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Streamlining Bridge Maintenance and Monitoring by Employing Augmented Reality (AR)

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Bridge inspections are vital for ensuring structural safety and serviceability. Most studies focus on surface defect detection methods with limited research addressing post-data collection and analysis processes. Typically, the inspector would need to return to the site, survey the bridge, and map the defect areas manually. The process is costly and inefficient, relying on inspector expertise. Therefore, to address these challenges, this study explores using augmented reality (AR) to improve defect mapping through enhanced visualization, geolocation, and access to previous inspection and maintenance reports. Existing research on AR in this context is minimal, prompting the need for this investigation. The proposed AR-based technique requires minimal hardware and software additions beyond what is typically available during inspection operations, making it easily replicable. Target defect will be delamination, and the mode of detection used are Infrared Thermography (IRT) and Impact Echo (IE). However, the method can be applied to any desired defect and detection method with 2D maps as the output. The technique was assessed on a mockup slab with mimic delamination and an in-service bridge. The results highlight that the proposed AR application has the potential to improve efficiency, accuracy, and collaboration during inspection and maintenance operations.

Keywords: Bridge Inspection; Augmented Reality; Defect Maintenance; Safety; 2D mapping; Visualization.

Introduction

As bridges age and begin to deteriorate, nearing the end of their service life, research has been focused on developing and optimizing inspection techniques (Peplinski et al., 2023; Sadhu et al., 2023). Surface defects, such as spalling or delamination, occur due to the expansion of corroded reinforcement and other factors, leading to the deterioration of concrete layers (Aljagoub et al., 2022). Therefore, several studies have been concerned with improving detection objectivity, efficiency, and accuracy through various non-destructive testing techniques.

The non-destructive testing (NDT) techniques studied include impact-echo (IE), ground-penetrating radar (GPR), ultrasonic tests (UST), and infrared thermography (IRT) (Aljagoub et al., 2022). While these techniques have added significant improvements to the surface defect detection process in concrete bridge decks, data processing typically occurs off-site, generating 2D maps that highlight defect locations (Kim et al., 2022). As a result, inspectors must return to the site to survey and map these defects on the bridge surface, making the process time-consuming, labor-intensive, and error-prone.

There is currently a missing link between data processing and the visualization aspects of bridge inspection and surface defect detection, highlighting the need for an improved visualization approach to streamline maintenance processes. Several studies have evaluated the potential improvement that visualization techniques under the Extended Reality (XR) umbrella, which includes Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR), can offer to the defect detection process. The consensus of these studies is that XR applications provide an interactive, informative, and collaborative inspection process, thus enhancing the efficiency of bridge maintenance and monitoring tasks (Kim et al., 2022). Furthermore, XR applications offer the added advantage of integrating historical data of past inspections and repairs during the inspection process, allowing for a comprehensive understanding of the state of the surveyed structure (Jin, 2020). Therefore, this study proposes a replicable AR approach to enhance the visualization and documentation process in bridge inspection and maintenance.

Literature Review

Augmented Reality Applications in Bridge Inspections

AR applications in construction, which fall under the low immersion side of the XR spectrum, as shown in Figure 1, have been on the rise. However, minimal research still exists on how to effectively employ it on-site (Kim et al., 2022). AR utilizes several integrated technologies to display virtual information about real objects in real-time in the real world (Kim et al., 2022). Due to AR's ability to provide immersive and interactive environments where information is better shared and accessed compared to traditional techniques, it has great potential to improve bridge inspection and maintenance operations.

Some studies explored utilizing headsets combined with real-time deep learning segmentation to detect defects such as cracks (Karaaslan et al., 2022). The results were promising, with the model able to successfully detect, measure, and assess the condition of the defect. Other studies focused on the integration of one or several NDT techniques results into the AR platform; the aim was to provide a comprehensive assessment of the bridge condition, enabling the inspector to make informed decisions with information on all NDT techniques present in one platform (Aguero et al., 2020; Kilic & Caner, 2021; Kim et al., 2022).

Others focused on AR applications to enhance the visualization aspect of data collection during inspections (John Samuel et al., 2022; Peplinski et al., 2023). At the same time, others advanced the process further and integrated past inspection and maintenance reports into the system, overlaying the results on the bridge (Jin, 2020; John Samuel et al., 2022). In those studies, a BIM model is developed, and the inspection and maintenance of past and current inspections are integrated. The recorded defects can be retrieved with their properties, such as dimensions, severity, location, etc., incorporated. The BIM model is continuously updated to include data from recent inspections (Jin, 2020; John Samuel et al., 2022). The proposed approaches enable a comprehensive and collaborative defects database per target bridge.

