Extended Reality for tunnel Inspection using BIM

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Abstract. The increasing challenges posed by aging infrastructure require innovative digital solutions to enhance maintenance and inspection processes. In this context, the adoption of advanced technologies such as Extended Reality plays a pivotal role in modernizing infrastructure management. XR enables the visualization and integration of information by superimposing data-rich models onto physical environments, thereby improving decision-making and operational efficiency. This paper presents the development of an XR application that utilizes Building Information Models to overlay inspection data onto the real world. The application is validated through a real-world case study, demonstrating its potential to streamline inspection workflows and enhance data accessibility in maintenance operations.

Keywords: XR, BIM, Tunnel, Inspection.

1 Introduction

Inspections are fundamental for assessing the safety and preservation status of road tunnels, providing essential information for maintenance and risk management. During the preliminary inspection phases, detailed visual assessments and non-destructive tests on the structure are crucial to detect damage and potential issues. If the data gathered in this process is meticulous and the documentation of the infrastructure's current status is correctly digitized, in-depth analyses can be conducted to understand risks and manage future interventions [1]. However, the digitalization process is often slow and prone to errors, which can compromise the efficiency of data utilization.

Currently, various systems employ advanced technologies such as laser scanning or robots to carry out inspections and capture the current status of the structure [2]. However, these systems can be expensive and difficult to use without proper training, making them unsuitable for small and medium-sized companies. This research aims to explore how user-friendly technology can support tunnel monitoring and inspection by facilitating the digitalization of on-site data collection.

Extended Reality (XR) is an umbrella term encompassing Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR). An early description of this technology was provided by [3], contributing to the definition of the virtuality continuum. XR applications offer a transformative solution by enabling inspection data to be directly added to digital models during the inspection process, streamlining digitalization and reducing errors. Furthermore, leveraging Building Information Modeling (BIM) [4] enhances this process by linking past inspection data to virtual objects, ensuring comprehensive access to historical information during tunnel investigations.

This article explores the current use of BIM in inspection and maintenance workflows for existing tunnels, alongside an overview of XR applications in similar contexts. The methodology section details the development process of a prototype XR application, demonstrating how it utilizes BIM models to superimpose inspection data onto real-world infrastructure and collect information effectively. Finally, the results section presents the application's deployment in a real-world case study, highlighting its potential to enhance tunnel inspection and data management processes.

2 Relevant papers

The use of BIM for infrastructure operation and maintenance has significantly increased over the past decade [5] driven by the methodology's inherent capability to store both alphanumeric data and geometrical information in an integrated manner. BIM's role as a centralized repository for inspection data, which can be linked to external sources such as sensors or monitoring systems, holds great potential to enhance decision-making processes, as explained in [6]. By enabling the association of inspection records with specific elements of the infrastructure, BIM provides a comprehensive digital representation that facilitates the understanding of structural conditions and supports data-informed interventions.

Recent advancements in data analysis have further expanded BIM’s application in infrastructure management. Advanced frameworks such as the TunGPR system, described in [7], integrate BIM with deep learning techniques for tunnel defect detection. These systems demonstrate how inspection data, combined with artificial intelligence, can prioritize maintenance tasks using risk assessment matrices. Another application of BIM and deep learning is present in [8] where the author described a method for the automated detection of damage on the underside of steel box girder bridges, starting from the preliminary stage of photography. These studies highlight that the proper development and enrichment of BIM models are fundamental for data-driven maintenance strategies, allowing better prioritization of repairs and offering detailed insights into structural health over time.

The integration of XR technology further enhances the potential of BIM by providing immersive and interactive visualization of digital models. XR applications that overlay information onto the real environment are widely adopted in sectors such as manufacturing and healthcare. For example, [9] present a mobile AR training system that assists non-expert users in understanding the functionality of complex automated industrial systems. The AR tablet application superimposes virtual information onto real machines, leveraging IoT sensor data to visualize dynamic behaviors and improve users' comprehension.

The combination of BIM and XR technologies has gained increasing attention in the AEC industry for supporting inspection and maintenance activities. [10] provide an overview of various BIM-to-XR processes, highlighting the growing efforts to integrate XR applications into infrastructure management workflows. XR applications such as overlaying as-built BIM models onto tunnel interiors enable inspectors to identify deviations from design specifications, aiding in displacement detection and alignment verification. In real-world settings, AR applications can be coupled with Simultaneous Localization and Mapping (SLAM) techniques to achieve accurate spatial positioning, allowing inspectors to efficiently map and document structural elements [11][12] .

