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 In worst case scenarios the documentation is missing, incomplete or out-of-date and often represent as-planned data instead of as-built data [5].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.

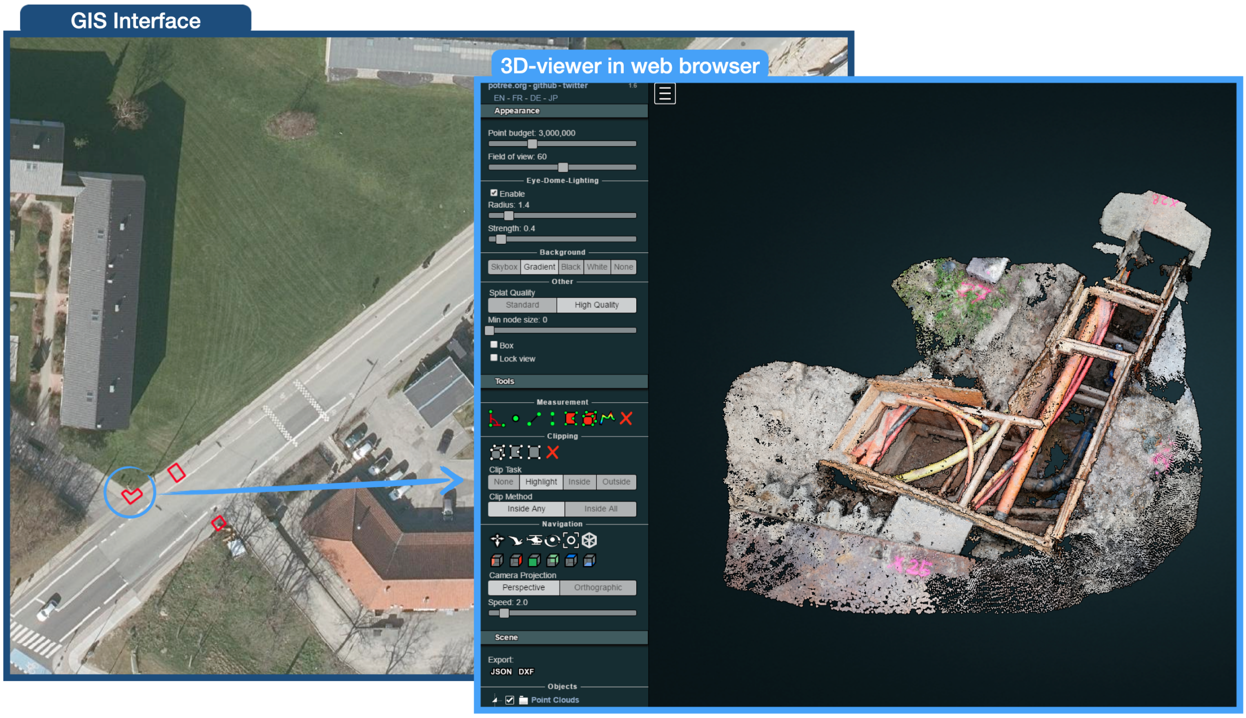

Figure 1. Right: Polygons boundaries in a GIS interface indicating the location of utility excavation point clouds. Left: A dense point cloud capture of an utility excavation displayed in an interactive 3D web-viewer using Potree

