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Rail Safety IDEA Program

Augmenting Reality for Safer Inspections of Railroad Infrastructure and Operations

Final Report for
Rail Safety IDEA Project 43

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Augmenting Reality for Safer Inspections of Railroad Infrastructure and Operations

IDEA Program Final Report

For the Period February 2021 through August 2022

Rail Safety IDEA Project 43

Prepared for the IDEA Program

Transportation Research Board

National Academies of Sciences, Engineering, and Medicine

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GLOSSARY

8WCSCM	8th World Conference on Structural Control & Monitoring
AAR	Association of American Railroads
AFRL	Air Force Research Laboratory
AR	Augmented Reality
AREMA	American Railway Engineering and Maintenance-of-Way Association
ARRA-Eye	AR for Railroad Attention using Eye-tracking
ASCE	American Society of Civil Engineers
BNSF	Burlington Northern Santa Fe Railroad
CCEE	Department of Civil, Construction, and Environmental Engineering
CN	Canadian National Railway
DAQ	Data Acquisition System
DOF	Degree of Freedom
DOT	Department of Transportation
ECE	Computer Engineering Department
EMI	Engineering Mechanics Institute
ERP	Expert Review Panel
HL1	(Microsoft) HoloLens 1
HL2	(Microsoft) HoloLens 2
HMD	Head Mounted Device
IR	Infrared
LANL	Los Alamos National Laboratory
MAHRES	Multi-Agent, Robotics, and Heterogeneous Systems Lab
ME	Mechanical Engineering
MMLDT-CSET	Mechanistic Machine Learning and Digital Twins for Computational Science, Engineering & Technology
NMDOT	New Mexico Department of Transportation
QR code	Quick Response code
SHM	Structural Health Monitoring
SMILab	Smart Management Infrastructure Laboratory
TTCI	Transportation Technology Center, Inc.
UNM	University of New Mexico
UP	Union Pacific Railroad
USDOT	United States Department of Transportation
VR	Virtual Reality

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INVESTIGATORS' PROFILE

PI:

Fernando Moreu is an Associate Professor at the Department of Civil, Construction, and Environmental Engineering (CCEE) at the University of New Mexico (UNM). He holds courtesy appointments in the Departments of Electrical and Computer Engineering Department (ECE), Mechanical Engineering (ME), and Computer Science (CS). He is the founder and director of the Smart Management of Infrastructure Laboratory (SMILab) (http://smilab.unm.edu/). SMILab's research interests include structural dynamics and control, Structural Health Monitoring (SHM), wireless smart sensor networks, cyber-physical systems, computer vision, earthquake engineering, augmented reality, unmanned aerial systems, bridge engineering, and aerospace structures monitoring and reusability. Prof. Moreu has published 38 journal papers and several conference proceedings. Prof. Moreu received his MS and PhD degrees in structural engineering from the University of Illinois at Urbana-Champaign (2005 and 2015, respectively). In 2019, Prof. Moreu received the CCEE Stamm Teacher of the Year award. His projects are funded by the National Science Foundation (NSF), Department of Energy (DOE), Department of Defense (DOD), National Academy of Science (NAS), Federal Railway Administration (FRA), US Department of Transportation (USDOT), NASA, Transportation Research Board (TRB), and the commercial sector. He is a Member of ASCE, ASME, SPIE, and AREMA. Prof. Moreu is a registered Professional Engineer since 2010.

Co-PI:

Victor Law is an Associate Professor at UNM. Victor Law received his PhD in Educational Psychology from the University of Oklahoma. His primary research interests include game-based and simulation-based learning, scaffolding, self-regulation, ill-structured problem-solving, and computer-supported collaborative learning. He has been conducting studies examining the effect of different scaffolding approaches, including massively multiplayer online games, computer-based simulation, and dynamic modeling, on students' complex problem-solving learning outcomes; the research results have been presented at prestigious national and international conferences, such as Annual Meeting of the American Educational Research Association, Association for Educational Communications and Technology, and International Conference of Learning Sciences. Dr. Law has published empirical studies in national and international refereed journals such as Educational Technology Research and Development, British Journal of Educational Technology, Computers and Education, Computers in Human Behaviors. Journal of Educational Technology & Society, Interactive Learning Environments, Interdisciplinary Journal of Problem-Based Learning, and Journal of Educational Computing Research.

EXECUTIVE SUMMARY

Augmenting Reality for Safer Inspections of Railroad Infrastructure and Operations
Safety IDEA Project 43

Research Agency:	University of New Mexico
Principal Investigator:	Fernando Moreu
Contact:	(505) 277-1784 fmoreu@unm.edu
Completed:	December 2022
IDEA Contract Amount:	$100,000

IDEA Concept and Product

This research project is dedicated specifically to the exploration of using Augmented Reality (AR) to enhance the accuracy and efficiency of monitoring railroad inspections and operations. The PI utilized AR as a scaffolding tool and develop a new framework that accelerated information acquisition and improve decision-making capabilities during infrastructure inspection. The proposed approach included modeling human cognition and learning process, and programming it into AR. Additionally, to reduce decision-making biases, a real-time data access/accumulation system through AR platform is presented for field inspections that can be applied to any railroad operation. Equipped with this new AR framework, railroad inspectors can access, collect, and share information in the field with higher efficiency. The new AR framework was tested at AREMA 2022 with over twenty railroaders.

Project Results and Planned Investigation

The tasks in this project were divided into two stages: Stage I and Stage II. The objective of the activity in Stage I was comparing inspections with and without the proposed AR framework. The software/hardware used in this stage was specifically designed/selected for track inspections and tested in collaboration with the Canadian National (CN) Railway (the industrial partner) in CN campus at the start of the project. At the end of Stage I new applications on AR were developed including robotic mediation with inspections and other applications that enhance inspector safety with hands off measurements.

Stage II activities included the training software that assisted the novice employee in the indoor facility on how to conduct an efficient inspection with AR in comparison with conventional means. This interest in training railroaders have been brought up by the collaborator as a first step that can also inform later on the timeline of actual field implementations/solutions that can assist inspectors to do their inspections faster. To achieve the goals of stage II activities the research team joined AREMA Conference & Expo 2022 to meet and present the AR developments to expert railroaders, on addition to visits to railroad tracks with the new application. The youth (new employees) were more interested in the technology and can provide with early feedback that can improve the implementation of the AR applications in a context that has value for the railroad.

Product Payoff Potential

A product of this research is an AR application that has been used to indicate the steps to be taken to conduct a better inspection with AR when compared with traditional tools (tape measurer) which can be implemented in the field after being tested. The result of the final report will include a feasibility and analysis of the experience of users using both methods and input for implementation of AR for faster training of railroad inspectors. The strong participation of industry in this research ensured that the early steps on the development are directed towards real applications that can have value for industry, with an emphasis on railroad inspectors who

participated in the AREMA 2022 conference. External review panel members include Volpe, Meta, CN railroad, Los Alamos National Lab, and the Air Force Research Laboratory.

Product Transfer

Working with industry partners ensured that the AR tools were transferred to practice for railroad inspections. The PI collaborated closely with CN to ensure this research identifies AR as a practical tool, and with AREMA committees 10 and 24, dedicated to bridge management and education and training, respectively. Collaborations with the public and private sector leaders in AR, railroad, research, and industry ensures that the results of this research can have an impact in both the public and private sectors, and it ensures the results of this research impact infrastructure stakeholders. The PI has discussed both with CN and Meta future opportunities to develop AR innovation that will enable faster training for new personnel in the railroad, but this information can also be shared in the form of applications, training programs, or different AR internships that prepare new employees to be safer for when they are getting ready to conduct their work in the field.

Figure 1 shows initial interface with CN railway to understand priorities on safety during rail gage measurements in the field (informing the programming and development of AR application for Stage I). Figure 2 summarizes the Stage II progress collecting input from railroaders at AREMA 2022 Annual Conference that will be included in the Final Report.

Figure 1. The research team using the input from the railroad industry interests in new technologies as well as their concern in testing the safety of new interfaces. The team is testing AR with CN employees in the CN Campus the new proposed interface for rail inspections.

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

Figure 2. AREMA 2022 AR survey from railroad industry to conduct inspections: (a) AR presentation to committees 10 and 24. (b) participant's effort for using tape measure, (c) AR training (d) participants AR measurement result.

REVIEW PANEL

This TRB SAFETY IDEA project is led by PI Fernando Moreu, Assistant Professor of Civil Engineering and Co-PI Victor W. Law, Associate Professor at College of University Libraries and Learning Sciences and the Program Director of the Organization, Information & Learning Sciences (OILS) Program at the University of New Mexico (UNM). The research group is composed by the various co-author who are graduate students in a multidisciplinary research group at UNM, which includes various colleges, departments, and research areas. The review panel composed of the following members:

Table 1. Expert Review Panel Members for TRB Rail SAFETY IDEA RS43 Augmenting Reality for Safer Inspections of Railroad Infrastructure and Operations.

	Last name	First name	Company
TRB Liaison	Mullen	Martita	Canadian National Railways
Industry Partner	Scola	Sandro	Canadian National Railways
Review Panel	Steve	Popkin	Volpe U.S. Department of Transportation Volpe Center
Review Panel	Hushman	Cari	University of New Mexico
Review Panel	Codd	Patrick	Meta
Review Panel	Mascarenas	David	Los Alamos National Laboratory

This final report has been checked by all members of the review panel. Additionally, a degree of collaboration with other experts in AR and Structural Health Monitoring (SHM) as listed in Table 2 took placed to improve the quality of the research. Their input has provided additional insights in the use of AR to advance railroader environment interfaces using AR.

Table 2. Technical experts.

Area of Expertise	Last name	First name	Company
Structural Engineering Expert	Darwin	David	Kansas University
Steel Structure Expert	Steelman	Joshua	University of Nebraska–Lincoln
Transportation Expert	Alampalli	Sreenivas	University of New Mexico
Structural Engineering Expert	Mosavi	Amir Ardalan	ARUP, Inc.

BACKGROUND

Concept of Application

The problem of deterioration of railroad system, in particular the decay of railroad bridges has been noted by the Departments of Transportation. Budgets for railroad infrastructure repair and maintenance are limited, but safety of operations must be ensured. Objective and frequent inspections control the railroad infrastructure condition [1], [2]. Some of the main challenges that are mentioned in previous studies include the following:

- Despite distinct advantages of railroad inspection performed by human in the field, their objectivity greatly depends on the human factors such as experience, knowledge, and skill. Today it is accepted that the quantification of inspection objectivity is a significant challenge.
- Data accessibility impose major limitations such as real-time data acquisition limitations, accessibility of the data collected in the past inspections, and data transfer among the inspectors. If the inspector can access data from current or past inspections at the site their inspection could be more effective.
- Traditional methods for training inspectors rely on shadowing of experts over a large period to ensure the new engineer acquires the knowledge by observation. It is accepted that learning could be accelerated if the new inspector could access the instructions overlaid during their learning. This has been tried in other disciplines such as manufacturing, and there is an interest in the railroad to advance the training for new employees using AR.

To address these problems, this research project advanced the railroad bridge inspector profession by transforming inspector's current abilities, procedures, and limitations using new human-infrastructure interfaces with AR. The designed framework is transformative in two ways: (1) it used a new human-technology partnership that augments human performance through an interdependent partnership; and (2) it enabled human cognition to be accelerated in real-time in the field, which is important for safety. Equipped with this new AR framework, railroad bridge inspectors could collect information in the field in less time. This new AR framework was developed through partnerships between experts in railroad bridge engineering (listed in Table 2) and AR research team (Moreu, Law and graduate students). Using this approach of modeling human cognition and human learning, and programming it into AR, the inspector-infrastructure interface can serve other inspection areas as well, such as tracks, crossings, etc.

