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Augmented reality for enhanced documentation and anchor inspection reporting in conventional tunnelling

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ABSTRACT

This study explores the feasibility of Augmented Reality (AR) technology for efficient quality inspection documentation on tunnel construction sites. Conventional tunnel construction relies heavily on paper-based documentation processes, leading to potential errors and increased documentation and site inspection time requirements. Introducing AR as a digital tool offers a promising solution to address these challenges. The paper identifies potential use of AR for tunnel inspection reports. The methodology involves Design Science Research, including prototype development and a case study in a tunnel environment. The findings of the case study show that the developed AR prototype facilitates quality management and speeds up documentation processes compared to the current paper-based solutions. Despite some input detection issues and current hardware limitations, the approach presents a promising and robust solution suitable for real-world environments.

1. Introduction

The construction industry has witnessed significant advancements in recent years, with Augmented Reality (AR) emerging as a transformative technology. Further, current tunnelling projects involve complex and challenging technical aspects that require effective project management, stakeholder collaboration, documentation, and quality control processes (Galler et al., 2018; Bilotta et al., 2022a). In this context, augmented reality offers a versatile tool set for construction professionals. By overlaying digital information onto the physical environment, AR can streamline documentation procedures by enabling real-time data capture and visualisation. This ensures that critical project information, such as structural measurements, material specifications, and progress tracking, is readily available to construction teams, reducing errors and delays. Specifically, conventional tunnel construction projects require a continuous structural design model from planning through execution to testing, with anchors being an essential support measure for maintaining structural integrity (Stadler, 2012). According to common standards, such as EN 1537 and Eurocode 7 (Stadler, 2012; ASI, 2015), these measures are critical for deformation-resistant structures or when large concentrated forces must be transferred to the ground. To ensure that regulatory and structural requirements are met, documentation and quality assurance reports are essential for the construction process (Oggeri and Ova, 2004; Chester Allen, 2009; Ma, 2011).

Previous research notices (Kvasina, 2018; Huymajer et al., 2022; Zach, 2021) that stakeholders in tunnelling rely significantly on paper-based documentation for most processes. Various processes generate a large number of reports, which include hydrological and geological characteristics of the site environment, activities performed, and materials used (Kvasina, 2018; Schiefer, 2018; Winkler et al., 2022). Researchers have stated that the potential time savings from adopting digital systems can reach as high as 87 % in daily documentation processes (Winkler, 2020; Kvasina, 2018). This transition can substantially increase time for on-site evaluation, as less time is required for data acquisition. Fast and reliable retrieval of documentation data can be further facilitated by recording and showing the information corresponding to a particular location within the tunnel. AR has the potential to aid in this aspect by facilitating precise inspections and non-destructive testing (Katika et al., 2022; Zhou et al., 2017; Jeon et al., 2021). Despite numerous advancements in the research of AR applications within civil engineering, there is a lack of scholarly literature that specifically explores its utilisation in conventional tunnel construction and operations (Zhou et al., 2017; Beer, 2012; Fenzl, 2022). This is

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due to the limited accessibility of tunnels and the inherent complexities of AR applications in such environments.

This article addresses the research gaps by investigating the general applicability of AR as a tool for documentation and quality control in conventional tunnelling. Specifically, this research presents a case study, aimed at assessing the practicality of integrating AR technology into tunnelling processes and evaluating the usability of the currently available hardware. The field test in the *Zentrum am Berg*[1] (ZaB) research tunnel examines critical aspects such as annotation accuracy and user acceptance. In contrast, the subsequent usability test identified potential issues associated with the current hardware limitations. The primary objective is to determine the adaptability of this technology within tunnel environments, with a particular emphasis on streamlining the anchor inspection reporting process and enhancing data consistency. In particular, we explore the potential benefits of centralising data through a digital database such as the Tunnel Information Modelling System (TIMS) (Huymajer et al., 2022; Melnyk et al., 2023), moving away from the prevalent analogue quality assessment reports commonly used in today's construction industry.

Section 1 of this article provides an introductory overview of AR applications in civil engineering and identifies potential research gaps that warrant further investigation. Section 3 outlines the methodological approach. Section 2 describes the prior work required for developing an AR prototype for documentation in a tunnel environment. Section 4 delves into the procedures for the conventional anchor pull test and the corresponding reporting process. Section 5 describes an AR-supported documentation process and subsequent implementation of the developed software prototype. The conducted field and usability tests are presented in Section 6. Finally, Section 7 presents the test results and proposes potential future developments for AR applications in tunnelling.

2. Related work

As mentioned in Section 1, AR has emerged as a promising technology that superimposes computer-generated information onto a real environment (Kipper and Rampolla, 2012). The combination of input and output elements allows users to capture digital information using a camera and display the captured data in an overlay (Kipper and Rampolla, 2012). AR also has the potential to enhance various construction site management (Webster et al., 1996; Katika et al., 2022; Davila Delgado et al., 2020), operations aspects (Kim et al., 2013; Shin and Dunston, 2008; Woodward et al., 2010) or to improve the accuracy and efficiency of setting out equipment operations, maintenance, monitoring, and documentation, among other activities (Lee and Akin, 2011; Bae et al., 2013; Meza et al., 2015; Chen and Kamara, 2011; Zaher et al., 2018). For instance, some early research (Feiner et al., 1995; Kakez et al., 1997; Ahlers et al., 1995), introduced the concepts of virtually documented environments, and distributed AR for various applications in the construction industry. Further, Hammad et al. (2009) researched distributed AR for visualising collaborative construction tasks.

One prominent area where AR applications for documentation and inspection have seen notable developments is in high-rise construction, with significant advancements reported in several studies. Firstly, Chen et al. (2020) has identified the potentials of AR in various project phases, including design, construction, and maintenance, for tasks like progress management and error detection. Olbrich et al. (2013), Ramos-Hurtado et al. (2022), Beer (2012), Li et al. (2024) have studied the application of AR in construction safety and the streamlining of site inspection processes. Also, Shin and Dunston (2010), Wang et al. (2019), Lee and Akin (2011) emphasise AR's utility in precise tracking, object sensing, and equipment operation support. In addition to construction activity monitoring and documentation (Zollmann et al., 2014), researchers highlight AR's role in structural inspection (Bae et al., 2015; Perla et al., 2016; Aguero et al., 2023). AR's effectiveness in spatial measurement and enhancing the comprehension of construction information through various display methods is demonstrated by Meza et al. (2015), Izkara et al. (2007), Boonbrahm et al. (2020), Qin and Bulbul (2022).

AR in infrastructure inspection received interest from the research community, suggesting promising approaches for tunnelling applications. Multiple studies focus on AR in construction (Shin and Dunston, 2008; Chung et al., 2023; Howard et al., 2023; Harikrishnan et al., 2021) and infrastructure inspections (Mascareñas et al., 2021; Maharjan et al., 2021). They explore AR's utility in enhancing the accuracy and efficiency of structural inspections, from steel column evaluations to underground pipe maintenance Schall et al. (2009), Li et al. (2023a,b). Furthermore, Fenais et al. (2020) assessed the accuracy of an outdoor AR solution in mapping underground utilities, while Dima and Sjostrom (2021) used camera and lidar-based view generation for remote mining operations. The research by Mascareñas et al. (2021), Pereira et al. (2019), Jeon et al. (2021) focused on AR in infrastructure inspections, and Janiszewski et al. (2021) on visualising rock mass properties, all highlighting the benefits of AR in terms of efficiency, accuracy, and safety. Other studies also explore AR applications in quality control (Havlikova et al., 2023; Machado and Vilela, 2020) and maintenance (Bruno et al., 2020; Frandsen et al., 2023). They investigate the effectiveness of AR in tasks like on-site piping assembly inspection, quality assessment during maintenance, and quality inspection of welded structures. Their findings suggest that AR can significantly enhance task efficiency, reduce mental workload, and improve overall inspection quality. Further studies showcase AR's application in quality control (Malek et al., 2023) and inspection processes (Choi et al., 2023). Moreover, Dunston and Wang (2005) presented mixed reality-based visualisation interfaces, while Dunston et al. (2008) focused on the spatial tracking challenges of implementing AR for construction sites. The successful implementation of these technologies indicates that AR applications can be effectively extended to include tunnel inspection reports.