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

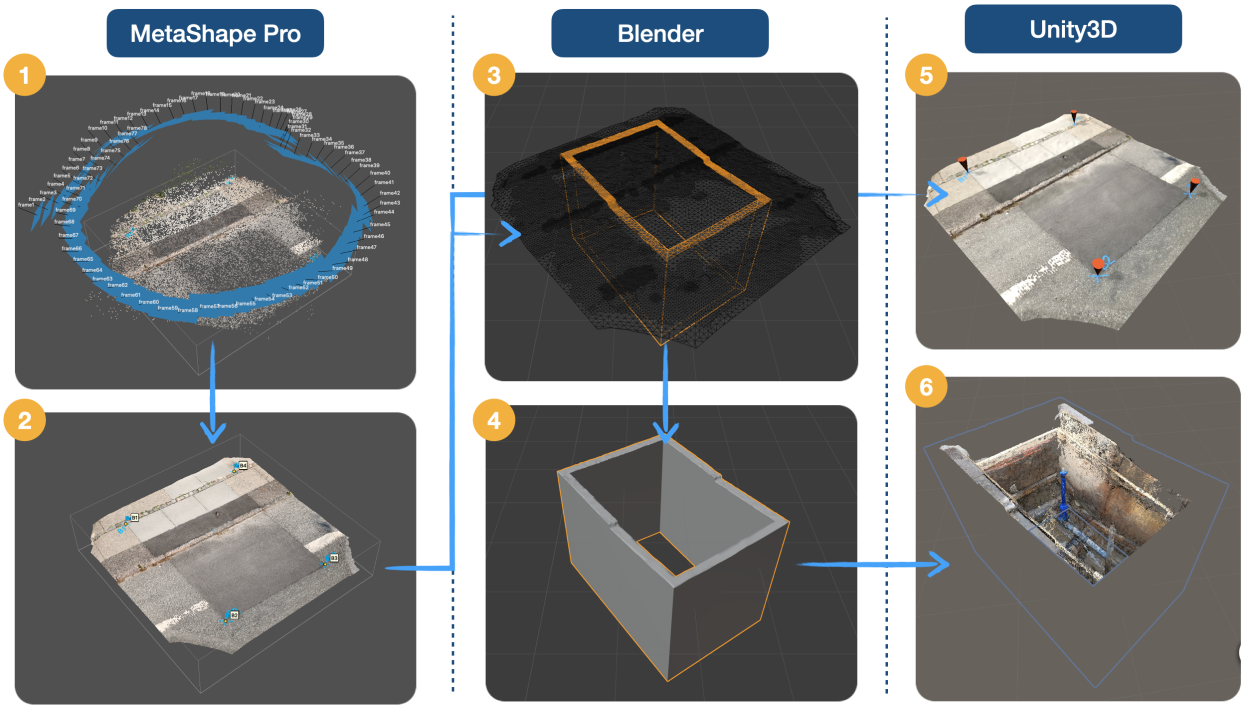

Figure 2. The overall workflow for creating occlusion box

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

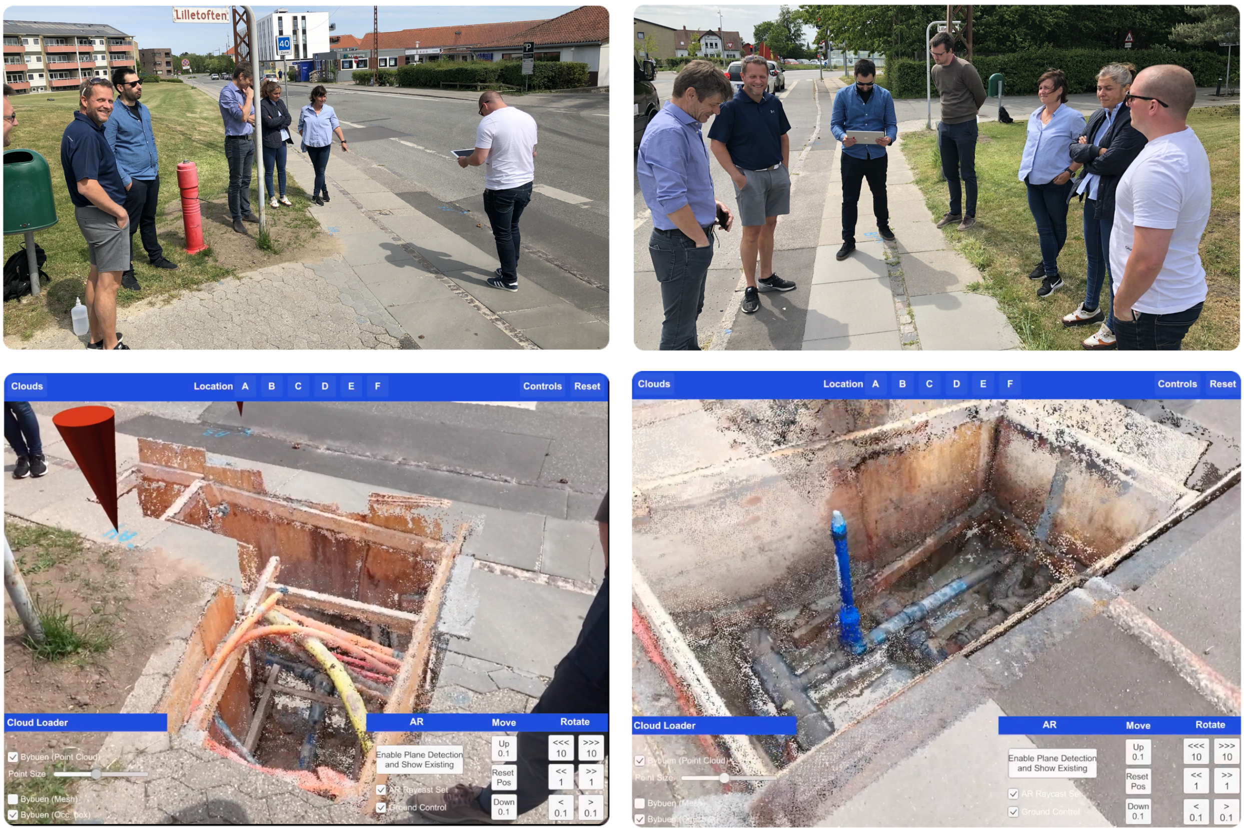

Figure 3. AR prototype in use during the hands-on demonstration seen from AR device view (bottom) and 3rd-person view (top).

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.

References

[1] USAG. Utility Strike Damages Report 2017-2018. (January), 2019.

[2] Lewis Makana, Nicole Metje, Ian Jefferson, and Chris Rogers. What Do Utility Strikes Really Cost? Technical Report January, University of Birmingham - School of Civil Engineerin, 2016. URL `https://www.researchgate.net/publication/321110173`.

[3] Energy Danish Ministry of Climate and Utilities. Udveksling af data om nedgravet infrastruktur. On-line: `https://kefm.dk/data-og-kort/udveksling-af-data-om-nedgravet-infrastruktur/`, Accessed: 01/06/2020.

[4] Lewis O Makana, Nicole Metje, Ian Jefferson, Margaret Sackey, and Chris DF Rogers. Cost Estimation of Utility Strikes: Towards Proactive Management of Street Works. *Infrastructure Asset Management*, pages 1–34, 2018. ISSN 2053-0242. doi:10.1680/jinam.17.00033.