The multidisciplinary approach ensured success in meeting the project's objectives, which are to: (1) explore and identify the governing limitations related to track engineers and railroaders in general, and the factors that increase accuracy and reduce the time of data collection in the track; (2) formulate AR frameworks that increase the speed and accuracy of infrastructure damage detection using human-machine interface, learning scaffolding, and machine learning; (3) develop technologies for a new human-centered, cyber-enabled railroad track inspector; and (4) ARRA-Eye software developed to quantify accuracy, speed, and safety of the new cyber enabled railroad inspector, and use test-beds to test the safety of these new technologies in collaboration with CN, first in the laboratory, CN campus track, and in the field. (5) More AR-inspection collaborative software is developed and updated based on the expert railroader's needs and discretion. The safety of using AR is prioritized when trying it on the track.

To ensure that the proposed innovation can advance railroad practice, the Canadian National Railway (CN; headquartered in Chicago, Illinois) indicated their strong support from the project and visited the SMILab laboratory and evaluated the AR inspection tools developed by the research team for real-world railroad operation and provided their professional feedback on the tools. Additionally, researchers conducted a field experiment in collaboration with the professional inspectors from the New Mexico Department of Transportation (NMDOT) in December 2021 and evaluated the AR tools in a normal inspection and received the comments of the NMDOT inspectors about the AR tools. Those comments helped the research team provide more practical AR tools for the inspector's needs described in this report. Additionally, the research team has presented the AR interface to experienced railroad consultants in the context of railroad inspection and collected their feedback. Also, the team presented in TRB to collect additional input in the feasibility of using AR to inform railroad inspections.

After all, the research team provided field experiments to validate the applicability of the developed AR software by testing them in collaboration with experts. The description and the results of those tests are provided in this Final report.

In addition, the research group provided a survey experiment to measure the experienced railroader's inclination to use AR during the field inspection. For this purpose, a questionnaire has been provided to ask the railroader's opinions before and after their hands-on experience using AR inspection developed software. Also, since none of the participants had experience using AR, the research team provided in-person training for each of them before using the software. The present report further describes all the stages and results of the mentioned experiment.

Finally, to inform the railroad community of the research conducted in this project, the research team presented the AR software developed and the inspection test results acquired in several papers, conferences, and meetings for the expert railroaders and scientific community to attract their attention and collect their feedback. The last part of the present report comprehensively describes these presentations conducted by PI or graduate students.

Potential Payoff for Practice

The US Department of Transportation reports that more than half of the railroad bridges in the US were built before 1920 [3]. The assessment of existing railroad bridges is key for sustainable, safe, and reliable railroad operations [4]. Bridge inspection reports inform Maintenance, Repair, and Replacement (MRR) decisions within the entire network [4]. Bridge inspections are required annually since 2010 as part as the bridge management program which follows the American Railway Engineering and Maintenance-of-Way Association (AREMA) recommended practices [5]. Railroad bridge inspections take time and money. In addition, three significant challenges affect railroad bridge inspections today. (1) Railroad bridge inspectors need to visually evaluate all bridge structural elements. This is a major challenge in tall and long steel bridges where elements are difficult to access. At times, inspections need to be scheduled in between regular traffic to allow inspectors visual access to bridge elements, reducing traffic capacity. (2) Visual observations without measurements cannot quantify defects; they are in general subjective and depend on the inspector carrying them out [6].

This project addressed the mentioned challenges by developing a method that ensured a transformation involving the practical implementations of AR in the context of the human interface with the track. The following steps are done in this project to overcome the above-mentioned challenges:

- Explored human attention during inspections and interactions with their environment with ARRA-Eye; quantified those relationships through experiments and simulations in real structures.
- More AR software was developed to enhance the quality of the AR inspections.
- AR inspection application was presented and described and tested by the experts.
- AR inspection inclination is evaluated by surveying the experienced railroaders.

Transfer to Practice

Collaborations with CN railway, NMDOT, and international railroaders ensured that the results of this research can have an impact in both the public and private sectors and ensures the results of this research impact infrastructure stakeholders. Working with industry partners ensured that the AR tools were designed in the context to practice for railroad inspections and other related operations such as access to real-time data in the field, or sensor deployment in the field. The collaborations with the railroads were documented and analyzed to optimize that these partnerships contribute to practice.

SCHEDULE

The project has progressed on schedule. Report summaries and task calendar are listed in Tables 3. Also, the project schedule is shown in a in Table 4.

Table 3. Tasks and reports for this project.

Stage I
Task 1: Cognition by Experienced Bridge Inspectors
Task 2: Mitigate Inspection Variability with AR
Task 3: Quantifying AR Effect in Inspection Quality
Task 4: Evaluation of New AR Inspection
Task 5: Report
Stage II
Task 6: Optimize the Performance and Robustness of the System in the Context of Field Measurements
Task 7: Adaptation and User Interface with the Railroad
Task 8: Draft Final Report and Final Report

Table 4. Schedule of the project.

Year	2021											2022							
Tasks	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8
Kickoff Meeting	■																		
Task 1 Cognition by Experienced Bridge		■	■																
Task 2 Mitigate Inspection Variability with AR				■	■														
Task 3 Quantifying AR Effect in Inspection						■	■												
Task 4 Evaluation of New AR Inspection								■	■	■									
Task 5 Stage I Report											■	■							
Task 6 Performance													■	■	■				
Task 7 Adoption and User Interface with Industry																■	■		
Task 8 Draft of Final Report and Final Report																		■	■

ACCOMPLISHMENTS

This section outlines the accomplishment of the eight tasks mentioned in the contract. Each accomplishment has been done based on the timetable proposed in Table 4.

TASK #1: Project kick-off meeting and railroad industry feedback

a. TRB kick-off meeting

The kick-off meeting was conducted on February 10th at 3 PM EST. The kick-off meeting covered: (1) motivation, (2) overview of the project, (3) objectives, and (4) expected outcomes. The research team presented the project to the review panel members, all present through teleconference. The detailed stages, their respective tasks, and the plans to accomplish the tasks within the given time were presented and discussed. A delivery schedule was presented to complete the project in the required timeframe. The ERP gave new ideas about emphasizing the interaction with the railroad industry directly to identify barriers for adoption in the field. The final edits of the schedule were made considering these suggestions.

b. Railroad industry feedback

The 1st railroad interaction took place with the visit of James Dewey from CN railroads to UNM on March 1619th, 2021. During this visit, the first input on the use of AR was collected and the first experience of researchers observing track inspections was documented to develop a new interface for track inspectors as demonstrated in Figure 1. From March to June, several online interactions with CN headquarters conducted through the Zoom platform. These interactions helped the research team with AR programming using the CN feedback on the developed AR software, as well as the preparation for the enhanced quantification of inspector's vision and the use of eye tracking for learning the inspector's performance while inspecting the track.

Figure 3. UNM team Interaction with CN: Railroad inspection test using Microsoft HoloLens 2nd generation.

The 2nd interaction to collect railroad input included a visit to the CN main office in Chicago on June 2nd-4th 2021. The CN professionals used and tested the developed AR software at the CN training campus, as shown in Figure 2. On this trip, the team collected feedback from CN about integrating AR technology into the human inspection process for railroad inspection and benefited from those to further AR software updates.

Figure 2 shows the CN expert rail track inspector describing his experience using AR at the rail track inspection. The research team trained him to utilize AR-developed software to benefit and improve railroad inspection. Meanwhile, the expert describes the essentials of railroad visual inspection and concerns that could potentially be addressed using AR.

Figure 4. AR software indoor test with railroaders (CN training campus, Chicago, Illinois).

Researchers considered the continuous input from CN to become aware of the railroad's priorities to develop AR applications that can mitigate the variability of inspections and are described in Task 2.

TASK #2: Mitigate inspection variability with AR

Visual inspection results have the reputation of significant variability due to several factors that affect human visual inspection [7]. This research took two approaches to provide a means to minimize human inspection variability, i.e., AR instructions and AR-data system. This section describes the two approaches and explores their implementation stages.

a. Inspection quantification with ARRA-Eye AR software

The future of railroad inspection is promising to rely on human-machine interface. AR technology helped to improve the quality of railroad track and railroad bridge inspection by quantifying the inspections quality. In this project the attention of the track inspector can be quantified using the eye gazing with AR. The input is the eye motion path identification and the measurement of the direction of the user's gaze [7]. This estimation is usually interpreted as the location recognition of the object to which the gaze collides at each moment [8]. The initial efforts for gaze estimation are made in 18th century but it was no sooner than 1939, when Jung's measurement of eye movements in two directions using electrodes placed on human face close to the eyes, offered the prospects of real-time processing of gaze data [9]. From 1980s to date, the development of minicomputers with high processing capabilities has led to computer-based real-time eye tracking and this has provided the possibility of using video-based eye trackers for human computer interaction. The AR technology has recently provided low weight and size see-through AR-headsets such as Microsoft HoloLens 2nd Generation (HL2) that enables realtime eye tracking capabilities [10].

This research developed and introduced a tool in AR platform i.e., "ARRA-Eye" that is designed to serve as a means of quantitative analysis for railroad infrastructure inspections. "ARRA-Eye" is an adapted eye-tracking software that can be used in the track to measure the observations from the railroader at the field to quantify their track operations. This eye-tracking has been used in the past to quantify the observation of structural damage in the infrastructure, and it is proposed for track inspections' quantification. In this case, the data collected aims to objectively quantify the interaction between the inspector and the infrastructure, with the tacit assumption that eye-tracking of an inspector in the field is a measure that quantifies the inspection visual coverage and inspector's attentiveness.

b. AR instructions towards mitigation of variability

From the professional feedback received from the railroad leaders and inspectors, the research team became aware of the potential for advancing AR technology for workforce training within the railroad community. For this purpose, the researchers first designed and implemented an AR platform in accordance with railroad reference documents such as [3], [6] that could serve as an instruction on railroad inspection. The aim of this platform was to provide the basic railroad training and AR-assisted inspection instruction new employees. Figure 3 shows the Microsoft training packages that were used as a reference, provided by CN as an example. The research team created video instructions similar that is an instruction for users in the railroad community.

c. AR-data system for inspection variability mitigation

The UNM's researchers developed an AR-enabled database that can be used for uploading and downloading data on real-time to the AR headset as a first step towards informing and collecting this information in the field that can reduce the variability. More specifically, the research team enabled, developed, and tested both data that can be provided to the inspector from the server or data collected from the inspector that can be upload on the server. This interface of humans with data can relate to the railroad database. The value of sharing information in the field with railroad databases has been identified as an advantageous new possibility to transform the experiences in the field and the interface with the railroader and the railroad during inspections.

Figure 5. Microsoft Training example suggested by CN [11].

Figure 4 shows the current interface of the cloud database proposed for the inspection of the railroad tracks. The example of crack collection and documentation data served as a test set for data acquisition practice, and the next step was the data acquisition from the parameters that are of higher value for CN track inspectors, such as track gage.

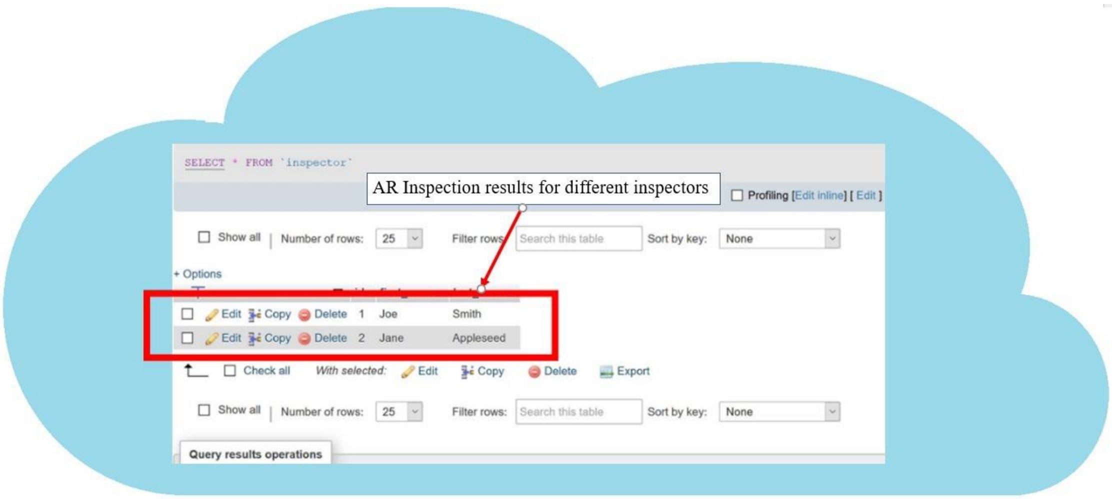


Figure 6. AR inspection software's cloud database.

