EXTENDED REALITY FOR REMOTE INFRASTRUCTURE INSPECTION

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Abstract

The management of critical infrastructure requires inspection processes capable of assessing asset conditions in a safe, efficient, and traceable manner, particularly for assets such as bridges, tunnels, industrial structures, and other facilities exposed to deterioration, demanding environmental conditions, or restricted accessibility. Currently, many inspections are conducted through on-site visits, photographic records, and technical reports, which may expose personnel to hazardous conditions, generate high operational costs, and create difficulties in integrating collected information into subsequent analysis and maintenance processes. Although technologies such as BIM, photogrammetry, LiDAR, and point clouds have improved the digital capture and representation of infrastructure assets, a significant gap remains in transforming these datasets into technical inspection environments that support integrated evaluation, documentation, collaboration, and decision-making processes. In this context, this research aims to develop a virtual reality solution for the remote inspection of critical infrastructure, integrating digital models, point clouds, and technical inspection criteria within a multi-user immersive environment. The methodology involves the design of an architecture composed of three main components: the structuring of inspection criteria within the digital asset model, collaborative immersive inspection, and the traceability and integration of generated inspection results. The results demonstrate that the proposed solution enables infrastructure visualization and analysis within a virtual environment, supports measurements, records inspection findings, applies technical evaluation criteria, and facilitates real-time collaboration among specialists. Furthermore, the integration between the real condition of the asset, its realistic digital model, and inspection records highlights the potential of virtual reality to reduce personnel exposure in the field, improve information continuity, and support decision-making processes related to infrastructure maintenance and management.

Keywords: Virtual reality; Remote inspection; Critical infrastructure; Digital models.

1 Introduction

1.1 Critical Infrastructure Inspection

Critical infrastructure plays a fundamental role in the operation, safety, and continuity of industrial, transportation, and urban systems [1]. Assets such as bridges, tunnels, industrial structures, walkways, pipelines, and support systems are continuously exposed to deterioration processes caused by environmental conditions, operational loads, corrosion, fatigue, and aging

[2]. Therefore, inspection activities are essential to assess asset condition, identify potential damage, support maintenance planning, and reduce the risk of failures that may affect operational continuity and human safety [3].

Traditionally, infrastructure inspection has relied on on-site assessments conducted by technical specialists through visual observation, photographic records, measurements, and manual reports [4]. Although these approaches remain widely used, they present important limitations regarding accessibility, operational costs, safety, and information management [5]. In many cases, inspections require personnel to access hazardous or difficult-to-reach areas, including elevated structures, confined spaces, or zones with operational restrictions. Moreover, the information collected is often fragmented across photographs, notes, reports, and isolated datasets, making it difficult to ensure traceability and continuity throughout the asset lifecycle. In recent years, digital technologies such as Building Information Modeling (BIM), photogrammetry, LiDAR, laser scanning, and point clouds have improved the ability to capture and represent the real condition of infrastructure assets [6]. These technologies enable the creation of detailed digital representations that support visualization, documentation, and analysis. However, despite these advances, significant challenges remain in integrating these data into inspection workflows that support collaborative analysis, technical evaluation, and decision-making in a structured and efficient manner [7].

1.2 Extended Reality for Critical Infrastructure Inspection

Extended Reality (XR), including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), has emerged as a promising technological approach for infrastructure inspection and management [8]. XR technologies allow users to interact with digital representations of infrastructure assets within immersive environments, improving spatial understanding, remote collaboration, and access to technical information [9].

In infrastructure inspection, XR has been increasingly used to support remote visualization, immersive navigation, training, maintenance planning, and collaborative analysis [10]. Previous developments have shown its potential to improve spatial perception, facilitate communication among specialists, and enable interaction with BIM models, point clouds, and digital twins [11]. In addition, combining immersive environments with reality capture technologies creates opportunities to analyze infrastructure conditions without requiring permanent physical presence in the field [12]. Nevertheless, many existing XR applications still focus mainly on visualization, training, or isolated interaction with digital models. Several approaches allow users to navigate infrastructure assets in immersive environments, but they do not fully integrate technical inspection criteria, structured evaluation workflows, traceability of findings, or interoperability with infrastructure management systems [13]. As a result, XR is often used as a complementary visualization tool rather than as an integrated platform capable of supporting the complete technical inspection process [14,15].

