data from our database, we use the geo-located 3D point clouds to show excavations at site. In Fig. 16, a scenario is shown with both the unaltered view of the user and the virtual excavation. Because our automatically generated occluders carve out the reconstructed areas surrounding the ditches of interest, the visualizations align with existing structures at the contours of the respective 3D excavation holes.

6.5 Semi-structured interviews with expert users

We performed semi-structured interviews with a group of domain experts in order to assess the plausibility and applicability of our virtual marking and daylighting approaches. Based on a previous series of interviews [17], it was expected that AR could potentially help prevent excavation damage. The interviews were conducted on site within the first half of 2021, comparing a live try-out of our AR prototype to commercial AR visualizations as shown in Fig. 2. Six experts from two companies with an average experience in the field of 20 years were interviewed, belonging to the contractor, utility and surveying sector. We put the focus on three topics: (i) current SUE and excavation practice, (ii) assessment of visualisation approaches and (iii) applicability during SUE and excavation work.

Current SUE and excavation practice The interviews exposed major issues and pitfalls, such as damaging existing infrastructure through the absence or the poor quality of documentation, particularly concerning soft cables in electric and telecom utilities. Statements such as *"Yesterday we just hit such a cable, and it's just so frustrating."* or *"You can not see from a utility drawing if it is in one or the other sidewalk tile."* are symptomatic for situations, which one expert summarized as: *"So, as a starting point, there is a presumption that there is something, but depth and width and such – we have to see what it is like as we continue to dig."*

Concerning spray markings, experts explained that the main issue is their application in practice: *"Spray markings also disappear. If it is wet, then you cannot spray. If there is dust, then you cannot spray. Therefore, utility marking with spray has a limited use, and, in addition, the road authority would like it removed again."* One expert stated, *"Yes, I think we should be able to avoid excavation damage more often. So if it was marked more often, then people in the field will probably be more attentive."* The cost of excavation damage was further elaborated, and one expert stated that just avoiding 10% of their insurance cases would already be a significant saving.

Assessment of visualisation approaches All experts were very positive towards the virtual utility marking and daylighting approaches, as it provided a more comprehensive understanding of the underground beneath the excavation site in terms of *what is there* and *where it is*. When asked about how understandable the visualizations were, one expert said regarding markings, *"It was almost better than in reality and it seems very useful."* Another one said *"It gave you a lifelike feel. Sometimes I asked myself, is it real spray markings?"* A third expert elaborated further, *"It was very comprehensible and somehow more pedagogical – especially, because it also said if it was a gas line or an electric line or something else and because the virtual lines had the colors that they [real spray marking] usually have."* We conclude from these statements that the experts could relate to the virtual markings and they created a sense of familiarity with their experience from real spray markings.

When compared to commercial AR visualisations, as shown in Fig. 2, the experts felt that our virtual markings were more suited for their work tasks. One expert described why she did not prefer the commercial AR visualizations by saying, *"It is very messy to look at, and the 3D effect is not intuitive to understand. It is as if you yourself have to move the 3D models parallel below the surface."* She followed up by saying, *"I like the other one [virtual markings] better. It was more understandable and more direct for our use."* Another expert said, *"It was floating-like."* This reinforced our assumptions that it is essential to overcome the lack of parallax in commercial AR visualizations, which causes the sub-surface models to appear as if they were floating above the surface.

Regarding virtual daylighting, one expert said, *"In our industry, we have always wanted some kind of X-ray glasses, and this is the closest we come; this is the closest I have seen to actual X-ray vision."* The majority of the experts said that having depth information about the utility lines was the most valuable aspect provided by virtual daylighting. One expert further elaborated that he believes the comprehensible overview

Fig. 15. Virtual utility markings overlaid onto real excavations. Because our algorithm is able to mark lines even during excavation works, it is possible to validate the accuracy of GIS data with respect to the actual physical location of utilities. Markings deviate by a few centimeters, in particular from soft cables, but the AR overlays successfully guide the daylighting.

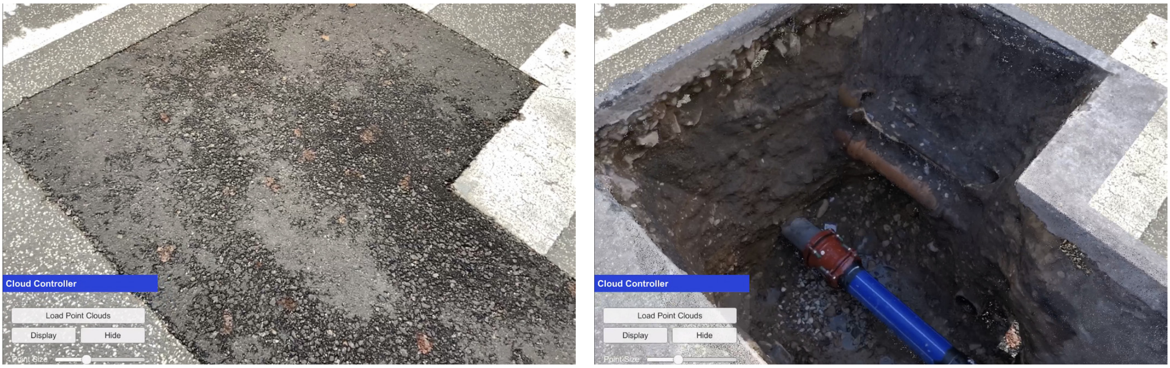

Fig. 16. Outdoor virtual utility daylighting: (left) The real world as seen by the user. (right) The virtual models from the excavations are overlaid at the respective locations. Due to the occluding geometry wrapping around the excavations, the embedded 3D reconstructions appear very realistic and deliver the impression of looking into real holes.

of the utility excavation is the biggest benefit. With virtual daylighting, the utility information is no longer just, as this expert phrased it, *"small blue and red lines in a drawing."*

Applicability during SUE and excavation work The experts deemed virtual markings useful, with one expert stating, *"I could really see this in the hands of our people in the field. It represents utility information that they are used to look at on drawings."* When asked how it would be useful, one experts summarizes as follows, *"This will provide direct value when planning and digging holes. It would reduce excavation damage and work environment risks associated with the excavation activities we do in the field."* Experts also valued that the virtual markings would always be visible, whereas real markings may disappear. It was also perceived as valuable that virtual markings are not permanently painted onto the surface, as physical paint would. One expert said: *"I could really see it in use, because you do not have to remove it afterwards."*

The experts were similarly positive towards the usefulness of virtual daylighting. One aspect compared to virtual markings that they found useful was the added depth information, which is often lacking in existing utility documentation. In this regard, all experts agreed that any tool that gives more insight to an excavation site reduces cost and efforts (time, damage and repair). One expert emphasized that a high level of realism in 3D-captured models is beneficial, *"As a contractor, you want to see it all."*.

Overall, the experts had surprisingly little concerns. One expert went as far as saying, *"I can't imagine why using this [virtual markings] would be a bad idea. Using this won't limit you to also use traditional printed or digital utility drawings."* One remaining concern mentioned by several experts comes from the inaccurate and incomplete SUE data sourced from existing utility drawings and GIS databases. The expert saw a danger that the virtual utility markings would convey a false sense of trustworthiness. One expert suggested, *"A kind of disclaimer must be added that the utility information that is displayed may be inaccurate and incomplete."* However, he did not think it would be a deal-breaker, as the information is still the same information that field workers would normally read from a drawing. Availability of AR may actually be an incentive to improve SUE data quality.

7 Discussion and Conclusion

In this work, we revisit the topic of subsurface utility engineering and refresh the perception that AR is important for this domain using contemporary technology. In particular, we described a hardware/software solution for highly accurate outdoor localization and use it to drive two novel techniques for visualizing subsurface infrastructure, namely virtual utility marking and virtual daylighting. We demonstrate how these visualizations come very close to reality as currently used in the field. The expert user interviews confirmed that our results are appealing and closer to practical usage than previous approaches.

Although we consider our methods mature enough for practical use, poor data quality in GIS databases remains a problem. Intervals between physical daylighting of subsurface utilities may be many years long, and updates to utility documentation are tardy. Many entries in current utility databases were originally imported from outdated or erroneous paper plans, often missing accurate location information. Nonetheless, the situation is improving. In an effort by the European commission to build *smart cities* [11], new regulations were put in place to collect infrastructure data in federated databases. We expect that such legislation, combined with the wider spread of GIS, will steadily improve data quality over time.

While standards for AR are still lacking, the availability of richer geo-located content for other purposes, such an urban planning or map services, will enhance the quality of AR experiences as well. Our work is an attempt to demonstrate the long way AR has come towards reaching a useful state for SUE and other outdoor applications. We believe the quality is now sufficient to convince even practitioners in conservative industries such as civil engineering.

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Supplementary material was created for this paper as well and is found in Appendix C. The Appendix includes further details regarding (i) the accuracy evaluation, (ii) the IMU to camera calibration, (iii) the AR demonstration and interview session, and (iv) testing of the AR visualization methods for indoor applications.

3.6 Additional discussion

The paper addressed all the challenges and incentives from Paper II. Moreover, the AR prototype system (version 1) was even developed into a more complete outdoor AR system (version 2) by adding a sensor cube for outdoor localization capabilities. This is something that extended beyond the research objectives set out in this thesis. Section 1.5 provides a clear overview description of the two prototype systems.

To briefly summarize the interview results. Overall, the respondents provided positive feedback towards both presented visualizations methods being comprehensible and plausible looking. Thus, indicating the AR visualizations had great visual perception compared to the naive AR visualizations often used in commercial AR systems. The statements regarding *virtual utility daylighting* also reaffirmed the statements from Paper II, which added to the credibility of the results. *Virtual utility marking* was a new AR visualization method presented to contractors and utility owners and was therefore interesting to test against the proposed design assumption from section 3.4. Based on statements from the respondents describing the AR visualization as *"understandable ... pedagogical ... direct to our use"*, it supported the design assumption, although more research is needed to make a final conclusion. However, it does pose the question if this design assumption could be further expanded to develop AR visualization methods for other types of data sources related to other work practices in different industry applications.

As mentioned in the paper, some respondents also had concerns regarding the reliability and accuracy of the data sources used in the AR visualizations. The concern was that incorrect data would lead to misinformed decision-making or as some respondents described it: *"create a false picture"*. This was both mentioned by respondents after interacting with the *virtual utility daylighting* and *virtual utility marking* visualizations. The concern opened a new challenge that extend beyond AR visualization, as it clearly underscored the need for more accurate and reliable surface utility information. More on this topic in Chapter 5 where Paper V addresses this matter.

Finally, on a more critical note, the interview study also had limitations. The

AR visualizations would have benefited from having been evaluated by more industry experts. However, compared to Paper II, respondents now included contractors with digging experience. Additionally, another hands-on demo of the *virtual utility daylighting* method was carried out, which will be presented in Paper IV in the next chapter.

Chapter 4

Towards AR-enabled informed decision-making in subsurface utility projects

Towards the end of the PhD project, another hands-on demo and interview session was carried out visualizing as-built 3D capture model in AR. Inspired by the research in this PhD project, a group of civil engineering students from AAU (supervised by the author of this thesis) held a similar try-out demo as in Papers II and III. The demo was held for 13 participants at one of the same locations as presented in Paper III.

Additional to this hands-on demo, a Trimble SiteVision[1] AR device was also available to try out for visualizing 3D capture models of as-built utilities. In figure 4.1 and in this video[2], the SiteVision is shown in action visualizing as-built 3D capture models of subsurface utilities similar to the virtual utility daylighting method demonstrated in Paper III.

[1] https://sitevision.trimble.com/
[2] https://youtu.be/BRYGhoWSJd4

Fig. 4.1: Trimble SiteVision visualizing as-built 3D capture models of subsurface utilities.

Since the hands-on demo and interview session were carried out at the same location as in Paper III and with a similar research question as in this thesis in mind, a combined data analysis of the collected data from both demonstrations and all semi-structured interviews was conducted. The results from this formative analysis are presented and discussed in the following paper. The paper focuses on presenting new insights and perspectives on how visualizing as-built 3D capture data in AR can support informed decision-making in subsurface utility projects.

4.1 Paper IV: Towards AR-enabled informed decision-making in subsurface utility projects

The following paper, referenced as Paper IV, is titled: *Towards AR-enabled informed decision-making in subsurface utility projects through visualising 3D capture data of as-built utilities*. The paper is currently an unpublished working paper.

Towards AR-enabled informed decision-making in subsurface utility projects through visualising 3D capture data of as-built utilities

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Abstract

This paper examines how AR-enabled informed decision-making can be facilitated through visualising 3D capture data of as-built subsurface utilities. Through semi-structured interviews with respondents from the underground construction industry, it was reviled that visualising 3D capture data in AR help prevent excavation damages and otherwise aid the decision-making processes involved in planning and excavating subsurface infrastructure through, 1) allowing evaluation of positional placement of subsurface infrastructure, 2) Showing underground utilities, not accessible through traditional utility records and 3) improving the visualisation of utility types and materials.

Keywords: Augmented Reality, Usability Testing, 3D Capturing, Subsurface Utilities, Underground Infrastructure and Excavation Damage

1 Introduction

In the construction industry, there is a need for more reliable and accurate information of subsurface utilities to facilitate more informed decision-making for utility owners and contractors, when planning for subsurface utility projects. Not having access to reliable and accurate utility information can cause poor decision-making that eventually leads to damaging of utilities or hazardous situations arising during excavation activities. Such utility excavation damages have huge economical costs for the society, and the Danish Ministry of Climate, Energy and Utilities estimates that excavation damages costs the Danish society around DKK 280 million annually (KEFM, 2019a). Similarly, in the UK and the US, costs of GBP 270 million and USD 30 billion respectively, are estimated alone in 2019 (USAG, 2020; CGA, 2020). The high cost-figures are supported by a British study by (Makana *et al.*, 2018), which further shows that indirect costs associated with excavation damage, such as project overrun, traffic delays and downtime of supply networks, are up to 29 times higher than the direct costs.

The link between reliable and accurate information of subsurface utilities and excavation damages is clear, according to KEFM (2019a), stating that better underground utility map records is the way to reduce excavation damages. This is in accordance with a US survey study (Al-Bayati and Panzer, 2019), in which 477 digging contractors participated. The study showed that the most frequent cause of excavation damage was a lack of vertical information (depth distance from utility to terrain) in the utility records. The second most common cause was inaccuracy in horizontal information (placement of utilities in map records) and in some cases the utilities were completely missing. A Norwegian (Geomatikk, 2015) study additionally showed that the second highest cause for excavation damage is due to inaccurate, out-of-date, and incomplete utility records.

1.1 Utility record exchange platforms

To accommodate the need for more reliable and accurate information of subsurface utilities most countries have established national platforms and programs to support the exchange of subsurface utility data between relevant actors in underground infrastructure projects. For instance, the Danish Register of Underground Cable Owners (LER) (SDFE, 2021) the Dutch Cables and Pipes Information Centre (KLIC) (Kadaster, 2021), and the British National Underground Asset Register in the United Kingdom (Geospatial Commission, 2020). However, these utility data exchange platforms are mostly acting as an online phone book focusing on availability and uniformity of the exchanged utility data, without directly addressing the issue of inaccurate, out-of-date, and incomplete utility records which is especially true for utilities installed before the establishment of these platforms as presented by Hansen *et al.*, (2021).

The Danish LER register was established in 2005 and today it includes about 750,000 km. of utility lines with 4,000 utility owners registered (SDFE, 2021). The main types of utility lines in the Danish underground are telecommunications, data, electricity, water, district heating, sewer and gas, whereas about 50% are telecommunications and data lines.

Exchanging utility records through LER is today a well-known procedure for digging contractors and utility owners in Denmark, because it is enforced by legislation. The legalisation is simply referred to as the LER law and states that utility records must be inquired through the LER platform before digging (KEFM, 2019b)

LER has made it easier to systematically collect utility records, but it is still far from effectively achieving its purpose of preventing excavation damage. A recurring problem for digging contractors has been the lack of coherent and unified utility record information received from utility owners. In the current version of LER, no specific data quality or uniformity requirements have been specified, which means that digging contractors receive a mix of types of utility records ranging from PDF-scans of utility drawings to more modern GIS-based utility maps which are sometimes also supplemented with the actual GIS and CAD files. Figure 1 (left) depicts a process diagram of LER.

With a goal of improving the current version of LER, the Danish Agency for Data Supply and Efficiency has from January 2020 begun LER 2.0 initiative, which aims to standardize and unify the exchanged utility information. From mid-2023, it will be mandatory for utility owners to exchange utility data that follows a self-developed common data model based on the GML vector format (KEFM, 2019b). Filling out metadata is also required, such as time of installation, cable owner information, etc. Specific spatial accuracy requirements are now also in place in the new LER law, which implies that all newly registered utilities should be within ±0.5 m for both horizontal and vertical directions. However, for soft cables, i.e telecommunication and electric, the vertical accuracy information is allowed to be only indicative. Figure 1 (right) depicts a process diagram of LER 2.0.