However, the discussed studies present some limitations. Some studies did not elaborate on how the AR system was developed, thus limiting the potential of replicating the process. Of the studies that provided details on how the AR system was developed, the proposed approach would require an advanced coding skillset to replicate, which is not widely available to all interested personnel. A few required using a headset or an internally developed AR platform, presenting some accessibility issues. Finally, a few of the reported studies relied on lab data and did not verify the AR platform in the field.

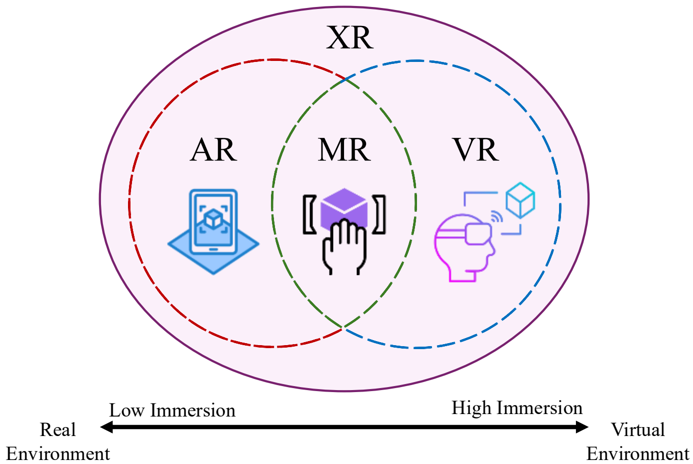


Figure 1. XR relationships, reproduced and modified from (Andrade & Bastos, 2019)

Problem Statement

As previously highlighted, there is still limited literature on XR applications to advance bridges' defect inspection and maintenance process (Kim et al., 2022). Also, the minimal current existing literature presents some limitations. Some of the studies focused on improving visualization of the defects, such as surface cracks on-site, by enabling real-time measurement and documentation (John Samuel et al., 2022; Peplinski et al., 2023). Other studies developed internal mobile applications for the XR process, requiring an advanced level of expertise for external parties wishing to adopt the techniques (Jin, 2020; Kim et al., 2022). Some studies only highlighted AR's potential use but did not provide an applicable adoption process (Kilic & Caner, 2021). Furthermore, several of these studies require advanced equipment, such as headsets, which can be costly (Aguero et al., 2020).

Therefore, this study intends to develop an easily adaptable and replicable AR process so that any interested and responsible party can utilize the technology to enhance its inspection and maintenance process. The proposed approach requires no advanced expertise in coding or app development. The technique does not require a headset and is compatible with smart devices, which are more commonly available. Also, the software utilized would be typically available for parties responsible for inspections, limiting the need for further investment into hardware and software.

The proposed NDT-AR integrated approach would streamline the bridge inspection to maintenance and repair process when adopted. AR integration will eliminate the redundancy of surveying the bridge post-analysis, thus minimizing error compared to manually mapping the defect location on the bridge. Therefore, the proposed methodology can potentially reduce time, cost, and labor needs.

As previously highlighted, delamination was selected as the target defect in this study. So, the proposed AR system will be tested on a mockup slab with mimic delamination and an in-service bridge deck. The test will illustrate the analysis results (2D map) overlayed on the surface, highlighting delamination locations through AR. Furthermore, the validation will include the results of two NDT techniques (IRT-UAV and IE), illustrating the robustness of the developed approach.

While this study focuses on the use of AR, XR can provide additional support to the bridge inspection, maintenance, and repair process. The application of XR is being explored in NDT for bridge inspections, if minimally. Several studies explored a continuously updated BIM model to reflect the most recent status of the bridge (Jin, 2020; John Samuel et al., 2022). In such cases, VR can be utilized to visualize the structure off-site for enhanced visualization of bridge conditions compared to 2D plans and reports. MR can be adopted on-site to augment inspection results on the bridge and allow interactions with defects such as delamination and cracks to obtain detailed information such as dimensions, depth, severity, type, etc. The combination of XR technologies for bridge inspection and maintenance operations has great potential to streamline the process, increase efficiency, enhance the accuracy of defect mapping, and improve collaboration and communication between stakeholders. However, as of now, there is limited research, and more studies are needed to fully evaluate XR's potential.