TASK #3: Quantifying inspection quality

This section outlines the various applications that have been used to test and explore the interfaces between humans and their inspections with AR:

a) The research team quantified the eye activity of railroaders and showed it to them with AR.
b) The UNM team provided instructions with AR for the novice user of AR.
c) Other applications that enhance human-database interfaces, towards new human-machine interfaces applied to the railroad.
d) The researchers developed more AR -inspection software and updated them based on the railroader's technical points of view.
e) The PIs and students provided surveys and experiments to quantify the expert's inclination to use AR during the inspection before and after their first AR experience.

a. Eye-tracking software ARRA-Eye

a.1. Background

ARRA-Eye software was designed based on the eye-tracking capability of HL2 headset for inspection quantification. This application quantifies the quality of inspections by pursuing the inspector eyeballs movement and saving the inspectors eye gazing points on the inspection surface.

a.2. Development efforts

ARRA-Eye software is a second generation from a crack tracking app originally developed with CN managers and inspector's feedbacks. The research team conducted a specific experiment at CN office with help of experienced and inexperienced inspectors. Figure 5 shows the experiment made in CN headquarters office with an experienced inspector putting on HL2 and the UNM's research team.

a.3. New Application (user interface and laboratory test)

Based on the railroader's opinions and the research team's need for a better understanding of the brain's inspection process the software's virtual menu has been updated (Figure 6). By doing so, the software automatically stopped the inspection after 30 seconds that guaranteed the same sampling rate and equalize the number of eye-gazing points collected during each experiment.

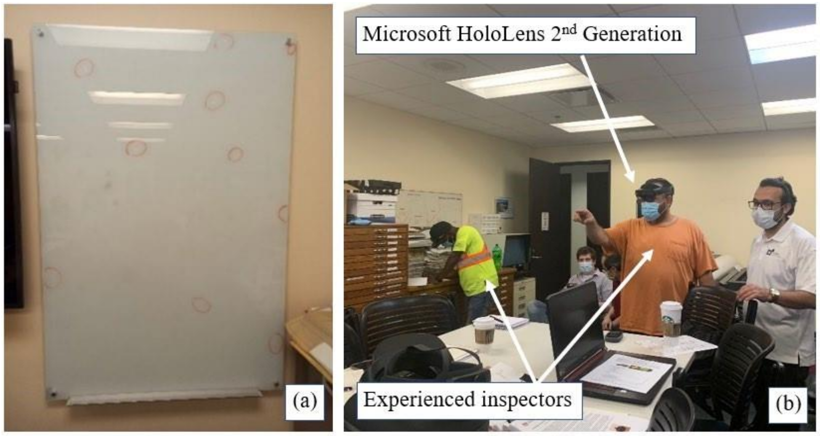


Figure 7. (a) Experiment setup, (b) CN inspector conducting ARRA-Eye experiment.

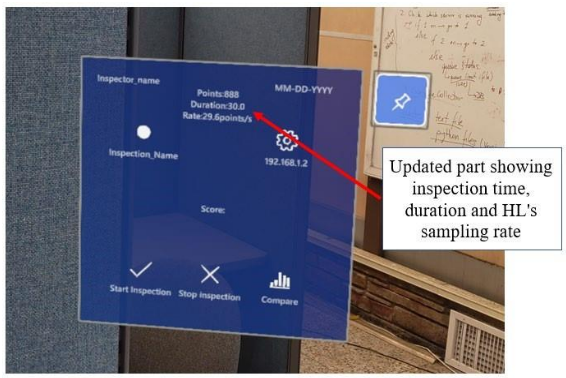


Figure 8. ARRA-Eye 's updated virtual menu.

To better understand the ability of the movement of the eye and the interface with AR, a series of experiments were conducted. In these experiments, a virtual yellow sphere was circulating in front of the volunteer's eyes as shown in Figure 7. The volunteers then followed the sphere just by moving their eyeballs.

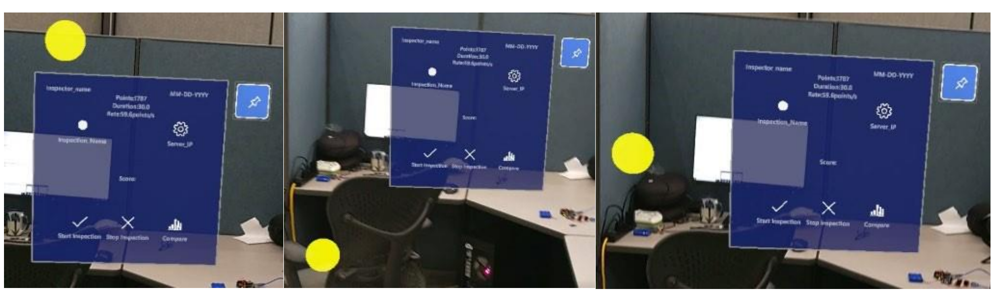


Figure 9. Virtual yellow sphere circulating in front of the volunteer's eyes.

Finally, the researchers collected their eye-gazing points using ARRA-Eye and plotted the results by MATLAB software as shown in Figure 8, which includes the results from two different experiments. Figure 8 (a) shows a uniform inspection process while Figure 8 (b) shows an inspection with several eyes-gazing jumps. This shows there is higher probability for the test operator in Figure 8 (a) to find all defects compared to the volunteer in Figure 8 (b). The results showed that the inspections quality changes user by user, even when the inspection activity and environment are the same.

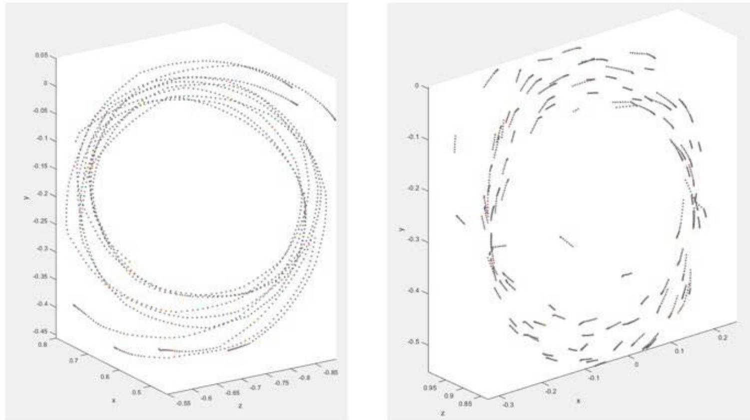


Figure 10. Rotating sphere experiment result of two different volunteers.

b. AR Holographic Inspection Cards

After introducing AR implementation for railroad track and bridge inspection, one of the feedback items received from the inspectors was to have some measure to guide new AR users with the steps involved. Therefore, a set of inspections cards were developed. These cards emphasized on safety, provided detailed step-by-step procedure of using developed software and helped ensure comprehensive inspection. The goal was to transform hand-held physical cards into holographic cards.

b.1. Instructions for inspections (portable cards)

Figure 9 shows how the inspection cards instruct the AR users to use the apps and perform the inspection with them in a step-by-step manner.

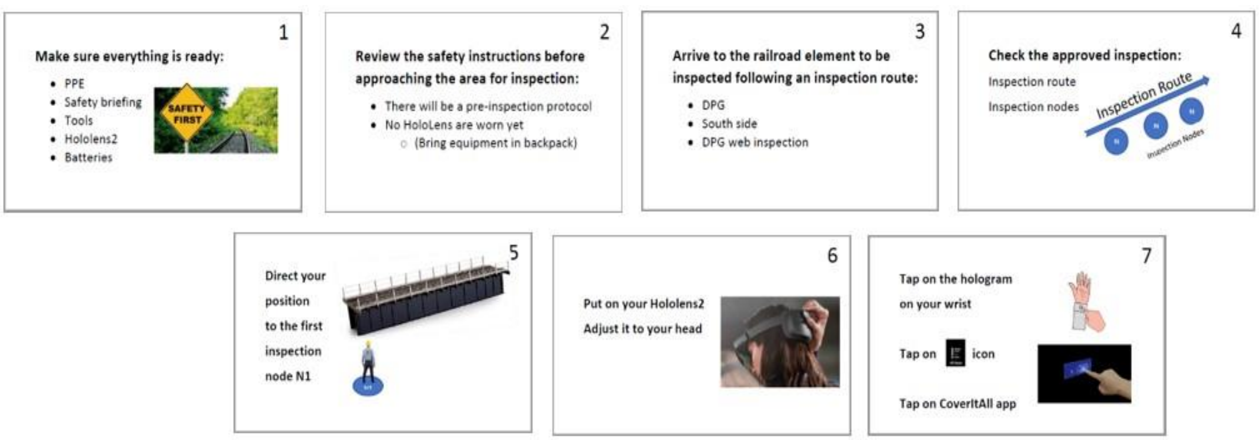


Figure 11. Inspection cards.

b.2. Instructions for inspections (holographic instructions with video)

A virtual platform for inspection cards was designed and implemented to enable inspectors to follow the instructions hands free during field inspections as shown in Figure 10. These are the first video instructions created for railroads that can be used to train the novice employees following the examples existing in the videos.

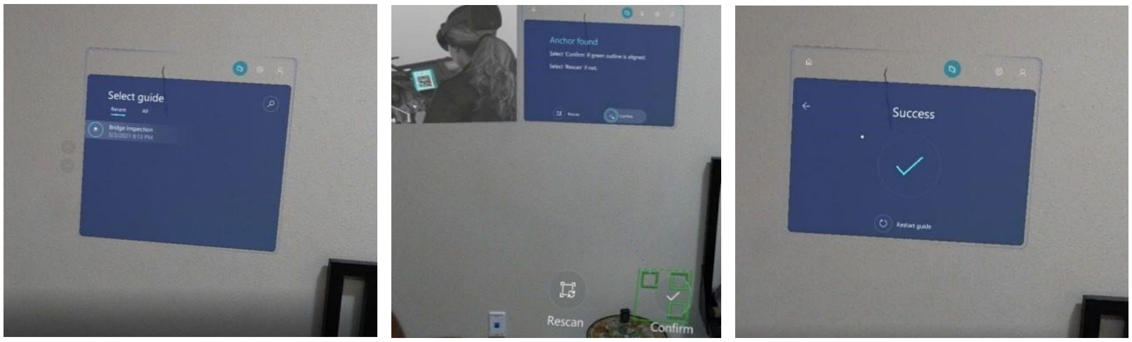


Figure 12. Virtual inspection guidelines.

As shown in Figure 11 (a), these Virtual cards were easily accessible by scanning the QR code pasted to the back of each inspection card. Inspectors or trainees could scan the mentioned QR code using a Headset and see more information about each card at a virtual headset view as shown in Figure 11 (b). Moreover, they could see some short videos at the virtual inspection cards as shown in Figure 11 (c), in which a trainer tried to describe the scanned card. The videos were also put on the YouTube website for the users who don't have access to Headset. The following step is a summary of how to use the virtual inspection cards: 1) Finding the barcode pasted at the back of the intended card 2) Scanning the QR code using Headset 3) Virtual card then pops up in front of the inspector.