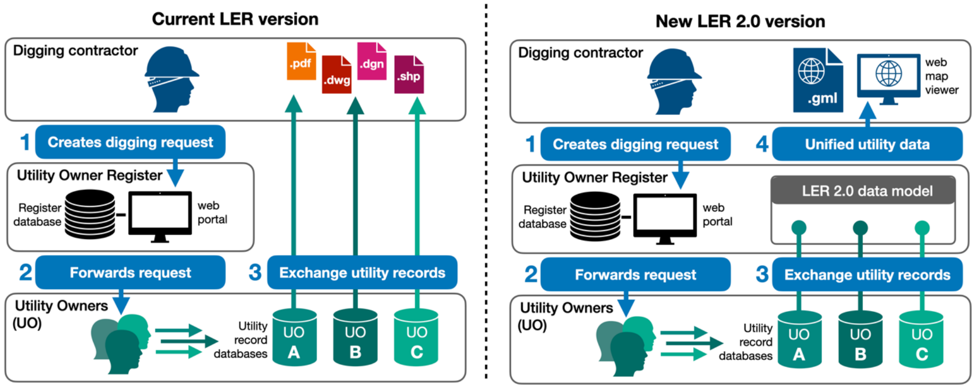

Figure 1: Process diagram of utility data exchange workflow in the current version of LER shown on the left side of the figure and the upcoming LER 2.0 version on the right.

1.2 Reality Capture of as-built utility work

The Digital Underground project in Singapore has directly investigated the issue of poor reliability and accuracy with regards to utility information. They have for instance investigated best practice methods for generating reliable underground 3D maps (Van Son *et al.*, 2018; Yan *et al.*, 2019) by testing the latest utility surveying and mapping technology, including 3D ground penetrating radar (GPR) (van Son, Jaw and Wieser, 2019). However, they concluded that the use of GPR as a one-off city-wide method for collecting utility information was considered infeasible because the process of analysing and converting radar grams into useful utility information was too resourceful. In the aftermath, they recommended to take advantage of the opportunity to update legacy utility records during open excavation work when existing utilities are visible and easy to survey (van Son, Jaw and Wieser, 2019)

In previous work by Hansen, Pedersen, et al., (2021) it was investigated how a smartphone-based Reality Capture (RC) solution could be used to document utilities during open excavation. In the study, a smartphone service allowing easy instructions for ground control markings and video capture of the exposed utilities, was used to generate 3D point clouds with a ± 5 cm geospatial accuracy by having the service provider handling the photogrammetry and georeferencing process as shown in figure 2.

The study showed that the 3D capture data of the as-built utilities had noticeable advantages compared to the processed data output from conventional surveying methods which are typically 2D vector line data. One such advantage was the automatic capture of other types of nearby placed utilities that was visible during excavation.

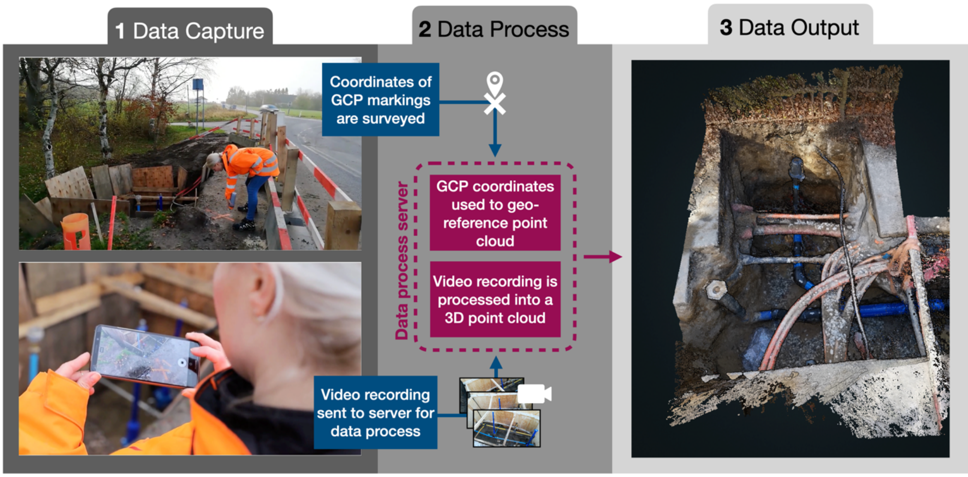

Figure 2: Process diagram of RC solution: From video recording to 3D capture data.

1.3 Augmented Reality for underground infrastructure

In research, the use of Augmented Reality (AR) for visualising subsurface utility data to better inform workers at site, has been a popular topic in research demonstrating AR system developments (Roberts *et al.*, 2002; Schall *et al.*, 2008; Cote and Girard-Vallée, 2015; Stylianidis *et al.*, 2016), as well as studies evaluating the usefulness of AR use cases on targeted end-users (Schall, Mendez and Schmalstieg, 2008; Fenais *et al.*, 2019; Stylianidis *et al.*, 2020). Overall results from end-user evaluations showed an attitude towards using it for real-world tasks at site. However, barriers and challenges for the adoption of AR systems in the underground construction industry are currently still present in the industry. In a recent literature review on the topic of AR implementation in the underground construction industry, Fenais *et al.*, (2020) highlighted 1) hardware limitations including sensors for global localisation, 2) outdoor tracking and 3) proper alignment and visualisation as the three most common challenges mentioned in the analysed literature (74%). On the other hand, recent commercial AR systems such as vGIS[1] and Trimble SiteVision[2] are now available as off-the-shelf hardware products which promise down to ± 1 cm geospatial accuracy, ensuring proper alignment of the AR content with the real world surroundings. However, despite commercially available ready-to-use AR systems that presumingly offer improved outdoor localization and tracking capabilities, it is safe to say that AR for underground infrastructure is still a niche use case and not something widely used by end-users in the underground construction industry.

The case is clear, either does these AR systems not work as intended in practice or other barriers and challenges exist. In this regard, it is worth mentioning that in a literature review by Fenais *et al.*, (2020), two other themes of challenges were also identified (26%). This included 4) difficulties in collecting utility data and 5) challenges with managing and storing such utility data so it is accessible in the future.

In previous work on using AR for visualizing underground infrastructure the presented AR systems have rarely demonstrated nor evaluated using as-built 3D capture data of underground infrastructure as visualization data source. Instead, the common approach has been to visualise 3D polygonal models, representing pipe-shapes, sourced from CAD systems, or converted from a 2D polyline data source typically stored in GIS (Schall et al., 2008; Fenais et al., 2020). In some cases data has also been sourced directly from BIM-based common data environments using as-planned 3D models for visualization (Hansen and Kjems, 2019). Similarly, are polygonal data types also the predominantly used visualisation data type in commercial AR solutions for underground infrastructure, as in the case of vGIS and Trimble SiteVision. However, vGIS, has recently also started supporting visualising 3D capture data.

1.4 Research aim

Motivated by the utility owners' preference (Hansen, Pedersen, *et al.*, 2021) for using 3D capture data to support informed decision-making in the planning and excavation process of utility projects, this paper explores how such 3D capture data could be useful for contractors and utility owners by utilizing Augmented Reality (AR) as a novel approach for visualisation such 3D capture data at project site. Previous studies by Hansen, Wyke and Kjems (2020) and Hansen, Fleck, *et al.*, (2021), showed that visualizing 3D capture data in AR had great value-creation in assisting workers in the field when planning and excavating for utility work, including helping prevent excavation damages. The studies predominantly interviewed employees from water utility companies and one noticeable limitation was that only a small number of digging contractors were interviewed to evaluate the usefulness of this AR use case. The contractor is an important actor as she/he carries out the site planning and excavation work.

This study therefore investigates the usefulness of visualizing the 3D capture data in AR with the inclusion of digging contractors through answering the research question:

> *How can visualising 3D capture data in AR help prevent excavation damages and otherwise aid the decision-making processes involved in planning and excavating subsurface infrastructure?*

To answer the research question, this paper will present interview results based on a demonstration of a 3D capture based AR demonstration, with respondents from the Danish underground construction industry. In section two, the methodologies applied for answering the research question is described, whilst section three presents and discusses the results from the empirical data collection. Finally, section four describes the limitations and future research opportunities for this research, which is concluded upon in section five, which presents the answer to the research question.

[1] https://www.vgis.io/
[2] https://sitevision.trimble.com/

2 Methodology

This research was divided into two parts. First an empirical data collection, utilising think aloud methods and semi-structured interviews, and secondly, a data analysis, revealing similarities and discrepancies between the statements made by the interview respondents.

2.1 Research design

Two handheld AR systems were used in this study, in order to demonstrate the usability and implications of using 3D capture data and AR in subsurface construction projects.

The first AR system was a self-developed prototype using an iPad Pro 12.9 inch (4th gen.) as hardware together with a small and compact sensor box equipped with a chip and antenna capable of GNSS-RTK connecting signal (figure 3 left). This allowed for accurate AR localisation and alignment of the virtual content with the real world. The AR prototype has previously been demonstrated in (Hansen, Fleck *et al.*, 2021) where further details about how the AR prototype operates.

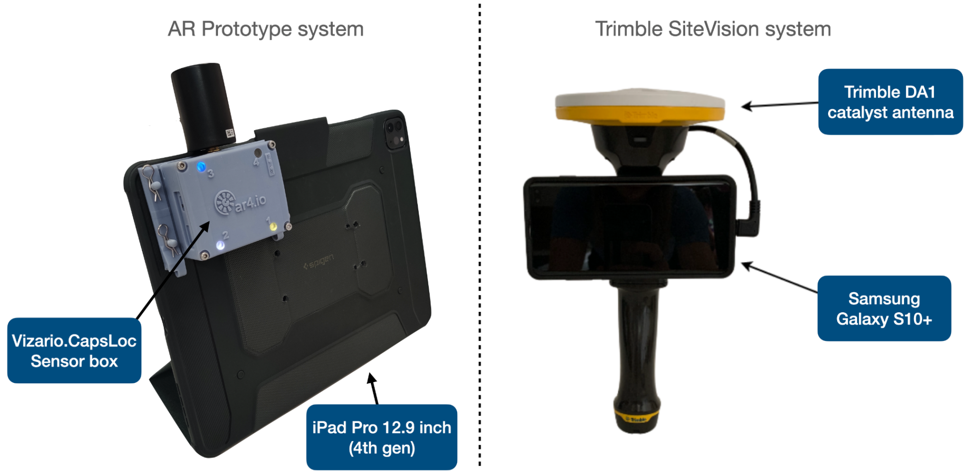

Figure 3: The AR-prototype system using a Vizario.CapsLoc sensor box[3] used in the demonstration on the left side of the figure and the Trimble SiteVision system on the right side of the figure.

The second AR system was a Trimble SiteVision unit (figure 3 right) where a custom workflow was developed to import 3D capture data. The SiteVision unit also included an RTK-capable Trimble DA1 antenna, that similar to the sensor box, allowed for accurate AR localisation and alignment outdoors.

Furthermore, to focus the study on answering the proposed research questions the demonstration sessions were prepared in a way that the outdoor localization and alignment of the 3D capture models were performed by the demonstrators before handing the AR systems to the respondents. Thus, limiting the scope of the participants to focus on other barriers and challenges related to outdoor localization.

All data used for the demonstration was captured, when subsurface utilities were accessible for documentation on the demonstration location, as shown in figure 4.

[3] https://www.ar4.io/vizario-capsloc/

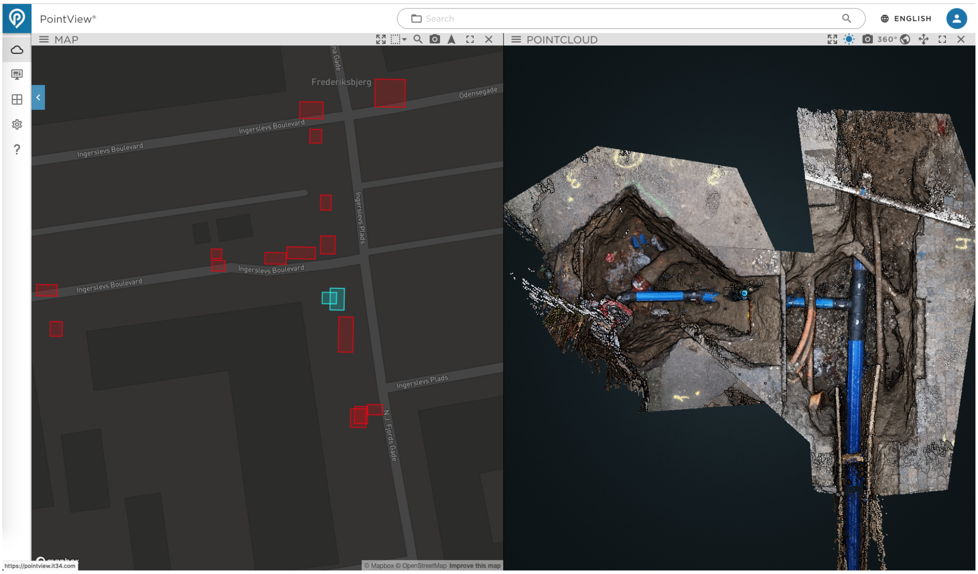

Figure 4: Overview of the 3D capture data provided by the utility owner and used for the demonstration.

2.2 Empirical data collection

The empirical data collection was conducted using semi-structured interviews, guided by Tanggaard and Brinkmann (2015) allowing the interviewer asking pre-determined questions as well as follow-up questions, arising based on the statements made by the respondents. In addition to applying semi-structured interviews, think aloud conversations were used in the interview sessions, following the recommendations of Nielsen (1992) allowing groups of respondents to comment on a demonstration or processed “on the spot”, before being interviewed individually.

17 respondents, from different professions, companies and with different levels of experience participated in the interviews and think aloud sessions, as shown in table 1. Prior to the interview session, some of the respondents participated in either a demonstration of the AR prototype (demonstration 1), a demonstration of Trimble SiteVision and the AR prototype (demonstration 2) or both, as also shown in table 1.

All interviews were sound recorded and transcribed, as also recommended by Tanggaard and Brinkmann (2015)

No.	Gender	Company Type	Role	Years of experience	Demonstration #
1	Female	Contractor	Project Manager, Water utilities	10	1
2	Male	Contractor	Site Manager, Digging Team, Water Utilities	25	1, 2
3	Male	Contractor	VDC Coordinator	3	1
4	Male	Utility Company	Foreman, Water Utilities	38	1, 2
5	Male	Utility Company	Team and Project Manager	8	1
6	Male	Surveying Company	Market Director, Geodata technologist	21	1
7	Male	Utility Company	Supervisor	-	2
8	Male	Surveying Company	Surveyor, Geodata specialist	16	2
9	Male	Utility Company	Supervisor	-	2
10	Male	Contractor	Foreman	21	2
11	Male	Utility Company	Project Manager	-	2
12	Male	Contractor	Digging	-	2
13	Male	Utility Company	Team Manager	4	2
14	Female	Contractor	Trainee	1	2
15	Male	Contractor	Sectional Engineer	10	2
16	Male	Contractor	Construction Manger	-	2
17	Male	Contractor	Digging	-	2

Table 1: Information about the participating respondents, including company type, years of experience and which demonstration type they participated in.

2.3 Data Analysis

The transcribed sound recordings of the semi-structured interviews and think aloud conversations were analysed in two parts. Firstly, an initial readthrough resulting in the identification of three recurring themes in the interview data. The three identified themes were, 1) excavation damage, 2) requirements and legislation, and 3) technology

The second part of the data analysis included a restructuring of the transcribed data, placing the various statements from the respondents within the three categories, allowing a better qualitative understanding of the commonalities and the discrepancies between the statements.

3 Results and discussion

Throughout the data analysis process three themes emerged from the respondent's answers to the interview questions, allowing a categorisation of the results presented in this section. The three themes or categories are, 1) excavation damage, focusing on current issues and best-practice related to on site planning and excavation work, 2) requirements and legislation, focusing on which laws and demands excavation work and documentation of subsurface infrastructure is regulated by, and 3) technology, focussing on the added benefits, challenges and further improvements associated with the presented use case of visualising 3D capture data of as-built utility work in AR.

3.1 Excavation Damage

The interviews showed that excavation-related damages to subsurface utilities is a major problem that can have both economic and hazardous implications. Respondent 1 explained that the cost of utility strikes ranges from 1,500 to 150,000 DDK depending on which utility type is damaged. The frequency of utility strike damages occurring varies a lot and is often depended on the type of excavation activity. Respondent 2, a site manager for a contractor team, carries out 5-10 open pit water-pipe installations per day, and estimates 10-20 damage cases per year. Whereas respondent 4's utility strike and repair team experience 2-3 cases per week.

When the respondents were asked about the cause of excavation damage in their work, the most mentioned cause was the lack of accurate and reliable utility map records received from LER. Respondent 2, further noted that LER data often consist of various PDF maps which can be a lot for the workers in the field to manage.

The respondents noted unreliability and inaccuracy both with regard to poor horizontal and vertical positional information. Respondent 5 further explained why this was the case. For instance, positional information was sometimes documented as a distance from the utility line to a road curb. This is not reliable, because a curb often gets moved over time, which will make the documentation of the utility line invalid. Respondent 3 further noted that vertical positional information (depth below terrain) often cannot be trusted and are only indicative information if available. A notion which was seconded by respondents 14-16 and in general by all the respondents was missing depth information considered a major issue as some utilities can be located closer to the surface than expected, as shown in figure 5. A study by Al-Bayati and Panzer (2019) similarly reported missing depth information as the main cause for excavation damage.

Some respondents also mentioned that some utility lines were completely missing from the provided utility records. Respondent 1 and 2 pointed out that private secondary utility lines (i.e. cables or pipes branching from the main line to a private cadastre) are almost always missing, as the utility owners are not obligated to provide map records according to the LER legalisation. This is often frustrating for respondent 1 and 2, as a substantial part of the secondary utility lines often crosses beneath public road areas.