[5] Ahmed Jalil Al-Bayati and Louis Panzer. Reducing Damage to Underground Utilities: Lessons Learned from Damage Data and Excavators in North Carolina. *Journal of Construction Engineering and Management*, 145(12):1–8, 2019. ISSN 07339364. doi:10.1061/(ASCE)CO.1943-7862.0001724.

[6] Paul Goodrum, Adam Smith, Ben Slaughter, and Fady Kari. Case study and statistical analysis of utility conflicts on construction roadway projects and best practices in their avoidance. *Journal of Urban Planning and Development*, 134(2):63–70, 2008. ISSN 07339488. doi:10.1061/(ASCE)0733-9488(2008)134:2(63).

[7] Kevin Vine. Subsurface Utility Engineering (SUE): Avoiding 4 Potential Pitfalls to Ensure a Successful Program. In *Transportation 2014: Past, Present, Future-2014 Conference and Exhibition of the Transportation Association of Canada*, pages 1–16, 2014.

[8] Gethin W Roberts, Andrew Ewans, Alan Dodson, Bryan Denby, Simon Cooper, and Robin Hollands. The use of augmented reality, GPS and INS for subsurface data visualization. *FIG XXII International Congress*, 4:1–12, 2002.

[9] Gerhard Schall, Erick Mendez, Ernst Kruijff, Eduardo Veas, Sebastian Junghanns, Bernhard Reitinger, and Dieter Schmalstieg. Handheld Augmented Reality for underground infrastructure visualization. *Personal and Ubiquitous Computing*, 13(4):281–291, 2008. ISSN 1617-4917. doi:10.1007/s00779-008-0204-5. URL `http://dx.doi.org/10.1007/s00779-008-0204-5`.