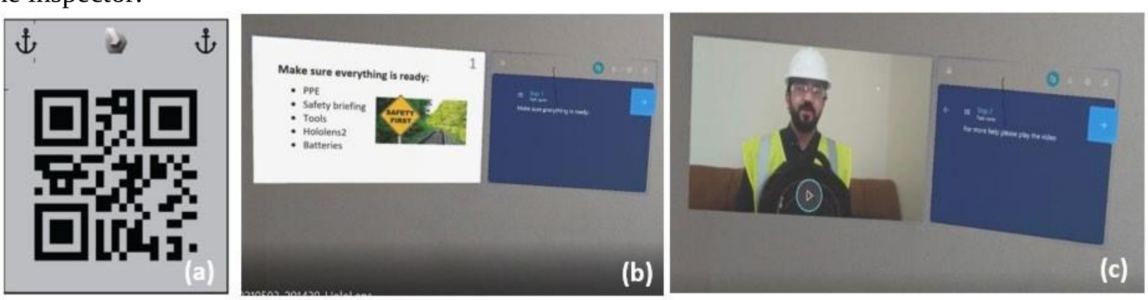


Figure 13. Virtual training with AR headset (a) QR code (b) virtual inspection card (c) virtual video.

b.3. Instructions feedback

The railroad evaluated the holographic instructions and provided specific directions to enhance the instructions such as: (1) the examples should be specific for one specific track component inspection (2) an example of the track detail or measurement should be shown in the field so that the inspector can follow the example using the cards and the holographic video simultaneously.

c. New AR Applications

The third development of AR for enhanced inspections of railroad infrastructure included a series of new applications that assist the railroader to enhance field measurements.

c.1. Dimensional measurer

Dimensional measurers are a category of AR tools that provides inspectors with real-time quantification of distances, areas, and volumes in the field. The case studies performed in relatively small inspection areas, shows an inspector can collect dimensional information while using an AR measurer software in site at shorter time compared to conventional inspection and with the same accuracy as the conventional measurement tools. Another interesting feature embedded in some of measurer tools is the ability to permanently record the measurement data. This application has been tested in the third interaction with the railroad experts and their feedbacks were included in the evaluation section (Task 4.)

c.2. Time Machine Measure

The time machine measure application is an AR tool that enables humans to save and restore a virtual representation of physical objects in real-world environment throughout the time [12]. The human can then measure and track changes that happen over time. Because these measurements are overlaid on the real environment, the human can see and understand the representation of the past as compared to the current environment. The user is aware of both the status of reality and the damage pattern progression over time which is applicable to Structural Health Monitoring (SHM). Time machine measure increases the efficiency and quality of structural inspections by informing inspectors on changes that may not be obvious to the eye. Additionally, this tool provides a mode of recording the representation of the real structure over time that is not possible without AR. Figure 12 shows an instance of the virtual representations of a laboratory room captured by time machine measure at two different times, where the green and blue represent the change in the environment. The railroad tested this application both in the laboratory and in the field and provided feedback about its value for field inspections as described in Task 4.

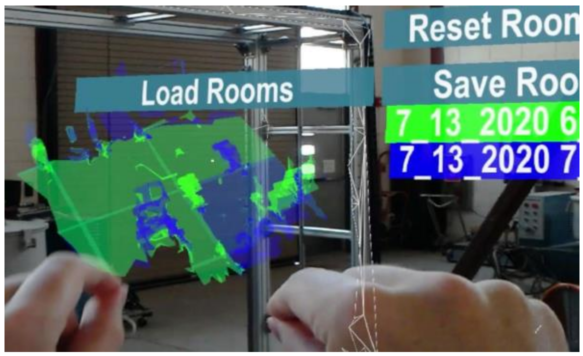


Figure 14. Time machine measure measurement and restoration of structures movement.

c.3. Sensors integrated AR tools

AR headsets have the capability of connecting to sensors and displaying sensor data in real-time. AR software designers have used this capability and developed AR tools that overlay physical objects with the sensor measurements of the objects' properties at real-time. It is important for any inspectors to maintain awareness the structure under evaluation while observing the sensor data corresponding to the dynamic behavior of the structure. Normally, the human's gaze shifts to a separate device or screen during the experiment for reading the sensor information, thus missing the structure's physical response as demonstrated in Figure 13.

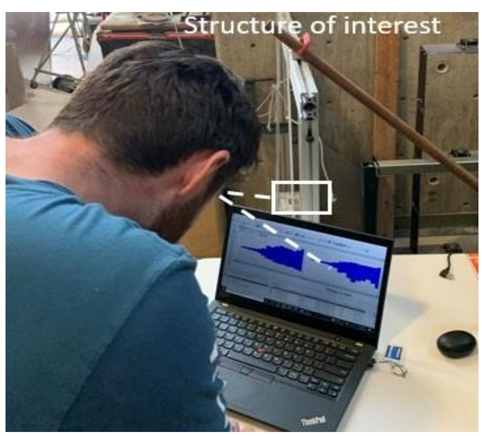
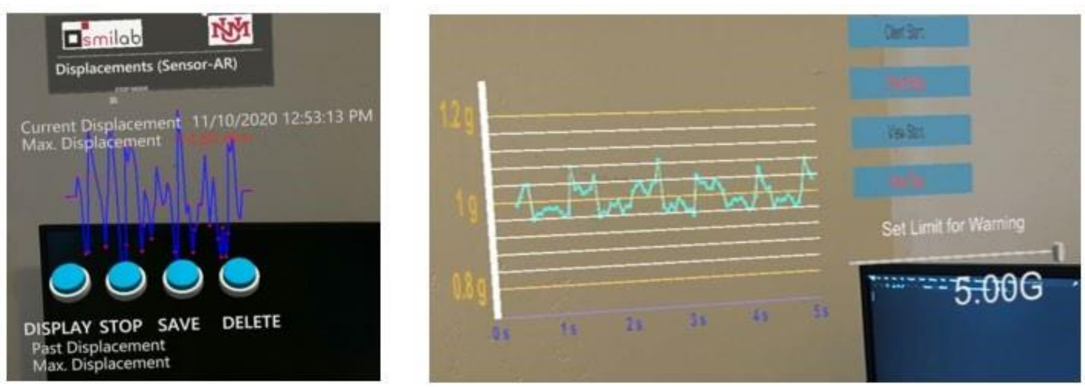


Figure 15. The researcher's gaze focuses on the data missing the physical response of the structure [13].

This human-computer interaction provides valuable information but prevents the human from maintaining awareness of reality which is important in railroad operations. Humans receive a large amount of information through vision, and therefore it is important to reduce distraction. As an example of the AR tools, this application was developed to augment sensor data on top of the area of interest. Therefore, the user can perceive real-time changes not encapsulated by the data while also monitoring sensor feedback. Two applications have been developed as seen in Figure 14 [14], [15]. The first application is developed to read and plot displacement data from a strain sensor. The algorithm calculates the maximum displacement and reads it to the AR user in real-time (Figure 14 (a)) [15]. The second application has been created to plot live vibration levels measured by an accelerometer-equipped smart sensor in an AR headset [13]. The AR headset connected to a smart sensor over Wi-Fi, which sent acceleration values that were plotted in the user's view (Figure 14 (b)) [15].



(a) **(b)**

Figure 16. Sensor data visualization in an AR headset: (a) displacements [15]; (b) accelerations [13].

c.4. Robot control in AR for railroad inspections

Robot automation is being implemented with AR technology for safer inspections. Robots are advantageous in situations in which humans lack the ability to perform a specific task. By designating an AR application for robot arm (Kinova Gen3 7DOF) control, an interface was developed that included the camera view from the robot and commands for sensor pick-and-place sequences as demonstrated in Figure 15a.

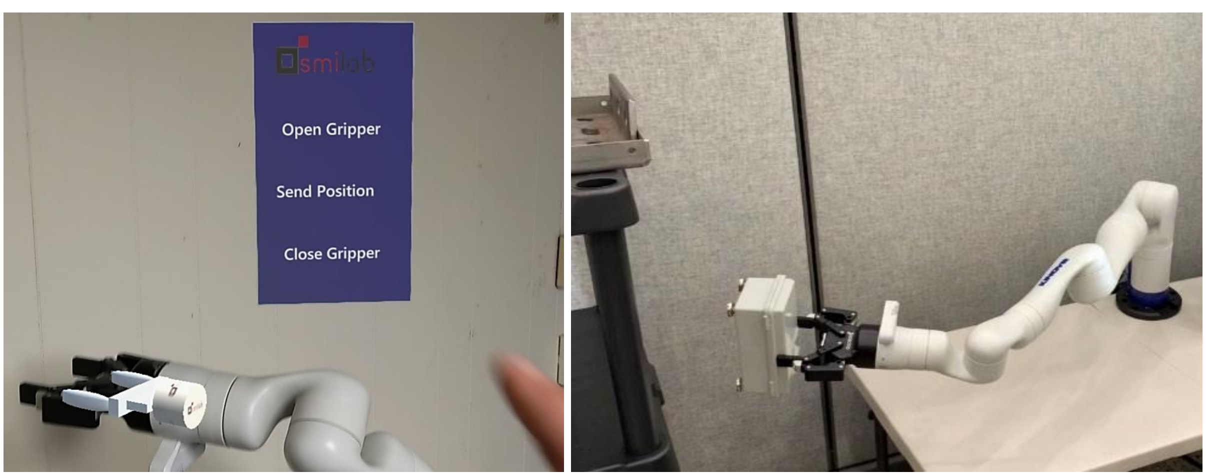


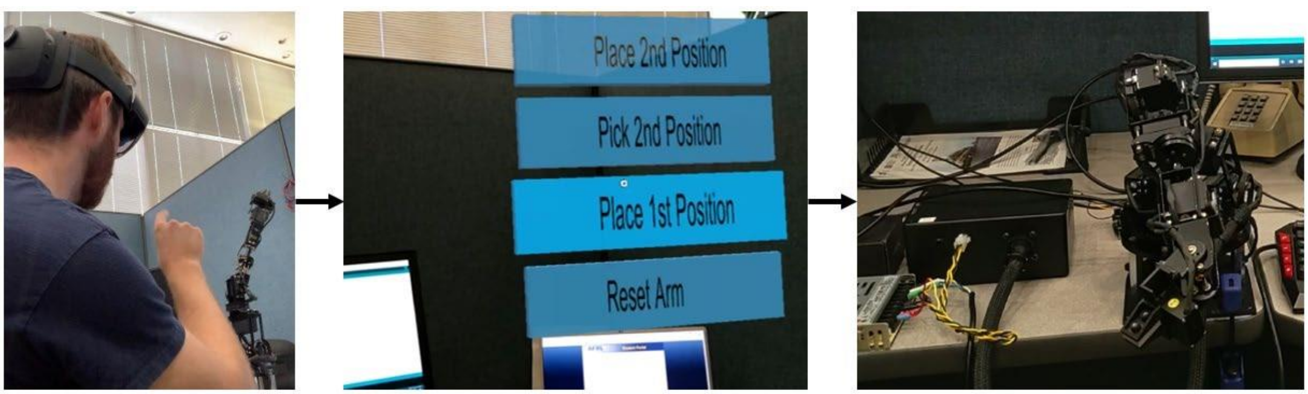
Figure 17. Kinova Gen3 7DOF robot arm with AR interface, (a) the interface including menu and holographic gripper (b) the robot places a sensor box on a structure while controlled with AR.

The pick and place task of attaching a sensor to a shelf is shown in Figure 15b. Additionally, mode shapes and finite element models were included in the interface to inform the human on expected results and correct location for sensor placement [16]. Together with the spatial mapping done by sensors on the AR headset, the human could select an arbitrary location within the robot's bounds for sensor placement on a railroad component. The mentioned capabilities proved particularly beneficial for the hard to access parts of railroads where traditional methods are unsafe, costly, and time-consuming.

The first iteration of robotic arm control in AR included an interface for pick-and-place commands along a pre-defined path using the Cyton Alpha arm. More specifically, the interface included appropriately labeled buttons 'Pick 1st Position', 'Place 1st Position', 'Pick 2nd Position', 'Place 2nd Position', and 'Reset Arm' as seen in Figure 16. Each command was a specific coordinate in space (1st and 2nd position), where each joint of the robot had joint positions that were calculated to move the robot's gripper to the desired location. The joint positions were sent as a command to the sensor board that controlled the robot. Therefore, the user could run a predefined pick-and-place route where selecting the 'Pick' command at either position closed the arm's gripper on an object and conversely the 'Place' command opened the gripper to set the object down at the position. Resetting the arm returned the joint positions to the positions defined as origin.