For instance, a study by Zhou et al. (2017) pioneered the application of AR for examining segment lining displacement in mechanised tunnel construction using *ARToolKit*(Perdan, 2023), markers, and cameras. This system improves manual inspection by superimposing virtual base models from Building Information Modelling (BIM) systems and 3D CAD drawings over real-time images of the construction site. The application assists in precise displacement detection, traditionally challenging due to segment placement, by aligning actual coordinates with virtual models, thereby facilitating the identification of deviations from specifications. This study highlights that the tunnel environment is also feasible for AR applications and suggests significant development potential. In conventional tunnel construction, one study by Beer (2012) suggests the potential use of AR for tunnel engineers to view monitoring results and 3D simulations during construction. However, this study is limited and does not fully explore or leverage the capabilities of AR devices for data input, processing, and retrieval, or their application areas, as demonstrated in the studies above for other construction domains. Beyond this study, there is a significant lack of scholarly literature examining AR applications for documentation or site inspection in conventional tunnel construction. According to Fenzl (2022), this gap can be attributed to the restricted accessibility of tunnels, hardware limitations, and the inherent complexities of implementing and testing AR technology in active construction sites or environments where device sensors may encounter difficulties during operation. To address this gap, the study aims to develop an AR software prototype, conduct tests in real tunnel environments, and gather user feedback. This process should help identify potential benefits, assess user acceptance, and determine areas for improvement in both hardware and software.

[1] https://www.zab.at/

The extensive development of AR devices and advanced development tools and algorithms has yielded multiple advanced tools that are helpful in prototype development for tunnel construction. These tools are designed to facilitate precise localisation for accurate location data recording, enabling, for instance, the referencing of documented data to specific tunnel segments. Also, they provide user-friendly input options for seamless data interaction and the flexibility to incorporate additional features if required. The utilisation of *AR* applications for *3D* visualisation of nearby elements, employing a markerless approach known as Simultaneous Localisation and Mapping (*SLAM*) (Durrant-Whyte and Bailey, 2006) has been explored in research (Cadena et al., 2016; Davison et al., 2007; Yu et al., 2020; Fenzl, 2022). Most *AR* frameworks incorporate this algorithm, including *ARCore* (Google, 2023), *Vuforia* (Vuforia, 2023), *ARKit* (Apple Inc., 2023), and *MRTK* (Microsoft, 2023c). Originally developed to address the challenge of mobile robots navigating in an unfamiliar environment, *SLAM* (Cadena et al., 2016) collects data from sensors in *AR* glasses, such as cameras, gyroscopes, and accelerometers and enhances accuracy through depth sensors, light sensors, and GPS (Jakl, 2018). In the front-end process, key points are identified through feature extraction and tracked for *SLAM* (Durrant-Whyte and Bailey, 2006). These key points represent prominent locations in an image and can detect changes in rotation, camera angle, shaking, lighting, etc. Jakl (2018). These points are linked to *3D* coordinates through ongoing tracking of the video stream. The backend establishes relationships between different frames in the video stream, locates the camera, and performs general geometric reconstruction of the environment. Building upon these insights, the subsequent research highlights how precise localisation technologies enhance inspection capabilities, particularly in structural health monitoring and tunnel construction.

For tunnel applications, including localisation, several promising technologies are essential for enhancing precision and efficiency in construction and documentation tasks. The central algorithm employed in our prototype is *BRISK* (Leutenegger et al., 2011), based on the *FAST* algorithm by Rosten and Drummond (2006). The fundamental process for feature detection is based on *FAST*, a corner detection algorithm that analyses the neighbourhood of each pixel within a circle. Further instructions are derived from the *ORB-SLAM* implementation by Mur-Artal and Tardós (2017), a similar algorithm to *BRISK* used to identify critical points known as *ORBs*, initially introduced by Rublee et al. (2011). This implementation evaluates each frame for key points and stores them in a map along with a reference to the key frame where they were first detected. The subsequent crucial step in *SLAM* involves mapping these key points from previously saved *2D* images to *3D* coordinates (Jakl, 2018; Fenzl, 2022). *ORB-SLAM* matches these key points in successive frames with those from each previous camera frame. Utilising this information, the algorithm can estimate the initial camera position in real time. The algorithm then projects the map onto the new camera image to identify additional key points. Triangulation is utilised to create new map points by matching key points across connected frames. This algorithm employs *2D* positions, rotations, and translations between frames to triangulate map points. Subsequently, this information is applied to establish the coordinates of the device's current location, after which the map is updated. It is important to note that companies developing *AR* frameworks such as *ARCore* (Google, 2023), *ARKit* (Apple Inc., 2023), and *MRTK* (Microsoft, 2023c) do not publicly disclose the specific implementations of their *SLAM* (Durrant-Whyte and Bailey, 2006) algorithms. The subsequent section offers an overview of current anchor pull test reporting methods in tunnelling. It delves into the potential of applying previously described research to implement AR-based documentation, aiming to improve this process.

3. Material and methods

To develop the prototype, we employed the *Design Science Research* framework, a comprehensive methodology described by Hevner et al. (2004), Weigand (2019). Due to the limited prior research, we selected this framework to support future research to develop AR applications for tunnelling. In the initial phase of the research, the environment where the AR solution is deployed is subjected to a qualitative examination. Following Hevner et al. (2004), key stakeholders in construction, such as site supervisors and engineers, are consulted to understand the challenges and technology usage. Following this methodology, the paper sections are structured accordingly to reflect the relevance, build, and rigour cycles, ensuring adherence to these principles.

The relevance cycle is an ongoing process where the AR solution is tested against the business needs and adjusted based on stakeholder feedback (Elshafey et al., 2020). This iterative process ensures the solution remains aligned with the industry's actual working conditions and requirements. Alongside the literature review in Section 2, which provides an overview of the current research on AR applications in construction, documentation, and inspection, additional semi-structured interviews were conducted to narrow down and collect further requirements for the potential solutions selected as prototypes (Fellows and Liu, 2021). The general outline of the applied methodological approach can be seen in Fig. 1.

With a clear set of requirements, the build cycle focuses on creating a functional AR prototype. First, the development involves designing a process model that aligns with quality assurance standards for AR and the actual construction of a software prototype that can be iteratively improved. Using this information, we generated two process diagrams adhering to the Business Process Model and Notation (BPMN) 2.0 standard by the Object Management Group (OMG) (OMG, 2011). The diagrams described in Sections 4 and 5 illustrate both the conventional and AR-supported inspection reporting processes. Using guidelines from Hevner et al. (2004), Weigand et al. (2021), we then developed an AR solution for tunnel construction documentation. This artefact (Weigand and Johannesson, 2023) is implemented as a software prototype using guidelines and approaches from our surveyed knowledge base and input collected from interviewed experts. Following the review of the current state of technologies in Section 2, including AR Head-Mounted Displays (HMDs) as well as software development kits, we have chosen HoloLens 2 as the platform for the prototype. We selected Unity (Unity Technologies, 2023) as a real-time *3D development platform* due to its abundant documentation and broad range of supported platforms. The main application is implemented in C# and utilises MRTK (Microsoft, 2023c) as the *AR framework*, developed by Microsoft. MRTK is available royalty-free and comes with many ready-to-use user interaction components, easing prototype development. For the markerless localisation and *3D* visualisation of nearby elements in the AR HMD, we employed the described *SLAM* (Durrant-Whyte and Bailey, 2006) method and World Locking Tools (WLT) (Microsoft, 2024).

In the rigour cycle (Hevner et al., 2004), we assess the AR prototype in a real-world tunnel case study and expert feedback, incorporating foundational knowledge and contributing new insights in Section 7. This step is crucial for validating the solution's effectiveness, ease of use (Son et al., 2012) and its practical benefits in construction settings. During the case study, seven participants tested the AR prototype in a section at a research tunnel ZaB. First, these field and usability tests (Guimaraes and Martins, 2014) are conducted to understand the practical constraints of the tunnel environment and ensure that the prototype functions effectively in such locations. Second, the field test evaluated the prototype's feasibility as a paper-based documentation alternative. Subsequently, a usability test identified hardware or software currently limiting user acceptance. Following Kallio et al. (2016), Yin (2012), the semi-structured questionnaire assessed the prototype functionality in quality assessments, compared it to paper-based systems, and collected improvement suggestions. The developed artefacts were evaluated through qualitative usability testing in the ZaB research tunnel using guidelines from Barnum (2011) and Fellows and Liu (2021). These test results outline the potential and current limitations of AR applications in tunnelling.