1.3 Gaps and Objectives

Although digital capture technologies and XR environments have significantly advanced the representation and visualization of infrastructure, there is still a relevant gap in the development of integrated immersive systems specifically oriented toward technical inspection workflows, data integration, and realistic asset models, beyond the simple projection of conventional 3D models. Current approaches often lack structured mechanisms to associate technical inspection criteria with asset elements, record findings in a traceable manner, support collaboration among specialists, and reintegrate inspection results into the digital ecosystem of the infrastructure. In this context, this research aims to develop an immersive virtual reality solution for the remote inspection of critical infrastructure, integrating digital models, point clouds, and technical inspection criteria within a collaborative multi-user environment. The proposed solution seeks to support infrastructure visualization, immersive interaction, technical evaluation, collaborative inspection, and the structured management of the results generated during the inspection process.

This article presents the proposed methodology and system architecture, including the main components and functionalities of the immersive inspection platform. It then describes an application example to demonstrate the implementation and operation of the proposed solution in a critical infrastructure inspection scenario. Finally, the study presents the results, discussion, and conclusions derived from the development and application of the system.

2 Methodology

The development and organization of the functionalities presented in this paper followed a three-stage process aimed at identifying the requirements of remote critical infrastructure inspection and translating them into a set of functionalities within an immersive virtual environment. The first stage focused on the identification of requirements for remote inspection processes. This stage included a review of the scientific literature related to infrastructure inspection, remote inspection practices, digital technologies for asset assessment, and the use of virtual reality in engineering applications. In parallel, the characteristics and needs of conventional inspection workflows were analyzed, considering aspects such as information access, defect assessment, collaboration among specialists, traceability of findings, and data management. Based on this analysis, a set of requirements for remote critical infrastructure inspection was established. The second stage consisted of defining the functional categories required to support the inspection process. The identified requirements were grouped into major functional areas that represent the different activities involved in remote inspections, including asset visualization, interaction and measurement, technical assessment, collaboration, information management, and integration with external systems. These categories were used as the basis for organizing the functionalities of the platform. The third stage involved the implementation and consolidation of the functionalities within the virtual reality platform. The functionalities were designed to address the requirements identified in the previous stages and to support the different phases of the inspection workflow. This paper focuses on presenting and describing the resulting functionalities, organized according to the defined categories, highlighting their role in supporting remote inspection activities for critical infrastructure.

3. Implementation

To support remote inspections of critical infrastructure, the proposed platform incorporates a comprehensive set of functionalities designed to facilitate visualization, interaction, assessment, collaboration, information management, and integration with external systems. These functionalities were developed to address the different stages of the inspection process, from the immersive exploration of the asset and the technical evaluation of its condition to the documentation, communication, traceability, and subsequent use of inspection results. For presentation purposes, the functionalities have been organized into six categories: (1) Asset Visualization and Immersion, (2) Interaction and Measurement in the Virtual Environment, (3) Technical Assessment and Findings Recording, (4) Multi-user Collaboration and Real-time Coordination, (5) Identity, Traceability, Continuity, and Process Governance, and (6) Output and Integration with Systems and Databases. The following sections describe each category and its associated functionalities in detail.