Research Approach

The methodology for this research focuses on utilizing augmented reality (AR) to assess surface defects in concrete bridges through the integration of 2D maps of detected defects based on a chosen NDT technique. Figure 2 details the necessary hardware and software to replicate this AR adoption process with minimal expertise.

The process begins with data collection, identifying the target bridge deck, and selecting a NDT technique. The detection modes in this study were IRT-UAV and IE due to the availability of hardware at the time of the study. However, this method is applicable to any NDT technique, with the output being 2D maps. Data was collected from a mockup slab with mimic delamination and an in-service bridge located in Newark, Delaware. Data collection details can be found in Table 1. Thermal and RGB images of the bridge deck were collected to identify delamination areas. Once the data is collected, it undergoes analysis, which employs the Level-set Method, an edge-based image segmentation technique developed for IRT delamination detection (LSM) (Cheng & Shen, 2020). Furthermore, an additional dataset was retrieved from historical inspection reports, and the mode of detection and analysis was IE and hammer-sounding. The processed data is then converted into a 2D map, allowing it to be exported for integration into the AR model.

Then, the digital assets for AR integration are collected and prepared for integration into Autodesk Navisworks. The 2D maps are converted into a suitable image format, the 3D model is developed in Autodesk Revit, and additional data can be incorporated if desired, such as original 2D construction plans, historical inspection and maintenance reports, and geolocation data. Geolocation is a crucial step, as the digital assets are aligned with the real-world location of the bridge using known geodetic coordinates. The geolocation step ensures that the delamination and model data overlay correspond accurately to the structure. Accurately placing these files within Navisworks allows for seamless visual and geospatial information integration. Note that the placement of the compiled Revizto file can be completed manually on-site by selecting a reference point in the app. Still, it is not recommended due to potential location and elevation discrepancies.

Next, the model is exported using the Navisworks Revizto plug-in to a new or existing Revizto project file. If the geolocation step is skipped, the Revit 3D model can be used instead. Model components, including the placement of critical elements and the delamination areas, are viewable on a compatible smart device to enable AR visualization in the field. Once on the inspection site, field testing is conducted by comparing the AR visualizations with the actual bridge structure. This process involves validating the accuracy of the geolocation and alignment of the digital model with the physical site. If discrepancies are found, key delamination and damaged locations can be noted in the AR system using Revizto issue stamps. These stamps will allow you to identify the exact locations of the damaged deck, add comments and pictures, and share them with other teams. Based on the results from the data processing and AR model visualization, maintenance recommendations are made to address the delamination areas.

The research will conclude by analyzing the effectiveness of the AR system in providing real-time insights into bridge conditions, followed by a detailed report of the findings, including recommendations for future improvements.