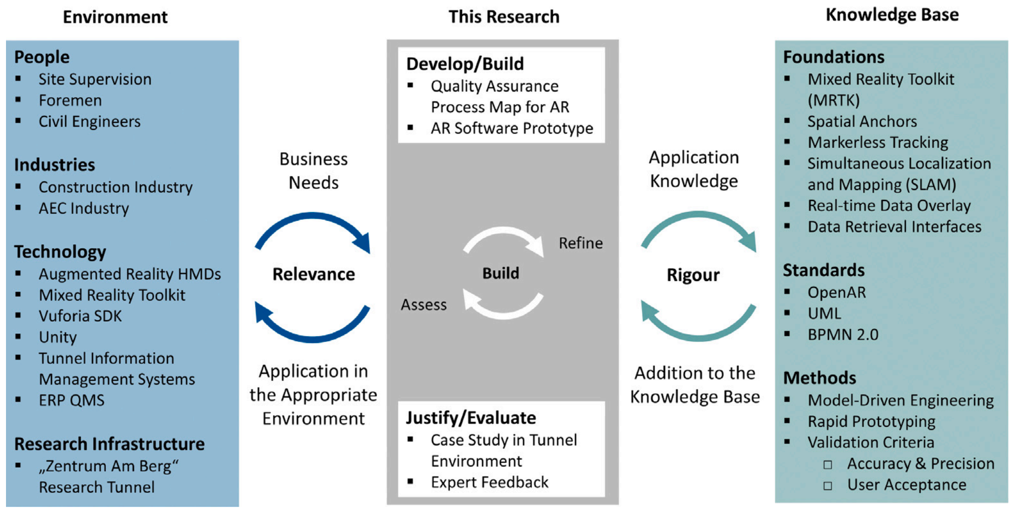


Fig. 1. Design Science Research approach for the AR application in a tunnel environment.

4. Conventional anchor inspection

Effective quality control and documentation are central in conventional tunnelling projects, especially when dealing with challenging geological conditions (Galler et al., 2018; Bilotta et al., 2022b). A key aspect of subsurface construction is the installation of anchors and the assessment of their load-bearing capacity, which are essential for maintaining the structural integrity of tunnels. The following section explores the conventional inspection process of anchor pull tests in tunnel construction.

4.1. Anchor pull test

Specified anchor lengths and systems are not always optimally designed for geological conditions. Unforeseen ground conditions such as the water-bearing layers, injection losses, and failure to reach the rock require transparency about the anchor installation (Schiefer, 2018). This is provided by installing test anchors in advance or by ongoing checks of selected structural anchors. A typical inspection of load-bearing capacity involves a compliance check with acceptance criteria, such as the pull-out test in accordance with the EN 1537 standard (ASI, 2015). Pull testing equipment is required for non-destructive and destructive pull-out testing of anchors and bolts (DSI, 2023; Alkhaddour, 2021), and different devices are used depending on the type and design of installed support measures. Pull testing equipment includes hydraulic components like cylinders, gauges, pumps, hoses, and converters — the mechanical parts include forks, housings, spindles, and nuts (DSI, 2023). The equipment used for the anchor pull test conducted during the construction of the ZaB research tunnel can be seen in Fig. 2.

One criterion used for the hydraulic anchor pull test is the test force, which is 80 % (ASI, 2019) of the nominal value for the ultimate system load specified by the support measure manufacturer. A standard testing configuration evaluates the suitability or acceptance of force transmission into the subsoil. The measured variables are the anchor force in kN and the associated anchor head displacement in mm. A hollow piston press (0.5 MN tensile force) is used as a tensioning press in the tests (ASI, 2019). The hydraulic pressure is registered with a calibrated precision manometer (class 0.6 of the calibration regulations), and the force is determined using a conversion factor (DSI, 2023). Parallel to this, the tensile force is measured directly with the aid of a force transducer. The extension of the clamped anchor is registered at the upper end of the press with a mechanical displacement transducer with a scale division of 0.01 mm (ASI, 2019). To ensure an uninfluenced measurement, the displacement transducer is attached to a measuring rod dowelled into the elms independently of the press and the anchor.

4.2. Conventional documentation process

The conventional reporting includes multiple steps, starting with a setup and execution of the pull test using relevant equipment. The testing should apply the applicable norms for inspection, such as the EN ISO 22477-5 (ASI, 2019). Then, the tested anchors in the inspection lot must be recorded. The number of tested anchors is predefined for each tunnel section and can be between 1 % to 11 % of the installed anchors. The more complex the geological conditions, the higher the percentage of tested anchors. Further documentation includes the anchor and grout type, the ultimate system load, and the corresponding test load, drawing the position and number of the tested anchors. After the inspection is complete, the results are recorded in a table. These results include the anchor number, tunnel station, anchor length, test load in kN, test result, and, if the test was negative, the cause of failure. Once the inspection is complete, the document has to be jointly reviewed by the contractor and the site supervision, after which the report is signed and archived. If any issues are detected, the anchor should be reset, and the test grid should be narrower.

The conventional process seen in Fig. 3 adheres to manual data collection techniques, necessitating handwritten notes, drawings, and paper-based documentation. The steps involve manually recording inspection results, drawing positions and numbers of tested anchors, and preparing detailed reports. The foreman reviews these reports with construction supervision, and multiple copies are made and distributed to various stakeholders, including shift site supervision and quality management. Plausibility checks by the site manager can lead to further consultation with the foreman if issues arise. Finally, the reports are signed by construction supervision and archived as paper documents.

The analogue documentation approach is inefficient due to the significant delay between data recording at the tunnel face and the final data evaluation, often causing an hourly lag before documentation reaches the foreman's office Schiefer (2018). Additionally, the need to digitise or manually transfer analogue documentation into proprietary ERP systems or spreadsheets stored on local storage mediums increases the risk of transcription errors, compromising data integrity and security. Further issues include redundant documentation of data, documentation by different individuals, duplicate paper recordings, inaccuracies in handwritten timekeeping, illegibility of handwritten notes, potential input errors, and data loss during transfer to software, as well as the use of various spreadsheets and software products Kvasina (2018). The AR-based approach offers the potential to overcome the challenges of manual methods, saving time and reducing the risk of transcription errors. With the semi-automatic localisation and centralised data recording options, the AR application has the potential to facilitate the inspection procedure of an anchor pull test shown in Fig. 3.

Fig. 2. Anchor pull test performed during the construction of ZaB research tunnel.

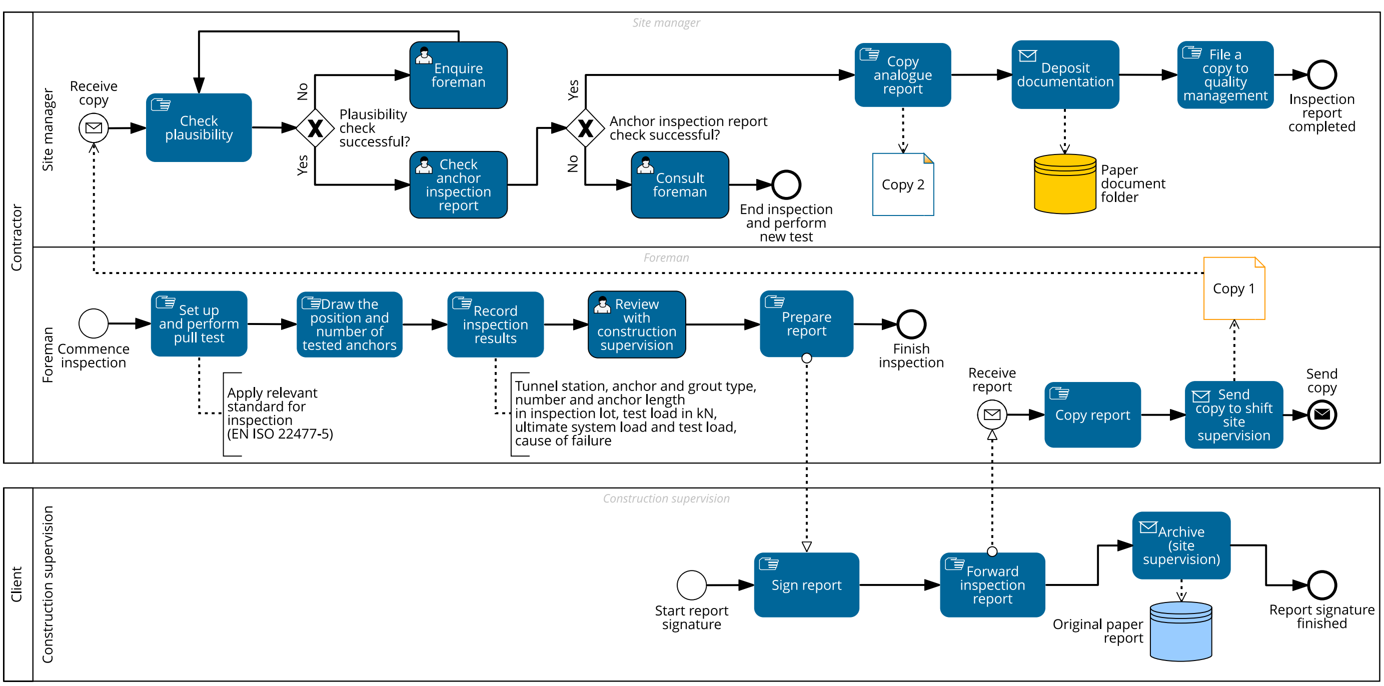


Fig. 3. Conventional anchor pull test documentation process.