Interoperability plays a crucial role in enabling seamless data exchange between systems and stakeholders. Therefore, a key component of the proposed methodology is the adoption of the OpenBIM strategy and the Industry Foundation Classes (IFC) format [13]. The IFC format allows consistent data exchange across different software platforms and disciplines, ensuring the continuity of information throughout the infrastructure lifecycle. Implementing the OpenBIM strategy from the early construction phases enhances document management and facilitates the structured collection of valuable data for the operational and maintenance phases of the tunnel [14].

3 Methodology

Methodology In this chapter, we present the development of a prototype application designed to support tunnel inspection activities. The primary objectives of the application are to overlay existing information and past inspection reports onto the real infrastructure and facilitate the collection of new data to improve the maintenance process. The development process of the XR application involves the use of various data types and tools. The workflow applied to create the prototype is illustrated in Figure 1.

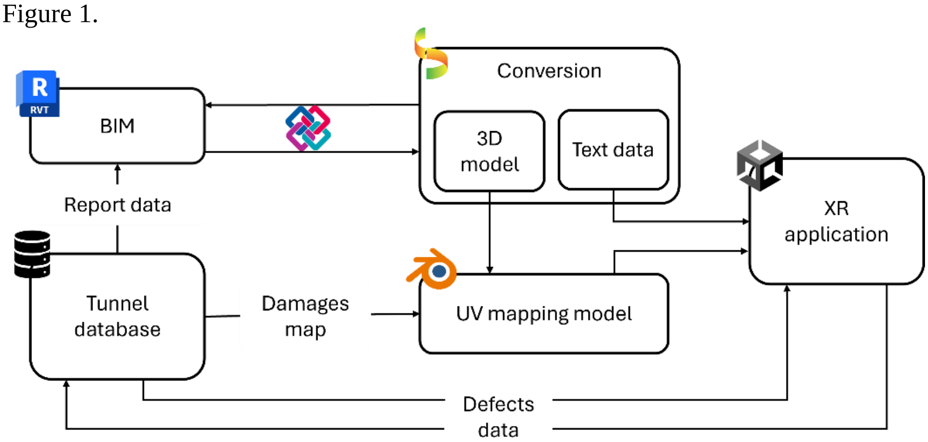

Fig. 1. Workflow for XR application development

The process starts with the creation of a BIM model of the infrastructure, based on As-Built data and inspection reports. This model is then exported in IFC format using Autodesk Revit software. However, since the IFC format is not optimized for XR

applications, a conversion process is necessary to separate geometric data from alphanumeric information. During this conversion, the BIM elements are renamed with the global ID created during the IFC export process and transformed into the .gltf format. This approach enables the straightforward linking of alphanumeric information, which is converted into .xml format, with the corresponding 3D geometry.
Before importing the model into Unity, the game engine software used to develop the application, a texturing process was performed on the geometric model. This process applies the defect maps to the inner surfaces of the tunnel segments. The Unity-based Android application is then developed to load both geometric and alphanumeric information. External data, such as past inspection reports, can be linked to BIM objects using alphanumeric data. Additionally, new information collected during inspections can be exported from the application to be uploaded to the tunnel database.

The creation of the BIM model for the selected case study begins with a simple drawing that contains the tunnel's geometric information and the locations of major defects. Figure 2 shows the drawing used for the modelling with defect information highlighted in green.

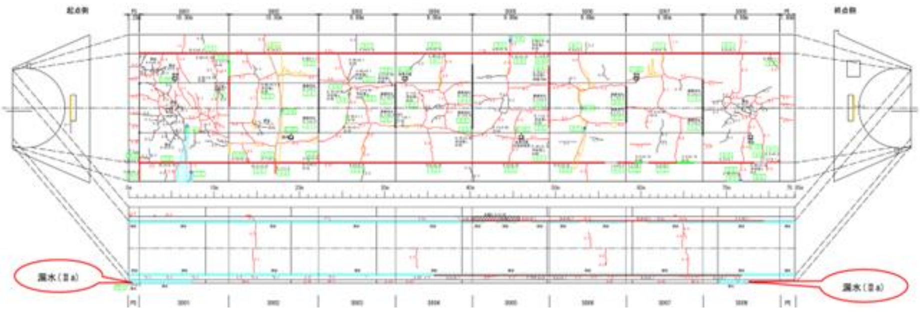

Fig. 2. Drawings of the existing tunnel used for the prototype

The resulting model, shown in Figure 3, has a low level of detail and includes objects representing individual segments of the structure, as well as objects associated with documented damages. These damages are appropriately coded to link the already collected information in the XR application