Another kind of inaccuracy, noted by respondent 5, is the lack of width information in the available utility documentation, explaining that encountering a 2-3-meter-wide sewer pipe during excavation can be a major surprise, if the only prior documentation available to the contractor is a graphical 2D line representation on a utility map. A third kind of inaccuracy was mentioned by respondent 2 who noted that soft cables were often mapped as straight lines, but in reality were often placed in loops and therefore covered a larger area than represented in the map records. Looping cables were similarly noted in research by Al-Bayati and Panzer (2019).

Figure 5: Big utility lines are often not explicitly described on 2D line representations on utility maps, and can sometimes be located closer to the surface than expected.

Other causes were related to the physical properties of the subsurface utilities. Respondent 4 and 5 noted that old pipes made of fibre cement or cast iron are very fragile making them vulnerable when exposed during digging as shown in figure 6. Respondent 2 further noted that “soft” telecom cables are vulnerable for damage as they are small in diameter and often lay unprotected in the ground. Respondent 15 further added that telecom cables are often placed just beneath the bound base layer in the road construction and thus also vulnerable for damage, when breaking through a road surface.

Some respondents additionally mentioned that the use of no-dig methods such as controlled drilling was another cause for damaging utilities. Respondent 3 noted that as a contractor, it is tempting to use these methods because it minimizes the need for open excavation, but it is not always the best solution. Respondent 5 furthermore explained that contractors might be too careless when using no-dig methods considering the poor data quality of utility records.

Figure 6: Damage on old utility line on the left and corrosion on utility pipes on the right.

In the end, respondent 10 summarized the problem with unreliable and inaccurate utility data, by stating that LER map records only allows one to presume something is present (in a focal area), however, it is first after excavation has begun, the exact placement, depth and disruption area is revealed. This is clearly noticeable in figure 7 which compares utility records from LER (left) and the exposed utilities from the same location (right).

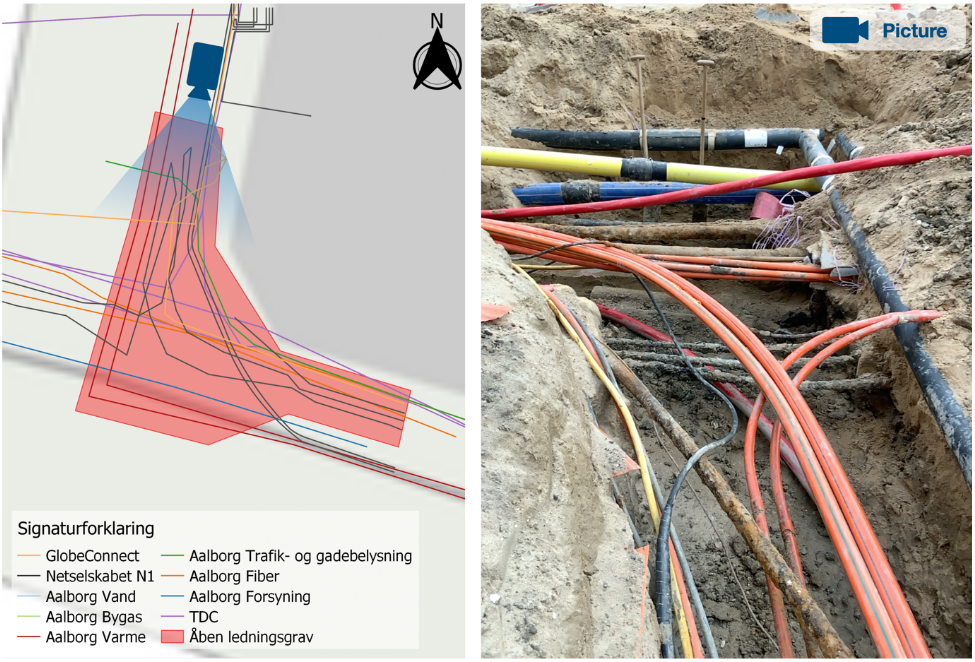

Figure 7: The LER documentation of a utility line area on the left and exposed utilities from the same area on the right.

3.1.1 Damage prevention methods

The most common method for preventing excavation damage was to collect utility map records and use them to locate existing utilities at the excavation site. The main source for collecting utility records is through inquiries from the LER web-portal. According to respondent 1 and 2 it is usually the site manager that holds the responsibility of collecting LER data and assuring its quality in participation of relevant actors on a project i.e. the digging team. This includes organising the many record files and sometimes also digitizing the PDF-drawings to vector line representations. Respondents 1-3 further explains how different mediums are used to view LER data, including both handheld devices, such as tablets and smartphones or paper prints of maps and drawings.

Another way of utilising the LER data, in order to prevent excavation, was described by respondent 3, who sometimes manipulates the LER data into a 3D model, allowing a better overview of the digging scenario. 3D models are, however, only utilised on digging projects with many utility lines crossing in different elevation levels. It can nonetheless be a challenge to make such 3D models, as depth information of utility lines are often missing in the available documentation of subsurface infrastructure, thus making the vertical placements a matter of guesswork.

Another tool which can aid the damage prevention on excavation projects is Ground Penetration Radar (GPR). However, the technology has according to respondent 1 and 3 not matured enough and is therefore not a feasible solution alone, for preventing utility strikes and other issues on excavation projects. Both respondents had previously hoped that GPR would be *the* X-ray solution, but it is unfortunately not, in its current form. Respondent 3 additionally added that use of GPR does not make sense on small projects in general, as the process to convert radargrams into useful utility data is too resourceful. This corresponds with findings by Al-Bayati and Panzer (2019) and van Son, Jaw and Wieser (2019)

In addition to utilising LER data such as maps and drawings or 3D models, respondent 2, explains how precautionary digging principles are also applied throughout the digging process. This includes, removing 10 cm thick layers of soil at a time, while continuous excavation checking with a handheld shovel.

3.2 Requirements and legislation

During the interviews it was made evident that the lack of reliable LER data was something all respondents were affected by and especially the contractors were strongly opinionated about it.

Respondent 1 and 2 for instance, felt that contractors were often the "victim" in excavation damage insurance cases. Respondent 1 explained that if damage happens on a utility line, then the contractor has to prove that the provided map records were incorrect or missing, otherwise the fault is on the contractor. When knowing the contractor's requirements, it is not surprising that many of the respondents found poor data quality of LER utility records as a major issue.

Even though lack of documentation and reliable information is something most respondents named as critical for their excavation work, they do not necessarily report wrongly placed utility assets or subsurface infrastructure, thereby improving the accessible information about a geographical area's underground utilities.

According to respondent 5, reporting of wrongly placed pipes are mostly done when such pipes are damaged during excavation or if the documentation is completely wrong. Respondent 10 further added that it is impractical to involve a utility owner with wrongly placed utility lines, given the owner only shows up five days after the request to move or resurvey their wrongly placed utilities is given, which is time a contractor cannot wait, before moving on with their work.

According to respondent 6, the challenges regarding the unreliability of existing utility records will likely not be fixed by the new LER 2.0 utility data requirements enforced from mid 2023. The reason being, that LER 2.0 has significant shortcomings which are that accuracy of existing utility records will not improve if the existing records are already incorrect. In respondents 6 view, the only benefit with LER 2.0 will be the exchange of standardized utility information in a unified digital format, which is a general improvement, but the challenges regarding excavation damage mentioned by many of respondents will still exist.

3.2.1 Reality Capture and Augmented Reality

After the demonstration of visualising as-built 3D captures in AR, most of the respondents and especially respondent 1, 2 and 5, noted that the availability of 3D capture data in LER would be preferable to make this a workable AR solution. However, the challenge is that LER does not support the exchange of 3D capture data. According to respondent 1 new legislation measures in the LER law is needed to support 3D capture data, otherwise the exchange of traditional utility data will continue to dominate. Moreover, the same respondent believed that small companies will not use the necessary 3D capturing tools, for creating such 3D capture data without it also being mandated. Clearly this indicated that the role of legalisation and requirements plays a major part in the adoption of the AR use case.

On the other hand, the AR use case of visualising 3D capture data could also lead to reconsideration of some utility work requirements. For instance, when installing new utilities, a 0.5 m respect distance is usually applied, according to respondent 4 and 5. This is however not always practical in dense city environments as this would lead to utilities being placed on private property next to public roads, in order to fit all underground infrastructure. Respondent 5 added that 3D capture data might provide a valid reason for slacking on the respect distances, as the data provides a higher degree of spatial detail and certainty regarding existing utilities not provided from LER utility records.

Another benefit, this time mostly related to the RC technology, is the ability 3D capture data provides for documenting misplaced subsurface utility assets, which could prove beneficial in potential legal issues between owners of side-by-side utilities.

3.3 Technology

When trying the AR systems all the respondents agreed on the perceived usefulness and comprehensiveness of the AR visualisation of 3D capture data, which is in accordance with findings by Hansen, Wyke and Kjems (2020) and Hansen, Fleck, *et al.*, (2021). According to respondent 13 the visualisation was as close to reality as possible, which he made clear by saying, *"it is like being here in person when this was dug out".* This is clearly visible in figure 8, in which the correctly alignment 3D capture data visualised in AR creates an experience of looking into a real utility excavation.

Respondent 1, 2, 3 and 10 noted that the AR visualisation of 3D capture data delivered a 3D "picture" of what is in the underground space. Currently miscommunication between foreman and the digging team often happens when only using map-based utility information to create an overview. Respondent said, "*with this [AR system] you can easily get the same picture in the head".*

Figure 8: Visualising 3D capture data in AR using the Trimble SiteVision system in the top of the figure and the AR prototype system in the bottom.

When asked if AR visualisation of 3D capture data could help prevent excavation damages all respondents believed it could. Largely the reason was again that the visualisations would provide a clear picture of what and where utilities were placed beneath the ground surface. When asked to elaborate, many of the respondents referred back to the aforementioned causes of excavation damages as something that this presented AR demonstration could help avoid. That included the possibility to view:

- Positional placement of the 3D captured utilities to obtain information about vertical properties such as depth placement and layering order, and horizontal properties such as correct cable alignment (e.g. in cases when cables loops), pipe width and area of nested utilities.
- Placement of missing utilities in the provided LER utility records such as secondary cables.
- Material types of the 3D captured utilities so that cautious digging around fragile materials can be applied.

Beside the AR visualisation of 3D capture data being useful to prevent excavation damages, the respondents also reported that it would ease the planning and excavation process on-site. Examples noted from respondent 5, 10, 13 and 17 included the possibility to:

- Obtain a better judgement of where and from which direction to connect a new pipe and thereby plan and execute the excavation work more efficiently. Traditionally the approach is to dig a large hole for then later to decide the direction to connect.
- View types of pipe mounts. This information is rarely provided in conventional utility data.
- Estimate what excavation equipment and methods should be utilised

The AR demonstration was not meant to compare the two different AR systems against each other as they presented the "same" 3D capture data although generated from two different photogrammetry processes using the same 2D pictures as the data source. However, respondent 16, who had tried both AR systems preferred the 3D capture data visualised with the AR prototype, as he claimed it was more detailed, allowing him to obtain a more clear view of the utility assets. The difference in detail is because the AR prototype visualizes the entire dense point cloud, whereas the Trimble SiteVision is visualizing a textured mesh 3D model which has a lower vertex count. The comment respondent 16 made can be used as an argument to strive for as much visual and geometric detail as possible from the photogrammetry process, to deliver the best basis of 3D capture data to support the above mentioned planning and decision-making use cases.

The interviews also revealed challenges regarding the presented AR demonstration materialising into a real-world practical solution which corresponds with findings by Hansen, Wyke and Kjems (2020) and Hansen, Fleck, *et al.*, (2021). That included the lack of availability and accessibility to 3D capture data from other utility asset owners as mentioned in section 3.2.1. For instance, respondent 17, noted that the presented AR demonstration would definitely be useful, if there existed more 3D capture data. Something that he believes will take a long time before utility owners have collected *enough* 3D capture data of as-built utilities to always have data to visualize.

Another closely related challenge was the concern that the 3D capture data over time would no longer reflect the current state of the subsurface utilities. Thus, the AR visualisation would become unreliable by presenting a false picture of the underground space.

Another challenge noted by respondent 3 was a concern that the 3D capture data would require too much data storage. Respondent 4, 5 and 6, did similarly note that network connectivity could be a challenge, which is a concern considering the large file size that would be needed to be downloaded at site. In respondent 5 experience connectivity issues occur both in dense urban areas where in some areas, connections are completely unavailable and also in rural areas which have poor network coverage.

Lastly, other challenges that were not directly related to the AR visualisation of 3D capture data, was noted by respondent 1, 2, 4 and 7. This included:

- Handheld devices with touch screens are difficult to operate in rainy weather. This was based on current experience, as many of the respondents used smartphones and tablets to view utility map records in the field.
- Sun reflections on handheld displays, which can make a display harder to read.

- Senior workers would probably be more reluctant to use the AR systems because of habits.

The respondents also suggested some further improvements and added functionalities that would have been beneficial for the presented AR systems to include. According to respondent 1, 2 and 5 it would be useful to have LER data and other GIS-based utility data visualised together with the 3D capture data. The respondents noted that this could help to:

- Verify the GIS utility data against the 3D capture data.
- Show metadata (attributes) from GIS utility data to help clarify type of utility or show asset owner information.
- Predict the positional placement of missing or inaccurate utilities in areas where 3D capture data is not present, but placed close by.

Other feature requests mentioned by respondent 1-6 and 10 included more interactivity with the 3D capture data in an intuitive way:

- Functions to show the vertical distance from utility asset to terrain surface (depth). Respondent 1 recommended a one-tap interaction in which the user would select a specific utility asset in the 3D capture data and then a vertical distance to terrain would automatically appear.
- Step and slider functions to view through the 3D capture data.
- Interactions to visualize temporal changes if more 3D capture data is present at the same location, but have been captured at different times.

3.3.1 Outdoor localization in AR

Even though both AR systems used an external GNSS antenna with RTK connection for the AR localization and alignment process, it was still challenging to keep a fixed RTK signal and thus sometimes the 3D capture models had to be manually adjusted for the sake of carrying out the demonstration. As the demonstration was taking place in an urban area this was likely the main cause. Despite trying to exclude this challenge, some of the respondents found it noticable and thereby commented on it. Respondent 2, 3, 5 and 6 mentioned that this localization process needed to be automatic in a workable AR solution. However, respondent 6, mentioned that the positional placement of the augmented 3D models does not have to be 100% accurate if there are intuitive functions to manually adjust the positions and orientation.

3.3.2 Trimble SiteVision

The respondents also had comments directly targeting the Trimble SiteVision system. Respondent 3, 5, 6 had already tried it before, but not for visualizing 3D capture data nor has anyone purchased it. Respondent 10 felt that the form factor and design of the product was suitable for a work environment. Respondent 3, who had recently attended another demonstration of the SiteVision system explained that his contractor company decided not to purchase it, based on the fact that in underground utility projects, they rarely have 3D model data to visualise because conventional utility data is predominantly stored as 2D vector line representation or as PDF-drawings. According to respondent 3 the SiteVision is mostly geared towards visualising 3D CAD/BIM models. It is therefore either not possible or just too cumbersome to convert 2D vector data into 3D polygonal models.

4 Limitations and future work

A key limitation of the study and its generalisability is that the participating respondents were all from the same four companies, two water utility companies and two contractors. Future research should thus include participation of a greater sample of the underground construction industry, including multiple utility company types.

Due to the local nature of the empirical data collection, the results of the study primarily fit within the scope of the Danish underground construction industry. Future research should therefore include an additional data collection with an international focus.

As the scope of this study was focussed on the use and visualisation of 3D capture data in AR only, future work should investigate the user needs and preferences on site facilitating, use, storage and exchange of 3D capture data and how it can be integrated with conventional utility data systems while considering legalisations and requirements. Future research should also investigate how a more direct connection between existing 2D polyline utility data and 3D capture data are achievable to accommodate the preferences on better interaction and accessibility to relevant metadata from conventional utility data while visualising 3D capture data. The first logical step would be to acquire a better semantic understanding of the 3D capture data to allow for a data integrating between the two heterogenous data sources.

Finally, it is important to mention that use of AR to visualise subsurface infrastructure can only be done on locations on which 3D capture data has been acquired.

5 Conclusion

Through 17 semi-structured interviews, with respondents from the underground construction industry in Denmark, and a discussion of said interviews with respect to current scientific literature, this paper answers the research question:

> *How can visualising 3D capture data in Augmented Reality help prevent excavation damages and otherwise aid the decision-making processes involved in planning and excavating subsurface infrastructure?*

The study showed that 3D capture data of utility excavation has a use case in Augmented Reality. 3D capture data, coming from photogrammetry and LiDAR, have previously mostly been used as a foundation to create polygonal data in CAD modelling software for geographic information system use.

The study further showed that the 3D capture data improves understanding of subsurface infrastructure, through its realism and comprehensiveness, for workers on underground construction projects, which helps supervisors and workers plan their work better with respect to avoiding excavation damages and provide a better foundation for decision-making. Thereby demonstrating that 3D capture data has other beneficial properties in the construction industry than as a data modelling foundation.

The study furthermore showed that augmented reality usage can be an incentive for workers and supervisors in collecting reality capture data and storing it for later use, due to the benefits it provides, through its well-descriptive nature. It further provides a better understanding of how much space utility takes up beneath the surface, compared to a graphical 2D line representation and therefore makes it easier for workers on site to select digging methods and define respect distances.