5. AR-supported anchor inspection

This section introduces the AR-based anchor inspection prototype, outlining its interactive features and benefits in facilitating the inspection workflow. The developed AR application has the potential to streamline and facilitate anchor pull testing by enabling real-time data visualisation, centralised reporting, and accurate documentation.

Comparing the conventional and the AR-based reporting methods demonstrates substantial disparities concerning data acquisition, operational efficiency and data handling practices. The AR-based inspection process begins with the localisation setup, ensuring precise anchor

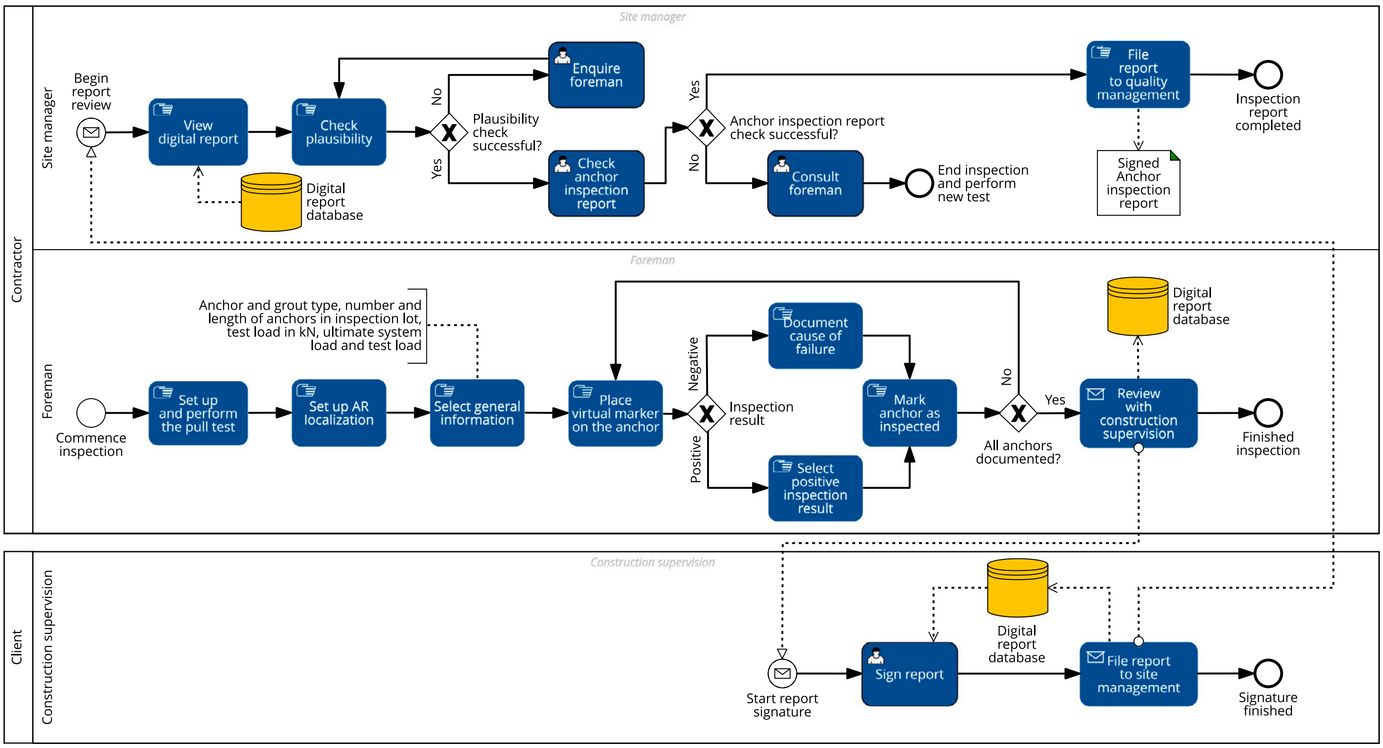


Fig. 4. AR-supported anchor pull test documentation process.

locations. This feature enhances accuracy compared to the conventional method, which relies primarily on manual judgment and sketching. Additionally, the AR-based process employs virtual markers and optional AR headset photos to facilitate data collection. Inspection results are recorded digitally, and failures are documented within the AR framework. The foreman reviews the digital report with construction supervision, and the site manager conducts real-time plausibility checks. Digital reports are filed with quality management and signed electronically by construction supervision, with all data securely stored in a digital database. The AR-based process leverages AR technology to facilitate inspections through quick data entry and real-time decision-making capabilities. This approach reduces the need for manual steps, enhances data accuracy, and provides immediate access to information.

The AR-based method further facilitates real-time inspection reporting eliminating manual copying and distribution. This real-time reporting enhances transparency and traceability throughout the inspection process. Accuracy is improved through direct digital data entry, minimising the risk of transcription errors. Conversely, the conventional process separates data collection from reporting, potentially causing delays and inaccuracies. Moreover, the AR-based process offers quality control advantages by allowing inspectors to identify promptly and document failure causes during the inspection. In contrast, the conventional method relies more on post-inspection reviews for quality control. Further, the conventional process involves the exchange of paper documents, necessitating additional coordination efforts. This further underlines the issue of data storage and accessibility, which differ between the two processes. The AR-based process stores digital data, ensuring easy retrieval, analysis, and reporting in the future. Conversely, the conventional process relies on physical documentation, necessitating paper handling, which is less efficient for data retrieval.

5.1. AR-supported documentation process

At the beginning of the implementation, a technology stack for realising an AR-support documentation process had to be chosen. The most fundamental decision was selecting the appropriate hardware. We decided on a dedicated AR device, the HoloLens 2 from Microsoft, which distinguishes itself from mobile devices through superior localisation capabilities. More research on HoloLens compared to other dedicated devices available at the beginning of the implementation was also considered. A head-mounted device has the additional advantage of keeping the hands of the users free.

The AR-supported documentation process is depicted in Fig. 4. When working in a location unknown to the AR device, the user must initially perform a localisation setup. We discuss technical details in the following subsection, but the localisation setup is achieved by placing so-called space pins, providing a stable coordinate system within the AR headset. The user initiates the placement by pressing a button and then waits for the spatial awareness system to detect the wall, as shown in Fig. 5.

This system generates 3D models that represent the real-world environment's geometry, enabling the placement of a pin marker at the intersection of a wall and an object. Once the space pin is correctly positioned, the user can establish the respective tunnel station on this pin and finalise the creation by clicking *Accept* checkmark, as depicted in Fig. 5.

When the specified tunnel section is localised, the contractor can run the inspection and document the anchor pull test results. To commence the inspection, the user selects an examiner from a predefined list and defines the inspection lot's section, specifying the starting and ending tunnel meters, as can be seen in the upper part of Fig. 4. Subsequently, the total number of anchors in the inspection lot is recorded, and the number of anchors to be examined (ranging from 1 % to 11 % of the total anchor count) is entered. The user then selects the type of anchor used, with the option to change anchor types depending on the construction site. Moreover, the user chooses the ultimate system load in kN. The corresponding test load required for the report is automatically calculated based on the provided input. Additionally, the user verifies the type of cement used for grouting before proceeding with the inspection, as can be seen in the middle part of Fig. 4.