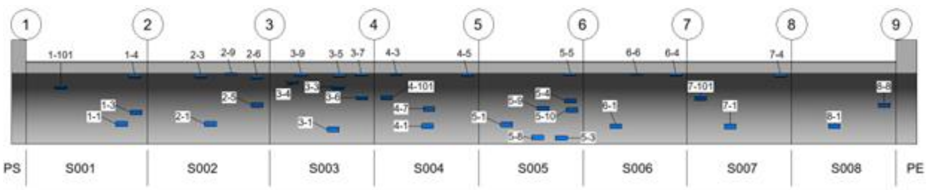

Fig. 3. Section of the BIM with segments and defects information

After exporting the model in IFC format and converting the geometry to .gltf format, the software Blender was used to apply the defect maps to each segment's inner surface. This process requires several steps to adapt the planar 2D maps to the curved

3D tunnel surface, making the information more suitable for XR applications. The steps to apply the images and ensure correct information visualization are shown in Figure 4.

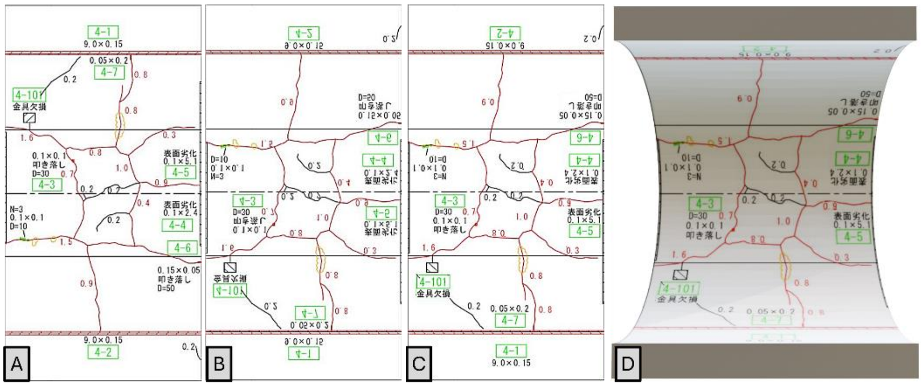

Fig. 4. Process for the model texturing on segment 4. In A, the original map of the defects; in B, the mirrored map; in C, the mirrored map with text adjustment; and in D, the map applied to the model.

In Image A of the figure, the original defect map of segment 4 is shown. Inspectors typically draw the defects from a vertical perspective, as if viewing the tunnel from above. However, in the XR application, the user is immersed in the environment and views the tunnel from below. To align the map with this perspective, the map must be mirrored, as shown in Image B. The measurement notes on the map must also be mirrored and rotated accordingly to ensure readability. The final image, shown in Image C, is used in Blender to texture the 3D model, resulting in the textured model shown in Image D.

This process was repeated for each segment of the BIM model, selecting only the inner faces of the tunnel segments for texturing.

The textured model is then imported into the Unity3D game engine, along with the XML file containing the alphanumeric BIM data. Unity was used to develop an Android application for smartphones and tablets that leverages the Google ARCore library to align the virtual model with the real infrastructure. The model's placement in the real world is achieved through environmental recognition using the device's camera. The plane detection functionality allows users to identify the sidewalk surface and place a 3D element that emulates the local coordinate system of the segment. By translating and rotating this element, users can anchor the BIM model to the real world without requiring GPS or target markers, which could obstruct parts of the structure during inspections.

As explained before, all the elements of the geometrical model were renamed using the global ID generated by the export of the IFC. In this way, by clicking on the virtual elements in runtime, it is possible to read the BIM data and send a web request asking for the report in the database with the correct code. This functionality allows saving time for data search during the inspection. Another core functionality consists of collecting new data using the application. The overlay of the defects maps with reality allows us to easily check the tunnel condition at the past inspection and monitor possible changes over time. Also, drawing functionality and a data-gathering menu allow the user to add new information on the model and then export it for post-process operation.