Finally, the study clearly indicated that the role of legalisation and requirements plays a major part in the adoption of the AR use case.

In summary, using 3D capture data for augmented reality visualisations makes it possible to:

- Evaluate positional placement of subsurface infrastructure
- Show underground utilities, not accessible through traditional utility records.
- Improve the visualisation of utility types and materials.

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Chapter 5

Next step: A need for reliable and accurate subsurface utility information

Driven by an incentive to mitigate the concerns regarding visualizing incorrect surface utility data in AR, this chapter takes a closer look at ways to address the reliability and accuracy issues related to subsurface utility records. Chapter 2 introduced the use of a Reality Capture solution that captured 3D point clouds of the visible subsurface utilities during open excavation. The paper introduced in this chapter returns to this 3D capture method while also looking at other data sources that could help improve the poor data quality of legacy utility map records.

5.1 Paper V: An Argument for the Integration of Heterogeneous Data Sources for Reconciliation of Subsurface Utility Data

The following paper, referenced as Paper V, is titled: *Addressing the Elephant in the Underground: An Argument for the Integration of Heterogeneous Data Sources for Reconciliation of Subsurface Utility Data* The paper has been published in *Int. Arch. of the Photogrammetry, Remote Sensing and Spatial Information Sciences* and presented at the 16^{th} 3D GeoInfo Conference, October 2021. The paper is published as an open access paper under the *CC BY 4.0 License*.

ADDRESSING THE ELEPHANT IN THE UNDERGROUND: AN ARGUMENT FOR THE INTEGRATION OF HETEROGENEOUS DATA SOURCES FOR RECONCILIATION OF SUBSURFACE UTILITY DATA

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KEY WORDS: Underground infrastructure modelling, geospatial data integration, data fusion, data quality.

ABSTRACT:

In this paper we address the issue of unreliable subsurface utility information. Data on subsurface utilities are often positionally inaccurate, not up to date, and incomplete, leading to increased uncertainty, costs, and delays incurred in underground-related projects. Despite opportunities for improvement, the quality of legacy data remains unaddressed. We address the legacy data issue by making an argument for an approach towards subsurface utility data reconciliation that relies on the integration of heterogeneous data sources. These data sources can be collected at opportunities that occur throughout the life cycle of subsurface utilities and include as-built GIS records, GPR scans, and open excavation 3D scans. By integrating legacy data with newly captured data sources, it is possible to verify, (re)classify and update the data and improve it for future use. To demonstrate the potential of an integration-driven data reconciliation approach, we present real-world use cases from Denmark and Singapore. From these cases, challenges towards implementation of the approach were identified that include a lack of technological readiness, a lack of incentive to capture and share the data, increased cost, and data sharing concerns. Future research should investigate in detail how various data sources lead to improved data quality, develop a data model that brings together all necessary data sources for integration, and a framework for governance and master data management to ensure roles and responsibilities can be feasibly enacted.

1. THE NEED FOR RELIABLE INFORMATION ON SUBSURFACE UTILITIES

Driven by a persistent and growing need to develop infrastructure above and below the surface, planners, engineers and contractors rely on information on the presence and location of unseen subsurface utilities. However, much of the available information is positionally inaccurate, not up to date, and incomplete. Reasons for this include but are not limited to a previous lack of or use of outdated survey practices, previous information representations utilising relative positions and schematic drawings, data conversion and digitisation introducing quality loss, and data quality requirements that increase over time such as the need to capture locations in full 3D. Also, the degree of quality is typically unknown, leading to increased uncertainty, costs, and delays incurred by infrastructure projects due to the need for verification.

Programs and platforms such as the Danish Register of Underground Cable Owners (LER) in Denmark (SDFE, 2021), the Cables and Pipes Information Centre (KLIC) in The Netherlands (Kadaster, 2021), and the National Underground Asset Register in the United Kingdom (Geospatial Commission, 2020) have been established to make data on subsurface utilities available in a standardised, digital format, addressing data availability and uniformity. However, accuracy and reliability of the provided records remain largely unaddressed. While legislative instruments may specify the required accuracy of utility records, it is unclear how compliance to such requirements is verified or how data owners can improve the accuracy of their data, in particular for legacy data representing utilities that were installed in the past.

2. LEGACY RECORDS: THE ELEPHANT IN THE UNDERGROUND

To improve the quality of available information, initiatives have been undertaken to increase the accuracy and reliability of "as-built" records of subsurface utilities which are captured at the time the utilities are installed. Standards and guidelines such as the Specifications for Utility Survey in Singapore (Singapore Land Authority, 2017) describe how utilities are recorded in absolute positions and with predefined positional accuracies. They prescribe the techniques, observation standards, or competencies and skills required to ensure that location information is captured with sufficient accuracy and the data attributes that are to be provided.

Such improvements address the recording of utilities directly after being built - typically when they are still exposed and direct or line-of-sight observations are possible - and do not cover the recording of pre-existing infrastructure, leaving legacy data quality issues unaddressed. As a consequence, unreliable information will continue to have a negative effect moving into the future. With multiple organisations working together on infrastructure development projects and - in dense urban areas in particular - multiple projects taking place in the same area over time, unreliable information will repeatedly lead to ineffective decision making, productivity loss, increased risks to the safety of workers and the operation of utility services, and, ultimately, extensive resources spent to deal with them.

Data on previously built assets above the ground such as buildings and transportation infrastructure can often be captured at an arbitrary moment in time to obtain data of the desired quality. The same principle does not apply to underground utilities that are not visible or accessible in their entirety and for most of their lifetime. Trials conducted in 2018 by the Digital Underground project in Singapore demonstrated that an one-off,

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area-based mapping approach using 3D ground penetrating radar is not feasible nor economically viable for the purpose of improving the quality of comprehensive legacy records (Van Son et al., 2019). Instead, a gradual, long-term strategy capitalising on various data collection opportunities was deemed necessary.

We refer to newly captured data on previously built utilities as "as-is" data. Viable as-is data collection opportunities are centred around ongoing construction and maintenance projects where reliable information provides direct benefits to the parties involved in the project. Commonly referred to as a part of Subsurface Utility Engineering (SUE) practices (Zembillas & Scott, 2010), survey methods ranging from above surface observations to non-destructive surveys based on geophysics and to trial hole excavation to locate, verify, and map existing utilities. While it can be argued that such practices establish a degree of data quality improvement in support of specific projects or tasks, results from these surveys are not sustained or sustainable. Often, they are not shared or stored beyond the scope of individual projects or organisations and may not be available in a georeferenced digital machine readable form to support future use.

This loss of information between individual projects and organisations is comparable to how building design information is lost between project phases due to handover requirements in a conventional design-bid-build paper-based process. At each point between project phases, all accumulated information is downgraded into paper drawings and a laborious recreation process by the next project phase team is needed to bring it up to digital form. As a solution, many in the AEC industry are now using a digital-only collaborative Building Information Modelling (BIM) delivery process (Eastman et al., 2011). Instead of using paper drawings as records, BIM relies on digital building information models where the accumulated building information is stored, updated, maintained and exchanged between designers, engineers, stakeholders, and others (Borrmann et al. 2018). A BIM-inspired approach could potentially help sustain a higher degree of reliability of subsurface utility information across underground-related projects for any given utility asset. Figure 1 illustrates how consolidating quality improvements leads to a (more rapid) increase of information quality.

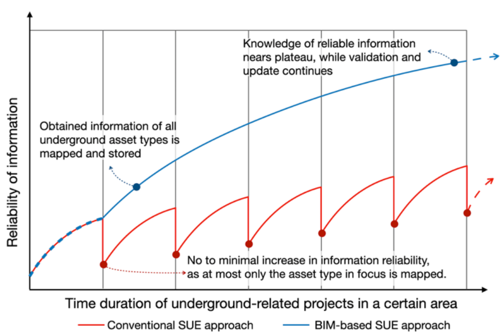

Figure 1. Loss of subsurface utility information quality caused by SUE results not being mapped and stored.

In summary, legacy data is not sustainably improved, repeatedly resulting in negative outcomes. The **purpose of this paper** is to pose the hypothesis that gradual reconciliation of legacy utility data is achievable and can be sustained through the integration of heterogeneous data sources collected at various opportunities. In the next section, a number of data reconciliation use cases are proposed and exemplified by real-world cases.

3. INTEGRATION OF HETEROGENEOUS DATA SOURCES: AN OPPORTUNITY FOR DATA RECONCILIATION

In this section, an argument is made for a novel approach towards subsurface utility data quality improvement that relies on the integration of heterogeneous data sources. Key motivations for this approach are (i) the necessity to change the status quo, and (ii) the use cases that such data integration would engender. These use cases include:

I. validation, control, and (re)classification of data quality and other attribute values of existing utility assets.
II. addition and inference of missing or incomplete utility asset alignments and attribute values.
III. improvement of positional accuracy by repositioning features or upgrading them from 2D to 3D.

The approach is to capitalise on data capture opportunities that occur throughout a utility asset's life cycle as shown in Figure 2. Opportunities to collect data on particular utilities may also occur when planning and executing nearby construction projects utilising SUE methods such as trial holes and non-destructive geophysical instruments.

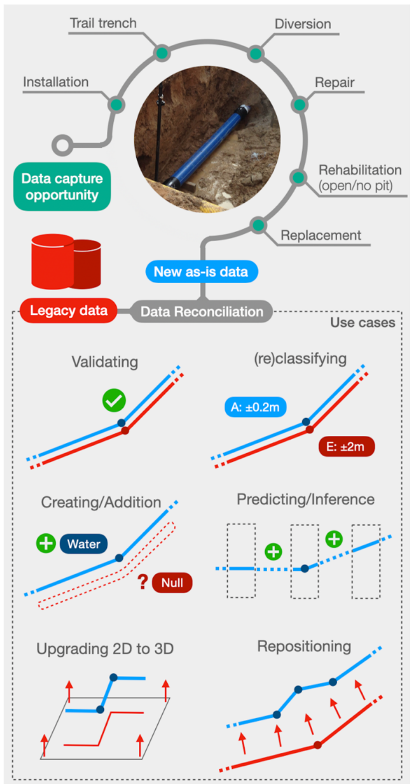

Figure 2. Data collection opportunities and data reconciliation use cases.

Throughout the mentioned data collection opportunities, a range of utility surveying and locating techniques can be utilised. In figure 3, a selection of common techniques is presented. The primary data output of these various techniques results in heterogeneous data sources that have relatively low value and an often manual processing of the data is needed to further enrich and transform the data sources into a meaningful and usable data format. In many cases this translates to 2.5D vector lines enriched with attributes, as most utility owners use a GIS-based asset management system. However, in some cases utility owners also may want to transform the primary data into a true 3D representation.

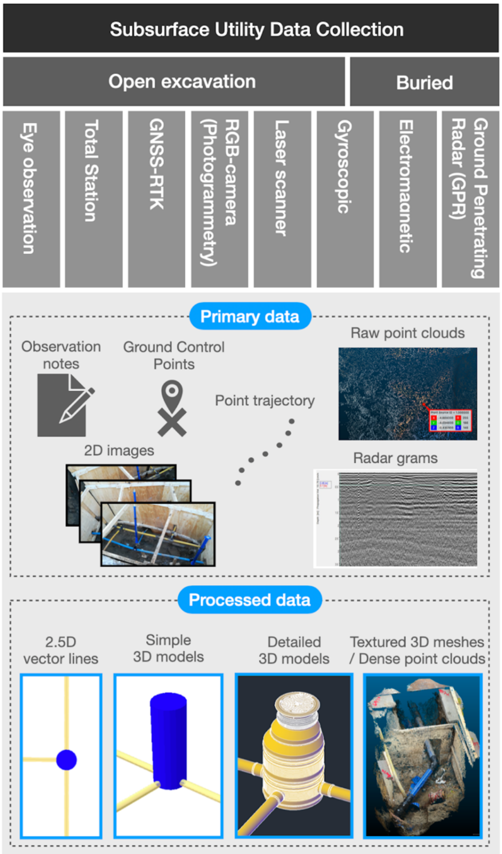

Figure 3. Common subsurface utility data collection techniques and its primary and processed data forms.

A notable category is that of "eye observation". While not a survey technique based on technology, eye observations are a potentially valuable source of data that requires a relatively low effort to capture. Platforms and programs such as KLIC and NUAR have provisions for reporting aberrant situations. In the case of KLIC for example, it is mandatory for excavating parties to report situations that differ from the situation described by the provided data. These situations are aberrant alignment, non-locatable utility, and unknown utility.

3.1 Cases of potential utility data sources

To further investigate the potential use of our data reconciliation approach, two cases from Denmark and Singapore are presented with a focus on how newly captured utility data compares to legacy records.

3.1.1 3D capture during utility replacement: 3D capture methods have become increasingly popular because of the technology improvement in laser scanners and democratisation of photogrammetry solutions. Over the past two years, two water utility companies in Denmark have tested a smartphone-based photogrammetry service as an as-built 3D documentation method during open excavation replacement of water pipes (Hansen et al., 2020a). The 3D capture solution benefits the utility companies by providing visually realistic dense point clouds of their installed water utility assets. The 3D model supports use cases such as (i) quality assurance of the agreed as-built work, (ii) visual feature extraction for completing the registration process in GIS for instance by identifying component type of the installed pipes and (iii) planning of future utility work at the same location of already 3D captured excavation holes.

A more unexpected benefit that was discovered by the utility companies was the included data capture of parts of other utilities placed near the installed water pipes. Having access to the location of these nearby utilities is expected to be highly valuable in the future when revisiting the same area as many of the other utilities were missing or wrongly positioned in the utility map records provided by the other utility owners. An example of this is visually illustrated in figure 4. Based on the utility companies experience this was a common scenario as "soft" cable records are often lacking accuracy and completeness (Hansen et al., 2020b).

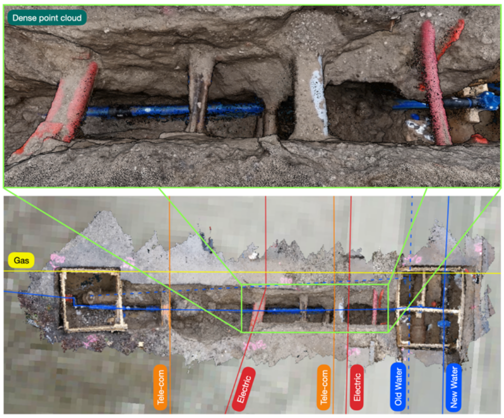

Figure 4. Comparison between existing GIS utility records and as-is excavation hole point cloud seen from above (bottom) and a zoomed in 3D view of a section of the point cloud (top).

Another common example is shown in figure 5. Besides some missing utilities it is evident that existing records are lacking completeness and detail. For example, map records do not show how many cables are located on a given utility vector line. In the point cloud, four more cables are visible compared to the utility line extracted from the map records, making the total area of occupied space larger than anticipated.

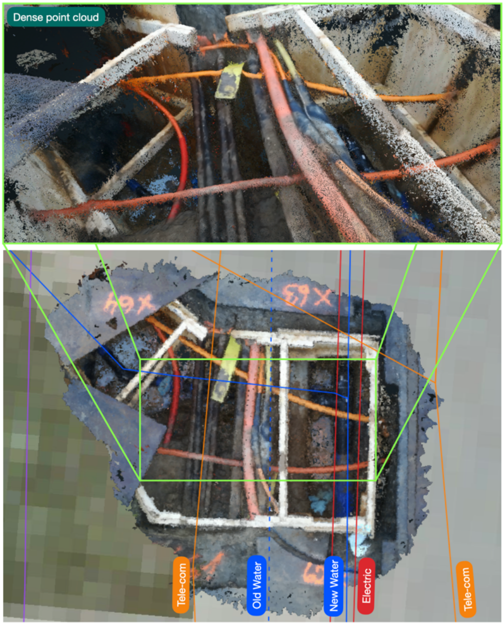

Figure 5. A similar comparison between existing GIS utility records and as-is excavation hole point cloud seen from above. The orange tele-com lines lack completeness.

For now, the 3D capture models are only used for internal use within the respective utility companies. However, the utility companies hope to potentially exchange their point cloud data with other neighbouring utility owners as 3D capturing solutions become more widespread.

3.1.2 3D ground penetrating radar data capture of large areas: Ground penetrating radar (GPR) is a non-destructive technique that can be used to detect and locate subsurface utilities using electromagnetic waves that are sent into the ground. Non-destructive techniques such as GPR can reduce and potentially even remove the need for techniques that rely on direct access or line of sight for mapping previously built utilities, reducing disruptions and nuisances, risk, and cost that come with excavations, in particular on public roads.

While a case study in Singapore in 2018 concluded that a one-off area-based mapping approach utilising a 3D or multichannel GPR is not feasible nor economically viable (Van Son et al., 2019), inspection of the data and the case study results shows that valuable information on underground conditions was obtained and that there were significant discrepancies between the detected utilities which were extracted as 2.5D points and lines and the available GIS information on existing utilities.

Notable observations from the case study were that many GIS records did not match their counterparts mapped from the GPR data with sufficient accuracy and that it was not possible to confidently match all GIS records with their GPR counterparts and vice versa. Moreover, legacy GIS records were available in 2D only, lacking elevation information that could be obtained from GPR.