The second inspection step entails walking within the selected tunnel section and using the airtap function to mark the locations of

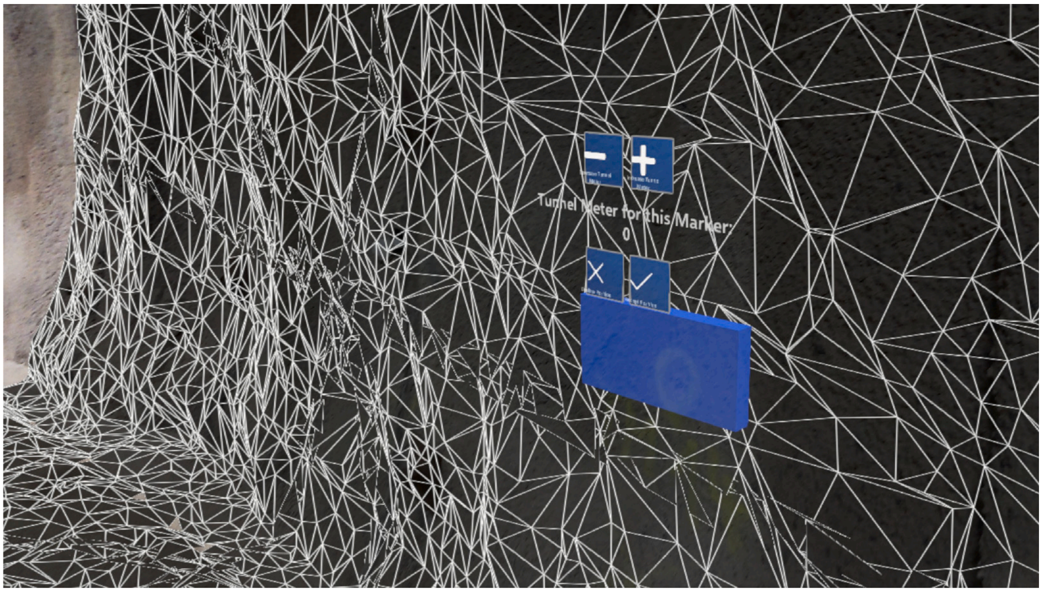


Fig. 5. Localisation process of the inspected tunnel section.

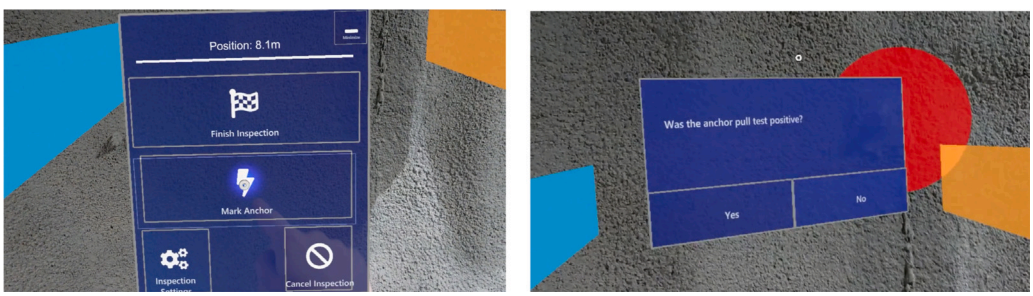


Fig. 6. Anchor marking dialogue window (left), and mark placement process (right).

the inspected anchors, as seen on the right side of Fig. 6. An air tap is a gesture allowing users to select apps, holograms, and buttons by pointing an index finger at them and tapping in the air (Microsoft, 2022a). Once the tested anchors are appropriately marked, the user is prompted to indicate whether the test yielded a successful or negative outcome. The positions of these marked anchor placements are then associated with the corresponding tunnel rounds. In the event of a non-positive test outcome, the user can document the cause of failure in a designated text box, which is later incorporated into the final report, as seen in the lower part of Fig. 4. Upon marking the locations of the inspected anchors in the prototype, the position and quantity of the tested anchors are automatically plotted in the report's diagram. Determining the inspected anchor points' locations is achieved by extrapolating from the angular position of the localised tunnel lining. The user repeats this process for specific rounds until all supporting measures or spots are documented. After examining the last round, the user saves the report by clicking the *Finish Report* button, as depicted in Fig. 7.

A report preview is available for the user to review and make necessary amendments. The report includes crucial data, such as anchor numbers, tunnel stations, anchor lengths, test load in (kN), test results, and, if applicable, the cause of failure for any negative test outcomes. Finally, the user clicks the "Create Report" button, and the report document is generated based on the provided information, as seen in Fig. 8.

Upon completion, the document undergoes a joint review by the contractor and site supervision, after which it is signed and archived. Corrective actions, such as anchor resetting and narrowing the test grid, should be implemented promptly if any issues are identified.

5.2. Application of the AR-prototype

Localisation, which is the ability to map the position of objects in the physical world to a consistent and persistent coordinate system, is an integral part of the implementation. Due to insufficient GPS reception within tunnels, the implementation must rely on markers or markerless anchors for localisation. Marker-based localisation is characterised by higher accuracy compared to markerless localisation. On the other hand, it is more implicated since the user has to precisely place markers during the setup. Our implementation utilises the WLT (Microsoft, 2023c) for localisation. WTK is a framework developed by Microsoft, which uses spatial anchors to lock Unity's coordinate system to the physical world. The framework strives to maintain the coordinates of automatically detected features even when moving around with the device. According to Microsoft, positioning errors of $\pm 10\,\%$ can occur, especially in feature-poor environments like tunnels. We use so-called space pins to decrease this positioning error. According to Microsoft, the maximum positioning error between two space pins can be reduced to the millimetre range (Microsoft, 2022c). The gathered data and the resulting report files can be stored locally on the HMD or in a centralised database, providing immediate access to other users. For the case study, we implemented access to the TIMS (Huymajer et al., 2022) database, which required an active wireless network connection, where report data is stored. The test tunnel featured a stable WiFi connection, facilitating stable data storage and retrieval without technical issues or interruptions. This setup reflects the efficient wireless networks common in international tunnel construction sites (Khademi and Sommer, 2020; Ma et al., 2021; Nielsen and Koseoglu, 2007).

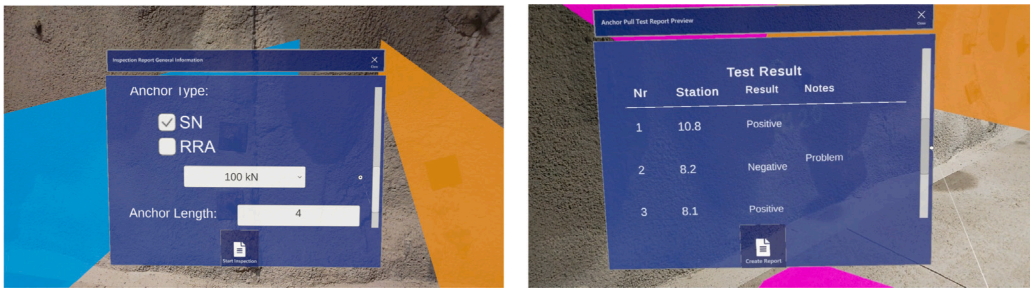
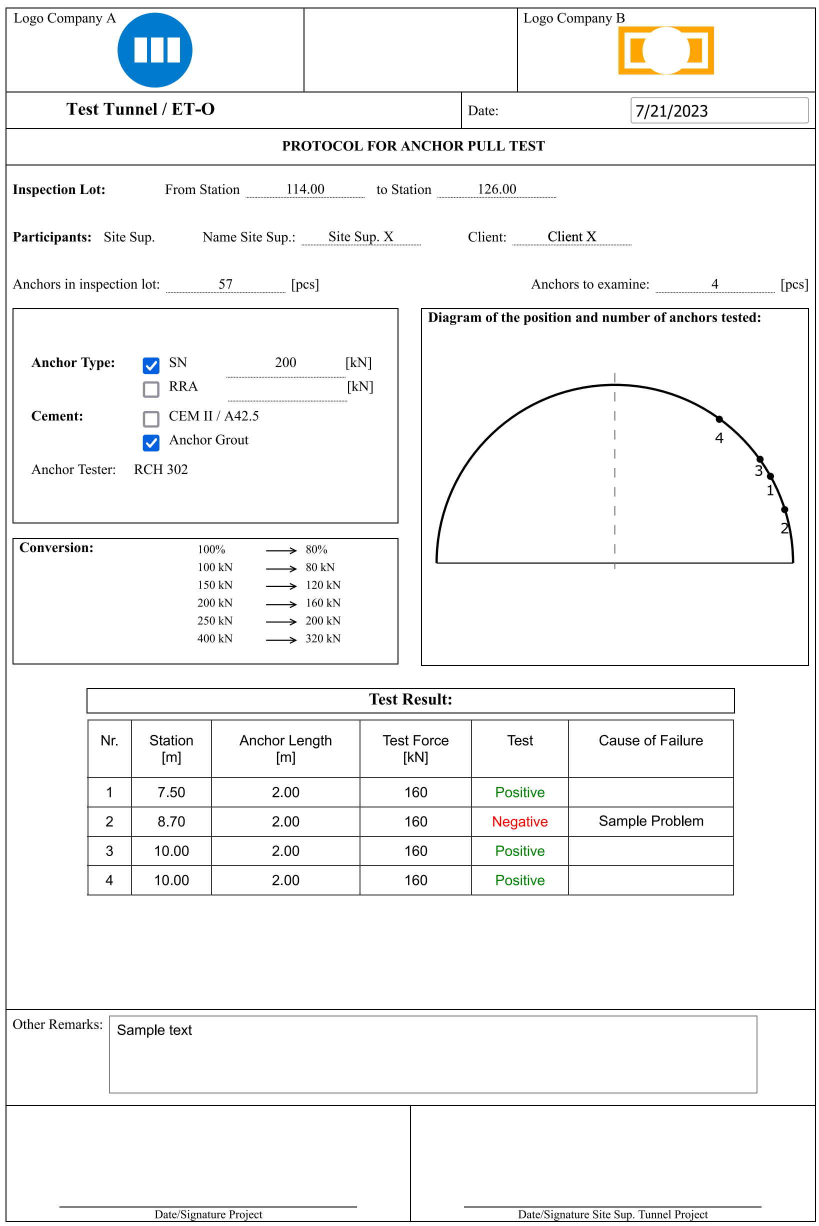


Fig. 7. AR-based anchor inspection input (left), and the report preview (right).