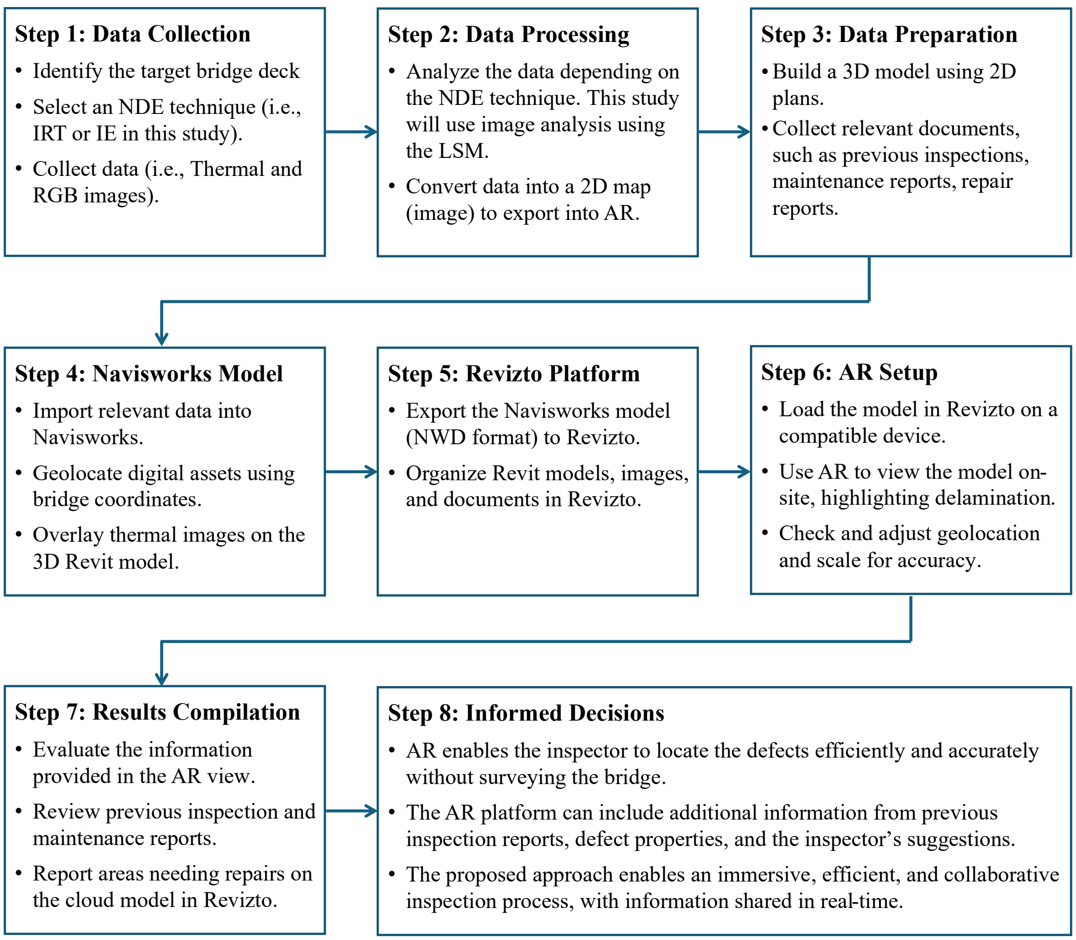


Figure 2. AR adoption and employment process

Table 1. Data collection details

Item	Data Collection Date	Time	Location	Detection Mode

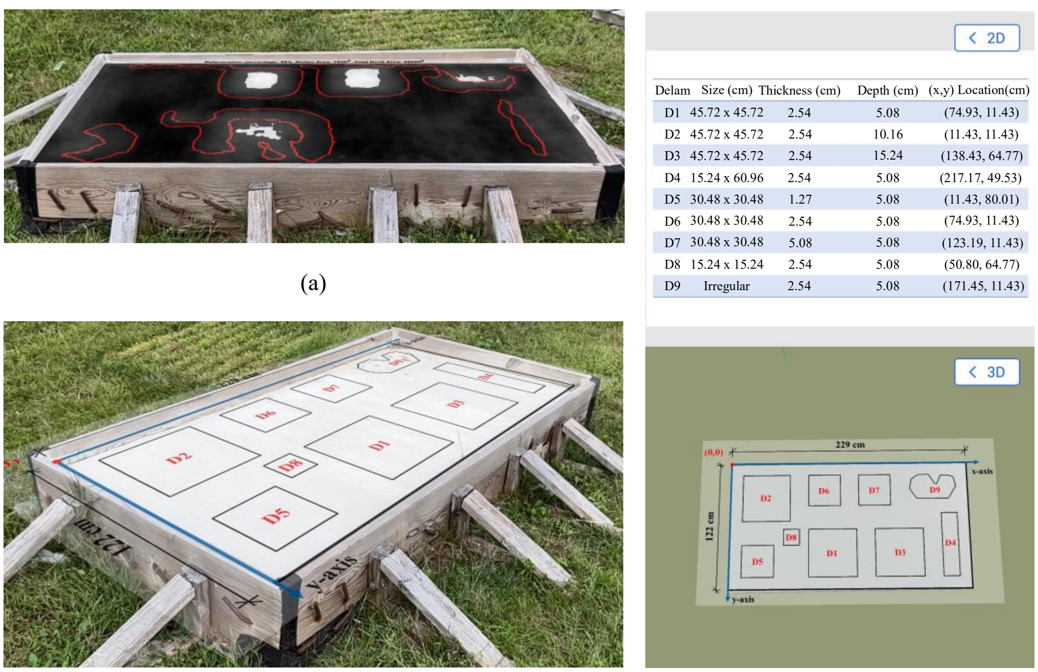
Apple Rd Bridge (1696-360)	7/30/2021	1 - 1:30 PM	X	IRT-UAV* IE** Hammer-Sounding
Mockup Slab	7/20/2022			IRT-UAV*

* Data was analyzed using the level-set method (Cheng & Shen, 2020).
** Retrieved from historical inspections.

