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Investigating Consistency Among Bridge Inspectors Using Simulated Virtual Reality Testbed

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16. Abstract

The current condition of US infrastructure requires a data-driven, risk-based approach to asset management. In the case of bridges, inspectors in every state visit these structures and collect data, and based on the information they report, state departments evaluate bridge conditions, predict deterioration, and make repair and retrofit decisions. However, the capacity of inspectors for defect detection might vary due to several factors, such as the inspectors' experience or eyesight, which results in differences when reporting their results. Through the development of a virtual reality (VR)-based testbed, the variability among inspectors in examination and documentation practices in steel and concrete bridges in Indiana will be measured and analyzed. As a result, training programs could be enhanced according to the outcome analyses of the VR system.

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EXECUTIVE SUMMARY

Introduction

The current condition of US infrastructure requires a data-driven, risk-based approach to asset management. In the case of bridges, inspectors in every state visit these structures and collect data. Based on the information they report, state departments evaluate bridge conditions, predict deterioration, and make repair and retrofit decisions. However, the capacity of inspectors to detect defects might vary due to several factors, such as the inspectors' eyesight or professional experience. In this project, a VR-based application was developed to engage users in immersive, photo-realistic 3D environments and provide a testbed to study the variability among bridge inspectors. The outcome will provide statistical information that will be used to enhance current inspection practices.

With the use of VR technology, current limitations of inspection evaluation, such as multiple districts and different types of structures, logistics of people and equipment, and weather conditions, are addressed. Besides improving inspection training, time and cost savings, safer conditions, and innovative training tools are also expected results. The final product is a modern VR set-up with testing models of concrete and steel bridges under controlled conditions that is open to assessing future needs. The system runs on a high-resolution tethered headset supported by a gaming laptop to increase portability across Indiana districts.

Findings

The VR-based application is comprised of two bridge modules—one for a steel truss bridge and one for a multi-beam concrete bridge. The 3D bridge models were synthetically recreated using reference images from two case studies. Through constant feedback and multiple demonstration sessions with the Indiana Department of Transportation (INDOT) and Study Advisory Committee (SAC) members, the bridge components, the defects and their severity, and the inspection tools to be modeled were defined. Nine types of defects were modeled, including efflorescence, cracking, corrosion, spalling, and delamination. Eight inspection tools were also recreated in the VR scene, such as chain drag, hammer, scratch or wire brush, flashlight, and tape measure.

Implementation

After completing the inspection in the VR scene, users are required to fill out an online survey for each bridge. Condition rating numbers and comments on the state of the deck, superstructure, and substructure are requested. Additionally, factors such as years of experience and work location are used to identify consistency patterns when compared with the rating numbers. The VR application also offers the possibility of taking screenshots that inspectors can later attach to their surveys to complement their reports. Statistical analysis, including pie charts and histograms, is automatically generated, giving a multi-faceted approach to consistent evaluation among inspectors.

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1. INTRODUCTION

Consistency in the inspection of bridges is pivotal for state and national level transportation agencies to manage highway systems efficiently and effectively. The collected data should be complete, accurate, and consistent among different inspectors, such that the evaluation of bridges' condition, prediction of deterioration, and repair and retrofit decisions should correctly reflect these structures' real and current behavior. (The left side of Figure 1.1 provides an example of bridge inspection with non-destructive tools.) However, prior experience suggests variability in detecting defects and anomalies among inspectors due to factors like training, years of experience, state of mind, and eyesight. Thus, efforts toward evaluating the inspector's variability in defect detection are needed to improve the reliability of the information obtained.

VR has proven to be a valuable technology to assess the performance and enhance the training of workers in different industries through the representation and interaction with objects in 3D immersive environments (see the right side of Figure 1.1). Some benefits of using VR have been reduced learning time, lower risk perception, and improved user safety (Monetti et al., 2022). The project described in this report develops a VR-based system that provides a testbed for the statistical assessment and identification of the key sources behind the variability among bridge inspectors. The testbed might lead to reforming and improving the current inspection practices, resulting in more precise and congruent assessments.

1.1 Problem Statement

Field inspection reports produced by bridge inspectors are used as a primary source of information by INDOT to make critical maintenance, repair, and replacement decisions. Nonetheless, the detection of defects is not always consistent or lacks uniformity among inspectors. Recognizing the major sources of variability will be instrumental in revamping the current training programs. Moreover, it will help to produce more precise and detailed post-inspection analyses, ultimately stirring more robust decision-making processes through the bridges' life cycle.

1.2 Objectives

This project aims to create a software system with a VR application that measures consistency between inspectors. The application runs through a VR headset with a simple interface to analyze, visualize, and seamlessly interact with various photo-realistic defects in virtual steel and concrete bridge models. The system has a portable and easy-to-use set-up supported by a high-end laptop.

After the deployment of the application by INDOT, several trained and experienced inspectors will be asked to inspect the simulated bridge models and identify the defective regions. Various personal factors will be tracked and tallied with the condition rating numbers assigned to the main bridge components. This data will be invoked later to investigate its correlation with the defects' detection rate and accuracy. The results of this study will be an indicator of the deficiencies in the current training course contents. They will help make necessary changes to the curriculum and the inspection manuals.

The main benefits of the system include the following.

- *Quality:* evaluation of consistency among inspectors will help identify areas of improvement or gaps in the current inspection practices and training procedures that, when addressed, will lead to a more effective inspection protocol enhancing the overall infrastructure safety.
- *Time savings:* mock inspection in a simulated virtual environment will save much time, which is otherwise expended on field visits, traffic control, safety measures, and logistics of people and equipment.
- *Safety:* a simulated virtual environment will reduce the risk of workplace accidents by eliminating the need to expose human inspectors to worksite hazards.
- *Cost savings:* consistency in defect detection will reduce the uncertainties and increase the confidence of the state agencies to opt for cost-effective retrofit solutions. It will

Figure 1.1 Examples of the inspection of bridges and VR applications in civil engineering.

also lead to quicker decision-making, which will reduce the costs imposed by downtime.

2. USER REQUIREMENTS

Users in this VR-based platform refer to the bridge inspectors, and the requirements are related to the on-site information they look for and collect while performing their jobs. To better understand the needs of the project's objective population, some research team members first took a training course on steel bridge inspection offered at the Steel Bridge Research Inspection Training and Engineering Center (S-BRITE) at Purdue University. The course gave insight into the magnitude of small defects (e.g., cracks as tiny as 1/16 in), the importance of light exposure for defects detection, and the challenges of modelling non-destructive inspection tools in VR environments.

The second step studied a list of thirty-seven steel bridges in the Crawfordsville District. Inspection reports dated between 2019 and 2021 were considered, and for each bridge, six components were analyzed, including decks, surfaces, superstructures, substructures, channels, and culverts. The first four bridge' parts were mostly affected by multiple types and levels of damage; nonetheless, cracking and corrosion, in all their spectrum, were the most predominant defects observed.

Simultaneously, in March 2022, the Federal Highway Administration (FHWA) published the new *Specifications for the National Bridge Inventory* (SNBI) (FHWA, 2022), that established the updated requirements and criteria for bridge inspection and documentation. These standards helped researchers comprehend the 0 to 9 scale defined to assign conditions rating numbers to bridge components according to the type, location, and severity of the defects detected. Furthermore, the document sheds light on the importance of considering the extent to which the defect exists and the degree to which it affects the performance and strength of the components.

With a clear framework of knowledge, various meetings with the SAC and INDOT members were held to define two bridges to be modelled in the VR testbed—one made of steel, and one made of concrete. In agreement with the expected damage condition for both structures, bridges with asset names (236)136-32-03506 B and I465-158-04459 B were chosen, respectively, from the INDOT repository located on the online platform of the AssetWise Inspections Software (Bentley Systems, 2022).

2.1 Case Studies

2.1.1 Case Study #1 Steel Bridge

The steel bridge (236)136-32-03506 B is a two-lane, two-span multi-beam bridge belonging to the Crawfordsville District, and it is on State Road 236 and West Big Walnut Creek. The structure length is 164.8 ft, and the deck width out-to-out is 29.3 ft. The structure is in serious condition due to the advanced deterioration of the superstructure. According to the inspection report dated March 3rd, 2022, the bridge is scheduled for replacement. Figure 2.1 shows photographs of this bridge from different angles (Gould, 2022).

2.1.2 Case Study # 2 Concrete Bridge

The concrete bridge I465-158-04459 B is a two-lane, four-span multi-beam bridge. It is part of the Greenfield District on Mann Road over Interstate 465. The structure length is 213.3 ft, and the deck width out-to-out is 36.3 ft. The structure is in fair condition with most of its bridge components rated number 5 and the wearing surface rated number 6. The inspection report used for this description is from July 9th, 2020. Figure 2.2 presents photographs of the bridge (Harvey, 2020).

2.2 Proposed Virtual Reality Testbed

Initially, the analysis of the case studies led to the finding of sixteen different defects present in at least one of the structures. Furthermore, according to the SNBI 2022, fifteen bridge components were identified as suitable to be modeled. They were divided into three groups depending on their location—deck, side, and underneath. Finally, it was proposed that when the users were in the VR environment, they would be free to inspect defects. However, when reporting the

Figure 2.1 Photographs of Case Study #1: steel bridge.

Figure 2.2 Photographs of Case Study #2: concrete bridge.

TABLE 2.1
Key components and features of bridges to be modeled in the VR testbed

Bridge Component	Defect	Inspection Tool
Deck	Efflorescence	Hammer
Superstructure	Corrosion	Scratch brush
Substructure	Pack rust	Tape measure
Joints	Section loss	Chain drag
Bearings	Spalling	Flashlight
Railings	Spalling with exposed rebar	Crack gauge
Channel	Delamination	Binoculars
–	Cracking	Compass

information, they would be guided through a series of questions to specify the damage type, severity, and extent.

As a result of sharing this draft plan with INDOT inspectors, they suggested reducing the number of bridge components and defects to seven and eight, respectively. In addition, they emphasized the importance of recreating the inspection tools and proposed a list of eight instruments to assess the examination performance of the users better. Table 2.1 provides a summary of key components and features to be modeled. Regarding the user experience, they advised avoiding the guiding questions to evaluate appropriately the user's understanding of the SNBI and the application of the documentation practices taught in training sessions. Consequently, the research team considered all their feedback, and the VR modules were developed accordingly.