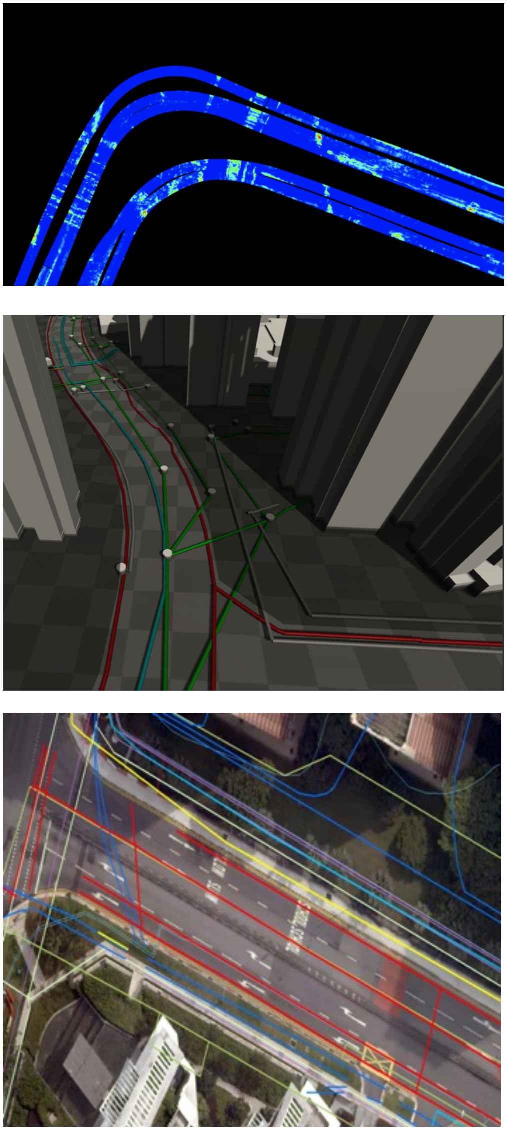

Figure 6. From top to bottom: (i) top-down view of primary GPR data, (ii) 3D render of extracted results, and (iii) comparison between utilities from GPR scans (red) and available GIS records

While additional observations would be necessary to confidently link GIS records and GPR vectors, the results demonstrate both the need for legacy data reconciliation in Singapore and the potential use cases that could be supported, which include validation, upgrading from 2D to 3D, and repositioning.

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4. CHALLENGES IDENTIFIED IN PRESENTED CASES

From the presented cases, a number of challenges could be identified that range from social to financial to technical ones. The first is technological readiness. Adoption of state of the art survey techniques such as those based on photogrammetry and geophysics was observed to be low in Denmark and Singapore and surveyors would usually opt for conventional, direct measurement techniques instead. However, the smartphone-based Reality Capture solution used by the two utility companies in the Danish case was concluded to be a feasible surveying solution indicating an encouraging sign of achieving higher technology readiness (Hansen et al. 2020a). Moreover, asset owners' data management systems are often not yet able to ingest, store, share, or use data captured in complex and rich 3D representations as well as data with varying degrees of quality and fidelity.

The second challenge is a possible lack of incentive to capture the necessary data or improve data quality. In many jurisdictions around the world, utility companies are not liable for the quality of information that they provide. Furthermore, the example cases show that there are opportunities to survey types of utilities that do not belong to or are of interest to the companies mandating or performing the work. It would be questionable to assume that such companies would invest effort and resources in capturing, improving and sharing such data. This links closely to the third challenge which is that of cost. Performing the necessary data capture during suitable opportunities and upgrading data management systems to handle new data sources requires a significant financial investment that is unlikely to yield a return in the short term. And fourth, it may not be desirable to make information on certain utilities known between parties due to security and business concerns.

5. CONCLUSSION AND FUTURE WORK

The integration of heterogeneous data sources captured at various opportunities during the life cycle of subsurface utilities could be used to improve data quality and reconcile legacy data. Example cases show that data captured using techniques such as photogrammetry and ground penetrating radar could be used for various quality improvement use cases.

To achieve the objective of gradual and sustained improvement of data quality, critical challenges need to be overcome. We propose that further research focuses on three key elements that together could form the basis of a robust framework for the reconciliation and improvement of subsurface utility data.

5.1 Investigate specific data quality improvement scenarios

First, future research should develop a comprehensive overview of relevant data sources for quality improvement. It should investigate what heterogeneous data sources with different quality (e.g., accuracy, reliability, resolution) can contribute to data quality improvement and in what way (e.g., validation, position accuracy improvement). Besides the techniques demonstrated by the examples in this paper, the research could consider eye observations which do not result in geometry or location information but rather information about it (e.g., on aberrant alignments, or confirmations of correct alignments). From a pragmatic perspective, it is recommended to focus on data capture opportunities that are already occurring but are not yet utilised to their full potential. Open trench excavations - both for when new utilities are installed and existing utilities are partially exposed and trial holes to verify existing utilities - are logical starting points as they are typically unavoidable.

5.2 Development of a data model

A data model needs to be developed that meets a number of requirements in order to facilitate data integration and data quality improvement. First, the data model needs to be able to integrate and connect various data sources, ranging from legacy data to newly captured data sources. To enable a degree of automation for quality control and quality improvement, Integration should be established through more than georeferencing alone, for example by establishing a common and persistent reference to physical utility assets or structures. Second, the data model needs to be able to support a range of data capture techniques and data types. For example, while legacy data may be available as 2D GIS or CAD files, newly captured data could represent utilities as 2.5D or true 3D geometry. It is also important that both primary and processed data can be integrated and stored, as primary data sources could serve as valuable sources for future data quality improvement. Third, the data model needs to clearly define data quality and its descriptors (e.g., accuracy, completeness, consistency) in order to measurably assess and improve quality.

It is recommended to further build upon data models for subsurface utilities that are designed to integrate various data sources such as the MUDDI model (Lieberman, 2019) and the Singapore Underground Utility Data Model (Yan et al., 2021).

5.3 Development of a framework for governance and master data management

There needs to be a clear definition of the roles and responsibilities of all stakeholders required for data reconciliation. National utility asset information exchange systems such as those in Denmark, The Netherlands, and the United Kingdom are all organised as variations of decentralised "registry" architectures where utility owners manage and maintain data pertaining to their own assets and make their data available to users through a common portal (Figure 7 top part). In such cases, the responsibility for data quality improvement is assumed to be primarily with the utility owner. For such cases, the effectiveness of legislation needs to be assessed. Relevant examples include the direct mandate of quality improvement in France (Zeiss, 2021) where utility owners are responsible for improving data quality when they are not able to provide them to requesting entities at the indicated quality level, output-oriented accuracy requirements for provided data (e.g., ±1m horizontal accuracy for utility data in The Netherlands), or indirect incentives imposed by regulators such as on asset resilience which is assumed to be affected by unreliable information resulting in excavation damages (OfWat , 2019).

However, identified challenges such a lack of technological readiness and incentive among individual utility owners may result in a siloed and ineffective approach to data reconciliation. Instead, a more centralised approach where data is stored and improved in a single, dedicated system could be explored as well (Figure 7 bottom part). Such a system would collect survey results directly from relevant opportunities such as construction projects, reconcile (legacy) data stored inside, and provide the updated and improved results to the individual utility owners and other beneficiaries.

This contribution has been peer-reviewed.
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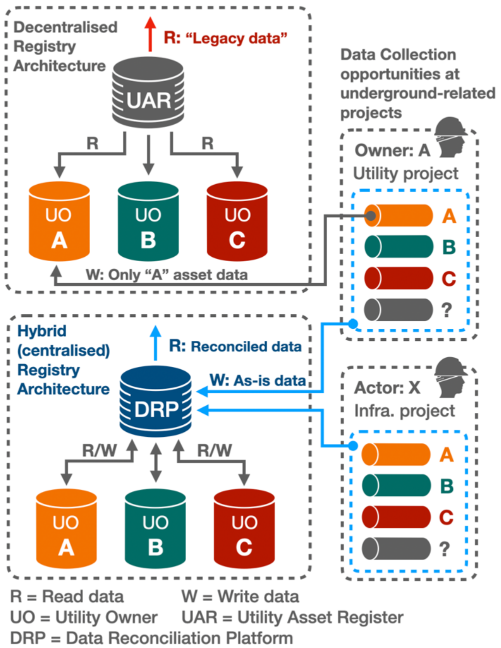

Figure 7. Traditional decentralised-based Utility Asset Register (top part) compared to a centralised-inspired approach (bottom part) that integrates a Data Reconciliation Platform to reconcile sourced Utility Owner data with new captured as-is data.

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5.2 Discussion and future work

To start this final discussion about Paper V, two challenges identified in the Danish use cases are elaborated and put in perspective to the other already presented papers in this thesis.

Firstly, we advocated for the use of 3D capturing methods of subsurface utilities as a data source to improve the quality of the existing utility records, however, it is only used by a few water utility companies in Denmark, which means only a one-way exchange for 3D capture data is possible between utility owners. While this is beneficial for the receiving part, it is not an incentivizing model for the sharing part. A more widespread use of 3D capturing techniques across utility owners are needed. However, as introduced in Paper I, the smartphone-based Reality Capture solution used by the utility companies was concluded to be a feasible surveying solution and therefore seems promising as well as other easy-to-use 3D capturing solutions targeting subsurface utilities (Zeiss, 2021). Despite the promising development in 3D capture solutions, the lack of platforms and legalisation to exchange and support such 3D capture data is an added challenge. The current Danish utility data exchange platform (LER) does not support 3D capture data nor will it likely do so in the nearby future. As mentioned in previous papers the Danish Agency for Data Supply and Efficiency is in the process of implementing a new utility data model, named LER 2.0, based on the GML format, which only supports 2.5D vector data. This means, utility owners cannot share 3D capture data as an integrated utility information data package through LER. Instead, this data exchange has to do be done separately and disconnected from the LER supported data.

Secondly, we expect it to be unlikely that utility owners' data management systems can effectively store data that only describes a small exposed segment of their assets. On top of that, a point cloud in its primary data form is a non-semantic 3D model. This means, that such 3D capture data merely represents a "3D picture" of the exposed utility assets at a given time, without actually being able to integrate with existing utility records other than through georeferencing. In other words, such sets of georeferenced 3D capture models alone just equals some systems like 2D photo-sharing services, e.g. Flickr, just in 3D and with higher geographic accuracy. Returning to AR, this also becomes a challenge, e.g. on site with our AR prototype and two heterogeneous data sets available. One data set as GIS-based poly-lines and another set as 3D capture data. Drawing connections between such two data sets is still subject to the mental capabilities and skills of the utility worker in the field. The mentioned example did actually occur in AR during one of the hands-on demonstrations as shown in figure 5.1.

Fig. 5.1: AR prototype displaying both a 3D point cloud and GIS-based vector line data representing the same subsurface utilities

For future work, an interesting challenge would be to segment the 3D capture data in such a way that it will match the semantics of a utility data model. For instance the upcoming LER 2.0 data model mentioned in Papers IV and V. To be able to automatically semantically label parts of the 3D capture models would be a first step to directly link 3D capture data to utility map data. In recent years, artificial intelligence, including 3D Deep Learning, has been a popular approach to achieve semantic segmentation of 3D point clouds (Guo et al., 2020). For instance to automatically segment 3D point clouds of street corridors (Behley et al., 2019; Hackel et al., 2017) into categories such as building facades, lampposts, trees, etc. However, little to no research has investigated using 3D Deep leaning with 3D capture data from subsurface utilities. Another approach, presented by Beil et al. (2021), demonstrated how semantic a 3D city model was used to segment 3D point cloud of a street corridor from the same city. A 3D buffer of the semantic city model was used to encapsulate and segment the corresponding part of the point cloud. This approach of course relies on both 3D model data sets being closely geospatial aligned, which is not given in the case of subsurface utility data sets, as demonstrated in Paper V. However, Beil et al. (2021) further demonstrated how the two 3D data sets could be integrated in the same data model by using the international OGC standard CityGML version 3.0 (Kutzner, Chaturvedi, & Kolbe, 2020) which provides a new PointCloud module allowing point clouds to be integrated directly in a CityGML data file or separately stored as point cloud file types, e.g. LAS.

A direct semantic integration and connection of semantic utility data (e.g. LER 2.0 data) with corresponding 3D capture would also meet some of the respondents preferences mentioned in Paper IV, which was to connect and read attribute information from LER utility data directly while visualizing as-built 3D capture data in AR and thus enabling entirely new forms of data interaction with 3D capture data in AR. Figure 5.2 shows a mock-up of such a concept in AR, which would allow for similar touch-to-interact capabilities as the ones presented in Paper VI.

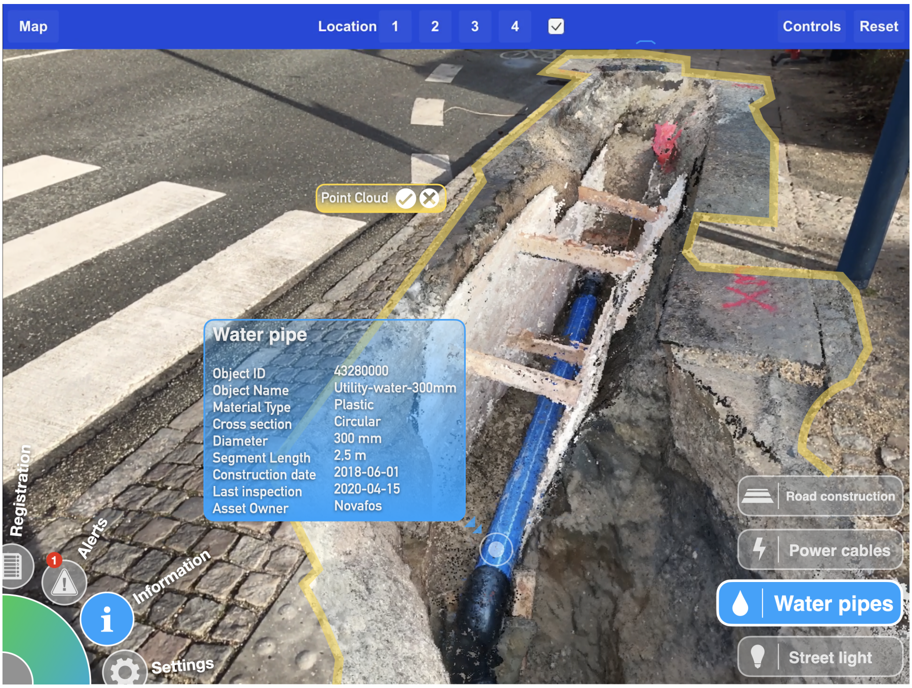

Fig. 5.2: AR concept of visualizing semantic 3D capture data displaying attribute information about a water pipe

Chapter 6

Conclusion

This PhD project aimed at exploring how the use of Reality Capture and Augmented Reality (AR) could aid contractors and utility asset owners when working at underground infrastructure projects on site. The research aim was phrased as a research question:

How can the exploration and the development of new AR visualization and 3D capturing methods of subsurface utilities lead to informed decision-making for utility owners and contractors when planning and managing underground infrastructure projects?

To answer this research question, five papers have been presented. Paper I explored the use of an easy-to-use smartphone-based Reality Capture (RC) solution. Two Danish water utility companies were interviewed that had experience in using this RC solution. When the RC solution was compared against using traditional open excavation surveying methods for collecting data of subsurface utilities, several advantages was revealed. These advantages included time-savings for the contractor because of the improved surveying workflow, and providing a more comprehensible data output used for better quality assurance, as well as for planning future subsurface utility projects at the same location. The last advantage was obtained due to the automatic data capture of other types of utilities that were exposed during the excavation job.

Papers II, III, and IV presented how the data output of the RC solution could be used in an AR use case for supporting subsurface utility engineering on site. The solution presented was an AR prototype that allowed for accurate and robust in-situ visualization of 3D capture data with close alignment to the real surroundings, which overall provided a comprehensible AR visualization that was greatly appreciated by the contractor and utility owners. The AR visualization of as-built 3D capture data allowed for a more informed foundation in the decision-making process during planning and excavation at site. The AR visualization provided a clear understanding of the positional placement of the utilities as well as providing enough realism and detail to identify the type of utilities and material properties. When planning for utility work, the interviewed respondents all agreed that this would be extremely useful for avoiding excavation damage. This was especially true since one of the major issue regarding excavation damages was caused by inaccurate and incomplete utility records according to the majority of the respondents interviewed in this PhD project.

Despite how clear the use case of visualising 3D capture data in AR to help inform utility owners and contractors in the planning process was, it was just as clear, how the availability of such 3D capture data was needed to support the AR use case. Through interviews it was further made clear how current legalisation and requirements regarding data collection of existing utility records would possibly act as a barrier for the adoption of this AR use case, because such 3D capture data is currently not supported in the Danish utility data exchange platform nor is it planned to be supported in the nearby future. However, what was evident from the interviews was the reliance on utility records sourced from the utility data exchange platforms as this data source was the best available when planning for utility work. This prompted the development and design of a new AR visualization method that targeted conventional poly-line utility data as visualization source presented in Paper III. The result was a method for visualizing subsurface utilities as virtual utility markings providing close and seamless blending with the ground surface as well as adapting current marking design schemes from industry guidelines. According to the respondents the new visualization method provided a clear overview of the available utility record data as the virtual marking was easy to comprehend. The respondents most noticeable remarks were their liking of how the virtual markings closely aligned with the ground surface and the familiar use of colors, line style, and abbreviation symbols.