Results and Discussion

Mockup Slab Data

As previously mentioned, the proposed AR platform was tested on a mockup slab with mimic delamination in Newark, Delaware. The IRT results detailed delamination locations on the slab were overlayed in AR, as shown in Figure 3a. Also, the ground truth image showing the real delamination location was illustrated (Figure 3b). Figure 3c shows how additional information, such as the delamination properties table, can be incorporated into the AR platform for a comprehensive overview of the structure's condition.



Delam	Size (cm)	Thickness (cm)	Depth (cm)	(x,y) Location(cm)
D1	45.72 x 45.72	2.54	5.08	(74.93, 11.43)
D2	45.72 x 45.72	2.54	10.16	(11.43, 11.43)
D3	45.72 x 45.72	2.54	15.24	(138.43, 64.77)
D4	15.24 x 60.96	2.54	5.08	(217.17, 49.53)
D5	30.48 x 30.48	1.27	5.08	(11.43, 80.01)
D6	30.48 x 30.48	2.54	5.08	(74.93, 11.43)
D7	30.48 x 30.48	5.08	5.08	(123.19, 11.43)
D8	15.24 x 15.24	2.54	5.08	(50.80, 64.77)
D9	Irregular	2.54	5.08	(171.45, 11.43)

(a)

(b) (c)

Figure 3. Revizto mockup slab AR field application, where (a) is the IRT thermal image, (b) is the ground-truth image, and (c) is in the app interface: delamination properties (extra documentation example).

In-Service Bridge Data

In addition to testing the proposed approach on the mockup slab, an in-service bridge was identified for field validation. The bridge data includes IRT-UAV, IE, and hammer-sounding analysis (Table 1). Figure 4a details the hammer-sounding results, as provided by the Delaware Department of Transportation (DelDOT), for four locations across the bridge deck. The hammer-sounding data will be used as a supplemental dataset, showing the exact delamination location as viewed in AR on the bridge deck, providing a link between all three methods. Figure 4b illustrates the results from the IRT-UAV data collection, which was analyzed using the level-set method displayed in AR view on the bridge. The hammer-sounding locations were marked, illustrating how accurately the AR view was able to capture the delamination location, especially in the case of Location 3. Next, Figure 4c displays the IE results in AR view, similar to the IRT-UAV data; the hammer-sounding results were incorporated as well. The results display the proposed approach's ability to effectively project the 2D maps to the bridge surface, providing automated, accurate, and efficient defect location mapping on the bridge deck.

Figures 5 show the IRT-UAV (Figure 5a) and IE (Figure 5b) results within the interface. The interface allows switching back and forth between documents and views; this would prove helpful on-site by providing a comprehensive set of information and data in a single interface.