3. SELECTION OF SOFTWARE AND HARDWARE SYSTEMS

Based on discussions with the INDOT and SAC members, it was concluded that the VR application must render the 3D bridge models accurately without any visible distortion or information loss. Consequently, a high-end VR headset had to support the application to deliver a high-resolution and fully immersive experience. Furthermore, the entire system must be portable for easy transfer among the different districts of INDOT, which resulted in the need for a high-end laptop. The following sections describe the exploratory process that was followed to define the best model generation technique and hardware system to achieve the mentioned requirements.

3.1 Comparison of Model Generation Techniques

Given the project's need for a high-resolution representation of bridges, initially, two different modeling approaches were considered: photogrammetry and synthetic modeling. The first aims to extract 3D information from 2D photographs while the second one artificially creates data to resemble the real world. Through practical experiments, the benefits and challenges of each technique were studied.

To employ photogrammetry, a small 3D steel sculpture available on the Purdue University campus was used as a reference, and one of its beams was modeled (Figure 3.1a). With the help of a professional Digital Single-Lens Reflex (DSLR) camera, between 400 and 500 raw images were taken from different angles for 2 to 3 hours. The images were processed by a desktop computer with 16 GB of RAM. Finally, two different software were utilized to reconstruct the beam—Alice Vision Meshroom (Figure 3.1b) and Agisoft Metashape (Figure 3.1c). Conclusively, Agisoft Metashape demonstrated more stability and better reconstruction results.

On the other hand, technical discussions with graphic artists were held to evaluate synthetic modeling and understand its pipeline. The evaluation process was the following. First, a search of premade 3D bridge and texture models in six web platforms (Figure 3.2). Second, geometric modeling following the dimensions of some bridge components of Case Study #1, which were taken as example objects. Third, using Blender (modeling and animation software), Substance 3D Painter (software to create materials and textures), and Unity (cross-platform game engine software), apply colors, textures, materials, and lighting conditions to match the real bridge's elements as close as possible. Figure 3.3 shows (a) the real objects and (b) their corresponding representations.

Comparing the two modeling methods, photogrammetry offers high fidelity and accuracy; however, it

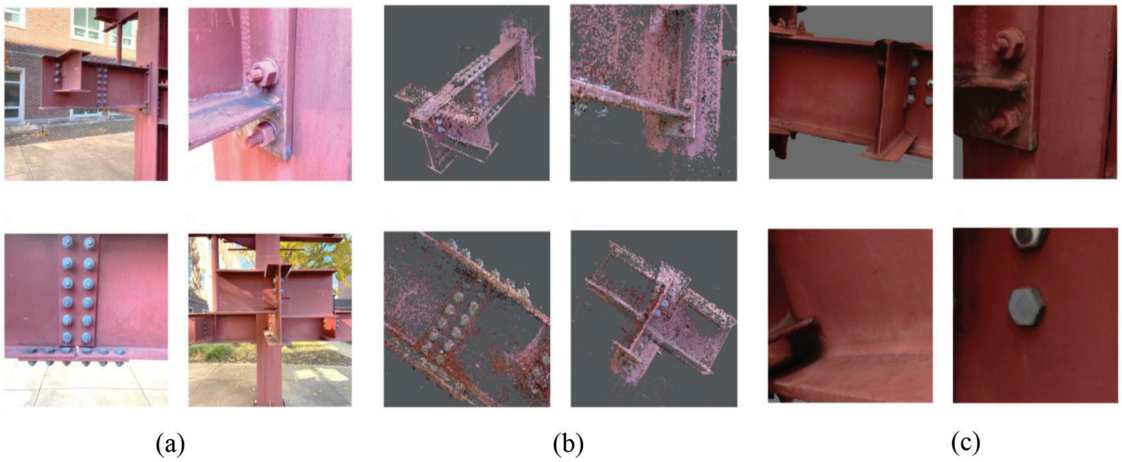


Figure 3.1 Evaluation of photogrammetry software: (a) original structure, (b) reconstructed beam with Vision Meshroom, and (c) reconstructed beam with Agisoft Metashape.

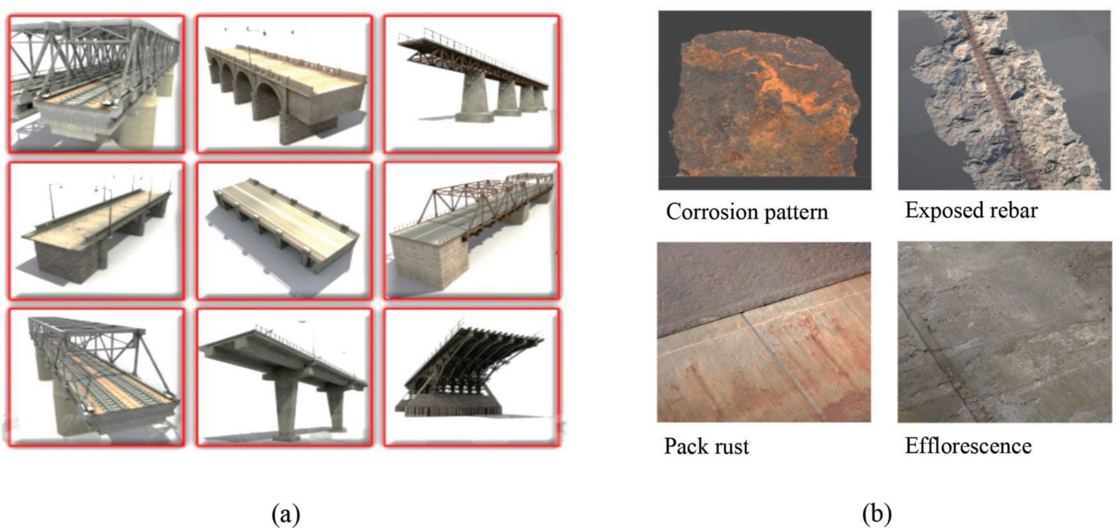


Figure 3.2 Samples of computer graphics-based bridge models and synthetic-generated textures of common defects in bridges (3D Graphics, 2012; Quixel, 2022).

heavily relies on weather conditions and proximity levels to the objects. Furthermore, huge amounts of photographs are needed even for inaccessible regions, making this approach cumbersome. For this part, synthetic modeling might lack realism in some levels of detail (LOD). Yet, it is versatile to work with 3D objects, which eases the construction of tailor-made models, saves time, and presents a good resolution from a high-level perspective. Hence, the latter method was selected for this project.

3.2 Comparison of Hardware

The project's required system comprises a display device to render the VR environment and a laptop to run it. Five different visualization technologies were studied to find the best possible display-computer match, and according to the chosen technology, a suitable laptop was purchased.

The explored options included one AR/VR screen with no Head-Mounted Display (HMD) required (Figure 3.4a (zSpace, 2023)), one planar tiled wall (Figure 3.4b (Full Compass, 2023)), two tethered HMDs (Figure 3.4c (VREXPERT, n.d.b) and Figure 3.4e (VREXPERT, n.d.a) and one untethered HMD (Figure 3.4d (Meta, 2023)).

During the first 6 months of the project, the research team thoroughly examined the systems mentioned above with the help of Purdue University's Envision Center. To this end, multiple demonstration sessions took place to assess each option's advantages, disadvantages, and cost. Table 3.1 summarizes the main findings in this regard.

The above comparative table was shared with INDOT and SAC members, and in March and May 2022, they were invited to the Envision Center to test the different technologies (Figure 3.5). In each case, the same models of steel beams and bridges were set up on

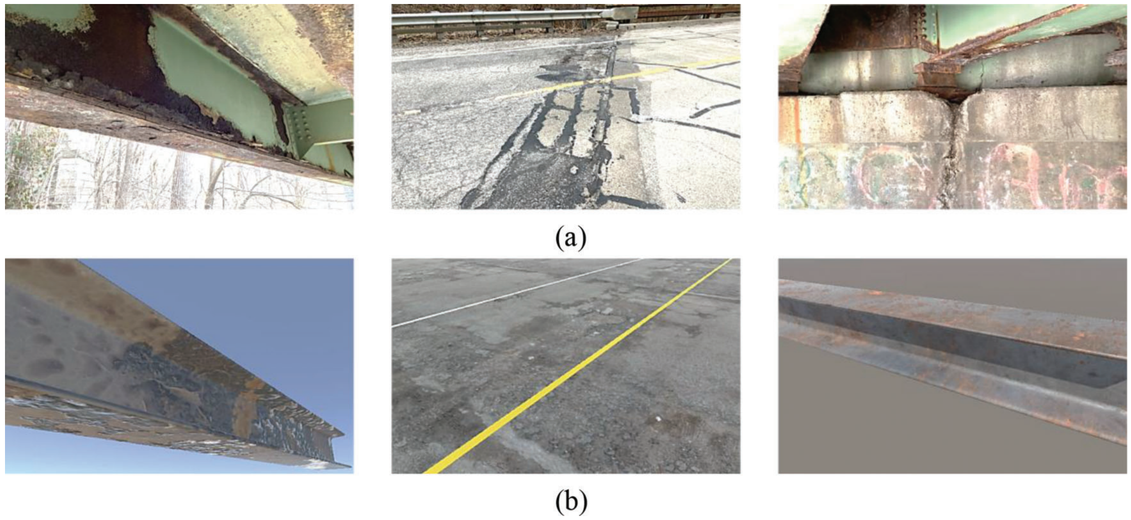


Figure 3.3 Representation of defects using synthetic modeling: heavy corrosion on steel beams and extensive cracking and spalling in concrete roads.