Logo Company A | Logo Company B

Test Tunnel / ET-O Date: 7/21/2023

PROTOCOL FOR ANCHOR PULL TEST

Inspection Lot: From Station 114.00 to Station 126.00

Participants: Site Sup. Name Site Sup.: Site Sup. X Client: Client X

Anchors in inspection lot: 57 [pcs] Anchors to examine: 4 [pcs]

Anchor Type: SN 200 [kN]; RRA [kN]

Cement: CEM II / A42.5; Anchor Grout

Anchor Tester: RCH 302

Conversion:

100%	80%
100 kN	80 kN
150 kN	120 kN
200 kN	160 kN
250 kN	200 kN
400 kN	320 kN

Diagram of the position and number of anchors tested:

Test Result:

Nr.	Station [m]	Anchor Length [m]	Test Force [kN]	Test	Cause of Failure
1	7.50	2.00	160	Positive	
2	8.70	2.00	160	Negative	Sample Problem
3	10.00	2.00	160	Positive	
4	10.00	2.00	160	Positive	

Other Remarks: Sample text

Date/Signature Project | Date/Signature Site Sup. Tunnel Project

Fig. 8. Anchor inspection report generated by the AR prototype.

6. Case study

In enhancing the rigour of our case study, we adhered to guidelines established by Kallio et al. (2016), Yin (2012). Initially, we identified organisations of varying types (such as Surveying and Geospatial Engineering, Construction Firms, and Software Development Companies) and sizes (ranging from small to large) across diverse sectors (including Consultancy and Construction). As indicated in Table 1, our interviews encompassed professionals with technical and managerial expertise

Table 1
Summary of interviewee backgrounds.

Interviewees	1	2	3	4	5	6	7
Domain	Construction	Surveying & Geospatial Engineering	Mechanical Engineering	Construction	Software Development	Software Engineering	Construction
Company type	Geotechnical and Mining	Engineering Consultancy	Research & Development	Engineering Consultancy	Research & Development	Machine Component Manufacturer	Construction Company
Company size	Medium	Small	Large	Medium	Medium	Large	Medium
Role	Junior Expert	Senior Expert	Safety Engineering Specialist	BIM Planner & Civil Engineer	Senior Software Engineer	Software Engineer	Junior Civil Engineer
Position	Surveyor	Chief Surveyor	Tunnel Safety Engineer	Project Engineer	Project Manager	Software Developer	Student Intern
Experience	10+ years	30+ years	5+ years	5+ years	20+ years	5+ years	2+ years

across seven distinct companies. Subsequently, we conducted semi-structured interviews with selected individuals from these sectors. A qualitative questionnaire was prepared to assess aspects of the prototype, like interface usability, the prototype's functionality in facilitating quality assessments, a comparison between the prototype and paper-based quality reporting systems, and the solicitation of improvement suggestions. This questionnaire comprised open-ended questions categorised by topic, as summarised in Appendices A and B. For the evaluation of the AR prototype, quantitative measurements of time for both localisation and inspection reporting were conducted and are documented in Appendix A.

The case study was conducted in the *ZaB* research tunnel. This is an underground facility primarily focused on research, development, education, and training (Galler, 2016). This facility comprises roughly 3 km of tunnels, encompassing portions passing beneath Erzberg's highest point, Erzbergspitz, and areas with minimal overlying material, facilitating the evaluation of various tunnel conditions. The research and experimentation complex consists of four tunnels, with a total length of over 4 km. *ZaB* includes two parallel road tunnels and two parallel railway tunnels interconnected by cross-cuts. The two parallel road tunnels adhere to the latest construction and equipment standards, collectively delivering around 800 m of tunnel space for research and educational use (Galler, 2016). Similarly, the two parallel railway tunnels comply with existing construction and equipment regulations. The adit system comprises remnants of previous mining activities at the Erzberg, spanning a total length of over 2 km and showcasing a diverse range of structural configurations.

The field test occurred in a 10 m tunnel segment in the cross passage of the *Railway Tunnel West*, which is outfitted with exposed preinstalled anchors (Galler, 2016). During the field test of the AR prototype, anchors that had been previously inspected were re-evaluated using AR glasses, and their condition was compared to the original quality assurance documentation. Five out of seven users unfamiliar with HoloLens2 interactions were asked to start the HoloLens2 Tips app to learn the basic actions, including air taps, hand movements, menu interactions, and exiting apps. The initial training for first-time users of the AR HMD prototype takes about 15 min. Users with prior HMD experience did not require basic training, only a brief overview of the prototype's functions. The training further covered localisation processes and steps for completing anchor pull test reporting. While learning to use the prototype is generally quick, some users need extra time to adapt to the limited field of view, such as the virtual keyboard and airtaps for interacting with the Hololens. Later, participants had to start the prototype application from the menu and perform the localisation setup. This setup involved placing two special anchors at specific tunnel chainage signs set 10 m apart and indicating the respective tunnel meters for the documentation procedure. After successful localisation, participants were asked to fill out the general information section of the inspection report, including details such as anchor type, grout cement, and ultimate system load. Each participant then walked through the tunnel section, placing visual markers over four preselected inspected anchors, specifying whether an anchor pull test was successful. Finally, they completed the inspection, previewed the report data, and pressed the "Finish Report" button, automatically generating a report with information fields identical to the paper-based version, allowing for digital review and signing. These results were then compared to the actual test outcomes for the same tunnel section. Subsequently, participants conveyed their findings, summarised in Appendices A and B and organised and discussed below.

Compared to paper-based documentation, the AR-supported process necessitates users to precisely position the AR headset within the tunnel, choose the pertinent anchor data, and indicate the inspected anchors for accurate location determination. Specific data, including test load information, is dynamically generated through user input, obviating the necessity for manual entry. The distinctions between the AR-supported and the conventional paper-based process lie in its precise anchor localisation capabilities and centralised data storage, which aim to streamline and enhance the documentation process.

7. Results

This section provides an overview and analysis of feedback from prospective users of the AR prototype. Our analysis of the gathered data led to insights regarding the practicality and effectiveness of the AR prototype, both technically and in terms of user experience. The primary aim of the field test was to assess the advantages of the prototype as an alternative to conventional paper-based documentation in tunnelling. Following this, a usability test was conducted to identify any hardware or software limitations encountered during usage that could impact user acceptance but could be addressed in future hardware iterations.

Table 2 below summarises the recorded times, comparing analogue and AR-based processes quantitatively. The detailed list of activities and corresponding times are provided in Appendix C. The activities are recorded and categorised as recording, storage, and review to provide an overview of the times required to complete a specific set of tasks. The review activities, including enquiry with the foreman and plausibility checks, are not included in these sums since they are the same for both processes.

As presented in Table 2, the time for the analogue documentation process described in the previous sections amounts to 15.1 min for recording and 14 min for storage activities. The activities are recorded and categorised into recording, storage, and analysis to provide an overview of the times required to complete a certain set of tasks. The analysis activities, including enquiry with foreman and plausibility checks, are not included in these sums since they are the same for both

Table 2
Quantitative results for anchor inspection reporting.