[10] Stefanie Zollmann, Denis Kalkofen, Erick Mendez, and Gerhard Reitmayr. Image-based ghostings for single layer occlusions in augmented reality. In *9th IEEE International Symposium on Mixed and Augmented Reality 2010: Science and Technology, ISMAR 2010 - Proceedings*, pages 19–26. IEEE, 2010. ISBN 9781424493449. doi:10.1109/ISMAR.2010.5643546.

[11] Gerhard Schall, Stefanie Zollmann, and Gerhard Reitmayr. Smart Vidente: Advances in mobile

augmented reality for interactive visualization of underground infrastructure. *Personal and Ubiquitous Computing*, 17(7):1533–1549, 2012. ISSN 16174909. doi:10.1007/s00779-012-0599-x.

[12] Stefanie Zollmann, Gerhard Schall, Sebastian Junghanns, and Gerhard Reitmayr. Comprehensible and Interactive Visualizations of GIS Data in Augmented Reality. In *Advances in Visual Computing. ISVC 2012*. Springer. ISBN 978-3-642-33178-7. doi:10.1007/978-3-642-33179-4_64.

[13] Mustafa Tolga Eren and Selim Balcisoy. Evaluation of X-ray visualization techniques for vertical depth judgments in underground exploration. *Visual Computer*, 34(3):405–416, 2018. ISSN 01782789. doi:10.1007/s00371-016-1346-5.

[14] Sebastián Ortega, Jochen Wendel, José Miguel Santana, Syed Monjur Murshed, Isaac Boates, Agustín Trujillo, Alexandru Nichersu, and José Pablo Suárez. Making the invisible visible—strategies for visualizing underground infrastructures in immersive environments. *ISPRS International Journal of Geo-Information*, 8(3), 2019. ISSN 22209964. doi:10.3390/ijgi8030152.

[15] Lasse Hedegaard Hansen and Erik Kjems. Augmented Reality for Infrastructure Information: Challenges with information flow and interactions in outdoor environments especially on construction sites. In *37th eCAADe Conf. Proceedings*, volume 2, pages 473–482, 2019.

[16] H. M. Yilmaz, M. Yakar, S. A. Gulec, and O. N. Dulgerler. Importance of digital close-range photogrammetry in documentation of cultural heritage. *Journal of Cultural Heritage*, 8(4):428–433, 2007. ISSN 12962074. doi:10.1016/j.culher.2007.07.004.

[17] Ruinian Jiang, David V. Jáuregui, and Kenneth R. White. Close-range photogrammetry applications in bridge measurement: Literature review. *Measurement: Journal of the International Measurement Confederation*, 41(8):823–834, 2008. ISSN 02632241. doi:10.1016/j.measurement.2007.12.005.

[18] Jingya Yan, Siow Wei Jaw, Kean Huat Soon, Andreas Wieser, and Gerhard Schrotter. Towards an underground utilities 3D data model for land administration. *Remote Sensing*, 11(17):1–21, 2019. ISSN 20724292. doi:10.3390/rs11171957.

[19] Michela Bloch Eiris. Videoindmåling - en ny teknologi til dokumentation af aktiver, GeoForum. Technical Report Oktober. URL `https://issuu.com/geoforum5/docs/geoforum_207_issue`.

[20] Lene Tanggaard and Svend Brinkmann. *Interviewet: Samtalen som forskningsmetode*, pages 29–53. Hans Reitzels Forlag, Danmark, 2. edition, 2015. ISBN 9788741252551.

[21] Markus Schuetz. *Potree: Rendering Large Point Clouds in Web Browsers*. PhD thesis, Vienna University of Technology, 2016. URL `https://publik.tuwien.ac.at/files/publik{_}252607.pdf`.

[22] Simon Maximilian Fraiss and Michael Wimmer. *Rendering Large Point Clouds in Unity*. PhD thesis, Vienna University of Technology, 2017. URL `https://www.cg.tuwien.ac.at/research/publications/2017/FRAISS-2017-PCU/`.

[23] Amr Fenais, Samuel T. Ariaratnam, Steven K. Ayer, and Nikolas Smilovsky. Integrating geographic information systems and augmented reality for mapping underground utilities. *Infrastructures*, 4(4), 2019. ISSN 24123811. doi:10.3390/infrastructures4040060.