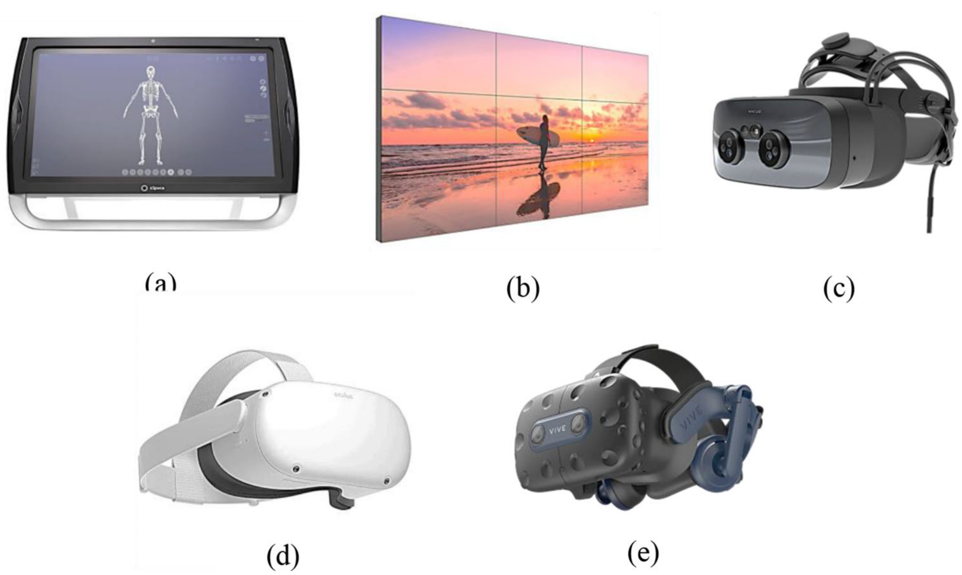


Figure 3.4 VR technologies explored to develop the VR testbed: (a) zSpace AIO, (b) Planar Tiled Wall, (c) Varjo XR-3, (d) Meta Quest 2, and (e) HTC Vive Pro 2.

the devices to provide a common evaluation frame. The invitees provided instrumental feedback based on their expertise and knowledge, ultimately leading to the selection of the headset HTC Vive Pro 2 as the display device to be used in the project (option (e) in Figure 3.4 and Table 3.1).

This tethered device provides one of the market's most stable and highest resolution experiences, with a combined resolution of 4,896 × 2,448 pixels. It has a wide field of view of up to 120 degrees in the horizontal plane and a smooth refresh rate of 120 Hz. To enhance the sense of immersion, the headset has high-fidelity certified headphones and an ergonomic design featuring adjustable interpupillary distance, variable lens distance, and head strap adjustment.

Furthermore, a search for laptops that fulfilled the operational requirements of the chosen HMD was performed. The technical specifications were split into six categories. The cost was included as an additional category. Multiple alternatives were studied, shrinking the final decision to three options (Table 3.2). With the technical support of Envision Center and the Engineering Computer Network at Purdue University, the laptop Dell Alienware ×17-R2 was acquired.

3.3 Summary Remarks

Synthetic modeling was chosen to create the VR testbed, given its adaptability and reduced number of constraints for data acquisition. Reconstructing the bridges from pictures and videos captured on-site, as

TABLE 3.1
Advantages, disadvantages, and cost of evaluated VR technologies

VR Technology	Advantages	Disadvantages	Cost ($)[1]
zSpace AIO	No additional equipment required Customer service	Limited 3D experience Low resolution	3,400
Planar Tiled Wall	High resolution Large display	High cost High maintenance	100,000 (4 × 4 screens array)
Varjo XR-3	High resolution High performance Immersive experience	High cost Stability issues	5,400
Oculus Quest 2	Low cost Lightweight Untethered	Low resolution Limited performance in objects' quality	400
HTC Vive Pro 2	High resolution High stability Immersive experience	High cost Base stations required	1,400

[1]Estimated price in US dollars as of December 2021.

TABLE 3.2
Minimum laptop requirements for the chosen headset and evaluated options

	Headset[1]	Laptop		
Specifications	**HTC Vive Pro 2**	**Dell Alienware m15-R7**	**Dell Alienware × 15-R2**	**Dell Alienware × 17-R2**
Processor	Intel® Core™ i5-4590	Intel® Core™ i7-12700	Intel® Core™ i7-12700	Intel® Core™ i7-12700
Graphics Card	GeForce® RTX 20 Series	GeForce® RTX 3080 Ti 16 GB	GeForce® RTX 3080 Ti 16 GB	GeForce® RTX 3080 Ti 16 GB
RAM	8 GB	64 GB (2 × 32 GB)	32 GB	64 GB (2 × 32 GB)
Video Out	DisplayPort 1.4 or higher	USB 3.2 Type C w/DisplayPort 1.4	USB 3.2 Type C w/DisplayPort 1.4	1 × USB 3.2 Type C 1 Mini DisplayPort 1.4
USB Ports	1 × USB 3.0	1 × USB 3.2 Gen 1	1 × USB 3.2 Gen 1	2 × USB 3.2 Gen 1
Operating System	Windows® 11	Windows® 11	Windows® 11	Windows® 11
Cost[2]	–	3,640	3,740	3,790

[1]Minimum operational requirement requested by the vendor.
[2]Estimated prices in US dollars as of June 2022.

Figure 3.5 Demonstration session with INDOT and SAC members to evaluate different VR technologies.

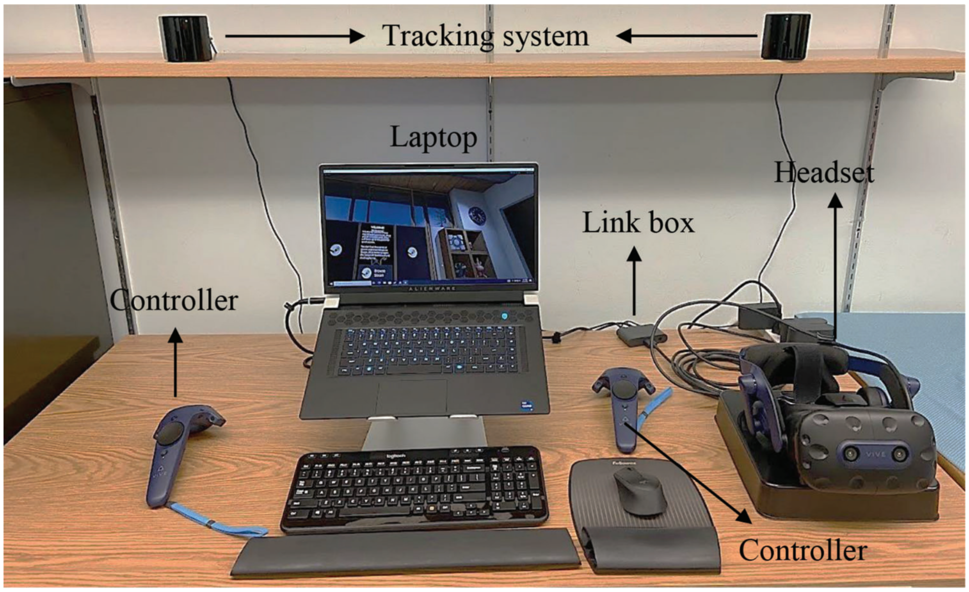


Figure 3.6 HTC Vive Pro 2 VR headset and Dell Alienware ×17-R2 laptop acquired.

would be the case of photogrammetry, implies challenges such as external light sources, difficult access to certain areas of the bridge (e.g., abutments), devices' limitations (e.g., camera's vertical angle of rotation), and low likelihood of collecting all the needed data in a single visit.

HTC Vive Pro 2 and Alienware x17-R2 were selected as the headset and laptop devices, respectively (Figure 3.6). The decision was supported not only in the final users' feedback but also in the trade-off of operational stability and rendering resolution offered by these devices when coupled. Their frame and refresh rate, RAM, field of view, and audio system were key features pondered in purchasing the hardware system.

4. VIRTUAL REALITY MODULES

The development of the VR application was circumscribed in the creation of a 3D virtual space, which includes the generation of the bridges' models and their corresponding environments, followed by the establishment of a set of relations between the user, the virtual objects, and the VR headset to create the user interface and define the user experience. To this end, each bridge module underwent extensive user testing for debugging and customization according to the feedback received and the identified needs. This section describes the process and results of these three steps.

4.1 3D Virtual Space Generation

A three-component workflow was defined to develop the 3D virtual space. See Figure 4.1.

4.1.1 Premade 3D Models

An initial search for premade 3D models was performed using the six web platforms mentioned in Section 3.1. Models of steel and concrete bridges were examined, aiming to find structures like those described in the case studies of Section 2.1. The most important criterion in performing the inquiry was the number of polygons each model had. In computer graphics, polygons are used to build 3D objects by connecting their vertices and edges through surfaces and then rendering textures on them. The more polygons in a model, the more the resolution is expected. Also, the format versatility of the model and its cost were considered throughout this process.

After a first round of investigations, nine candidates were found with a threshold of seventy thousand polygons (Figure 4.2 (TurboSquid, n.d.)). All options represented existing bridges, e.g., the Sidney Harbour Bridge in Australia and the Bacunayagua Bridge in Cuba. Their polygons went up to millions in some cases; all were convertible upon request, and their prices varied between seventy-five and three hundred dollars.

After exploring the models in depth, two main conclusions were drawn. First, there was no direct relation between the polygon count and the model's quality. Evidence showed a bigger number of polygons as the dimensions of the structure increased or if there were surrounding elements present, such as vegetation or crossing roads, while the bridge components' resolution was not necessarily improved. Second, finding models like those indicated by INDOT for such high defined threshold was challenging. Most of these premade structures resemble landmark bridges, not the ones the inspectors encounter daily. Thus, a new strategy was adopted, and a second search was performed.

The second search intended to find models whose geometry and dimensions were closer to the case studies of Section 2.1. A trade-off was needed regarding the number of polygons to achieve this goal. Subsequently,

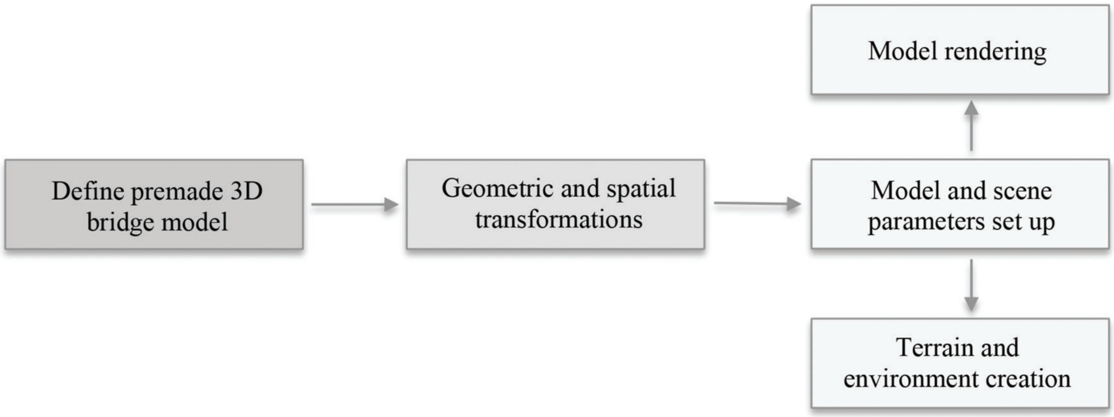


Figure 4.1 Workflow defined to develop the 3D virtual space of VR bridge modules.