3.1 Asset Visualization and Immersion

The first category corresponds to visualization and immersion of critical infrastructure, which groups the functionalities that enable the spatial representation of the infrastructure within the virtual environment. Figures 1(a) to 1(d) show the immersive visualization of point clouds, used to represent the real condition of the critical infrastructure based on field surveys. Figure 1(e) presents the immersive visualization of BIM models, corresponding to the original design of the infrastructure. Figure 1(f) shows the model visibility control, which allows the BIM model, the point cloud, or both elements to be activated or hidden during the inspection. Figure 1(g) illustrates the adjustment of visualization scale, ranging from real scale (1:1) to reduced scales. Finally, Figure 1(h) represents the free exploration of the infrastructure from different perspectives. Overall, these functionalities support the spatial understanding of critical infrastructure, enabling the analysis of dimensions, proportions, relative location, and the general conditions of the inspected environment.

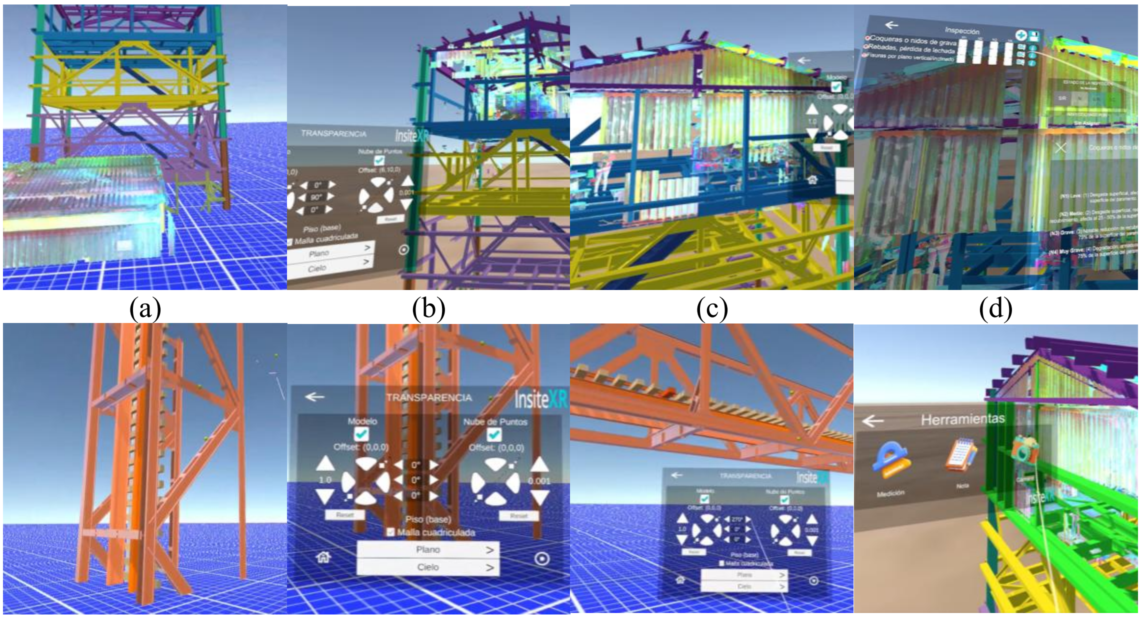
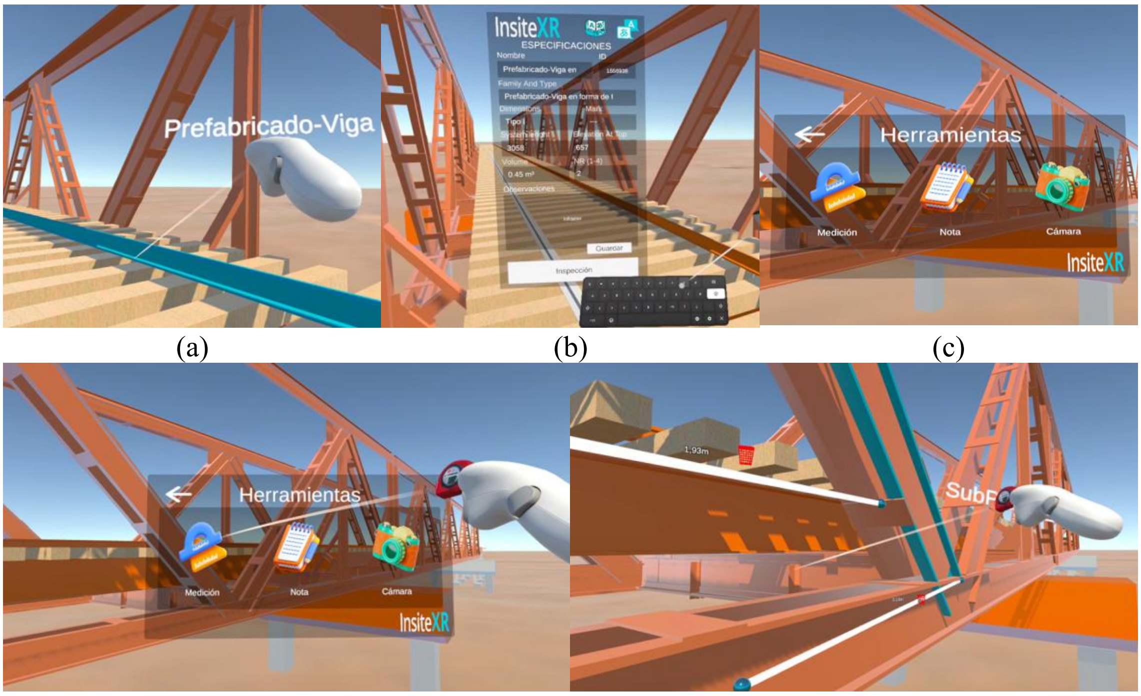