Lastly, in Paper V, the scope focused on the issue of unreliable and inaccurate subsurface utility information found in legacy records, which also previously has been highlighted by the interview respondents in Papers I-IV. In the paper, an argument was made that 3D capture data as well as other data sources captured at various opportunities when surveying and collecting data of underground infrastructure should be used to improve data quality of legacy records. While the paper does not directly contribute to answering the research question in this PhD project, it does argue that the RC solution presented in Paper I as well as other data capture methods should be utilized more so as to mitigate more quickly the issue of inaccurate utility data. Whether that improved utility data ends up as conventional poly-line vector data or 3D capture data, it can be used as visualization data by the two developed AR visualization methods. Ultimately, using AR or not, this will allow for a more informed decision-making foundation for utility owners and contractors when planning and managing underground infrastructure projects.

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Appendix A

Paper VI: Augmented Reality for Infrastructure Information

The following paper, referenced as Paper VI, is titled: *Augmented Reality for Infrastructure Information: Challenges with information flow and interactions in outdoor environments especially on construction sites.* The paper has been published in the *Conference proceedings of the 37th eCAADe, 2019* as an open access paper through The Cumulative Index of Computer Aided Design (CumInCAD)

Augmented Reality for Infrastructure Information

Challenges with information flow and interactions in outdoor environments especially on construction sites

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This paper discusses Augmented Reality (AR) as means to interact with information regarding infrastructure projects before, under and after construction. For that purpose, two different prototypes were developed using Apples ARKit and Unity's game design platform and tested on two use cases. However, the main focus of this paper is interacting with infrastructure information through AR rather than researching core AR technology. We learned that using AR under the constructing phase with subsurface utilities is still facing several difficulties. Especially when it comes to accessing and interacting with information in a changing construction environment. These difficulties will be discussed and also the challenges regarding information flow between civil engineering and AR software.

Keywords: *Augmented Reality, ARKit, Information flow, Subsurface utilities , Highway construction project, Construction site*

INTRODUCTION

Construction projects in the infrastructure and building domain are frequently experiencing cost overruns and delayed time schedules. Consequently, governments are facing budget overruns and using more money than expected since especially infrastructure projects are public funded. The problem is among other things related to the construction sector being one of the least digitized sectors. Therefore, an EU task group emphasizes that Building Information Modeling (BIM) must be the digital driving force to streamline workflows in their 2017 report [1]. This is a must if the infrastructure and building domain wants to be more efficient, minimize errors and avoid bad communication.

Meanwhile in the age of the fourth industrial revolution digitization is appointed as the foremost driving force of continuous economic growth and hereby the Boston Consulting Group has further appointed Augmented Reality (AR) as one of the nine technological building blocks (Brunelli et al. 2017). They believe that workers will use AR to access and interact with graphical information at the factory floor that are connected to a digital copy of the entire factory. These days, some might want to call this connected digital copy of the physical environment a Digital Twin. Similar on a construction site AR can be used to ease access to project information and thereby support faster and better decision-making. A recent evaluation test on using AR visualization techniques compared to traditional PC-based visualizations has shown that using AR on site increases the use and understanding of technical construction information (Meza et al. 2015). Compared to a user perceiving a 3D model on a normal PC monitor the study showed AR was up to 20% better in understandability and usability. Additionally, it was concluded that a well-formed digital model, similar to BIM models, was needed before architects and engineers could take full advantage of AR.

In recent time AR is going through a lot of popularity in the media. Pokémon GO, a location-based AR game for smartphones, was one of the big headlines in 2016. Also, Microsoft released HoloLens and Apple and Google released AR tracking frameworks native to their mobile operating systems. Regardless of the popularity; there still exist a need to advance the field of AR applications within the building and infrastructure domain, as well as other use case domains. Surely the phenomenon of Pokémon GO made AR evident for everyone and in the slipstream of that, even executives started asking for AR in a professional context expecting the technology to be mature for a broader utilization.

Scope / Aim

The presented paper is partly an outcome of such demands where BIM models designed at engineering consultancy companies are suggested to be "used for more". They are pointing at Virtual and Augmented Reality technologies to be used towards their clients and project partners to ease communication dealing with technical information, but also to improve model design before construction. Therefore, a research project, which is still on-going, was established together with a large Danish based consultancy company (COWI), a small software developer company (Epiito) and Aalborg University to explore these possibilities. The overall aim was to develop an AR prototype to access infrastructure information in the field by using the already made 3D design models by the engineering consultancies. Another goal was to use a device type that was accessible and familiar to use for partners and clients to ease a possible future implementation of a finalized AR solution.

We present our initial findings based on our prototype developments and tests from two use cases. The prototypes were developed over a period of one year in a two-step process as prototype 2 is a further development of prototype 1. Both prototypes were designed for a specific infrastructure project and specific AR use case in mind. The infrastructure projects

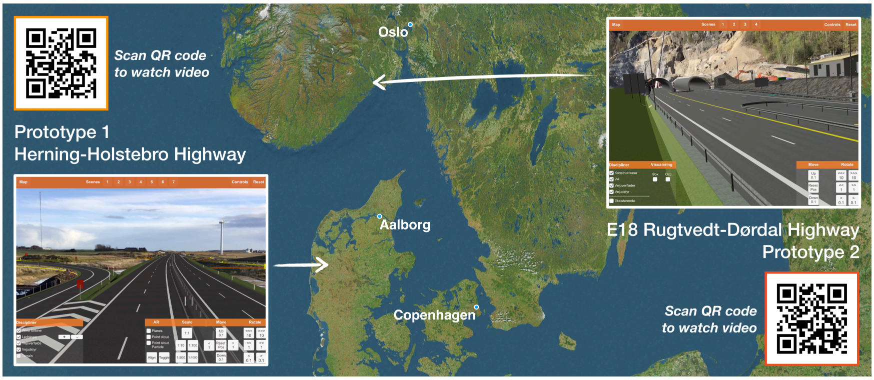

Figure 1
The two infrastructure AR use cases located in Denmark and Norway.

consist of two major highway constructions respectively located in Denmark and in Norway as shown in Figure 1. Prototype 1 is related to the planning and design phase showcasing the new infrastructure project as a possible new development on site in relations to for instance politicians and neighbours as well as engineers inside the project. While prototype 2 aims at the construction phase helping the contractor to visualize the progress of the construction work by visualizing the project on site and enabling the alteration of status information to infrastructure sub-utility elements on the construction site. This is done by implementing the open IFC data model together with the Building Collaboration Format (BCF).

Paper structure
In the following section previous AR work done in the academic field is presented together with the current commercial AR development. It is focusing on similar AR application use cases for inspiration and to address current challenges and limitations prior to the development. Next in the third section the prototype development and functioning are presented as well as the reasoning behind the selected AR hardware and software. It continues by presenting the information flow between civil engineering software and the AR prototype 1. Continuing in the fourth section with results from prototype development and findings from the AR prototype 1 test, but mostly findings from the more mature prototype 2 tested on a construction site. Finally, in the conclusion, we revisited our findings and discuss recommendations and further work for the ongoing research project.

BACKGROUND
AR is a technology that combines the virtual and physical world by placing virtual content directly in the user's surroundings. Recent examples of AR in everyday life is the popular mobile game Pokémon GO released in the summer of 2016, where virtual monsters appear in parks and cities by looking through the smartphones video feed. Snapchats face-filters is another example and perhaps the most widely used AR feature today.

Previous work
Using AR for games and social media is not the only use case. Neither is the idea of using AR for construction projects to optimize workflows and ease communication. In fact, the building and infrastructure domain has been a popular area of showcasing the potential of AR. One could even say that it dates back to the first outdoor Augmented Reality system which visualized a 3D model of a historical building on its former site (Hollerer et al. 1999). Here after Roberts et al. (2002) made an AR system to visualize the subsurface utilities beneath the ground. The system also manages to archive centimeter level positioning and orientation by the integration of Real-time kinematic GNSS and an Inertial Navigation System (INS) unit. A quite impressive achievement at its time. This was before the mobile revolution, which meant the fact that all mentioned AR systems needed to be carried with backpacks to contain all the necessary computer power and sensors. This made it nearly impractical to use in everyday tasks. Computer graphics were still very poor, and calibration was a big issue compared to what today's AR systems are capable off. Though, enough to show the potential of AR.

AR applications that enabled users to look into the ground and see subsurface utilities continued to be a popular theme. As technology progresses and AR hardware shrinks in size and weight Schall et al. (2009) made a handheld AR system that visualized underground infrastructure to aid field workers of utility companies. An AR application to perform virtual redlining in outdoor environments (previously done manually by annotating on printed maps or 2D GIS systems) was also made on the same AR system Schall et al. (2008). The AR system was substantially more compact than previous systems and featured different visualization techniques to archive a better depth perception - like making a virtual cut-out in the surface. The reason was to aid the user in perceiving a comprehensible AR visualization, since the human brain is not used to see through an opaque surface. Even though the AR systems were able to operate in a handheld manner an evaluation showed that the ergonomics of the device still has potential for improvement before broader implementation among field workers. This was as well done on a rather clumsy device compared to modern smartphone and tablets. Still the AR system was comprehensive by combining Real-time kinematic Global Positioning systems and computer vision techniques to obtain a tracking solution with centimeter-level accuracy Schall et al. (2013).

After the first smartphones became available - pre iPhone era - it was soon used for Augmented Reality purposes. Also in the research field, as Woodward et al. (2010) presented their mobile handheld Augmented Reality system for construction site visualization and communication to support BIM tasks. They were able to use an IFC file of a proposed building design and thereby achieve object-based level of interaction with the augmented design model. An example of this is their work on time scheduled (4D) simulation presented on the same AR system (Hakkarainen et al. 2009). AR used in the construction phase are also demonstrated by Zollmann et al. (2014) AR system for construction site monitoring and documentation. The system could perform tasks such as annotating and surveying that will stay situated and attached to the underlying 3D reconstruction model of the construction project.

AR applications for the construction phase have shown to be a popular area in recent time. In a literature review done by Brioso and Calderon-hernandez (2018) a total of 46 articles from a five year period containing AR and BIM was reviewed. It showed that approximately ¾ of all AR applications were from the construction phase. Their review also showed that the three biggest limitations/challenges (out of ten) was (a) visualization techniques with occlusion as the main issue, (b) alignment of the virtual AR content with the real surroundings and (c) limited device/hardware capabilities. It is worth mentioning that ergonomics was the least occurring limitation/challenge found in the review. A shift compared to challenges addressed in Schall et al. (2009) AR application evaluation.

Looking at the more broader AR research field the challenges found in AR/BIM seem to be consistent. A recent article reviewing the past 10 years of AR research presented at the International Symposium on Mixed and Augmented Reality (ISMAR) shows that these five topics are the most cited in 2018; (1) mobile AR - possible because of the evolution in powerful and sensor-rich mobile devices, (2) spatial reconstruction of real surroundings - which can be used to make occlusion for visualization techniques, (3) Tracking and positioning techniques - which can help align the virtual with the real, (4) AR application and (5) Evaluation. Where the latter two topics most likely are related to each other, and the reason behind might suggest that AR is maturing, because more evaluations are conducted on real users. (Kim et al. 2018)

Commercial AR development

Another sign of AR is maturing, is the recent and frequent announcement of AR related products and software support from big tech companies like Apple, Google, Microsoft, Magic Leap etc. It already seems like a while since HoloLens was released in March 2016. And just to show how tremendous the development has unfolded; consider this. In 2015 a comparative study of AR SDKs was conducted comparing AR tracking SDKs from Metaio, Vuforia, Wikitude, D´Fusion and ARToolKit (Amin and Govilkar 2015). Today, this comparison study is almost useless because of the release of native mobile tracking SDKs for Apples and Googles handheld devices; respectively ARKit (iOS) and ARCore (Android). Today these SDKs are the default choice. Now developers can use these well-functioning AR frameworks that does not require calibration, because Apple and Google (to some extent) make their own devices and then already are pre calibrated. Thus, also making the tracking more robust and reliable. This newfound easily accessible tracking framework encourages developers to develop AR applications even more. As an additional consequence, popular game design platforms like Unity and Unreal Engine have incorporated the frameworks in their platform editors. Even though these platforms are mainly focusing on game developments their editors are widely used for other professional domains for AR and VR related applications.

Also, product companies within the building and infrastructure domain have been showing involvement with AR. Trimble now lets SketchUp support AR by using Apples ARKit framework on iOS devices and also supports Microsoft HoloLens. Trimble also has a working mobile outdoor AR prototype system called SiteVision, running on an Android device with Googles ARCore framework and connected to an external GNSS receiver. As mentioned, combining a GNSS receiver has been done before by individuals in academia, but the interesting part is that it soon becomes accessible in a ready-to-use commercial package. If so, high accuracy location-based AR technology will be available for professionals as well as academics. The AR marked is moving fast so properly by the release of this paper the mentioned and new AR products will already be available.

AR PROTOTYPES

From studying previous work, it got evident that an outdoor AR system needed to integrate some kind of high accuracy external GNSS receiver combined with advanced vision-based methods to instantly obtain a high precession global position and orientation of the visualized AR content (Schall et al. 2013). However, such a comprehensive system was beyond our capabilities to develop and no commercial solution could offer this. Perhaps the Trimble SiteVision would be suitable, but this solution was not at our disposal at that time and was a working prototype still connected to the Google Tango device.

Beside that, several existing solutions were tested based on mobile or tablet devices. They were based on either Vuforia or similar AR frameworks. But none of the tested solutions gave a convincing performance and impression of quality, which would fulfil the demands of a useful professional application. This led to further encouragement in pursuing our own development of a prototype.

It was decided to go for a handheld device that was familiar to use and easily accessible from the market i.e. a modern smartphone or tablet. Whereas the preferable option was a tablet, because of the larger screen size. A head-mounted display (HMD) with optical see-through was quickly declined based on experiences with the Microsoft HoloLens (the HMD available at our disposal at the time) in outdoor daylight conditions and by studying previous work from Schall et al. (2008;2009;2013) and others. However, a hands-free AR experience would be preferable, the trade-off in using video see-through display technology is the better option for our use cases.

As mentioned in section 2 the state-of-the-art tracking AR framework for handheld smart devices is now considered by most being either ARKit or ARCore. Since it was decided a tablet was the preferred device the obvious choice was to use ARKit, and an iPad Pro 12.9" (2. gen.) was selected. This was also due to the limited Android devices supporting ARCore which at that time did not include tablets. As for the app development Unity was chosen, which had released a plugin for Apples ARKit. Figure 2 shows the handheld iPad in action running prototype 1 in AR mode.

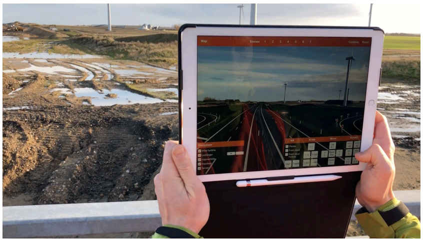

Figure 2
Prototype 1
running in AR mode
visualizing a
highway
construction.

Developments and practical implementations

There were primarily two main challenges building the prototypes; (a) developing an application for the handheld device enabling the user to *geo pose* a virtual model into the real world at a defined geographical positioning and orientation, and (b) establishing an *information flow* that enabled acceptable data exchange between the civil engineer CAD software and the Augmented Reality prototype application.

The following subsections explain the fundamentals of the developments which for a large extent were similar on both prototypes. Although the Prototype 2 looks very similar to prototype 1 they differ on several important parts which are essential to cope with for a future development of a professional AR application.

Geo Pose

There exist several methods to geo pose a virtual model in the real-world view, and most of the AR developments have been focusing on sensor fusion to deal with this challenge as described in section 2. The following workflow on the other hand is built around the functions available in the ARKit SDK provided by Apple. By design ARKit version 1.0 is a model-free tracking framework, and its main feature is to place virtual models randomly onto a planar surface. ARKit uses the RGB camera on an iOS device to detect patterns in the texture of a given planar surface. Once detected it generates a surface that can be used to place a virtual model on top by tapping on the surface displayed on the iPad screen. The virtual model then appears on top of the planar surface though with a random orientation. This method works really well for indoor environments on a texture-rich wooden floor or table to show furniture, but it is not ideal for a large-scale AR outdoor situation where the model should appear in a specific position and orientation. However, by programming some additional functions it was possible to come up with a method to manually adjust the virtual model. The following steps describes the process.

Step 1. The AR prototype is developed in such way that it allows the user to select a predefined spatial position (x, y, z) in the virtual model, which must correspond to an identifiably position in the real world. Therefore, the user must first place himself on the physical predefined position as shown in figure 3 (left)

Step 2. The AR system detects the surrounding surfaces when the user is panning the device around in a circular motion while the camera points down at the ground. This is the process where the ARKit functionality is detecting natural features in the surroundings from the video input.

Step 3. The user taps slightly with the finger on the iPad display where the defined virtual position is supposed to appear in the real world. This places the virtual model on the registered surface connecting two dots. To help the user to tap the right place, the defined positions should be marked physically or should be easily recognizable like for instance a well on the pavement surface.

Step 4. The user selects the virtual position by using the scene buttons to adjust the user's physical position for instance the height of eye placement. Thus, the virtual model is moved to its correct position and matches the correct point of view by the user.