Figure 4.2 Sample of premade computer graphics-based bridge models identified in round one of model selection (TurboSquid, n.d.).

five options were found (Figure 4.3). Furthermore, various meetings were arranged with the graphic artists of the Envision Center to select the best-fit models based on their quality and the complexity of implementing future changes to them. As a result, a model of around fifteen thousand polygons was selected for the concrete bridge (Figure 4.3d), and a model of approximately thirty thousand polygons was chosen for the steel bridge (Figure 4.3c).

As per the investigation done by the research team members, it was not possible to get a steel bridge model like the one in Case Study #1, so an alternative steel truss bridge was presented to INDOT and SAC members, who later approved the proposed change. Still, the level of damage to be implemented on the bridge remained the same. Thus, a bridge located in the Crawfordsville District, with asset code 015790, with an overall condition rating number between 5–6 and 175 ft main span, was taken as a reference for the subsequent modeling phases. Figure 4.4 shows photographs of the bridge. Photographs were taken from the INDOT repository on the online platform of the AssetWise Inspections Software.

4.1.2 Geometric and Spatial Transformations

With the Blender Software, the next step was performing changes in the geometry of the models to

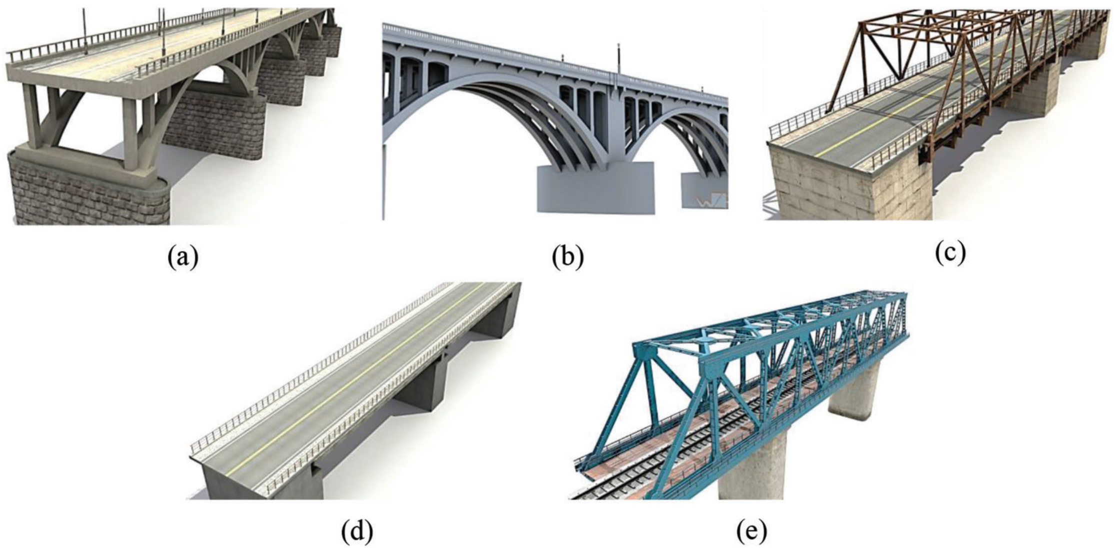


Figure 4.3 Sample of premade computer graphics-based bridge models identified in round two of model selection (3D Graphics, 2010, 2011).

Figure 4.4 Photographs of the alternative bridge for Case Study #1.

resemble the main span length, the vertical clearance, and the deck width of each bridge. Similarly, it was the procedure for the dimensions and locations of the bridge components defined in Table 2.1. Figures 4.5 and 4.6 present some samples of dimension and scale transformations. Besides, it was decided to model each bridge as a single-span structure to reduce the user's exposure to the VR environment.

In performing all these transformations, geometric data from the inspection reports of the case studies were carefully followed. On multiple occasions, the models were reviewed by faculty members to check their accuracy. Finally, in March 2023, INDOT bridge inspectors tested both structures and gave their feedback to obtain the final versions.

4.1.3 Model and Scene Parameter Setup

This stage of the process consisted of two steps. First, rendering the model and second, creating the surrounding environment and the terrain that provides context to the bridge inspection module.

The work on the models was done using Substance 3D Painter to generate the textures of some of the defects, for instance, efflorescence and spalling. Others, such as pack rust and rust stain, were downloaded from the web. Afterward, a graphics pipeline was followed in Blender to obtain the final versions. The sequence included the creation of colors and materials on top of the textures and then adding shaders and lighting conditions to highlight some features of the defects (e.g., severity or depth). See Figures 4.7 and 4.8.

High Dynamic Range Images (HDRI) were used to model the surrounding environments to improve the viewing experience, among others, through a more precise color, level of detail, saturation, and brightness control. In addition, skyboxes (6-sided cubes drawn behind all graphics in the system) were used to wrap up the scene with cube map textures. See Figure 4.9.

As the last step, terrains were generated through the built-in function of the game engine Unity. Given the dimensions of the bridges, short hills were created, with space for the abutments and the main spans. Various grass, soil, plants, and trees were added to create a more immersive experience (Figure 4.10a). At some point, the

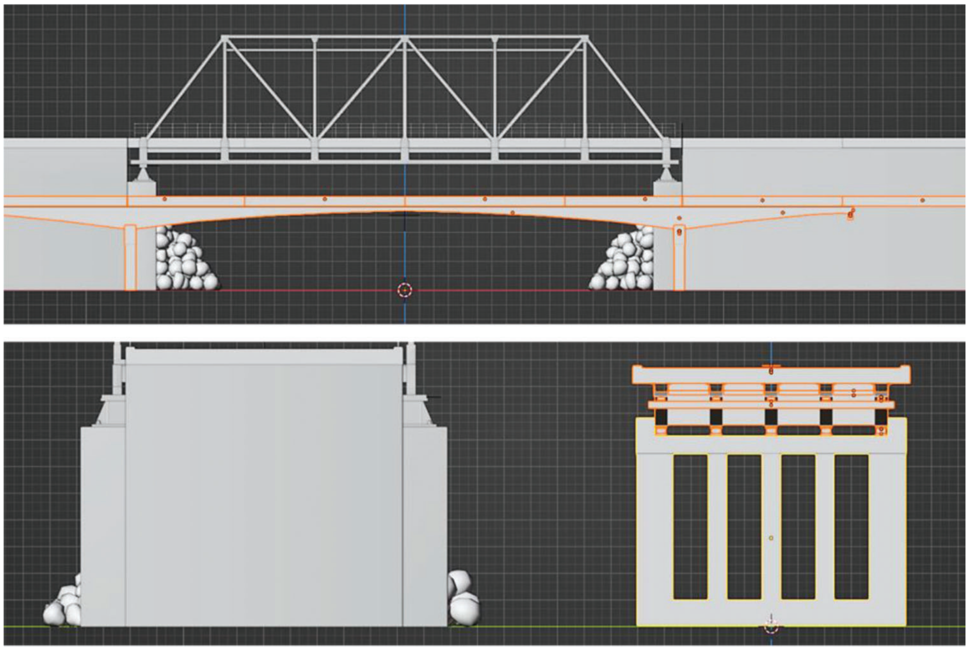


Figure 4.5 Samples of dimension and scale transformations in bridge models.

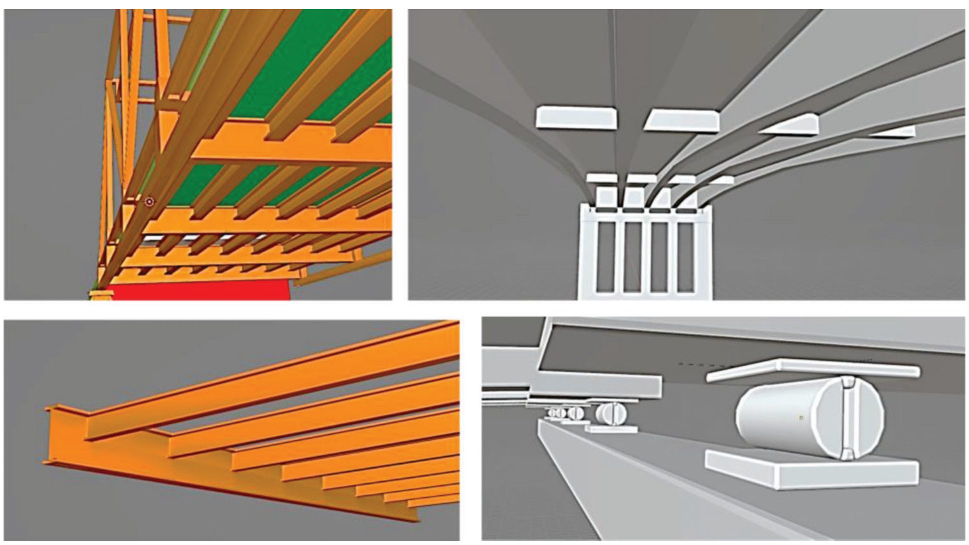


Figure 4.6 Samples of geometric and spatial transformations in bridge models.

elimination of trees was proposed to avoid detouring the attention of the inspectors from the bridges they were to examine (Figure 4.10b). However, after sharing both options with INDOT members, they suggested keeping the trees in the scene.

4.1.4 Final Models

The final version of the bridge models is presented as follows, considering the geometric, material, and damage level characteristics discussed before and agreed upon with INDOT and SAC members: steel bridge (Figures 4.11 and 4.12), and concrete bridge (Figures 4.13 and 4.14).

Trees were intentionally removed from Figures 4.11 through 4.14 so the reader can fully appreciate the final aspects of the bridge models. Trees are still in the definitive version of the VR modules.