Figure 1. Asset Visualization and Immersive Exploration Functionalities.

3.2 Interaction and Measurement in the Virtual Environment

The second category corresponds to interaction and measurement in the virtual environment, encompassing the functionalities that enable users to directly interact with the infrastructure represented within the immersive environment. Figures 2(a) and 2(b) illustrate the element selection functionality, through which users can identify, highlight, and interact with specific components of the critical infrastructure. Figure 2(c) presents the interactive inspection tools, designed to support the review, assessment, and documentation of infrastructure elements during the inspection process. Figures 2(d) and 2(e) show the point-to-point spatial measurement functionality, which allows users to estimate distances and dimensions directly within the virtual representation of the infrastructure.

These functionalities extend the inspection process beyond passive observation by enabling technical actions such as selection, evaluation, and measurement within the immersive environment. As a result, inspectors can perform detailed assessments, obtain quantitative information, and document findings while maintaining a comprehensive spatial understanding of the asset throughout the virtual inspection experience.



(a) (b) (c)

(d) (e)

Figure 2. Interaction and Measurement Functionalities in the Virtual Environment.

3.3 Technical Assessment and Findings Recording

The third category corresponds to technical assessment and findings recording, integrating the functionalities aimed at technically documenting the condition of the inspected elements. Figure 3(a) shows access to BIM technical information associated with the selected elements. Figures

3(b) and 3(c) present the technical assessment functionality based on parameters and ordinal severity levels. Figure 3(d) shows the chromatic damage coding, which visually represents the condition of the evaluated elements. Figures 3(e) to 3(g) illustrate the recording of technical observations associated with complete elements or specific parameters. Figure 3(h) presents persistent visual markers, used to locate observations within the virtual environment. Finally, Figures 3(i) to 3(k) show the recording of photographic evidence associated with inspection findings.

This set of functionalities enables the immersive inspection to be transformed into a documented technical process, in which each finding can be linked to technical information, severity level, spatial location, written observations, and visual evidence. Thus, the platform supports a more structured, traceable, and evidence-based inspection workflow within the virtual environment.