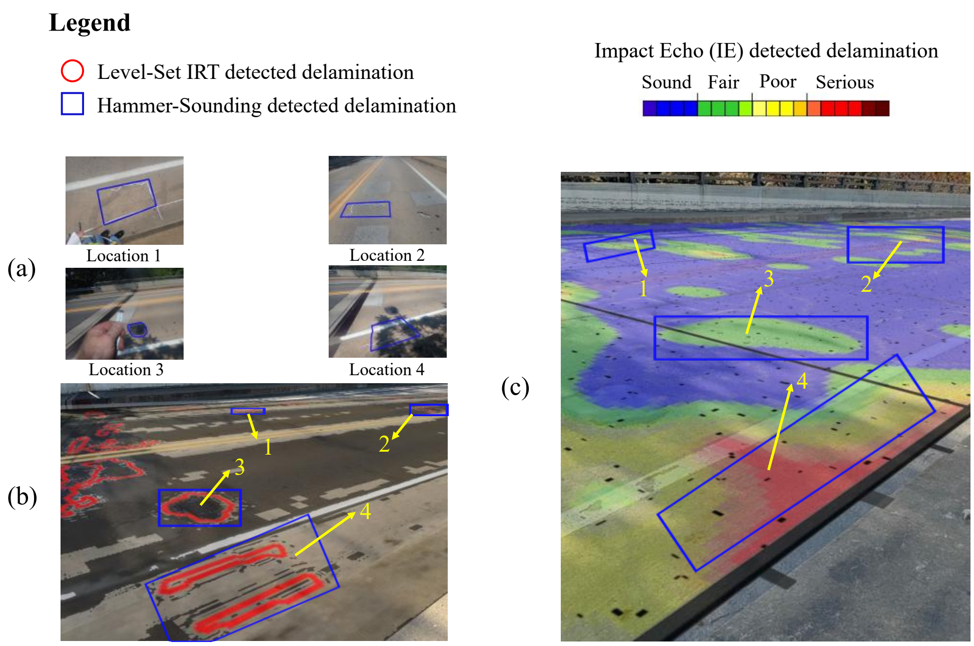
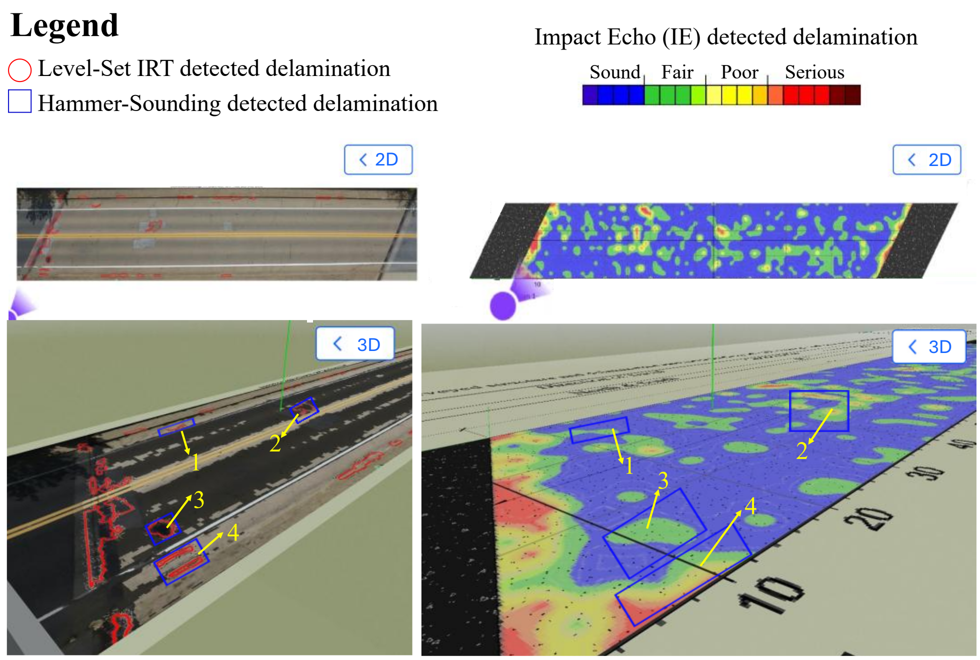


Figure 4. Revizto Apple Rd Bridge, where (a) hammer-sounding results, (b) the level-set AR view, (c) the IE AR view.



(a) (b)

Figure 5. Revizto Apple Rd Bridge, where (a) IRT-UAV interface, (b) IE interface.

Conclusion

The presented study aimed to provide a replicable AR-integrated inspection process. The current literature on AR adoption in bridge inspections is limited. Therefore, the proposed approach focused on using readily available hardware and software to adopt the method easily, thus streamlining the bridge inspection and maintenance process. The focus defect was delamination. The proposed AR platform was tested on a mockup slab with mimic delamination and an in-service bridge. The mockup slab data was collected using IRT-UAV, as for the in-service bridge, data was collected using IRT-UAV, IE, and hammer-sounding. As illustrated previously, the proposed AR system can be adopted with any desired defect and detection method with 2D maps as the output. Several features were assessed during the test, such as overlaying 2D images, retrieving historical inspection reports, and reporting features within the AR platform. Settings in the Revizto AR platform allow adding “issues and stamps,” including comments, recommendations, and images collected on-site, providing a comprehensive, collaborative inspection platform. The results highlight the proposed AR approach’s benefits to bridge inspection and maintenance by eliminating the redundancy of surveying the bridge to identify defect areas through 2D maps and instead locates defects through the AR platform. Also, access to historical reports integrated with current inspection results allows evaluation of defect progression, aiding the inspector in making informed decisions on recommended repairs and maintenance actions. Furthermore, being able to track issues with the same platform, which can be accessible to all involved parties, promotes improved communication and collaboration. The study presents some limitations where 2D maps are strictly needed, limiting the choice of NDT techniques. Also, the proposed approach relies on post-inspection analysis to produce said maps. Future works will focus on real-time defect detection through an AR-deep learning integrated platform and evaluate alternative hardware and software.

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