4.2 User Interface

After completing the 3D virtual space, how the user and the VR application would interact was defined. To facilitate the usage of the VR headset, it was decided that all the interactions would be directed through one controller out of the two the headset comes with. Besides, the user would have access to the inspection tools established in Table 2.1 and, across a

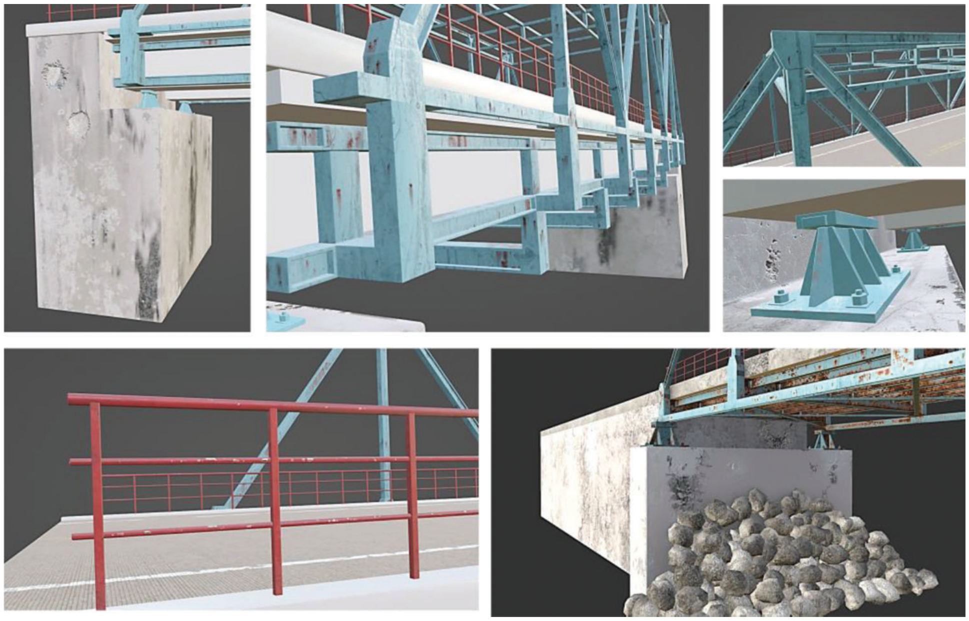


Figure 4.7 Rendering of defects on the steel bridge model in Blender.

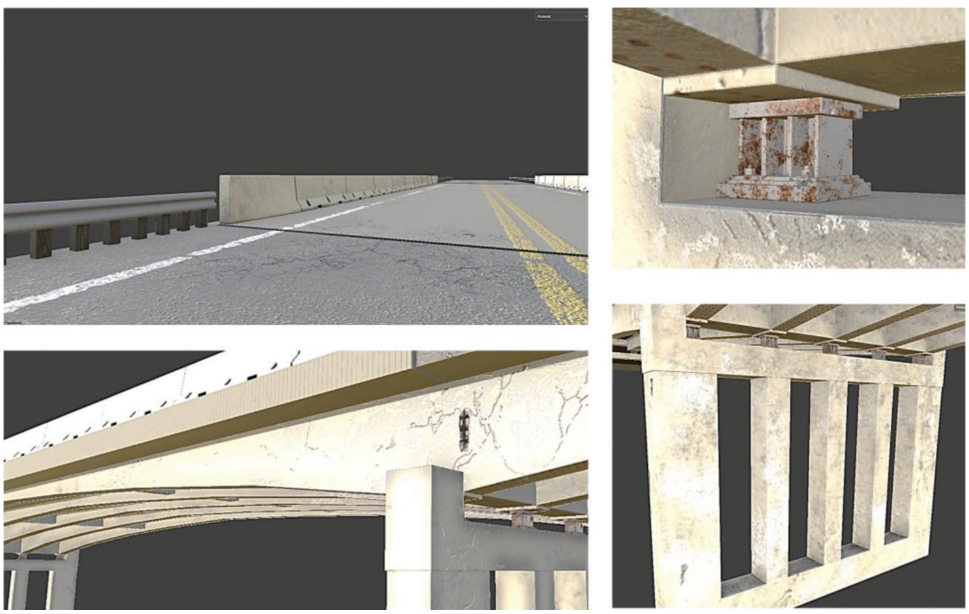


Figure 4.8 Rendering of defects on the concrete bridge model in Blender.

Figure 4.9 Samples of HDRI skybox elements used to create the surrounding environment of the 3D virtual space (Majboroda, 2021, 2023).

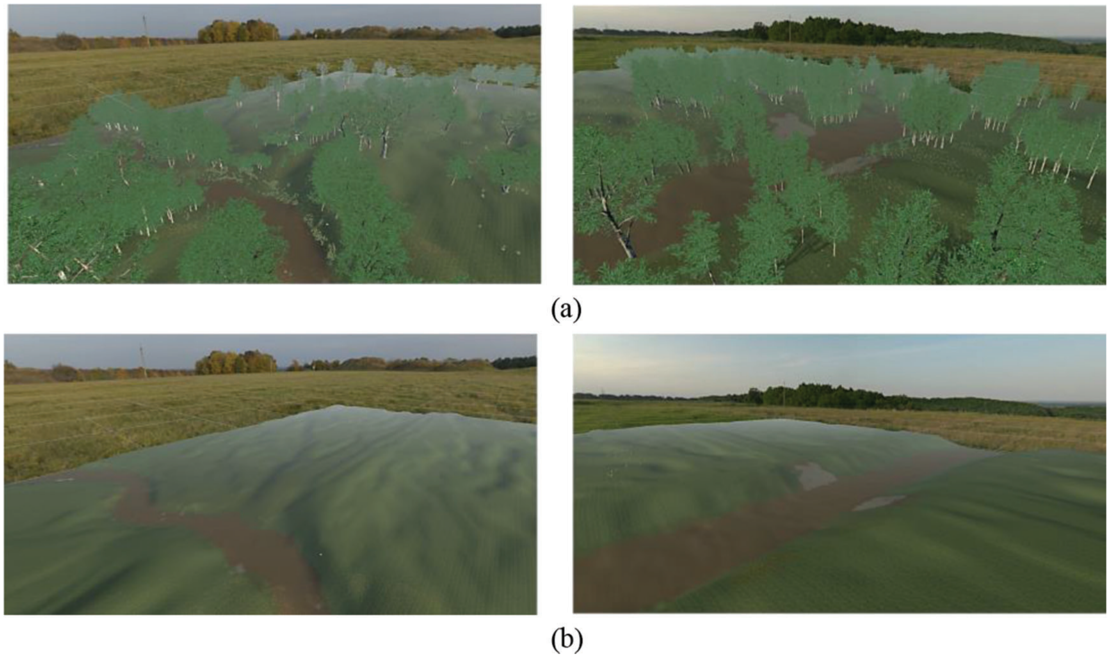


Figure 4.10 Samples of synthetic-generated terrains: (a) with trees, and (b) without trees.

Figure 4.11 Top view of the final version of the steel bridge.

sequence of dialogue boxes and on-screen buttons, would be given instructions on moving and interacting with the bridge.

Figure 4.15 presents the setup of the controller (SeekPNG, n.d.). Each of the five available buttons was configured to a single and specific function; multiple functions assigned to one button proved confusing for the user and troublesome for the smooth running of the application. The user manual and the VR environment further explain how the controller works. Nonetheless, it is noteworthy that the *GRIP* button allows screenshots of whatever the user sees, simulating how inspectors take photographs in the real world to complement their written report.

The inspection tools were synthetically recreated; some were purchased online, and some were developed in-house. All the tools were presented for the first round of testing with INDOT inspectors. Seven tools are part of the modules, as shown in Figure 4.16, including a compass, chain drag, hammer, scratch brush, flashlight, tape measure, and zoom window. The VR headset controller was also modeled.

Going into detail with the binoculars, after discussing with Envision Center professionals some of the challenges associated with its VR modeling, a zoom window was proposed as an alternative. The user only needs to direct the small rectangular frame to the desired point of augmentation, and the area will be zoomed in, as would happen with standard binoculars. Finally, to remind the user of the physical appearance of the controller, a virtual representation of it also appears in the VR environment.

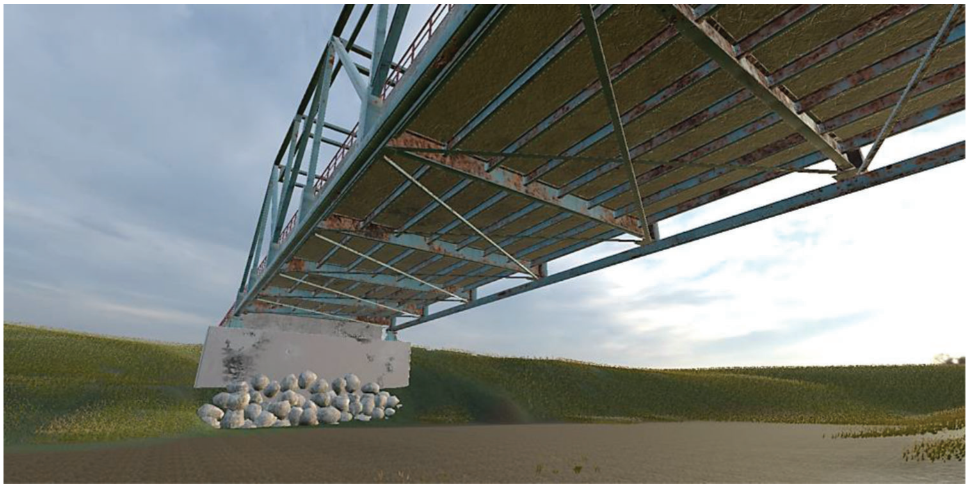


Figure 4.12 Bottom view of the final version of the steel bridge.

Figure 4.13 Top view of the final version of the concrete bridge.

Figure 4.14 Bottom view of the final version of the concrete bridge.

The controller allows users to make selections in the dialogue boxes, rotate, and teleport (move virtually) more easily.