To advance the project, the Gen3 arm was used which could grasp sensor boxes for deployment to structures as shown in Figure 17. First, manual control of the arm was designed for AR where the arm was moved with virtual joysticks in the AR interface through several control modes. The user chose which joint they wish to move and could manipulate the angles of the joints as well. This is demonstrated in Figure 17 where the AR user manipulates the robotic arm using manual control in the AR display.

In terms of enhance field safety, robots can also be used controlled by AR for hands free intuitive access to areas of interest. Figure 18 shows Brutus, a robot that can interrogate the properties of mechanical surfaces with multiple taps which can be of value for critical components that need to be inspected without fouling the track. Figure 18 (a) shows the tap testing device and Figure 18 (b) shows the operator moving Brutus with an AR interface. The two elliptical bottoms move the robot forward and sideways, while the square activates the tapping.

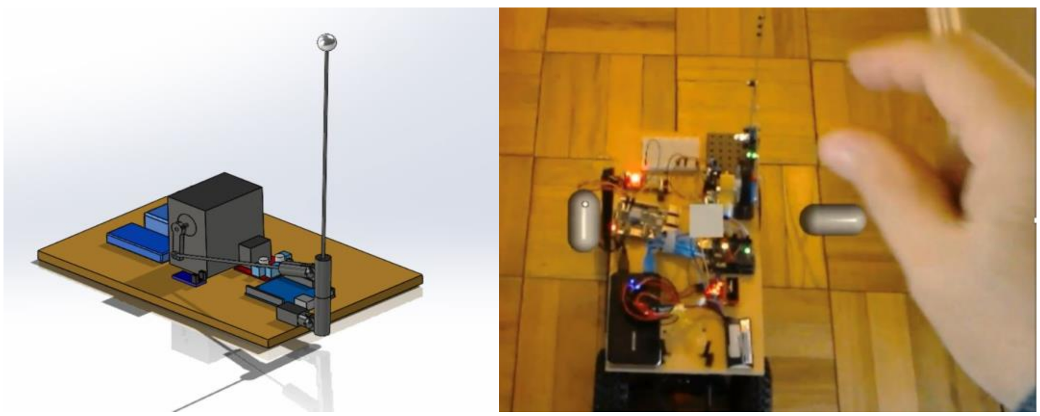


(a) (b) (c)

Figure 18. The first iteration of robotic arm control in AR with the Cyton Alpha: (a) The user operates the control interface in AR; (b) A command is selected in the AR interface; (c) The arm moves to the position and opens its gripper.

(a) **(b)**

Figure 19. The second iteration of robotic arm control in AR with the Gen3: (a) The virtual joysticks, control modes, and other information is shown in the AR interface; (b) The user operates the arm in AR manually.



(a) **(b)**

Figure 20.Tap testing robot (Brutus): (a) Brutus tap testing design; (b) Brutus controlled by AR.

TASK #4: Evaluation of new AR inspection

This task is focused on the feedback from railroad industry about the developed apps and the recommendations for implementation of the apps in the railroad environment.

a. Rail inspection and crack deployment

Railroad industries develop their inspection and maintenance strategies based on the challenges they face in the field. Rail inspections are one of the major concerns in railroad industry because of its associated safety risks. The cracks in steel structures are a significant safety concern due to their tiny size and ability to rapidly grow and propagate. During the visit at Chicago, crack deployment software was presented to CN headquarters, and they mentioned that the rail cracks on the rail are a priority in their inspections. Figure 19 (a) describes the presentation and test of this software at CN's training campus in Chicago and Figure 19 (b) shows crack's hologram created by this software on the railroad track.

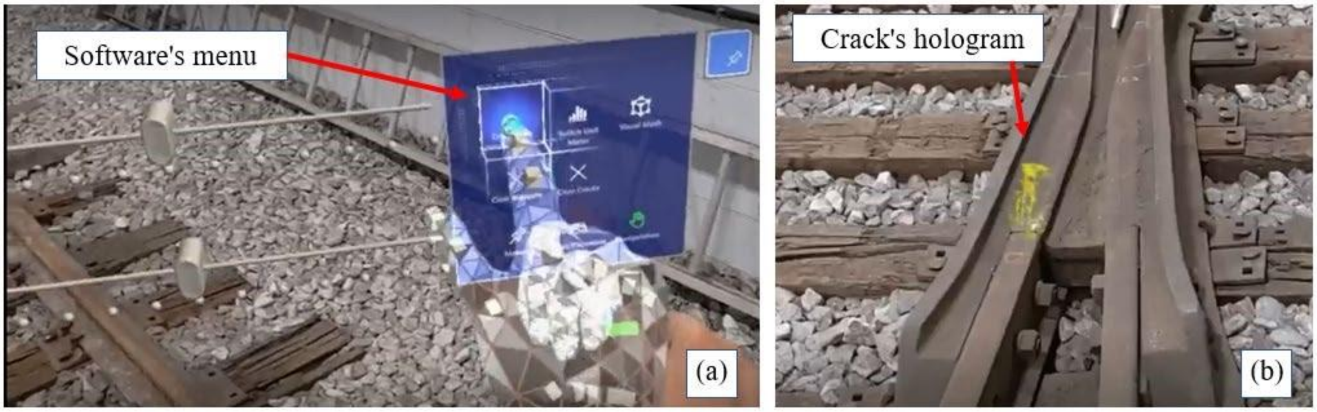


Figure 21. Track inspection evaluation: (a) Steel fatigue crack finder virtual menu (b) crack's hologram generated by this software on the railroad track.

b. ARRA-Eye testing in track environments

The research team tested the ARRA-Eye application in a real track inspection conducted by a track manager in the CN campus. Figure 20 shows the vision coverage results of the application on real-time during a rail track inspection. The value of collecting this information is that the quality of the inspection can be quantified by the railroader conducting the inspection, and by the entire management team interested to quantify the quality of the inspections in the field.

Figure 22. Vision coverage results of rail track inspection (ARRA-Eye software interface).

Figure 23. ARRA-Eye AR inspection software visualization for railroad bridge's pier.

Figure 21 shows the AR tool enabling an overlay of coverage data of an inspector's eye gaze in the CN campus. In this context, it shows the information of the inspector, and other important documenting that can be automatically saved for quantifying the quality of this inspection.

c. Crack interfaces and owner's feedback

During the collection of the railroad feedback about the AR tools, the research team unveiled a new tool that collected and quantified the width of concrete cracks in the field. This application created an AR crack characterization tool for real-time crack inspections. We tested this application with an experienced railroad bridge engineer in the laboratory to collect their feedback about its value for the railroad (Figure 22.) The feedback from the engineer assisted the researchers to improve this tool by adding additional information and features to the AR tool.

Figure 24. Laboratory experiment at UNM to validate the tool with experienced by private industry.

To test the implementation of the AR crack-detection in the field with bridge managers the research team contacted the bridge bureau in New Mexico and identified a bridge that was accessible for inspection and the team compared the accuracy of the new application with traditional crack width gages in terms of convenience and accuracy in the field. Figure 23 (a) shows the crack gage commonly used to measure the crack width at a given location; Figure 23 (b) shows the AR software examining a given strip of a surface crack, and Figure 23 (c) shows the result in AR view. Finally, the crack measurement algorithm is shown in Figure 23 (d).

The crack measurement precision depends on the camera-to-crack distance and crack orientation in relation to camera [19], [20]. The size of a single pixel of HL2 headset's photo at different distance from 100mm to 1m is quantified in a recent study. This size demonstrates the measurement resolution of the AR app for HL2 headset at the mentioned distance range. Figure 5 provides the measurement resolution of the AR app at several distances from the mentioned past study [21].

Table 5. Effect of distance on the measurement resolution of the AR app.

Distance (mm)		200	250	350	450	640	815
Pixel Size (mm)		0.068	0.087	0.119	0.152	0.215	0.278

The researchers are currently evaluating different approaches to developing concrete crack measurement capabilities for addressing railroad inspectors concerning concrete cracks. These efforts include increasing the measurement resolution of the app for measurement from further distances for example by integrating a higher quality camera into the AR headset hardware.

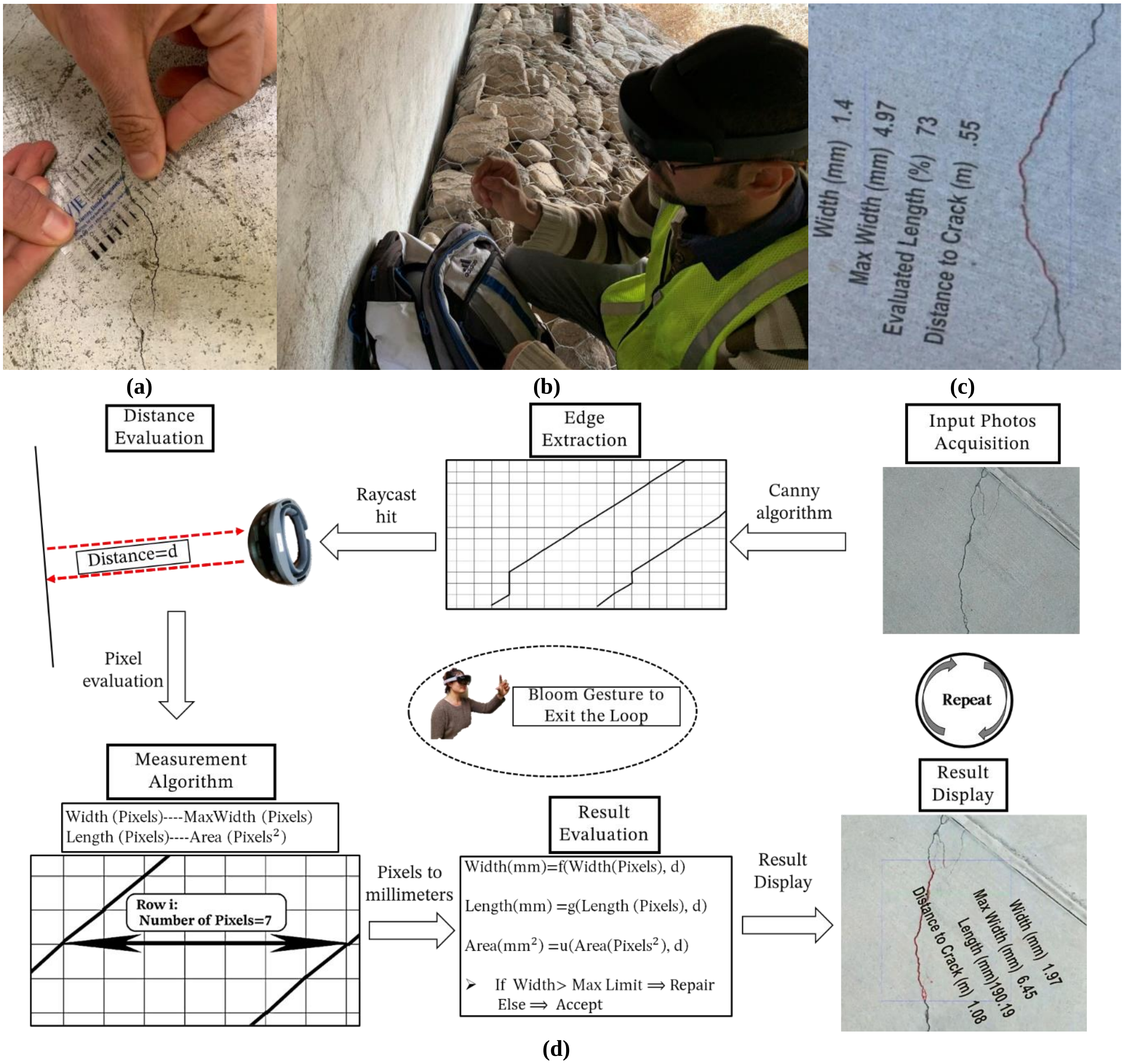


Figure 25. Crack measurement comparisons used in a New Mexico: (a) current crack gage: (b) AR inspector; (c) results from AR collected on real-time [17] (d) crack measurement algorithm [18].

d. Railroad testing of updated applications for augmented human-railroad interfaces.