Step 5. As mentioned initially the orientation of the virtual model has been chosen arbitrary by the sys-

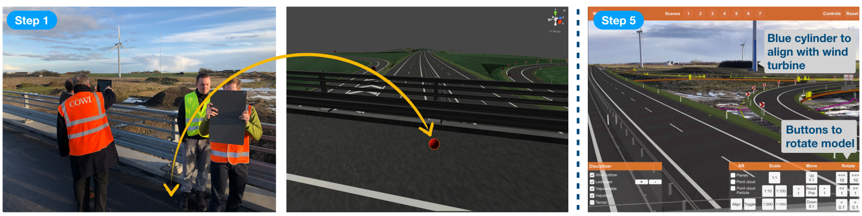

Figure 3
Left: The yellow arrow indicates the same physical and virtual positioning. Right: Orientation of the virtual model relative to the real world.

tem and has to be adjusted so it aligns with the real world. The rotation is done manually using the control buttons. An example is shown in figure 3 (right) where a virtual blue cylinder has been inserted into the model representing the existing wind turbine. Thereby the wind turbine acts as a landmark and is used to adjust the virtual model primarily by rotation. The control buttons are placed on the lower right side of the view.

Information flow

In prototype 1 and 2 the initial design model was created using professional CAD systems such as MicroStation/InRoads and Novapoint/AutoCAD. During prototype 1, the data exchange was carried out manually converting and recreating model files into either the FBX or OBJ format, which is a readable object file format within Unity. Figure 4 shows a flow chart of the process which consists of the following steps:

1. Move the model from a global to a local cartesian coordinate system.
2. Import model into 3DS MAX (or some other modelling software) using the DWG format.
3. Make sure all normal vectors of the surfaces are pointing in the direction towards the user.
4. Create a corresponding material library with textures.
5. Attach the materials to the model.
6. Export the model in FBX or OBJ format together with the material file.
7. Load the model and materials into Unity

TESTING OF THE PROTOTYPES

Prototype 1: Herning-Holstebro Highway (Denmark)

The Herning-Holstebro highway project was selected as the first case to explore AR applicability in the field. Therefore, one of the goals were to actually build and test a working prototype which used the ARKit tracking frameworks in order to test the tracking ability in an outdoor environment. As can be observed in the video (www.vimeo.com/276430462) the movement of the combined view consisting of a real-world video capture and augmented virtual 3D model is very smooth and stable. There was hardly any drifting in the model and the interface developed turned out to work as intended. Even though the model con-

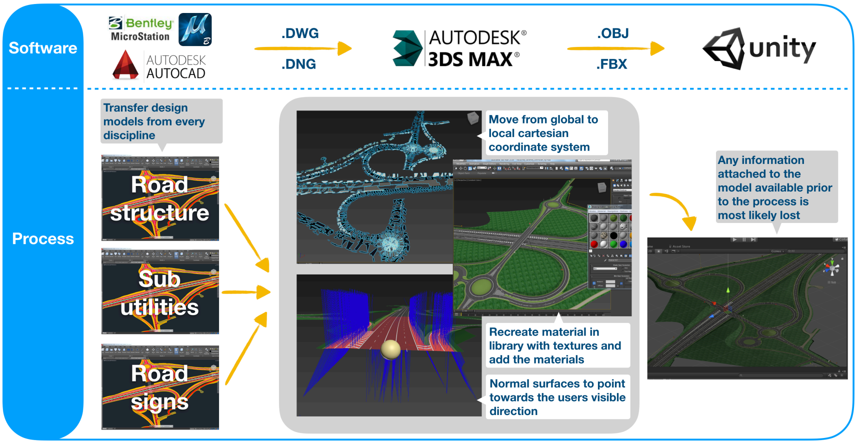

Figure 4
Workflow of how to transfer design models from CAD software to a game design platform. This method was used in prototype 1.

tained around 1.4 million polygons the iPad had no trouble handling the data.

Results from the manual geo pose method. As soon as the model is fixed into the real world view it handles very steady and the iPad can easily be passed to another person without any major drift in the situated virtual model. It was also possible to turn around 360 degrees without any loss of orientation. Compared to other systems we tested this was a very uplifting experience.

Results from information flow. The 3D model of the Danish highway which was chosen for prototype 1 had a high level of geometry detail but had no attribute data attached to its design objects, which in principle meant that it didn't really apply to a BIM model but merely consisted of a "dumb" CAD model missing any semantic definitions. Explained in another way the model was well-formed, but not well-informed. In this case though it was sufficient because only the visual experience was in focus. However, the transfer the design models from CAD tools to the Unity Editor it turned out to be one of the most tedious challenges. As illustrated in figure 4, a manual workflow transferring the design model from CAD software to AR system was found, but only to obtain one way information flow - not an information round-trip. The model had been modified so much that every possible information attached to the design model would had been lost. It was evident that the data exchange process between CAD software and AR system has to be improved considerably before AR can become practical in a day-to-day work environment.

Prototype 2: E18 Rugtvedt-Dørdal Highway (Norway)

The second prototype development differ mainly due to the data quality and enhanced user experience rather than enhancements with regards to the rather poor manual handling of the virtual model which was not developed further. A video can be seen here: www.vimeo.com/276431890.

The 3D model of this project situated in Norway had an equivalent high level of detail in geometry but in comparison to the Danish 3D highway model it also had a lot of attribute data attached to well-defined design objects of infrastructure elements. The Highway project used the design software Trimble Novapoint and Quadri; a cloud-based collaborative platform with its own object classification library for infrastructure elements. This represents in many ways an information model known from the building domain and suited for the open IFC data model format.

It was obvious to try to use this new possibility and use the identification and information retrieval of single objects in the model, and in the AR view. This prototype development was aimed at the constructor and the construction phase, and therefore the development had to determine functionality the constructor could benefit from. It was decided to develop a kind of progress indicator for certain objects. This way it should be made possible to tap on specific objects in the view and indicate the state of progress during construction. The idea was to use the Quadri platform and a direct link to the model database, but this turned out to be impossible due to a lack of a suitable API but also the fact that Unity and ARKit not is able to handle huge numbers used as coordinates i.e. a placement far away from origo.

The development during prototype 1 clearly showed a huge gap between the CAD design world and the game design platform environment. Therefore, efforts were on improving the data exchange workflow in prototype 2 trying to avoid the huge loss of information. A collaboration with the Danish software house Epiito, which at that point already had developed a software solution for importing IFC files, and also developed VR/AR apps in Unity, lead to prototype 2. Epiito had also developed their own cloud service solution (Epiito Cloud) for mobile VR applications. The original prototype 1 was then redesigned using Epiitos Cloud solution and IFC import.

It was investigated whether it was possible to make an IFC export directly from the Quadri model. It was, but the problem was that the IFC Road data

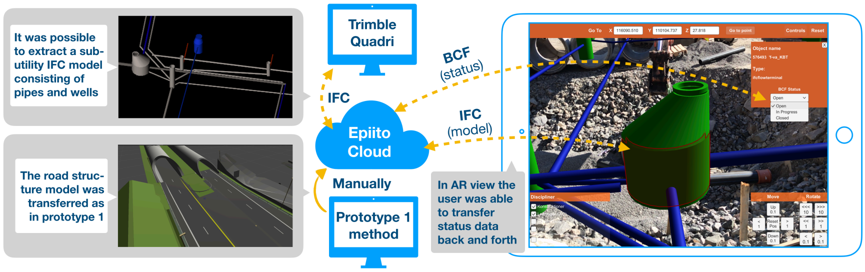

Figure 5
Illustration of data exchange in Prototype 2 using a combination of the IFC and BCF data model.

model (IFC 5) is yet to be developed by BuildingSMART [2]. The objects showed as proxy elements with no name. Wells and pipes however are two objects that are also found in the IFC 4 data model, hence these two were defined as *ifcFlowTerminal* and *ifcFlowSegment* in the current IFC model. That meant the remaining road model and other elements had to be converted similar to the workflow described in prototype 1 with a huge loss of data since the data model was much richer on information than the one in Denmark.

The user interface was optimized so the user could interact with the sub-utility elements by tapping on them, thereby reading the actual status and assigning a new status if desirable. The prototype uses the Building Collaboration Format (BCF) to transfer status information from the Epiito Cloud to the AR prototype. This new workflow is illustrated on figure 5.

The prototype worked as intended though the primitive manual positioning turned out to be less useful since this was on a construction site, and therefor subject to temporal changes. This makes it evident to use preselected marked points which equivalent spatial location do not change over time, like nearby buildings or bridges because for instance the earthwork is reshaping the terrain continuously. Certainly, a minor thing since a similar application in a professional edition would need GNSS enabled positioning anyway. A minor flaw experienced was lightning conditions even though we chose a video-see-through technology the sun reflecting on the screen could be annoying. A piece of cardboard helped to take care of the problem. The model was not as smooth tracking as in prototype 1. An obvious explanation was probably that the model in prototype 2 is 6 times bigger than in prototype 1 - 7,8 million triangles in all to handle for the iPad. Also missing a horizon as visual tracking guidance could have played a role together with the many movements occurring at a construction site. The view experience though was still fully acceptable.

CONCLUSIONS

The paper questioned; How can infrastructure information be accessed and handled using AR, and how can we interact with these virtual models, and retrieve or add information using AR in the field? For that purpose, two prototypes were developed with focus on content not technology. They were built with relatively ease and should encourage others to take advantage of the current state of development and free accessibility to AR SDK's. The presented AR prototypes combined an off-the-shelf tablet and the latest available mobile AR tracking framework from Apple. The iPad form factor has become familiar to most people and thereby provided a straight forward experience to access a model of a concrete construction site, therefore the majority of users had no problem to accommodate to the "new tool". However, the user interface design and interactions with the device needs to be improved, before a finalized AR solution can be implemented by the consultancy companies. Both engineers and workers expressed that the AR prototypes had great potential, but it needed to be more user friendly. Therefore, this is an area to improve in the further development and conduct more structured experiments with professional partners in the research project.

From the test results it could be concluded that the tracking part, which is one of the most important visual perceptions, is almost solved. In close relation to tracking is global positioning and orientation, which still needs to be a more automated process before AR becomes useful in outdoor environments.

Looking ahead these technological challenges are on the agenda of both small and major tech companies and recent announcement of AR related products and software support from big tech companies like Apple, Google and Microsoft proves that AR are beginning to mature. Therefore, if we want to embrace the age of the fourth industrial revolution we need to think of AR as a new media in which we can interact with embedded digital objects placed in the physical world.

ACKNOWLEDGEMENTS

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[1] http://www.eubim.eu/handbook/

[2] https://www.buildingsmart.org

Appendix B

Supplementary material: Smartphone-based Reality Capture for Subsurface Utilities

In Paper I an accuracy evaluation was carried out using a sample size of 41 point clouds measuring the error distance of 52 Check Points (CPs) that was marked at the placed water utilities (figure B.1). In the same figure three out of the 41 point clouds are shown, which ranged in area size from 1-20 m^2.

Fig. B.1: Three out of the 41 point clouds used in accuracy evaluation with area size displayed

Additional to what was presented in Paper I, the results of the RMS error measurements are also depicted as a normal Q-Q plot for the horizontal errors (figure B.2) and the vertical errors (figure B.3). The linearity of the points indicated by the high R^2 value suggests that the error data are normally distributed.

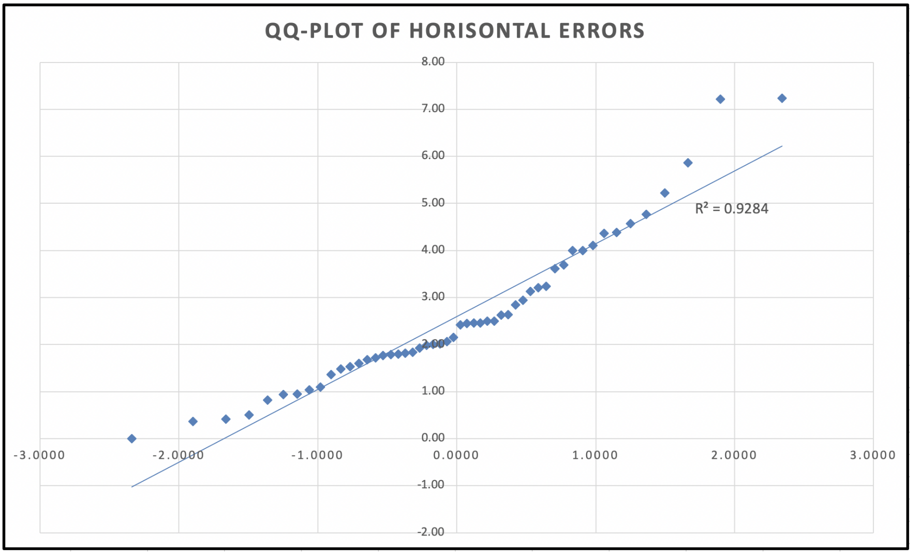


Fig. B.2: Q-Q plot of vertical RMS error distances. Y-axis values in cm.

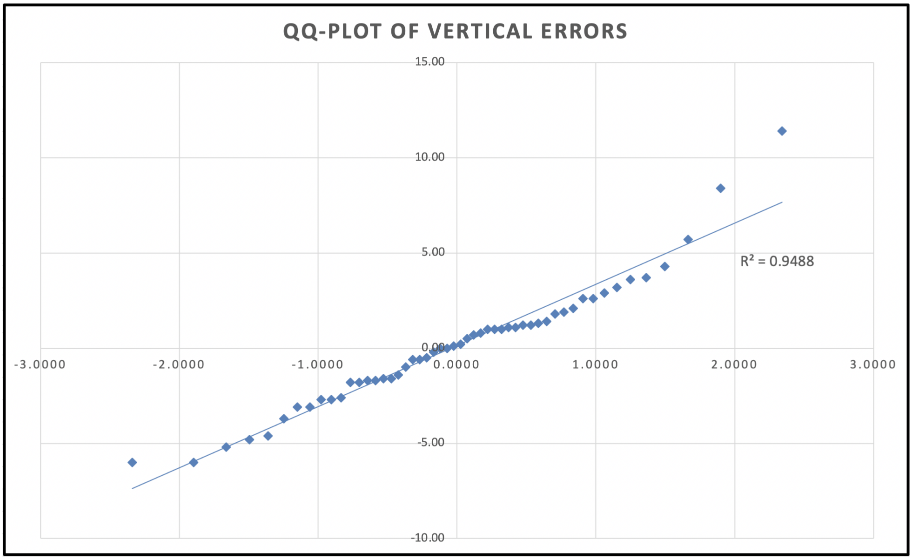
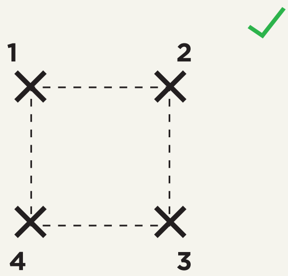
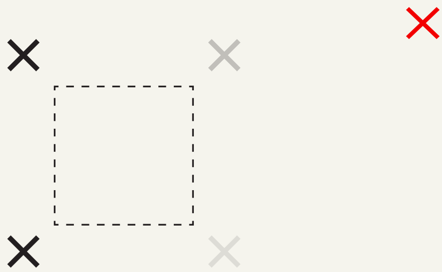


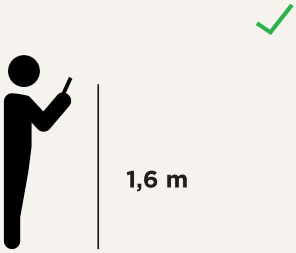
Fig. B.3: Q-Q plot of vertical RMS error distances. Y-axis values in cm.

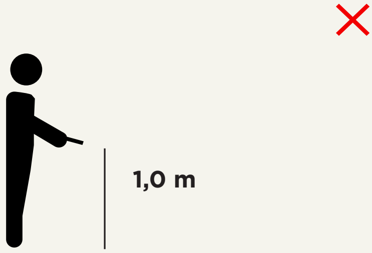
Lastly, the illustrative guides to promote correct and smooth video recording while using the Reality Capture solution are presented below. Reprinted with permission from IT34, ©2021 IT34 A/S.