A series of dialogue boxes were created to conclude the user interface development. They can be open as often as needed; options to continue, go back, or skip are

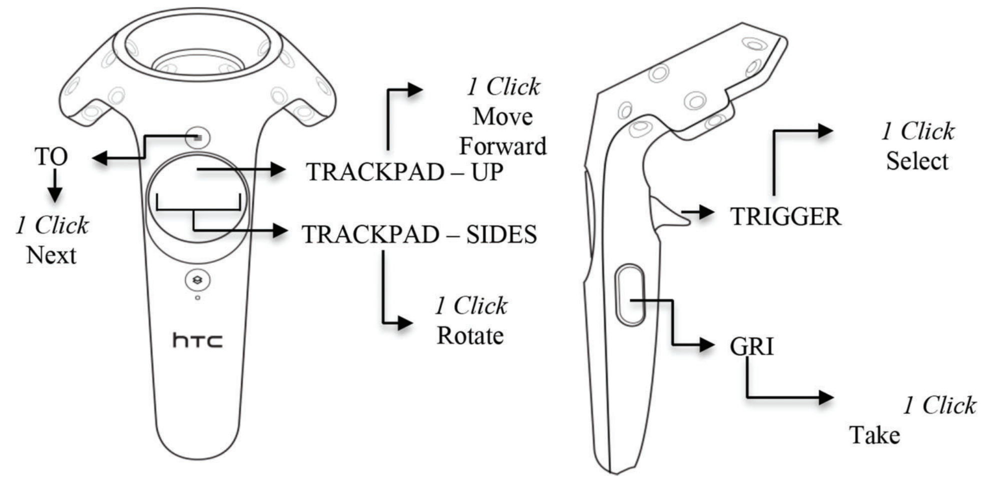


Figure 4.15 Description of functions assigned to each button of the VR headset controller.

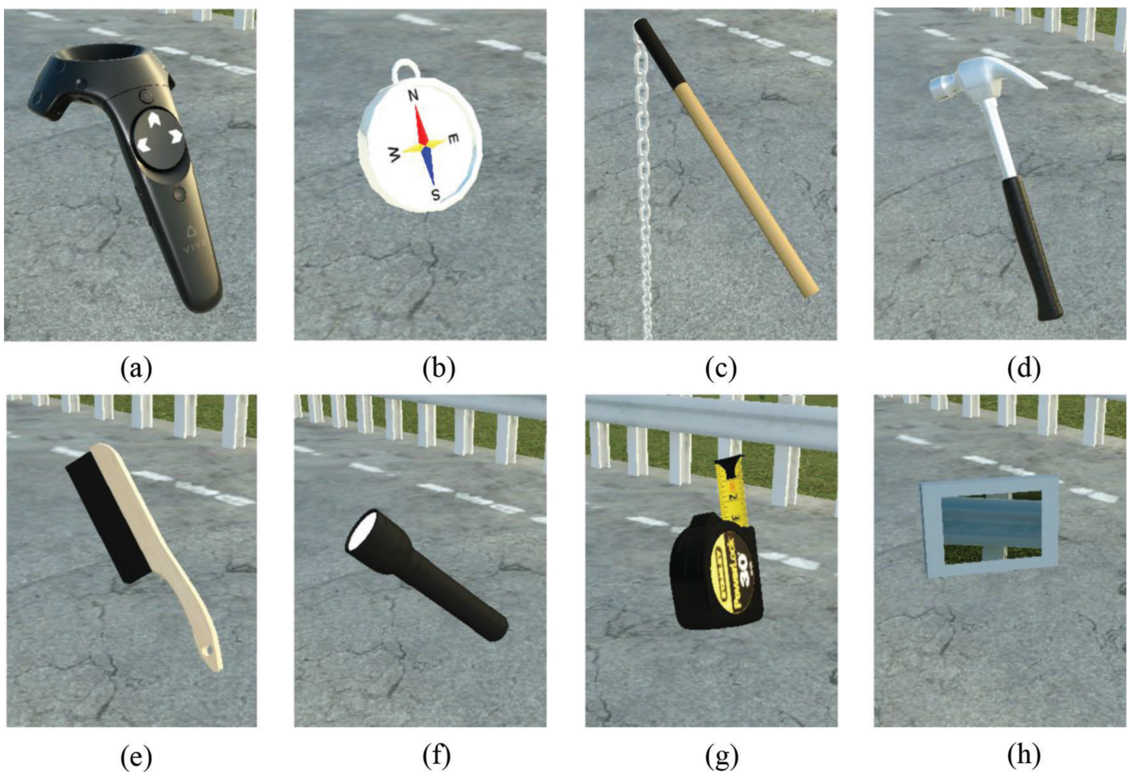


Figure 4.16 VR headset controller and inspection tools modeled: (a) controller, (b) compass, (c) chain drag, (d) hammer, (e) scratch brush, (f) flashlight, (g) tape measure, and (h) zoom window.

available. The dialogue boxes cover three main functions: module usage instructions (tutorial), bridge module switching, and application exit. Two permanent buttons are on the screen to reduce the tasks on the controller—Main Menu and Warp to Spot. The former gives access to the main functions, and the latter shows a map with locations to teleport. Figures 4.17 and 4.18 show sample dialogue boxes for the Main Menu and locations to teleport for the Warp to Spot button, respectively. For additional information, please refer to the user manual.

4.3 User Interaction

After both bridge modules were completed, an extensive user interaction study occurred. There were twenty participants—eleven graduate students, six industry professionals, and three professors. Each participant was asked to complete a short survey after using the VR application. The survey collected data regarding experience quality, ease of use, and sense of immersion.

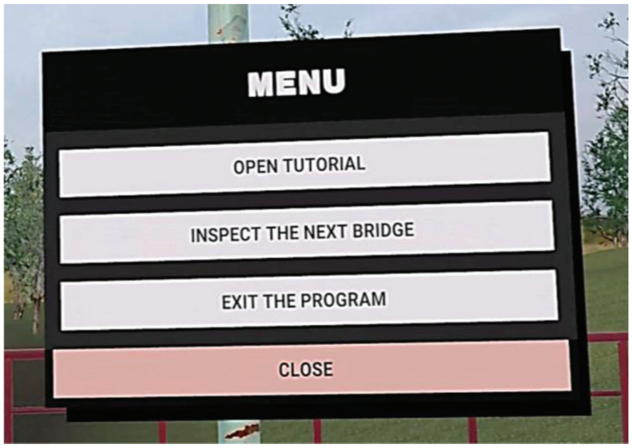


Figure 4.17 Sample dialogue boxes of the permanent button: main menu.

Figure 4.18 Sample dialogue boxes of the permanent button: warp to spot

4.3.1 Experience Quality

Two questions were asked—(1) have you used VR before? and (2) are you able to control the system? Among the users who had previous exposure to VR, 82% answered strongly agreed with the ability to control the system. Of all the participants, 95% either agreed or strongly agreed with the ability to control the system. See Figure 4.19.

Regarding the comments expressed, some people suggested turning off virtual rotation because of motion sickness and only allowing it if the user rotates physically. Nonetheless, keeping just the physical rotation could imply a risk of falling if the participant gets wrapped in the headset cord. Thus, it was decided to maintain both physical and virtual rotation types.

4.3.2 Ease of Use

For this part, participants were asked to express the extent to which they agree or disagree with the statement: I think the system is easy to use. Additionally, they were asked using the same qualitative scale: are the inspection tools easy to use? A full 100% of the users agreed or strongly agreed on the easiness of the system, which is consistent with the results of the ability to control it mentioned before. Besides, 85% of the participants found the inspection tools simple. Just 5% (one person) disagreed. See Figure 4.20. However, after talking to the participant, he explained his answer was based on his inherent shaky hands' condition, making it more difficult to press the buttons and hold the controller appropriately.

Additional feedback was provided regarding creating an instructional video besides the written user manual so users can have different sources to understand the correct way of using the tools according to their learning style. Also, discussions were held around the most convenient button to assign the screenshot function. Finally, some participants advised changing the sounds of the chain drag and the hammer to beats closer to concrete and steel in different states of deterioration.

4.3.3 Sense of Immersion

To conclude the survey, another two statements were posed to assess the participants' sense of immersion in the VR scenes. The perception of being physically present in an artificial environment is crucial in successfully deploying VR applications. The statements were (1) the defects implemented on the bridge are realistic and have good resolution, and (2) I think the virtual scene is immersive. A qualitative scale was used again. A total of 90% either agreed or strongly agreed on the high realism and quality of the defects. Similarly, 80% strongly agreed with the sense of immersion within the bridge modules. See Figure 4.21.

On side comments, participants suggested providing additional instructions on teleporting in the scenes. Besides, they proposed that the user could test the inspection tools directly on the bridge before starting the inspection. Regarding the surrounding trees in the environment, they expressed either neutrality or preference because they believed trees contributed to the immersive experience.

In May and June 2023, INDOT and SAC members were invited to a final demonstration session where these findings were shared. As a result, it was decided to create an additional scene called practice scene. The new scene will teach the users how the inspection tools work and how they can move within the virtual

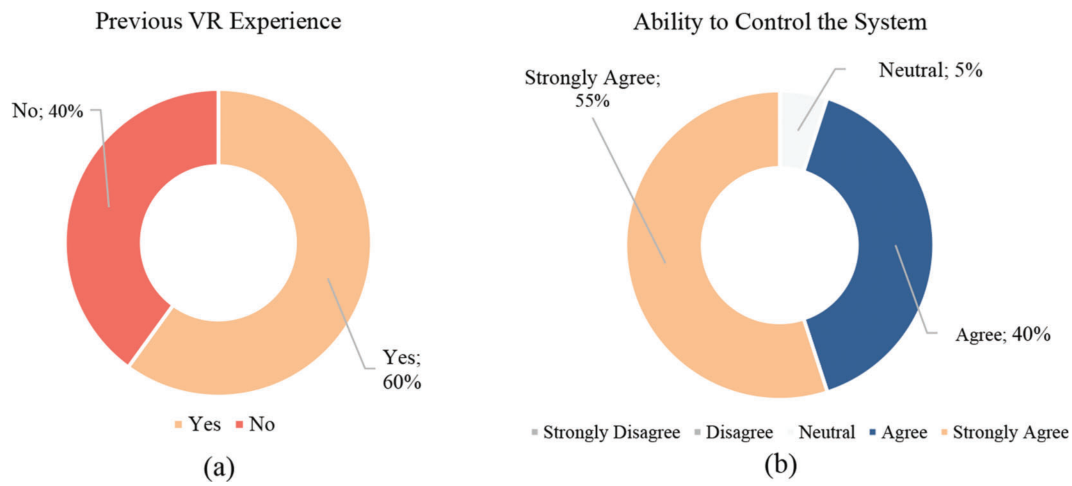


Figure 4.19 User testing results: (a) previous VR experience, and (b) ability to control the system.