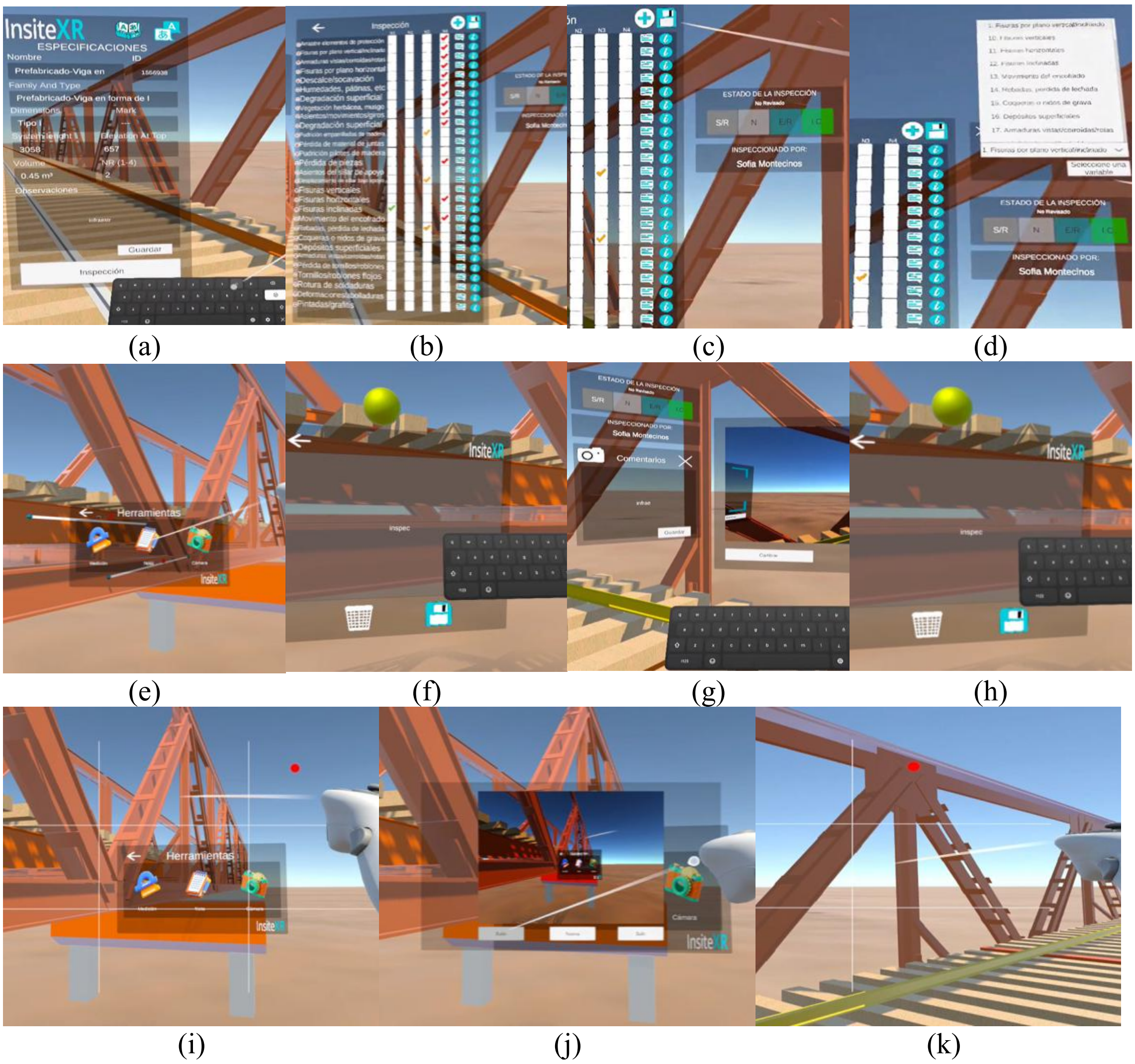


Figure 3. Technical Assessment and Findings Recording functionalities available within the virtual inspection environment.