Process	Recording (min)	Storage (min)	Total time (min)
Analogue	15,1	14,0	29,1
AR-Based	12,8	4,0	16,8

processes. Specifically, these activities include joint inspection with local construction supervision, report preparation, and the delivery of analogue documents to the foreman container for further processing. The distance for document delivery is a significant variable that can influence the total recording time depending on the construction site. The storage category encompasses making the first copy of documents, handing over copies to quality and site management, obtaining signatures and archiving, among other activities. The presented AR-based process eliminates or speeds up many of these steps, reducing inspection time as a consequence.

The total time for the analogue documentation process, including report creation and storage, is 29.1 min. In contrast, the total time for the AR-based anchor inspection process, including report creation, obtaining signatures and storage, is 16.8 min. On average, first-time prototype users completed the localisation step of a 10-metre section in 1.38 min. The inspection task for four anchors in the same section took 11.4 min, while the storage time, including the signature and forwarding a digitally signed report to quality management, took 4 min. However, faster hardware response times and more robust input functionality could reduce the inspection time for an AR-based process, as discussed in the sections below.

7.1. Field test

During the field test, the individuals were assigned to employ the developed AR prototype for anchor inspection. Despite occasional shortcomings in the HoloLens 2's responsiveness to user taps, most participants completed the task without significant obstacles. Subsequently, participants were required to complete the inspection and generate a report preview.

Several significant observations were made regarding the user interface of the prototype. The participants preferred the AR-based documentation solution over the conventional paper-based approach. Participants found the interface user-friendly and well-equipped with essential information for generating quality inspection reports. They specifically commended the ease of defining anchor and cement types, streamlining the initial setup process. However, users did acknowledge that the input window size was small and difficult to navigate, requiring some adaptation. It is important to note that this limitation is inherently linked to the field of view of the hardware and does not represent a design flaw. Nonetheless, future applications should consider enabling users to hide windows when not in use to optimise their field of view and focus on the assigned tasks.

Participants expressed positive feedback regarding the functions of the prototype. For instance, the automatic definition of the test force was considered practical and precise. However, a point of concern emerged in the analysis of failure causes, which was hampered by the slow responsiveness of the keyboard – a limitation attributed to the current hardware capabilities. Conversely, the automatic creation of diagrams to depict tested anchor positions was well-regarded, as it preserved the precise locations of tested anchors, eliminating potential drawing errors. Furthermore, participants praised the prototype's ability to store data centrally, expediting access for relevant parties and enhancing the efficiency of on-site inspections and decision-making processes.

Participants were asked to compare the prototype to traditional paper-based quality reporting methods. They emphasised the prototype's advantage, which is its automatic centralised reporting feature. This functionality was deemed effective in mitigating issues related to paperwork and input errors. Furthermore, participants emphasised the significance of the centralised digital repository for inspection reports, highlighting its effectiveness in minimising redundancy and tackling issues related to paper handling. These include interpretation errors and the damage or loss of paper documents due to environmental factors at construction sites, often associated with analogue media.

Participants identified an important area for improvement: the inability to edit a report once it has been finalised. While they acknowledged that the report could be reviewed later, the absence of editing capabilities within the AR headset was noted as a limitation. In addition to the identified improvements, integrating new use cases further enhances the potential of future AR applications in tunnel construction. These use cases include shotcrete thickness inspection, waterproofing membrane inspection, tunnel convergence measurements, concreting reports, and others. By incorporating these novel applications alongside the suggested enhancements, AR technology's usability and user acceptance in tunnelling can be significantly advanced, offering improved efficiency and accuracy in various inspection and documentation tasks. Participants acknowledged that despite the prototype's promise, current hardware limitations, as discussed in subsequent sections, may pose challenges to its widespread adoption.

7.2. Usability test

The conducted field test of the developed AR prototype was supplemented by a usability test of the current hardware to identify and address potential hardware issues that could be resolved in the future. The usability test revealed several areas for enhancement in future AR applications for tunnelling. Firstly, the floating user interface *near menu* (Microsoft, 2022b) proved to be more user-friendly than the *interactable object* (Microsoft, 2023b) input options. However, it was observed that the airtap interaction type, while suitable for users familiar with the HoloLens 2, posed reliability issues for beginners, leading to longer inspection times. Nevertheless, this interaction method demonstrated utility in placing objects on intersecting meshes, such as tunnel walls. Utilising hand menus to toggle between floating windows effectively cleared the field of view when menus were not in use. To optimise performance, spatial mesh detection in *Unity* should be disabled when not required, as the meshes created during detection can obstruct the user interface if left active.

Furthermore, users required time to familiarise themselves with the virtual keyboard, and creating text using the keyboard was generally slower than traditional paper-based solutions. Although speech recognition offers an alternative, it may be impeded in noisy tunnel construction sites. In this regard, implementing a scrollable list of predefined elements tailored to specific tasks in tunnel inspection could significantly accelerate processes. The world lock tool demonstrated satisfactory performance within the chosen tunnel environment; however, additional testing at longer distances is essential to validate its effectiveness across all use cases. Spatial mesh detection effectively identified tunnel walls despite occasional delays in recognition. Moreover, the recognition of partial spatial meshes of walls exhibited robust functionality.

Users also demonstrated effective navigation capabilities while wearing HMD in suboptimal illumination scenarios within tunnel environments. The installed construction lighting provided adequate visibility conditions for all participants. Nonetheless, the presence of semi-transparent UI elements in AR HMDs presented visual obstruction challenges for first-time users, necessitating some adaptation. The participants did not encounter significant issues navigating the main menu during the test. However, a notable usability problem arose with the airtap interaction, which required participants to hold or pull the airtap. The localisation prototype exhibited pink visual artefacts during usability testing, possibly linked to a white mesh texture bug related to spatial mesh detection. This issue persisted even when spatial mesh detection was disabled. Moreover, in some instances, spatial mesh detection took longer than 30 s to detect the wall mesh. Another concern surfaced when the HoloLens 2 displayed a low battery warning during the usability test, necessitating a power bank to charge the device. Most of these hardware-related issues could not be addressed during the prototype development phase. However, they are potential areas for resolution in future iterations of the HoloLens hardware and software ecosystem. To address these issues, developers should focus on refining the HoloLens hardware and software ecosystems in future iterations. Researchers conducting usability testing should be mindful of these HoloLens-related challenges to gain comprehensive insights into the solution's usability independently of device-specific limitations.

This study demonstrates the pressing need for modern solutions in the construction industry, particularly for large-scale infrastructure projects. It highlights the inefficiency of current paper-based documentation practices and the security issues in tunnelling projects. The study emphasises how digital tools can streamline documentation and reporting processes by showcasing the advantages of automatic information linking and location-specific data. Projects can be executed faster and cost-effectively by reducing reliance on paper-based documentation and improving data handling. Additionally, this research drives technological adoption by paving the way for broader use of AR and similar technologies in tunnel construction, encouraging ongoing innovation and technological advancement in the industry.

Still, the research has several limitations that should be considered in future research. Firstly, the prototypes developed were specific to HoloLens 2 AR HMD, and there is a need to extend the analysis to include a broader range of devices for comprehensive evaluation in tunnel environments. Furthermore, the study focused on one inspection type, necessitating the creation of new prototypes for diverse inspection tasks and comparing time efficiency against traditional paper-based methods. These prototypes could also employ an open and vendor-neutral standard, such as Industry Foundation Classes (IFC), as a centralised documentation format for tunnel inspection reporting, as demonstrated by Huymajer et al. (2024). With this approach, the report data generated from AR-HMD could be further instantiated as IFC properties for all relevant support measures, enabling further use of digital documentation in BIM applications. Additionally, long-term testing of AR HMDs in tunnel construction settings is essential to assess their durability and suitability over extended periods. The use of a convenience sample in usability tests provided initial insights. Still, more extensive and diverse participant groups, including geologists and site supervisors, are required for a more comprehensive analysis. The simplification of test tasks in the initial assessment offers only preliminary usability impressions, prompting the inclusion of more complex tasks in future studies. Moreover, long-distance assessments within tunnels should be conducted to evaluate continuous localisation accuracy and address potential issues like *wormholes*. A *wormhole* (Microsoft, 2023a) is an erroneous location detection due to similar environmental features, which could potentially occur in homogeneous low-contrast environments like tunnels. Lastly, participants' learning curve and time required for confident interaction with HoloLens devices should be explored through multiple testing sessions. Addressing these limitations will enhance the development of effective and robust AR solutions for tunnel inspections and similar industrial applications.