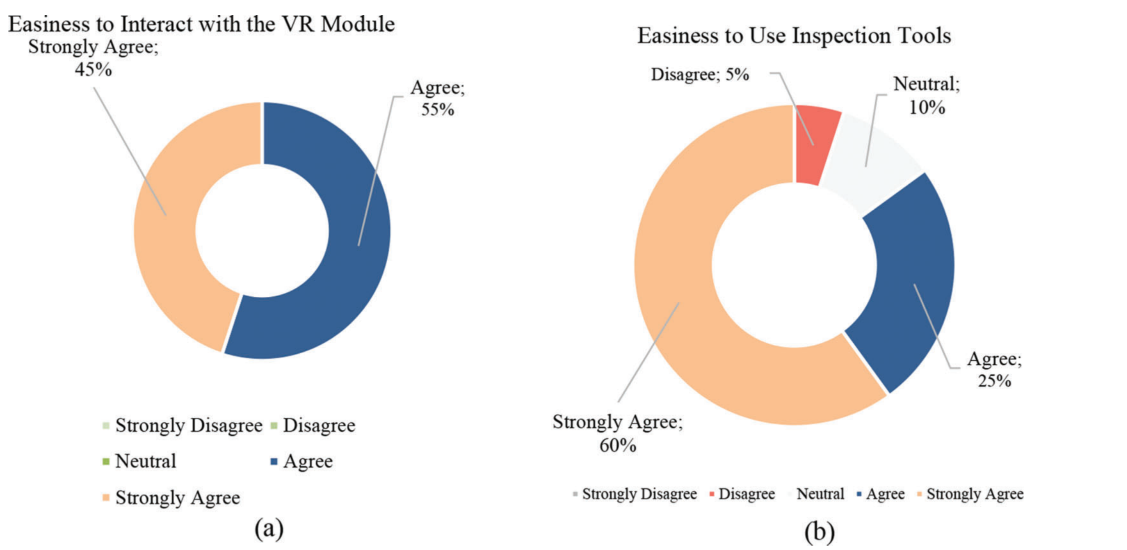


Figure 4.20 User testing results: (a) easiness to interact with the VR module, and (b) easiness to use the inspection tools.

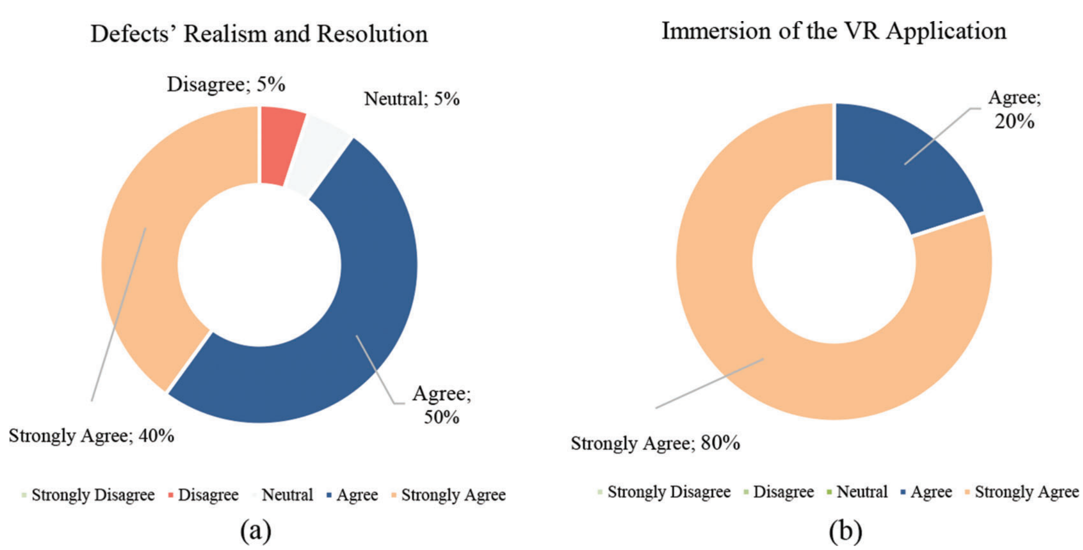


Figure 4.21 User testing results: (a) defects' realism and resolution, and (b) immersion of the VR system.

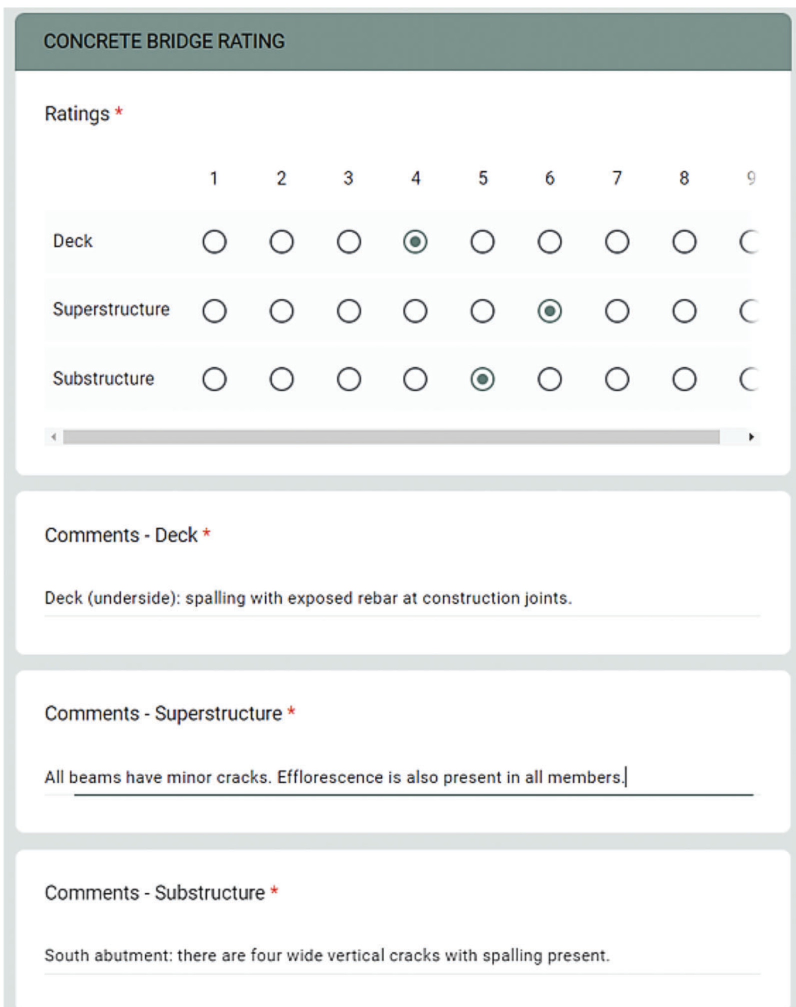
environment. Consequently, the users will be familiarized with the interaction system before inspecting the bridges, reducing the bias in the results due to a lack of practice or expertise with the application. The details of the Practice Scene are in the user manual.

5. CONSISTENCY EVALUATION

As mentioned in Section 1.1, there is a need to evaluate the sources of variability among inspectors. Identifying the causes of a lack of consistency in the information reported after inspecting bridges will help improve the training processes. Moreover, it will promote more accurate decisions regarding these structures' maintenance, repair, and replacement. In evaluating consistency, VR applications are handy due to their portable setup, the controlled conditions under which the experience is conducted, and the reusability and replicability of the testing models. The proposed method of evaluation for this project is described below.

An external survey based on Google Forms is filled out right after the VR headset is used. Furthermore, screenshots can be taken while in the VR scene. These screenshots serve as a visual inspection record and are automatically saved on the laptop connected to the VR headset. Regarding bridge components, just the three most relevant are asked about deck, superstructure, and substructure. Two surveys are available: one for the concrete bridge and another for the steel bridge.

The survey consists of three sections, which are completed anonymously. The first section requests details such as the inspection date, the district where the users work, the users' years of experience, and the users' ID. The second section asks users to rate the three bridge components using the 0–9 scale of SNBI 2022. Along with these ratings, users are expected to provide comments explaining their assessments. The third section is to upload the screenshots that support the findings during the inspection. Furthermore, users are required to rename the screen captures in a manner that includes a brief statement on the identified deficiency. For instance, a file could be renamed as "Pack_rust_northeast_bearing.png." Figure 5.1 shows parts of what the surveys look like.


CONCRETE BRIDGE RATING

Ratings *

	1	2	3	4	5	6	7	8	9
Deck	○	○	○	◉	○	○	○	○	○
Superstructure	○	○	○	○	○	◉	○	○	○
Substructure	○	○	○	○	◉	○	○	○	○

Comments - Deck *

Deck (underside): spalling with exposed rebar at construction joints.

Comments - Superstructure *

All beams have minor cracks. Efflorescence is also present in all members.

Comments - Substructure *

South abutment: there are four wide vertical cracks with spalling present.

Figure 5.1 Samples of the inspection report filled out for the concrete bridge.