3.4 Multi-user Collaboration and Real-time Coordination

The fourth category corresponds to multi-user collaboration and real-time coordination, encompassing the functionalities that enable the simultaneous participation of different specialists within the same inspection session. Figure 4(a) shows the real-time multi-user inspection functionality, where multiple users can interact within the same virtual environment. Figure 4(b) presents real-time voice communication, which allows users to coordinate observations, discuss findings, and support decision-making during the inspection process. These functionalities are particularly relevant for remote inspections of critical infrastructure, especially when specialists are not physically located in the same place. By enabling shared presence and synchronous communication, the platform supports collaborative analysis, interdisciplinary discussion, and coordinated decision-making within the immersive inspection environment.

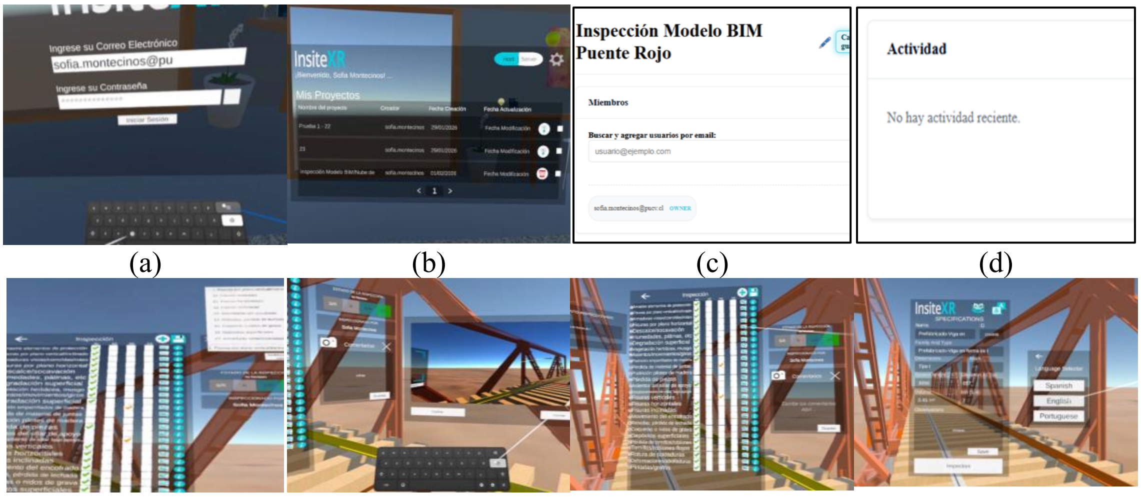
(a) (b)

Figure 4. Functionalities enabling multi-user collaboration and real-time coordination during immersive infrastructure inspections.

3.5 Identity, Traceability, Continuity, and Process Governance

The fifth category corresponds to identity, traceability, continuity, and process governance, encompassing the functionalities designed to control access, record user actions, and maintain the continuity of the information generated during the inspection process. Figures 5(a) to 5(c) show user authentication and role assignment, which allow permissions to be differentiated within the platform. Figure 5(d) presents the automatic action logging functionality, aimed at maintaining traceability by user and by project. Figures 5(e) and 5(f) show the persistence of the inspection state, including assessments, colors, and markers when closing and reopening a project. Figure 5(g) represents the association of each assessment with a responsible user and a specific timestamp. Finally, Figure 5(h) shows multilingual interaction, which enables access to technical information in different languages.

These functionalities strengthen process traceability by making it possible to identify who performed each action, when it was performed, and how the information is preserved across inspection sessions. In this way, the platform supports a more controlled, auditable, and continuous inspection workflow, improving information management and governance within remote infrastructure inspection processes.