The University of New Mexico hosted the CN from September 9th to 11th. During this visit the research team provided the basic training of working with HL2 and described several AR tools developed for railroad inspection by SMILab research team. Figure 24 shows the eye tracking in the research teams office at Albuquerque.

Figure 26. CN engineer's indoor training testing new software in HoloLens at Albuquerque.

Next, the CN engineer tested the ARRA-Eye during a visit to Arroyo del Oso park's steel pedestrian bridge as shown in Figure 25 and evaluated the app and provided feedback on how the research team can update the existing versions of the software.

e. Railroad input on the value of AR for augmented human-railroad interfaces.

The railroad's comments are categorized in two categories of positive and negative as follows:

<u>Positive comments:</u>

- AR can help the inspectors to improve their accuracy during the inspection.
- AR can evaluate the inspector's work and motivate them to improve the inspection quality.
- Inspector's may welcome using new technologies like AR for inspection.
- By advancing AR headsets technology the inspection accuracy and speed may improve.
- AR would help to improve the inspector's safety.
- It's a useful device for brand-new inspector's training.

Figure 27. CN engineer's outdoor evaluation of ARRA-Eye (Arroyo del Oso park's bridge.)

<u>Negative points:</u>

- Current AR headsets are heavy and may cause fatigue in long-term inspections.
- Its battery does not last long and needs to recharge soon.
- Inspectors need train and motivation to use AR for their inspection.

f. Railroad feedback

f.1. Prior to the CN visit in June 2021

The researchers compiled a survey (Appendix A) and sent it to CN office. The experienced inspectors working for CN filled out the survey and wrote down their opinion about using AR and its effect on the railroad inspection.

The survey was analyzed and some of the findings include:

1. Railroad workforce and leaders have currently limited knowledge of AR and Virtual Reality (VR). **Action Item:** To extend the AR knowledge within the railroad workforce, the research team designed an introductory instruction on AR and presented it in the interaction with the railroad.
2. Railroad inspectors and leaders mentioned that the HoloLens was uncomfortable mostly because it was integrated to their hard hat. The field requirement for inspectors to permanently have hardhat on their head, caused real concerns about the extra weight and other limitations caused by HoloLens. **Action Item:** Battery can be carried outside of the HoloLens to make the device light weight.
3. Railroad workforce and leaders mentioned several limitations of the integration of AR with railroad field inspection and preferred to continue with the traditional inspection methods in the field. **Action Item:** This research prioritized AR application first for indoor activities such as training and then for outdoor applications.

f.2. Prior to the CN visit in September 2021

To complete this task, the research team addressed the results (1-3) and used the data from the field observation performed in the visit to CN headquartered in Chicago from June 2 to 4. Also, the team conducted the following progression before the CN visit to SMILab in Albuquerque from September 9 to 11:

1. The results of the visit to the CN headquartered in Chicago showed that creating an introductory instruction about AR and VR for the CN track inspectors is necessary for extending the use of AR for railroad inspection. To do this, the researchers prepared a different setup for the developed AR training platform that served as an introduction of AR prior to the CN visit. The tests of the developed AR software were not only utilized for introducing AR to CN leaders and inspectors but also for collecting data for the SMILab future analysis.
2. For the visit of CN to Albuquerque, the research team prepared an indoor training that consisted of the following:
    a. Training on how to run and use HoloLens.
    b. Description of different branches of the research team's work in railroad health monitoring such as AR, sensors, etc.
    c. Running and description of several applications developed by our team.
    d. Detailed training of the ARRA-Eye software which was developed specifically for railroad inspection.
    e. Indoor inspection and tests using HoloLens.
    f. Outdoor bridge inspection training and test (Arroyo del Oso park's steel pedestrian bridge)

f.3. Final recommendations

After introducing the mentioned AR tools to the CN Engineer, an evaluation survey was completed based on the feedback of the AR prospects for railroad inspection and of the AR tools tested. The feedback included the followings: Future generation of light weight AR headsets would have higher value. If the safety in the field is tested, this hardware has the potential to play a significant role to transform the railroad operations and would improve railroad infrastructure inspections and operations. The current AR headsets are best for training purposes. The application of the current AR headsets for field inspection operations is limited to certain tasks because of the bulkiness of these headsets that cause safety concerns. However, based on the tested applications, the current headsets can improve safety of railroad infrastructure by designing possible dialog boxes that give a summary of the current conditions of tracks and alerting any hazards on the tracks Additionally, the eye-tracking tool can be used to quantify the improvement in a specific inspector capability after a few inspections. While measurement tool has the potential to reduce the objectivity of rail track measurement, the accuracy of this tool increases if the users can drag the pinned points without clearing it or if the inspectors can enlarge the images and edit the points based on the augmented image. The concrete crack detection tool should be updated by adding a dialog box that points out whether the detected crack is an urgent or priority for a fix.

TASK#5: Stage I report

This report has been submitted after the 50% of the tasks considered on the contract have been done. The present final report also includes the task done in Stage I.

TASK #6: Optimize the Performance and Robustness of the System in the Context of Field Measurements

This task is composed of several subtasks that are directed to identify how the AR applications can be beneficial to the railroad by interacting directly with the railroads. There are three different approaches of interaction with AR and the railroads:

- Student shadowing railroad operations (student internship at Burlington Northern Santa Fe Railway)
- Visiting/interviewing railroad leaders in different sites in the country (AREMA Conference & Expo 2022, Albuquerque’s rail runner meeting, Second CN visit at Chicago, meeting with Japanese Central Railway Company at UNM)
- Testing the AR in the context of real sites (Union Pacific bridge inspection in Kansas City)

The following section provides the details on relation to the use of AR based on specific activities focused on augmenting the human factor component of this research. This purpose has been achieved by shadowing, meeting with railroad leaders in different sites and testing the AR in the context of real sites.

a. Internship at Burlington Northern Santa Fe (BNSF) Railway

BNSF Railway is one of the largest freight railroads in North America. As one of the seven North American Class I railroads, BNSF has 35,000 employees, 32,500 miles (52,300 km) of track in 28 states, and nearly 8,000 locomotives. BNSF Railway has promoted technological advances in railway industry for a long period of time. Therefore, the research team has been in contact with BNSF office in Belen, New Mexico (Figure 26) to evaluate the developed railway-related app being used since 2016.

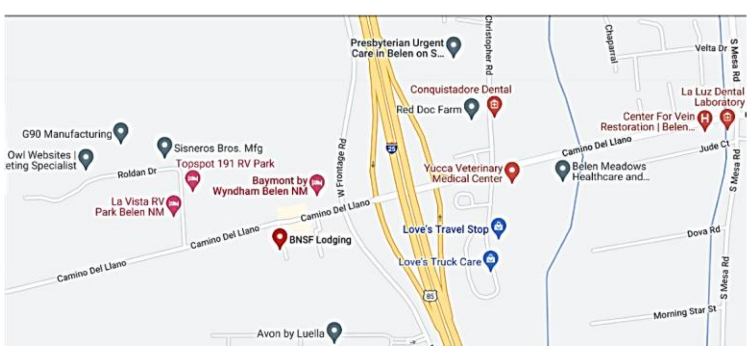


Figure 28. The location of Belen office New Mexico [21].

Figure 27 shows one of the past meetings between the researchers and the BNSF at Belen office. The meetings were aimed at assessing the practicality of the technologies developed by the research team in real-world railway operations. Another collaboration with BNSF Railway included sending the researcher for BNSF summer internship programs to evaluate the use of the developed tools by shadowing the railway experts during their routine working hours.

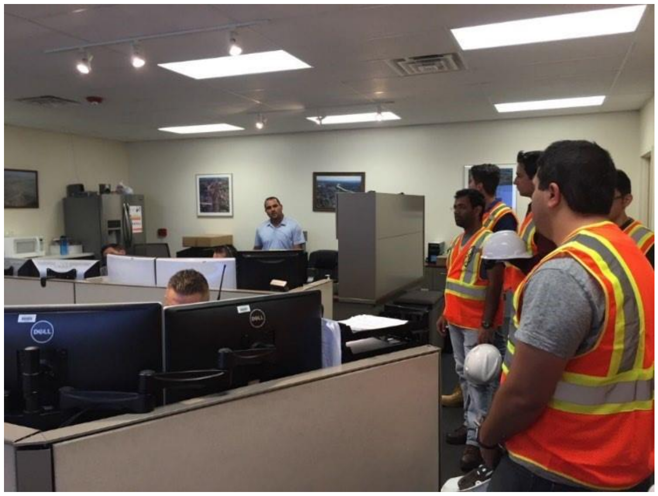


Figure 29. The past meeting between the researchers and the BNSF at the Belen office.

An SMILab researcher (Jennifer Restrepo) attended an internship in the BNSF Railway to explore the practicality of AR in railroad industry. The internship, which started on June 1st, 2022, and continued for 10 weeks, started with a few days of onboarding orientation to familiarize the interns with basic company procedures. After this orientation, the intern worked the different shifts at the field location while spending time in shadowing different departments. The last two weeks were dedicated to project presentations and an offboarding ceremony.

The internship was project oriented, meaning that the intern worked on a given project as it pertained to issues in her specific division. The goal laid out before the intern was to attempt to understand the leading factors causing service interruptions. Service interruptions were defined as any event that delayed or prohibited a train from reaching its destination. The Southwest Division at the time was experiencing more service interruptions than they ever had before. Any factor including fueling or weather that could cause delay or permanent motion prohibition were considered as an interruptions. Not all factors that were investigated were of significant value. Weather, for example, is something that can't be controlled.

The two main types of interruptions inspected by the intern were Mechanical and Engineering types: more specifically, locomotive and car on the mechanical side and track and signal for engineering. Therefore, track related issues were investigated throughout the intern's division as a key Engineering factor in interruption to understand their impact on operations. The job included two shifts: the morning shifts that were from 7am to 3pm and the night shifts that took from 5pm to 5am.

The use of AR for enhancing the safety of operations was explored by the intern during the internship. Safety is of utmost importance to the BNSF Railway. Different departments have different safety concerns. For example, the Engineering department, which overseas track health, have different concerns than members in the yard fueling locomotives. The intern concluded that AR showed a significant potential for increasing the safety of inspection, maintenance, and other engineering operations regardless of department and position. Additionally, day and night shifts for the different departments have their own unique safety concerns. Based on the result of the shadowing, AR implementation to enhance the safety shows several merits at both shifts. However, depending on the environmental circumstances that form the setting for any railroad mission, the AR apps should be contextualized in the future steps of this research. For example, the blur vision of AR headset under direct sunlight gives raise to either exploring the illumination aspects of the apps or prioritizing indoor situation such as machine shop operation, or specific applications at night.

The application of AR in learning of the new BNSF employees was also explored by the intern. AR training uses AR technology to add interactive digital elements to the world through a phone, tablet, or headset. For new hires of the BNSF Railway, there would be in class and in field learning for 6 months and the intern believes the AR technology demonstrates potential for learning both indoors and outdoors learning in this context.

b. AR and railroaders in AREMA Conference & Expo 2022

The research team provided a new survey for their meeting with expert railroaders. The survey is available in Appendix B of the present report. This questionnaire surveys the railroader's experience and opinion regarding the applicability of AR for railroad track inspections. The questionnaire was designed for railroaders who have no or little experience of using AR. Therefore, they were asked to complete the survey two times: first without receiving any instruction on AR and second after the research team had provided a short AR inspection training for the railroaders that made them ready to test the developed AR inspection software. Figure 28 shows the railroaders while testing the AR inspection software.