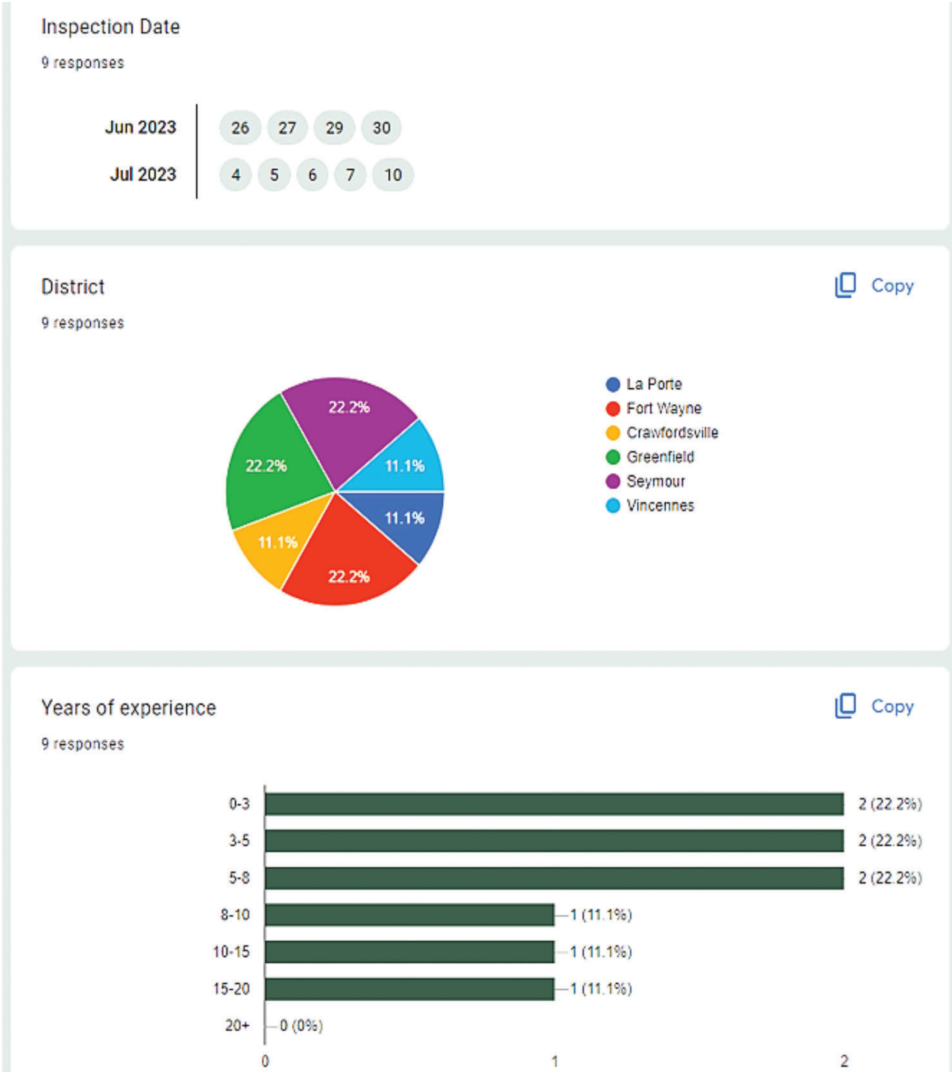


Figure 5.2 Samples of the consistency report, section 1: general information.

The heart of the consistency evaluation lies in analysing the collected survey data. This analysis is performed by the inspection manager, who can review the survey responses through the Google platform, which provides an array of metrics and charts for data analysis.

For the first section of the survey, data visualization is provided in the form of a pie chart for the districts and a bar chart for years of experience. The second section offers a more detailed analysis. A bar chart represents the ratings for the deck, superstructure, and substructure, allowing the manager to easily visualize the rating distribution and understand the consensus among inspectors compared with the ground truth. Additionally, the comments given by the users are organized sequentially for each bridge component, offering the manager a quick overview of common themes or trends in the inspectors' observations. See Figures 5.2 and 5.3.

Lastly, the manager has access to the screenshots stored on Google Drive. These screenshots and the user's comments can be manually reviewed to gain a comprehensive understanding of the inspection results.

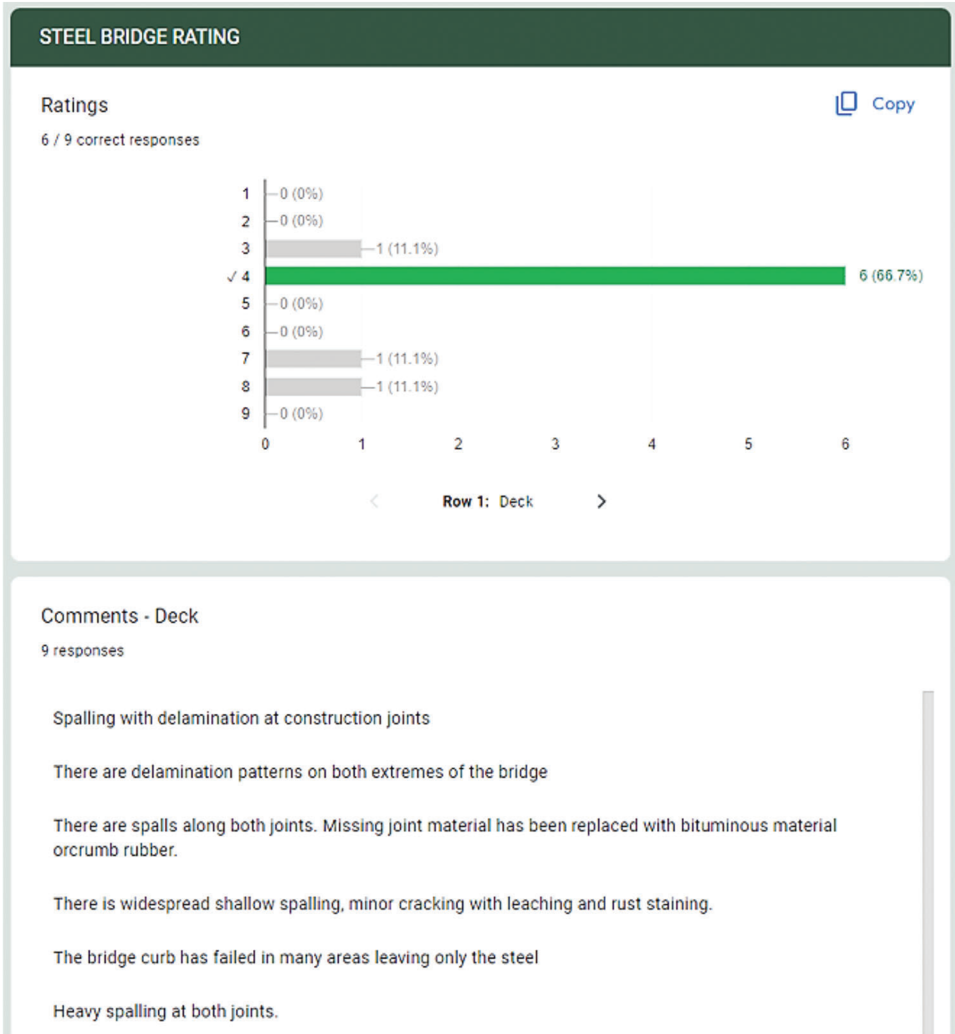


Figure 5.3 Samples of the consistency report, section 2: ratings and comments.

6. IMPLEMENTATION

The deliverables of the project, along with the suggested procedures and recommendations for the successful use of the VR application, are described. The discussion also includes the expected benefits of the project developed for the INDOT bridge inspection program, particularly those related to assessing consistency among inspectors. The benefits are summarized in Table 6.1.

6.1 Deliverables

- A software system containing the VR application. The system includes one virtual module for a steel truss bridge and one for a concrete beam bridge. Both bridges have various types of defects and levels of damage, according to the SNBI 2022. In addition, a practice module is delivered so the users can practice and get familiar with the VR environment before inspecting the bridges developed.
- A fully equipped hardware to run the VR application. The equipment comprises a tethered VR headset with corresponding controllers, base stations, a link box, and connecting cables. The headset is supported by a gaming laptop with all the required specifications and programs installed to sustain the computational demand of the software. All the equipment pieces are delivered with a backpack to facilitate transportation among the different districts of INDOT.
- A detailed written user manual covering the VR system setup, the usage of the modules, the filling of the inspection surveys, and the analysis of the surveys' results from the management perspective. Moreover, two instructional videos are delivered to complement the explanation given in the manual regarding using the practice module and the inspection surveys platform.

6.2 Deployment

During the initial implementation stage, a graduate student of the research team in charge of developing the VR application will visit the different districts of INDOT to assist and train the personnel in using the headset, the bridge modules, and the inspection surveys. During these visits, technical and practical questions are expected to be addressed so that the technology and knowledge transfer is smooth and complete.

In coordination with the inspection program manager, multiple inspectors will be requested to use the VR headset, and the results of their findings after the inspection of the virtual bridge modules will be recorded online through surveys. Data will be collected anonymously, and only the manager will have access to the records of each person. The manager will get automated statistical data analyses through the online platform that supports the surveys, which could be downloaded and further fine-tuned if needed.

After data have been collected, internal discussions at INDOT are expected to investigate the correlation between the consistency in the detecting rate of defects and the areas of strength and improvement in the training programs. If time allows, the graduate student, in collaboration with some research team members, expects to produce a scientific article summarizing the findings of the implementation process.

6.3 Expected Benefits

TABLE 6.1
Expected benefits after the implementation of the VR testbed

Benefit	Description of Benefit
Quality	Assessing consistency among inspectors will contribute to improving inspection processes and the associated reports produced.
Employee Training and Development	The findings of the assessment will help enhance the existing training modalities, which will eventually lead to the production of better-trained inspectors.
Time Savings	Conducting simulated inspections within VR offers a significant time-saving advantage, as it eliminates the need for field visits, traffic management, safety protocols, and the coordination of personnel and equipment.
Safety	By utilizing the VR application, the necessity of exposing human inspectors to on-site hazards will be eliminated, reducing the risk of workplace accidents. Furthermore, limitations associated with the logistics of equipment and weather conditions are also removed, as the assessment happens in a room with controlled conditions.
Cost Savings	Study consistency in identifying defects will mitigate uncertainties and bolster the confidence of INDOT in selecting economical retrofit solutions. Additionally, this will expedite decision-making, taking prompt actions, leading to long-term savings, and ultimately diminishing expenses attributed to downtime.
Innovation and Technology	The acquired knowledge product of the consistency study could be disseminated to the broader scientific community through conference and journal publications, promoting the adoption of cutting-edge technologies and more effective solutions for infrastructure asset management.

7. SUMMARY

In this project, a VR-based application was developed to measure consistency among bridge inspectors in Indiana. VR technology reduces variability by controlling the bridge models and the conditions under which the inspectors perform their jobs. Accurate statistical analyses are automatically generated based on multiple factors tracked on post-inspection surveys. With these results, revamping the inspection training procedures is expected, deriving in better decision-making processes regarding the repair, retrofit, or replacement of current bridges.

A steel bridge module and a concrete bridge module are delivered. All the components modeled within the VR scenes—bridge components, defects, and inspection tools—were discussed with INDOT and SAC members, reaching a development level to the final users' needs and the current capabilities of the hardware and software systems. The lists of defects and inspection tools modeled are presented in Table 7.1.

The modules are run through a VR headset and a laptop, which were carefully assessed purchasing to ensure high resolution and versatility per the project's request. A detailed user manual and instructional videos are provided in separate files to deploy the application successfully.

TABLE 7.1
List of defects and inspection tools

Defects	Tools
Efflorescence	Compass
Corrosion	Chain drag
Pack Rust	Hammer
Section Loss	Scratch brush
Spalling	Flashlight
Spalling with Exposed Rebar	Tape measure
Delamination	Zoom window (binoculars)
Cracking	
Stain Rust	

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On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

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