(a) (b) (c) (d)

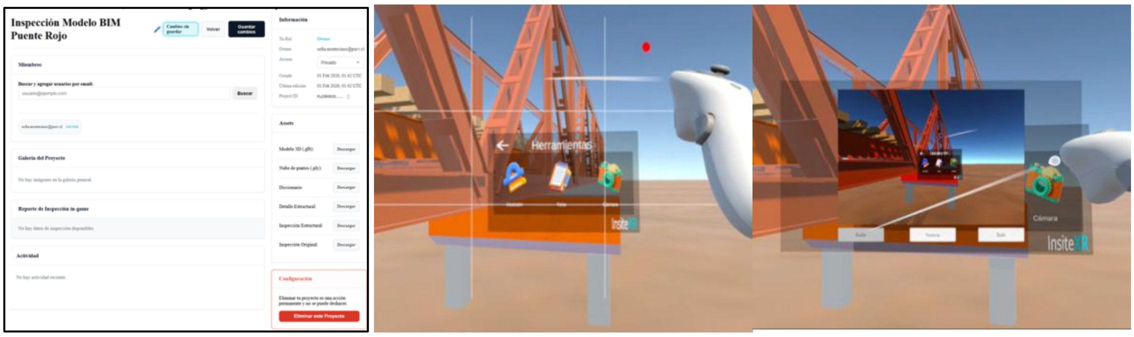
(e) (f) (g) (h)

Figure 5. Identity, Traceability, Continuity, and Process Governance functionalities integrated into the virtual inspection platform.

3.6 Output and Integration with Systems and Databases

The sixth category corresponds to output and integration with systems and databases, bringing together the functionalities that allow the results generated during the inspection to be queried, reused, and exported. Figure 6(a) shows the subsequent visualization of results through the project's web platform. Figures 6(b) to 6(d) present subsequent access to the photographic evidence recorded during the inspection. Figure 6(e) shows the export of structured results, for example in CSV format, for reintegration into BIM models or other external systems.

This set of functionalities ensures that the information generated within the virtual environment does not remain isolated, but can be subsequently used in analysis processes, technical documentation, results management, or project information updating. In this way, the platform supports continuity between the immersive inspection environment and broader asset.



(a) (b) (c)

(d) (e)

Figure 6. Functionalities supporting output generation and integration with external systems and databases during immersive infrastructure inspections.

4. Conclusions

This research enabled the identification of the requirements associated with remote inspection processes for critical infrastructure within the Architecture, Engineering, and Construction (AEC) industry, as well as the definition and implementation of the functionalities required to support these activities within a virtual reality environment. The results demonstrate the potential of immersive technologies to move beyond visualization purposes and support complete technical inspection workflows.

First, the study highlights the growing need for new inspection approaches capable of reducing the risks associated with field operations while improving the efficiency and continuity of infrastructure condition assessment. Traditional inspection processes often expose personnel to hazardous environments, require significant logistical resources, and generate fragmented information. In this context, remote inspection technologies represent an opportunity to strengthen preventive and predictive maintenance strategies, reducing dependence on reactive maintenance interventions and improving decision-making throughout the asset lifecycle. Second, the research identified six functional categories that collectively address the requirements of remote infrastructure inspection processes. These categories range from visualization, interaction, and measurement functionalities to technical assessment, collaborative work, information traceability, and integration with external systems. Together, they provide a comprehensive framework capable of supporting the different stages of a technical inspection process within a single digital environment.

The implementation of these functionalities in a virtual reality platform demonstrates the feasibility of conducting inspection activities in immersive environments. While several functionalities, such as measurement tools, information retrieval, and interaction with BIM models or point clouds, are commonly available in conventional digital platforms, their integration within a first-person immersive environment provides additional benefits. These include enhanced spatial understanding, full-scale (1:1) asset perception, and the possibility of real-time collaboration among multiple specialists within the same virtual inspection session. Furthermore, the proposed approach centralizes inspection criteria, technical assessments, observations, and evidence management within a unified environment. This facilitates bidirectional information exchange between immersive inspection environments and digital asset repositories, such as BIM models and associated databases, contributing to improved traceability, information continuity, and asset management processes.

Future research should focus on evaluating the effectiveness of these environments through additional case studies and validation scenarios. Particular attention should be given to usability, user acceptance, and performance analyses involving domain experts, as well as comparative studies assessing the effectiveness of immersive remote inspections against conventional on-site inspection methods.

5. References

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