Figure 30. Railroaders is testing AR inspection software after receiving the training.

c. Albuquerque's rail runner meeting

The meeting with Albuquerque's rail runner team held at their office, and UNM's research team presented the latest AR software developed for railroad inspection. During this meeting, the rail runner asked many questions about the AR software developed for railroad inspection. More importantly, they wanted to know how AR could benefit rail track inspection and the research team replied to all their questions and concerns. In the end, they found AR as a practical tool that would find its place in inspection automation in the future. In addition, the rail runner management provided some valuable feedback that research team would use for their future research work on the app. The feedback included:

1. Improving the saving and documentation process during the inspection using AR.
2. Combination of AR and drone to enable the inspectors to check out-of-reach distances.
3. Applying AR to improve the inspector's safety.

Additionally, the interaction with the rail-runner provided the opportunity for the research team to take youngsters to the railroad field to familiarize them with this industry and the steps that expert railroaders take to keep the train travels safe. Figure 29 shows the New Mexico juveniles at Albuquerque's train station under supervision of rail runner.

Figure 31. Youngsters learning about the railroad inspection, Albuquerque, NM.

d. Second CN visit at Chicago

The research team met with expert railroaders in the CN office in Chicago in Jun 2021. During that meeting, the CN employees asked to see more updates on AR software developed for railroad inspection. Therefore, the research team scheduled an appointment with CN employees to present the latest AR software updates and had their opinion to improve the applicability of the AR software. The research team went to the CN office in Chicago again in late May 2022. During that meeting, the research team talked about the new features added to the AR software, which upgrades the applicability of that software for railroad inspection. In addition, the research team found the chance to evaluate the AR-developed software in Chicago. Figure 30 shows the research team in the CN office.

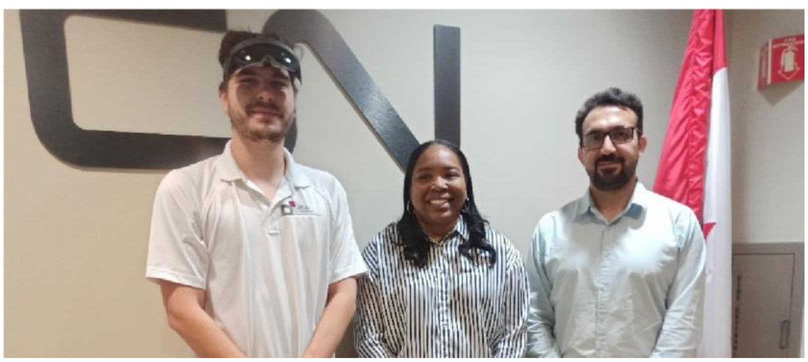


Figure 32. Meeting with CN headquarters, Chicago, Illinois.

e. Union Pacific Bridge Inspection in Kansas City

The AR apps were tested during the inspection of Union Pacific bridge (Figure 30a) on September 6, 2022, in Kansas City. The experiment targeted evaluating the value of AR in a real bridge environment with concrete, also in tunnel inspections with limited light. Figure 31(b) demonstrates the effort made by the research group to apply the eye-tracking AR app to enhance the cognition of inspectors during a real railway bridge inspection using the data of inspection coverage and missing parts. Figure 31(c) shows that the researchers are evaluating the concrete crack characterization app using the crack on the railroad bridge.

(a)

(b)

(c)

Figure 33. The experiment with the AR apps on the Union Pacific railroad bridge (a) the image of the bridge (b) eye- tracking (c) the inspectors.

The concrete crack experiments showed that AR had the potential to quantify the concrete cracks during railway tunnel inspections in poor lighting conditions. However, the inspector vision of the AR app is unclear in direct sunlight that can be a ground for further exploration of that AR tool. The test of eye-tracking app showed that the app detected the parts of the railway that are missing during the inspection.

f. Industry Validation with Japanese Central Railway (JRC) Company

On February 23rd, 2022, the research group hosted the chief executive and the regional sale executive of JRC company at a one-day workshop called "The Railroad of the Future." This event included two parts: (1) the introduction of the AR apps to the visitors in the morning, and (2) conducting laboratory experiment with the visitors in the afternoon.

Figure 32 shows the first session of the workshop held in a conference room at UNM's Centennial Engineering Center. The presentations in the first session included the following five discussions: (1) Augmented Reality Tools for Dynamic Experiments and Robotics Applications; (2) Human Machine-interface of New Technologies and the Railroad; (3) New Bridge Inspection and Monitoring Using Human-Machine Interface; (4) Application of RGB-D Camera in Structure's Inspection; and (5) Augmented Reality Training Opportunities.

Figure 34. First session of the workshop.

Figure 33 shows the second session of the workshop, the demonstration phase. The demonstration in the workshop included:

1. Elijah Wyckoff presented collaborative robot operation with AR-sensors integration (Figure 33(a)) and AR interface for monitoring vibrations and other measurement.
2. Mahsa Sanei demonstrated the RGB-D camera (Figure 33(b)).
3. Kaveh Malek demonstrated crack detection and other AR technology related to railroad applications (Figure 33(c)).
4. Ali Khorasani demonstrated AR technology related to finding fatigue crack on railroad tracks (Figure 33(d)).
5. Saiqa Mustari Susmita presented on implementation of eye gazing feature with AR based inspection of critical infrastructures (Figure 33(e)).
6. John Wesley Hanson exhibited the rail track measurement method with AR (Figure 33(f)).

(a) (b) (c)

(d) (e) (f)

Figure 35. Second session of the workshop demonstration of (a) ROBOT operation with AR and sensors (b) RGB-D camera (c) AR app for concrete crack (d) AR app for fatigue crack detection (e) implementation of eye gazing AR feature (f) AR measuring app.

TASK #7: Adaptation and User Interface with the Railroad

In this task, the research team ran an experiment with the collaboration of expert railroaders at the AREMA 2022 Conference & Expo in Denver. In this experiment, the research group's goal was to understand receptiveness to using AR in the field of railroad inspection. Students in the research group provided surveys, AR training, and measuring tasks (using the tape measure and AR). The steps of the experiment and the collected results are described in this task.

AR software testing and training with experts - Experiment

After the research team presented the work done in this project, several of the attendees showed their interested in testing AR measuring software and offered their contribution to the experiment. For the experiment, the research team provided a survey inquiring into the participant's perception of using tape measures versus AR in railroad inspection measurements. This survey asked the participants to score their tendency to use tape measures or AR providing 6 questions (Score of 1-5: 1 means the lowest tendency and 5 means the highest). This form is attached in Appendix B of the present report. The research group also asked participants to sign an AR consent form and researchers' permission form to use the experiment results for scientific purposes (both forms are attached in the Appendix B of this report). The researchers asked the participants to complete the questionnaire once before starting the test secondly fill out the same questionnaire before getting any experience utilizing AR for measurement.

Tape measure experiment

In this part of the test, the research team asked participants to measure a specific distance using the tape measure. All the participants measured the length and reported the rough result. The measuring distance was a diagonal line started from the wall to corner of the table. The participants had to measure this distance alone using the tape measure and were not allowed to ask others help. They understood that although measuring by tape measure seems easy, it could be challenging at the diagonal-spatial distances beyond the tape's length. Also, the accuracy of using the tape measure on this situation could go under question and may take longer than expected. Figure 34 shows one of the participants using the tape measure.

Figure 36. One of the experiment's participants measuring the diagonal-spatial distance using the tape measure.

AR training

Each student was provided a private AR measurement training using HL2 for the participants. The research team first ran the measuring software in HL2 and provided the local host interface for the trainee using the laptop. Therefore, the research team member could monitor what the student was doing on a separate laptop screen. By doing some sample measurements, the researchers taught the participants how to easily apply this software to measurements. The researchers provided more information, such as how to clear the measurements, how to change the measuring unites or how to take photos or videos of the measuring procedure or results for documentation. Figure 35 shows the training setup and sample measurement result using HL2.

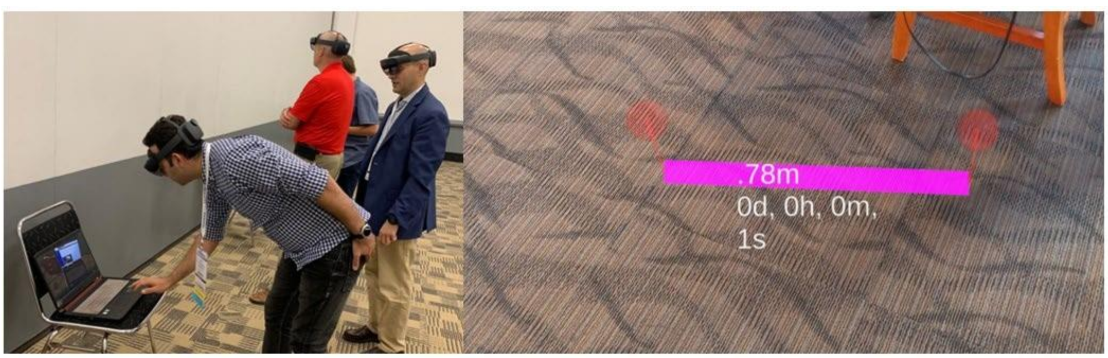


Figure 37. Training setup and sample measurement result using AR.

AR for measurements

The research team then asked the participants to put on the HL2 and first try a sample measurement. Thus, the research group ensured that the participant learned how to use AR measuring software and that s/he was ready to make any measurements. In the next step, the researchers asked the participants to measure the same diagonal spatial distance they were trying to use a tape measure to measure. The main impetus behind this test was not only to remind the trainee's tape measure limitations but also to measure the change in their tendency to use a tape measure and AR. As a result, most participants could quickly and accurately measure the same distance using AR. Figure 36 shows the participant AR measurement using HL2.

Figure 38. Participants used AR for measurements after training.

Post experiment

At this point, the participants had gained experience using AR for measurements and experienced the differences between AR and tape measuring. The research team asked them to fill out the questionnaire again, and this time the attendees tended to reply to the same questions differently. The following section shows the experiment result; however, the research team plans to conduct more experiments with the help of experienced rail roaders and would publish the results in the scientific railroad journals. The participants provided AR observations and ideas after the experiment which could shed light on the future research path.

Experiment result and discussion

20 individuals participated in this study. Most of the participants were experienced engineers in the field. They first filled out a survey regarding their perceptions about safety issues when using tape measures and HoloLens to complete measuring tasks (such as measuring distance on the floor, giving attention to the measurement while measuring, contact with what was being measured, measuring vertical distance, and measuring distance 10 feet from the floor; the survey items are listed below):

Q1. Concern about measuring distances in the floor and safety? (1 lowest – 5 highest)
Q2. Concern about safety when attention to the measurement? (1 lowest – 5 highest)
Q3. Is contact with what is being measure a concern? (1 lowest – 5 highest)
Q4. Is measuring vertical distances of concern? (1 lowest – 5 highest)
Q5. Is measuring distance 10 ft from the floor a concern? (1 lowest – 5 highest)

After filling out the survey regarding their perception, the participants used a tape measure to conduct some measuring tasks (including distance from the ground, vertical distance from the floor, and horizontal distance 10 ft above the ground). Then, they completed the same task using the HoloLens. A HoloLens expert helped and trained the participants to operate the HoloLens during the measurement tasks. After the measuring activity, the participants filled out the same survey again. Four sets of data were collected per participant: (1) their perception of safety concerns of tape measure *before* a measuring task using a tap measure, (2) their perception of safety concerns of HoloLens *before* a measuring task using HoloLens; (3) their perception of safety concerns of tape measure *after* a measuring task using a tap measure; (4) their perception of safety concerns of HoloLens *after* a measuring task using HoloLens.

A set of repeated measure ANOVAs were conducted to compare the differences of participants perceptions of safety concerns between using tape measures and HoloLens. First, we compared the statistics between the pre-activity perceptions of tape measures and HoloLens. Participants' perception of safety concerns between using tape measures and HoloLens were between 1.84 and 3.05 (showing they had low to medium safety concerns no matter they used a tape measure or HoloLens), and the safety concerns difference between tape measures were insignificant. The results showed that before the participants experienced using tape measures and HoloLens, they had thought that both methods were equally safe. The team compared the statistics between the post-activity perceptions of tape measures and HoloLens. The results are depicted in the following Figure 37.