8. Conclusion

The construction industry is faced with complex challenges requiring robust project management, collaboration, and documentation, especially in large-scale infrastructure projects. Conventional tunnelling projects still predominantly rely on paper-based documentation, which is inefficient, error-prone, and can cause significant delays between data recording and evaluation. In this context, digital documentation techniques, such as AR, offer promising solutions that help reduce paper handling, save time and enhance on-site evaluations. However, despite the potentials there is a significant gap in research addressing AR applications in conventional tunnel construction, mainly due to the challenges associated with deploying the requisite hardware in such environments. This research aims to fill this gap by demonstrating the utility of AR for documentation and quality control in underground construction.

This research addresses the practical challenges and demonstrates the feasibility of deploying AR in subsurface environments. For this study, we developed a HoloLens 2 software prototype for anchor inspection reporting to evaluate the efficiency and feasibility of AR relative to paper-based documentation in conventional tunnelling. We first created a process model for paper-based documentation for this use case, then developed an AR-based equivalent, focusing on improving data consistency, security, and potential time savings. The AR prototype encompasses several key functionalities, including localisation to identify the specific tunnel meter, selecting technical specifications and placing virtual markers for tested anchors, documenting test results and comments, and generating a digital anchor pull test report. The case study conducted in a real tunnel setting with seven participants provides empirical evidence of the clear preference for AR-based solution over traditional methods, emphasising the advantages of automatic information linking and location-specific data.

The findings show that the implementation of AR in tunnel construction can be beneficial for accurate mapping and construction documentation. Despite identified areas for improvement, such as editing capabilities for the prototype and hardware limitations of the HoloLens 2, this research demonstrates the adaptability of AR technology within tunnel construction environments. Future research should expand on these findings by exploring a broader range of AR devices, developing new prototypes for multiple inspection tasks, and conducting long-term evaluations in diverse tunnel environments.

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CRediT authorship contribution statement

Oleksandr Melnyk: Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Marco Huymajer:** Writing – original draft, Software, Formal analysis. **Dominik Fenzl:** Software, Investigation. **Christian Huemer:** Writing – review & editing, Supervision, Resources, Funding acquisition. **Robert Wenighofer:** Writing – review & editing, Resources, Data curation. **Alexandra Mazak-Huemer:** Writing – review & editing, Supervision, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Summary of field tests

See Table A.3.

Table A.3
Summary of usability test findings of anchor inspection reporting using AR.

Category	Summary of Responses and Observations
Participant Definition	The test involved seven individuals familiar with tunnel construction, with two having prior experience using HoloLens.
Localisation Observations	The task of placing two space pins in a 10 m section was completed in an average time of 1.38 min. Despite occasional recognition issues with the HoloLens air tap function and glove use, participants mostly felt confident.
Time for Inspection	This task, involving the inspection of 10 m section, was completed in an average time of 11.4 min. Participants confidently executed the marking process but encountered difficulties with the virtual keyboard and navigating the user interface. A notable concern was the slow responsiveness of the virtual keyboard, linked to the current hardware limitations.
Time saving potentials	AR decreases the time needed for data acquisition, providing time-saving opportunities for on-site operations and decision-making processes. In contrast, paper-based reports necessitate physical transportation, which can be time-consuming in a tunnel environment. The use of AR diminishes the likelihood of transcription errors or misinterpretations related to the legibility of handwritten notes. Faster communication is offered by centralised data storage in the foreman container.
Overall Observations	No major issues were observed with the main menu interactions. However, air tap holding/dragging challenges and obtrusive informational dialogue windows were noted. Additionally, issues like pink artefacts and inconsistent mesh detection by the HoloLens were identified.
Interaction with AR HMD	Participants reported that interacting with the HoloLens was generally intuitive. Challenges included adapting to the restricted field of view, difficulties with air tapping, and navigating the menu system.
Localisation Setup Feedback	Feedback on the localisation setup was largely positive, with participants suggesting potential automation and user interface design improvements. Opinions on the white grid used for space pin placement were mixed, highlighting both utility and visual discomfort.
Prototype Feedback	The inspection process was intuitive, with suggestions for more detailed instructions for first-time users and user interface enhancements. Participants strongly preferred this AR solution over traditional paper-based methods, citing its numerous advantages. The automatic definition of the test force was appreciated for its practicality and precision. The feature for automatically creating diagrams to depict tested anchor positions was praised for preserving precise locations and eliminating drawing errors. A crucial area for improvement identified was the inability to edit reports once finalised, especially within the AR headset.
New Use Cases for AR HMDs in Tunnelling	Participants suggested integrating additional use cases such as shotcrete thickness inspection, waterproofing membrane inspection, tunnel convergence measurements, concreting reports, to enhance the AR technology's potential in tunnel construction.
Future Considerations	Near-interaction user interfaces were easier for participants compared to far-interaction menus, particularly for those with less experience with the HoloLens. Recommendations include providing adjustment time and training for HoloLens users, enhancing spatial mesh detection, and improving overall user interface design for AR applications in tunnel construction. Participants recognised that current hardware limitations might hinder its widespread adoption.

Appendix B. Summary of usability tests

See Table B.4.

Table B.4
Summary of responses to Hololens usability questionnaire.

Category	Summary of Responses
General Interaction with the Hololens	– Confidence varied among users, with some feeling confident quickly. – Instructions were helpful, but UI popups were obstructive. - Previous VR/AR experience was beneficial. – Restricted field of view was initially challenging. – Desire for a more unified application interface.
Airtap function and Buttons	– Difficulties with airtapping buttons. – Near interaction buttons were generally easier. – Air tap gestures often not detected. – Preference for buttons closer to user. – Difficulty with air tap should decrease over time.
Wearing the AR HMD	– Comfort varied; some users felt dizzy after a short period. – Generally comfortable for extended wear. – Resolution and eye strain were concerns for some users. – Users effectively navigated tunnels under low–light conditions while wearing a HMD. – Adequate construction lighting mitigated visibility challenges. – Semi-transparent UI in AR HMD obstructed first-time users' field of vision in low-light conditions.
Position of UI Elements	– Participants exhibited varied preferences regarding window placement. – Some windows were misplaced or too close. – Some users prefer dynamic placement. – Needs adjustment for far-sighted users.
Menu Usability	– Participants exhibited varied preferences on the combination of hand and floating menus. – Confusion initially, but practicality recognised over time. – Preference for unifying menu types for consistency.
Localisation Setup	– The marking process generally worked well. – Airtapping issues noted. – Applicable for longer distances. – Preference for simplified setup with extrapolation.
Spatial Mesh of Tunnel Lining	– Mixed responses; some found it irritating, others helpful. – Users suggest adjusting the grid's colour and saturation for a better experience. – Grid was helpful on irregular surfaces but less so on smooth surfaces.

(*continued on next page*)

Table B.4 (*continued*).

Category	Summary of Responses
Inspection Prototype	– Generally intuitive. – Simplification and separate report generation were suggested. – Need for clearer next-step indications for first-time users. – Unified wording in instructions preferred.
Information Window	– Clear and easy to obtain information. – Placement of check-boxes is potentially confusing. – Suggestion for table format for support measures.
Preference over Paper-Based Solutions	– General preference for the prototype over paper-based methods. – Advantages in navigation, photo geolocation, and immediate stakeholder access. – Concerns about environmental suitability and hardware reliability in tunnel construction.

Appendix C. Quantitative results for anchor inspection

See Tables C.5 and C.6.

Table C.5
Time for analogue anchor inspection report.

Party	Activity	Recording	Storage	Review
Foreman	Joint inspection local construction supervision	5,0 min		
Foreman	Report preparation	5,5 min		
Foreman	Delivery of analogue documents to the foreman container (380 m)	4,56 min		
Foreman	Copy 1		2,0 min	
Foreman	Copy handed over to shift construction management		2,0 min	
Foreman	Copy received		1,0 min	
Supervision	Signature		1,0 min	
Supervision	Copy 2		2,0 min	
Supervision	Storage		2,0 min	
Site manager	Plausibility check			2,0 min
Site manager	Enquiry with foreman			15,0 min
Site manager	Check fulfilment of requirements		1,0 min	
Site manager	Scan and file report to quality management		3,0 min	
Total time		**15,1 min**	**14,0 min**	**17,0 min**

Table C.6
Time for AR-based anchor inspection report.

Party	Activity	Recording	Storage	Review
Foreman	AR HDM Localisation	1,38 min		
Foreman	Joint inspection local construction supervision and report preparation	11,4 min		
Supervision	Check fulfilment of requirements		1 min	
Supervision	Digital signature		1 min	
Site manager	Enquiry with foreman			15,0 min
Site manager	Plausibility check			2,0 min
Site manager	Digitally signed report to quality management		2 min	
Total time		**12,8 min**	**4,0 min**	**17,0 min**

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