4 Results and conclusions

The developed application was tested in a real-world case study involving a road tunnel in Kochi Prefecture, Japan. The testing phase evaluated the XR application's capabilities for information overlay, as well as the usability of features for viewing data and adding new damage records. Support from the inspection company facilitated the identification of improvements and the development of new features to enhance the inspection process.
Figure 5 illustrates the application's different functionalities. Image A shows the model anchoring phase, where the yellow plane is detected and the local coordinate element is placed between two segments to align the virtual model with reality. Image B displays the overlay between reality and virtuality, with adjustable transparency to compare current and past tunnel conditions. Image C demonstrates the retrieval of past inspection reports from the external database for a selected defect. Finally, image D presents the data collection feature, with the data-gathering menu open and annotations on the model's surface.

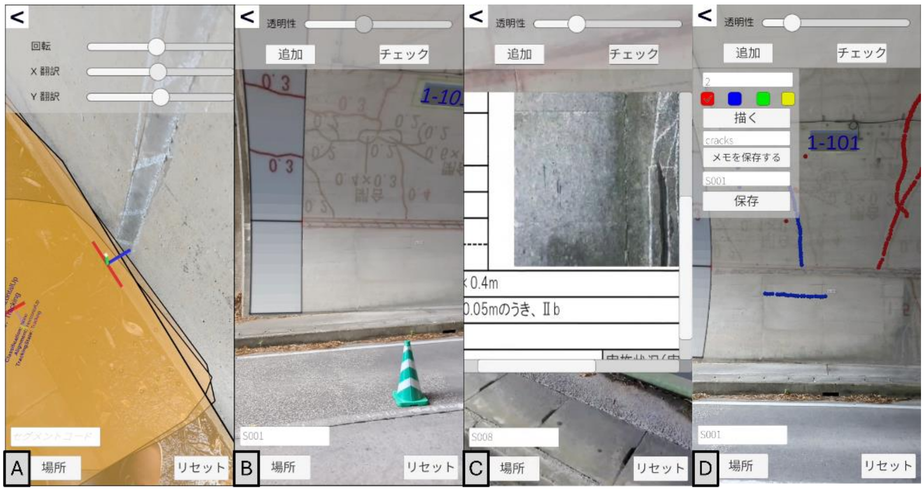

Fig. 5. Different features of the application. In A, plane detection for anchoring the model in the real world; in B, the loading of the textured model with transparency changing; in C, the reading of past report of a selected defect; and in D, data collection of new defects data

Figure 6 provides an overview of the application during testing. The results show that the application effectively streamlines data visualization and collection during tunnel inspections. These findings highlight the potential of XR and BIM integration to improve inspection workflows, offering a more efficient and accurate approach to infrastructure management.

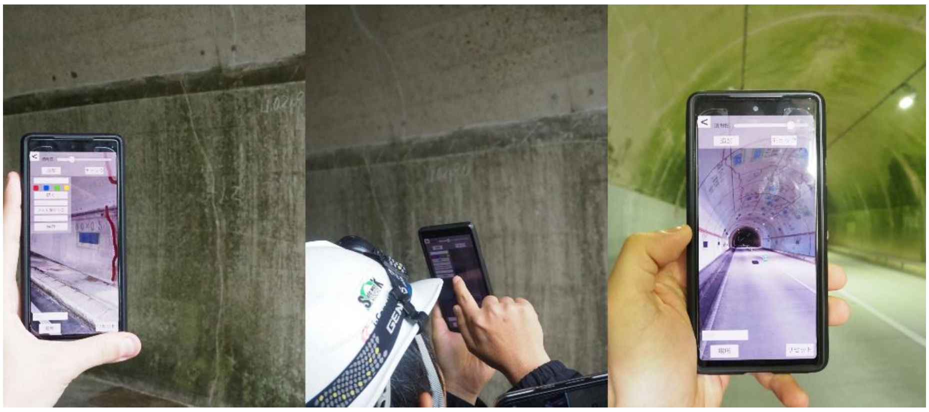

Fig. 6. Photo related to the testing with inspectors

The integration of BIM and XR technologies represents a promising advancement in the field of tunnel inspection, bridging the gap between digital information and physical infrastructure. Future developments could focus on expanding the functionalities of the application, such as implementing automatic defect recognition using AI algorithms and enhancing multi-user collaborative features. This approach not only enhances the efficiency and accuracy of inspections but also contributes to the creation of a more data-driven and resilient infrastructure management system.

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