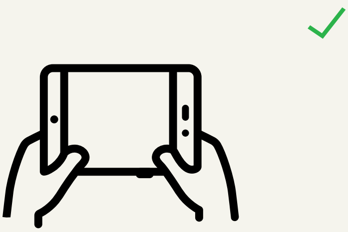
SmartSurvey™ Quickguide

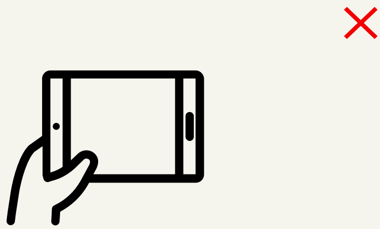


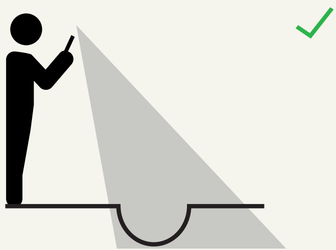


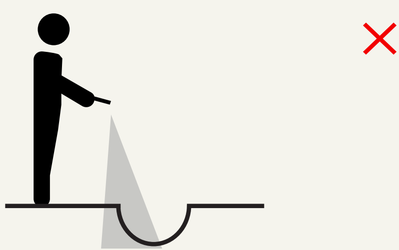




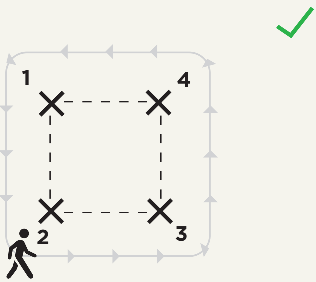


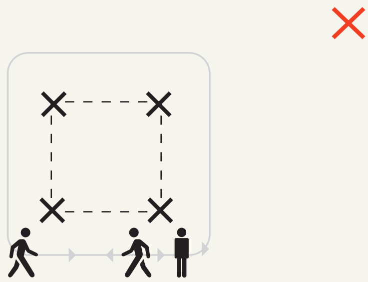


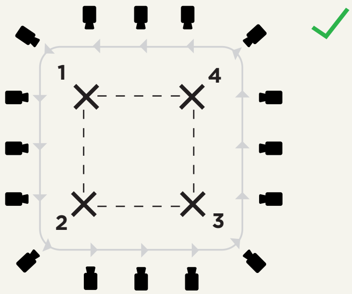


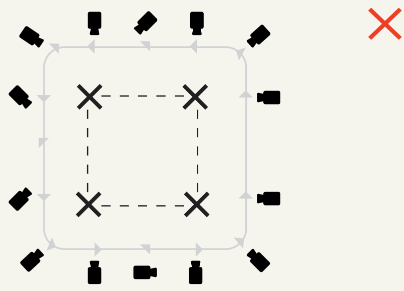


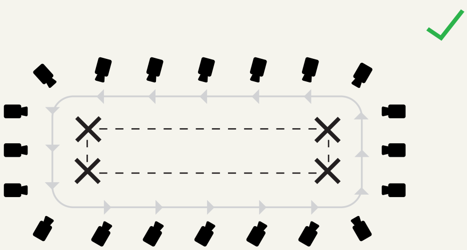
SmartSurvey™ Quickguide

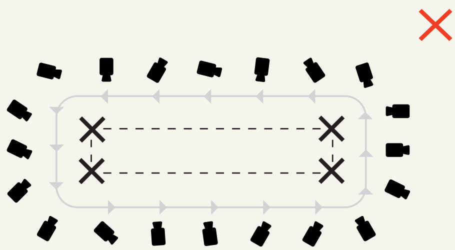












Appendix C

Supplementary material: Augmented Reality for Subsurface Utility Engineering, Revisited

Augmented Reality for Subsurface Utility Engineering, Revisited
Supplementary material

Lasse H. Hansen, Philipp Fleck, Marco Stranner, Dieter Schmalstieg and Clemens Arth

Fig. 1: Experienced local tracking drift: (left) Close to the RP with $< 1m$ initialization distance. (right) After moving $3m$ away, we clearly observe a displacement around $9cm$.

1 Accuracy Evaluation

We performed the accuracy evaluation of the spray paint with 3 different GPS antennas from different pricing categories:

- a low budget ($\sim$ 10 Euro) single-band GPS Antenna acquired over Amazon for usual car navigation use, paired with a circular metal base plane;
- a higher priced ($\sim$ 40 Euro) single-band GPS antenna, also acquired from Amazon paired with a circular metal base plane;
- a professional grade, dual-band high precision RTK antenna priced around $\sim$ 450 Euro from Novatel with an integrated base plane.

Basically all antennas have been working plausibly, *i.e.*we were able to acquire fixed-integer solutions for all of them. However, better performance comes at higher prices. For our localization use-case, the localization error was negligible once the fixed-integer mode was reached. In terms of initialization speed and stability (*i.e.*to maintain fixed-integer GPS) over time, the expensive antenna clearly outperformed the single-band antennas. Figure 1 show the local tracing drift when moving over longer distances and Figure 2 shows four out of fifteen initializations with varying displacements from the RP.

Throughout further evaluation, our initial impression, *i.e.*that the local ARFoundation based tracking might suffer from accumulating drift under certain environmental conditions, manifested in certain cases. This problem cannot be fixed easily, as there is no way to fix the local reconstruction (*i.e.*perform some bundle adjustment or loop closure given external GPS reference measurements). In a future iteration of our developments, a tighter fusion of the global GPS localization with the local tracking is envisioned. This can be facilitated by updating the global-to-local transform using an error minimization scheme based on a multitude of GPS positions and corresponding positions from the local map. As a result, a reduction of the overall visual inconsistencies is aspired.

2 IMU to Camera Calibration

We have extensively studied the impact of having an improper calibration between the IMU and the device camera. Following the example in the main paper, Figure 3 shows some more examples in visualizing a set of building models.

As a reference we created the building models on the fly out of a PostGreSQL database with PostGIS extension, by intersecting aerial LIDAR height fields and OpenStreetMap data. For this purpose we have implemented several functions in the database which finally delivers a set of surrounding 3D building models directly using an API call to the database and providing the actual GPS position of the user. Obviously the created 3D buildings suffer from some minor deficiencies, as roof structures cannot be resembled perfectly. However, this method essentially works wherever OpenStreetMap data and height fields are available. As both sources expose an error of up to $50cm$ (*i.e.*community-curated OpenStreetMap data is not geodesically verified and height-field data have a standard resolution of $50cm - 1m$ pre point), the alignment cannot be absolutely perfect, even under the best circumstances. However, the impact of a wrong calibration as opposed to a proper calibration becomes apparent.

In Figure 4 another example of 11 calibration runs with different input parameters is shown. As described in the paper, even slight errors in measuring the required input parameters, such as tag size or tag spacing of the calibration target might cause the results to deviate clearly from the optimum.

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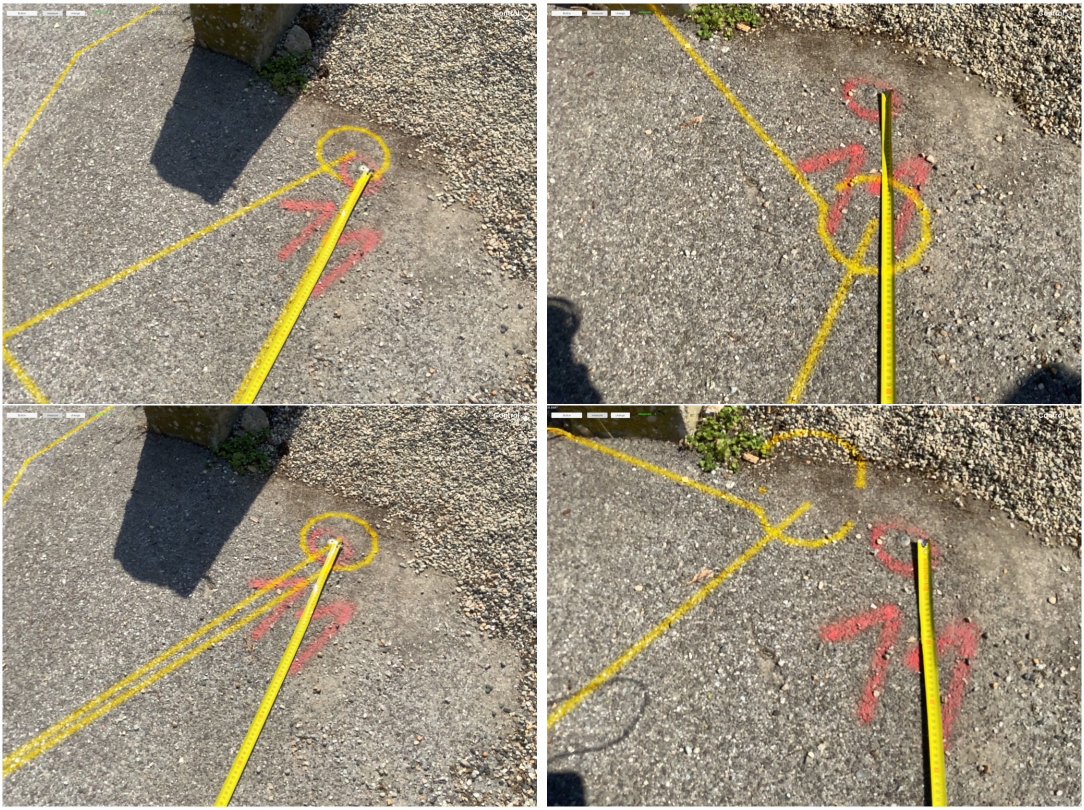


Fig. 2: Representative initialization: The left columns depicts more accurate results with $< 10cm$ and the right column less accurate initializations $> 10cm$. The yellow markings are the virtual one, where the circle is drawn with a radius of $10cm$.

3 Expert Interviews

In the second half of 2020 we demonstrated our virtual daylighting approach to domain experts as seen in Figure 1 of the main paper (mid right and right) and in Figure Figure 15. Luckily we had another chance in mid 2021 within a (COVID-tested and secure) environment to demonstrate our virtual utility marking approach as seen in Figure 5. Feedback was gathered based on the experts experience. All were very pleased on how it worked out and confirmed the feedback from the video interviews.

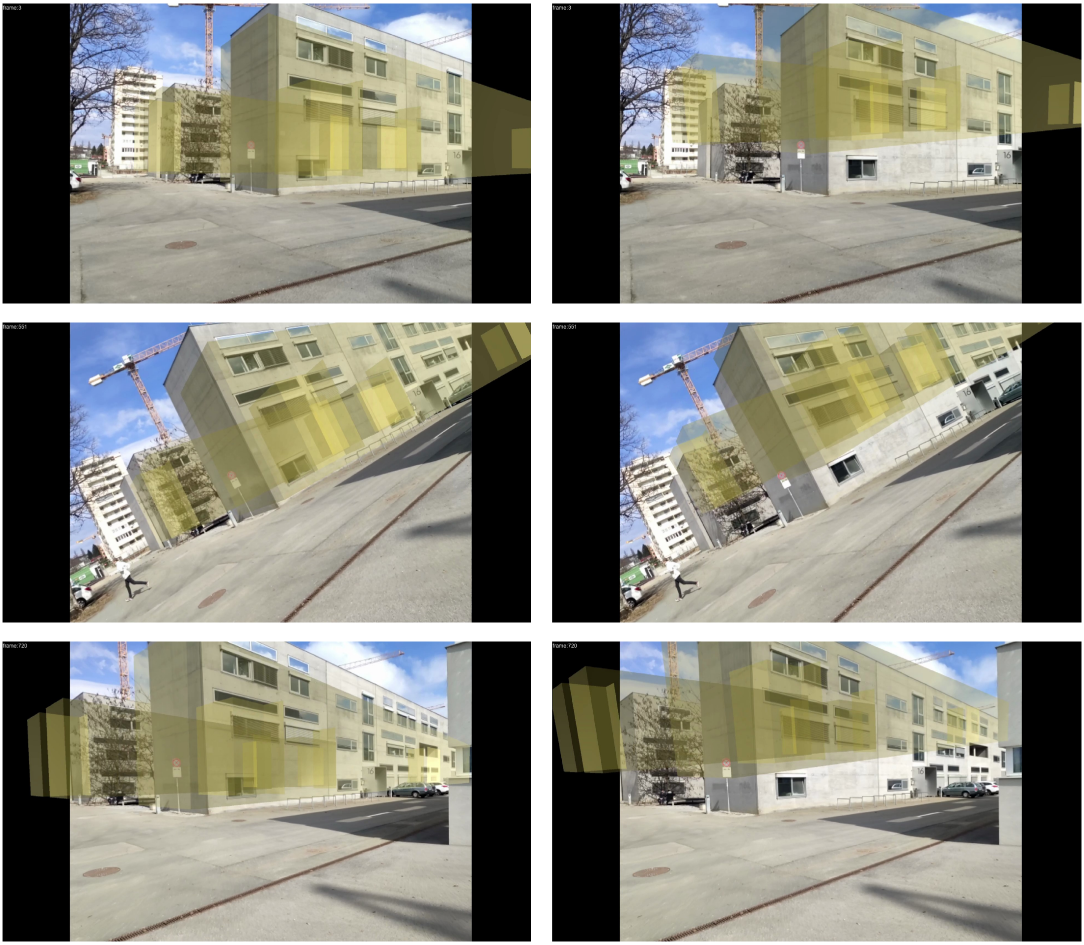
The demonstration also featured 3D captures of excavation holes aligning with the virtual marked utility GIS data as seen in Figure 6, which made for an interesting comparison between the two types of SUE data to visual inspect the accuracy and completeness of the existing utility GIS data. Something that the experts often finds lacking in existing utility documentation as reported in the video interviews.

3.1 Indoor applications

While outdoor SUE applications were the main motivation for this work, SUE also has many indoor uses, such as in basements or sewers. Particularly for the construction industry, AR applications recovering infrastructure hidden in concrete walls are important to avoid damages to utilities and tools (*e.g.*, hitting a water pipe or an electricity line when drilling holes).

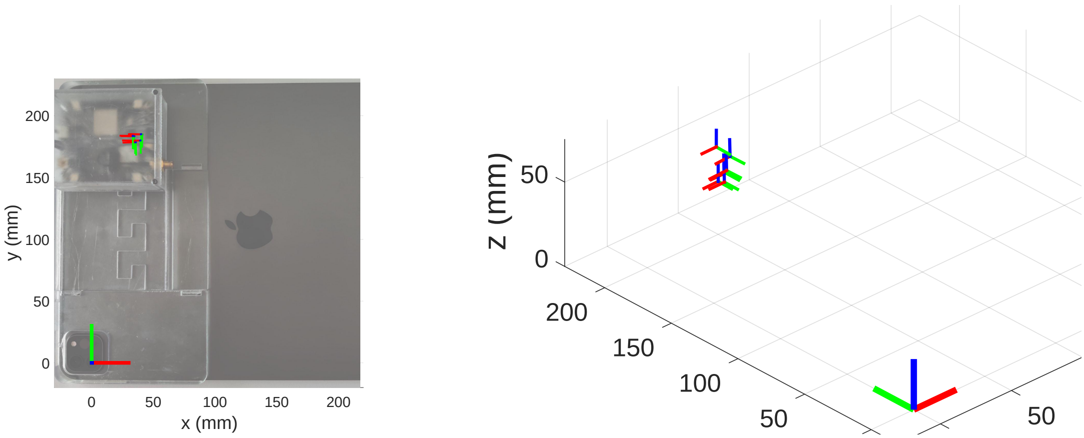
Because we can leverage the indoor localization capabilities offered by ARFoundation, and GPS sensing generally works poorly indoors, the sensor box is not required. We re-purpose the outdoor visualization techniques to derive on-surface markings from building information models rather than GIS. Examples are shown in Fig. 7.

Our visualizations are targeting video-see-through devices, but work in optical-see-through mode as well. We reconstructed the interior of a fire hose reel cabinet using the LIDAR of the iPad Pro and present the result as X-ray vision on a Microsoft Hololens 2, similar to previous work by Zollmann *et al*. [42]. The model was placed in a room using Hololens world anchors. The effect, while less spectacular, is similarly informative as a virtual excavation hole to provide a detailed preview of the hidden infrastructure.



(a) calibrated IMU　　(b) uncalibrated IMU

Fig. 3: AR visualization of GIS data using hardware based tracking, (a) with calibrated IMU and (b) with uncalibrated IMU data. Although, sensor placement is just of a bit from the camera including a maximum rotation offset of about 6 degrees, the visualizations have significant displacements compared with the actual real world buildings.



(a) (b)

Fig. 4: Calibration results for our prototype (similar to the image shown in the main paper, but with some error in the estimated parameters for Kalibr). First row with provided noise parameters, second row with self-calculated. (a) Camera coordinate system and individual coordinate systems overlaid on a top-view of the calibration setup. The individual IMU estimates cluster around the real IMU location (axes colour coded as x=red, y=green, z=blue). (b) Side-view revealing the offset in z-dimension.

Fig. 5: Experts in the field: We showed and let experts try our virtual utility marking approach in the field based on real SUE data. (top row) one expert inspecting the draw SUE data and his view from the iPad Pro tablet. (bottom row) Experts giving feedback on their experience on site in Copenhagen and a map view of the location and its underground utilities (SUE data).

Fig. 6: Left column: Existing SUE data of underground utilities visualised with the virtual utility marking approach at two separate locations. Right column: 3D captures of excavation holes visualised with the virtual utility daylighting approach together with the virtual markings at the same two separate locations.

Fig. 7: Several indoor showcases: (left) Indoor navigation showcase, where the spray paint effect is used to fuse the navigation information with the ground surface. (mid) The location of power and telephone cables are shown, targeting the inside of the wall rather than a subsurface area. (right) X-ray visualization of a fire hose reel cabinet on the Microsoft Hololens 2. In an optical-see-through display, the physical surface cannot be fully occluded by the visualization, but the user can get an overall impression of the cabinet interior.

SUMMARY

On-site planning and excavation of underground infrastructure requires easy access to reliable and accurate subsurface utility records to ensure an informed decision-making foundation. In this thesis new methods using Reality Capture and Augmented Reality technology were explored and developed to provide informed decision-making visualization for utility owners and contractors when planning and managing underground infrastructure projects. That included an AR visualization method for displaying 3D capture data of underground infrastructure for supporting subsurface utility engineering on site. The method was implemented in an outdoor AR prototype system capable of accurate and robust in-situ visualization of 3D capture data with close alignment to the real surroundings. Another AR visualization method was also developed, however, this time using conventional utility map data as visualization source. The method focused on visualizing the utility data as virtual utility markings providing close and seamless blending with the ground surface as well as adapting real utility marking design schemes from industry guidelines. Overall, the AR system and visualization method provided a comprehensible visualization that was greatly appreciated by the interviewed contractors and utility owners.

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