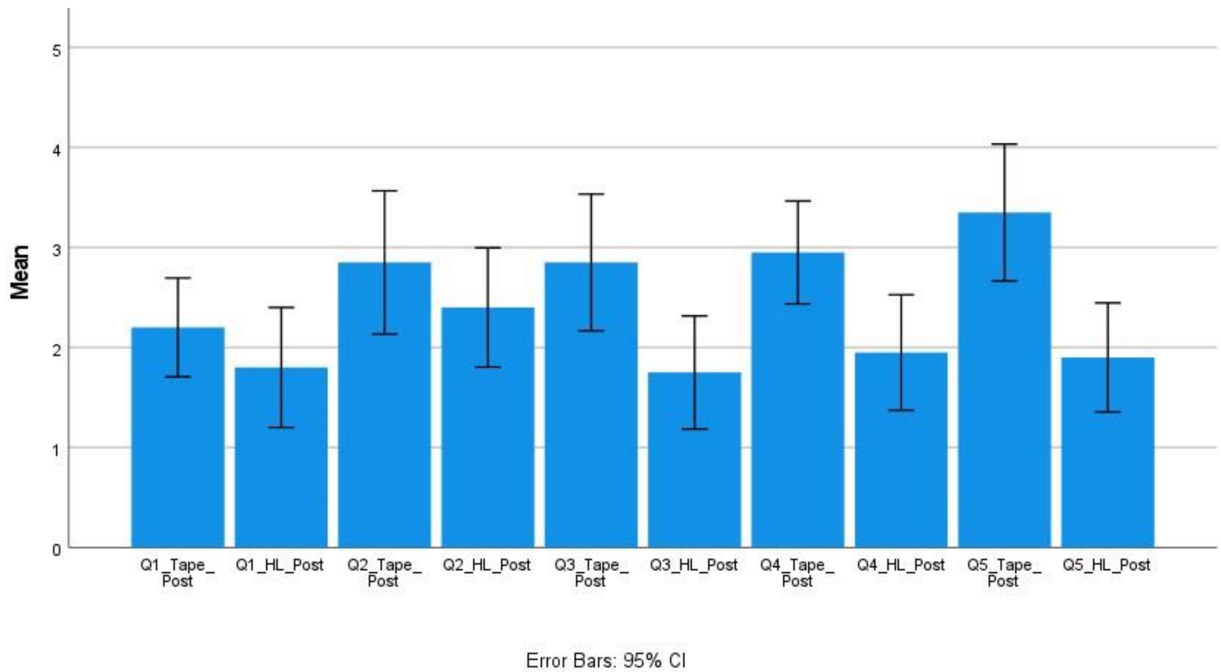


Figure 39. Mean perception scores of the safety concerns between tape and HoloLens.

The vertical axe in figure 37 shows the participants' safety concern level while measuring in the inspection field. The vertical axe is a score between 1 and 5, with 1 representing the lowest concern and 5 representing the highest level of concern. Also, each bar represents the mean value of all participants' concerns regarding each question. Each pair of bars is related to one question of the questionnaire. The left bar represents the mean value of the safety concern of the relevant question after using tape for the experiment (before utilizing the HL), and the right one shows the amount of safety concern after using the HL for the same measuring task. For example, the first two bars are relevant to the first question (Q1) after using the tape measure and before utilizing HL. Comparing those two adjacent bars shows that the participants' safety concerns decreased from higher than 2 to less than 2. However, both the bars show the participants' relative low safety concerns (2.2 and 1.8 out of 5). Its acquirable that using HL decreased their safety concern. The decrease of the safety concern is more intangible in question 5, which is related to the measurements higher than 10 ft. Finally, even bars are related to the post tape experiment result and even bars represent post HL experiment results.

The results found that the participants did not find HoloLens as a significantly safer tool compared to tape measures in general (as seen in Q1 and Q2). However, the participants found that HoloLens was a significantly safer tool in situations where there was contact with what was being measured, measuring vertical distance, and measuring distance 10 ft from the floor. When the participants were prompted to some specific tasks (especially ones that are more difficult to measure), they prefer HoloLens over tape measures. Although our sample size is relatively small, we still found significant differences between the perception of safety using tape measures comparing to safety using HoloLens. Therefore, we conclude that AR tools such as HoloLens have a strong potential to improve workplace safety in the context of bridge inspection.

FUTURE DIRECTIONS

During the in-person meeting with expert railroaders, the research team provided a demonstration of the applicability of AR to enhance railroad inspection accuracy and speed. The experts had ideas and raised suggestions and concerns in response to the AR inspection. This part of the report is devoted to describing the expert railroader's perspective and the future direction the research team could take to advance AR inspection technology and satisfy the needs of railroad inspectors in this area.

The research team found that the railroad managers and experienced railroaders have four major concerns outlined in Figure 38. The railroaders were worried about the inspector's safety during the rail track inspection and were suspicious of the reliability of the AR inspection results. Based on the experience obtained from the in-person meetings and presentations, the research team became able to categorize their concerns into five area.

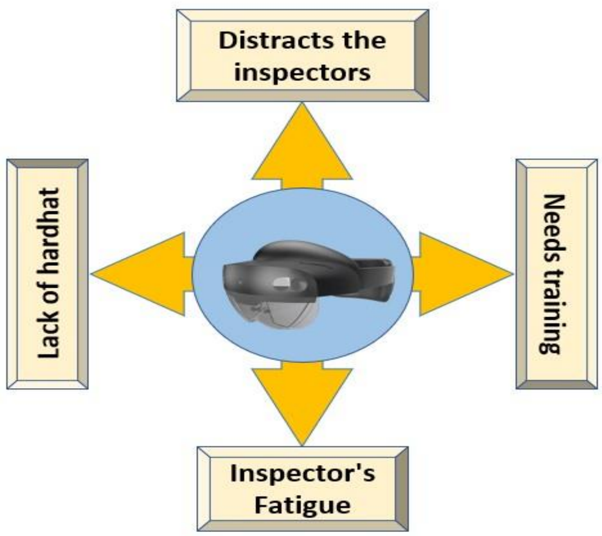


Figure 40. Main railroader's concerns related to AR inspection.

1. First concern: AR could distract the inspectors during the railroad inspection.

Some of the experienced railroaders were worried about the distraction that AR could cause to inspectors during their inspection. They believe that distraction could endanger the inspector's health during the inspection, and as a result AR could decrease the safety of the inspectors.

The research team mentioned the benefits of using AR during the visual inspection, like providing real-time information and connection with the management team. In response to the specific concern with distraction, the research group proposed to develop a safety alarm smart system to automatically alarm the inspectors while they are getting into a dangerous situation.

2. Second concern: Lack of hardhat.

Another safety concerns mentioned by the expert railroaders is the possibility of using both a hardhat and Head Mounted Devices (HMDs) during the inspection. The research team noted that the Trimble HoloLens (Figure 39) could solve this problem completely. As a future research direction, the UNM team can develop and deploy AR software in a Trimble and evaluate its applicability in railroad inspection.

Figure 41. Trimble (HL2 attached to a hardhat to satisfy the safety concerns) [22].

3. Third concern: Fatigue.

Moreover, the inspector's fatigue due to the use of AR during the inspection was a concern of the railroad experts. However, the research team showed that the AR software could decrease the burden of some inspection tasks. For instance, the AR measuring software could help the inspector measure any distance without bending over and carrying a tape measure. Also, using this software leaves the inspector's hands-free to do or carry the other stuff.

4. Fourth concern: Training.

The fourth concern is that the application of AR for the inspection requires training, which can be considered as a future direction. The research team can schedule training sessions for the inspectors to completely describe the usage of HMDs during their visual inspection for every goal. Also, the research team can provide training materials such as videos, virtual classes, or AR inspection manuals to help in this regard.

5. Fifth concern: Accurately evaluating the rail track displacement after train crossing event.

The railroaders always need to ensure that the rail track keeps its original position or stays in the standard displacement limitations after a train crossing event. Therefore, they use track geometric cars to inspect the railroad's tolerance. However, these cars help check rail displacement; the inspectors inside the vehicle have no vision of the track. Figure 40 shows the place that needs to inspect after a train crossing event carefully.

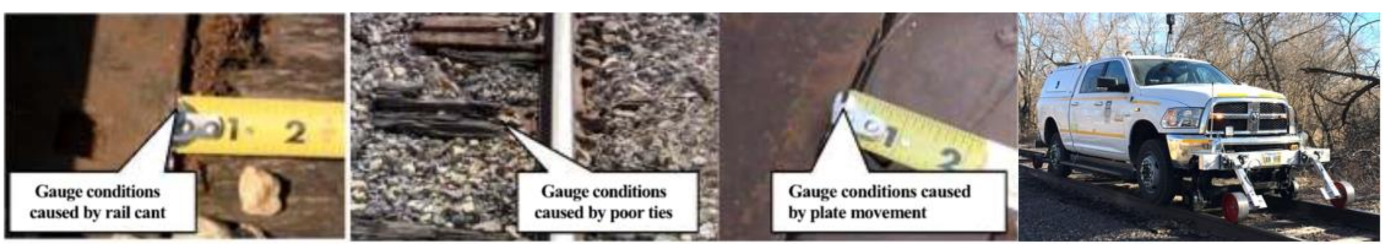


Figure 42. Track displacement checks and geometric car.

Overall, the research team received valuable feedback to apply to AR development. Those feedbacks are from the railroad expert managers whose primary concern was to find or develop AR inspection methods to bring the AR railroad inspection application into practice. The research team agreed that the future investigation should reflect the current limitations on these factors and apply it for future developments. The following steps could lighten the future path of this research taken from experts' concerns.

a. Providing smart AR alarm system to improve the inspector's safety during the inspection.

b. Evaluate the applicability of using AR in the inspection under different temperatures and humidity. Addressing its working temperature limitations. Also, provide a mechanism to show the weathering condition to the inspectors in real-time.

c. Evaluate the AR ergonomics along-side other safety equipment (PPE) utilized during the inspection.

d. Providing AR inspection training sessions and materials for the inspectors.

e. Improving the accuracy and features of the developed AR inspection software based on the needs understood during the meeting with experts.

f. Developing AR software and provide creative solutions for AR inspection such as robots for inspection situations that are hard to reach for humans.

g. Addressing the blur vision of AR headset under direct sunlight by exploring the illumination aspects of the apps.

h. Evaluating different approaches to developing concrete crack measurement tool for addressing railroad inspectors concerning concrete cracks.

i. Increasing the measurement resolution of the concrete crack app for measurement from far distances for example by integrating a higher quality camera into the AR headset hardware.

j. The research team could implement AR software to help the inspectors to make sure that the railroad displacement stays within the standard limitations after the train crossing event. Figure 41 schematically shows the proposed idea of the research team.

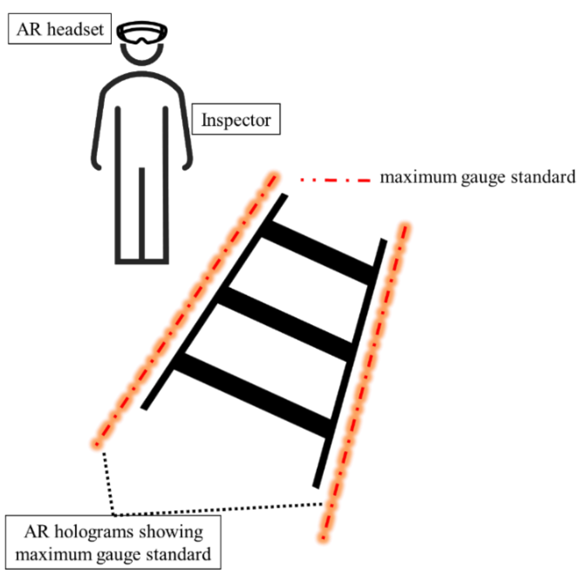


Figure 43. The research team's idea for the future AR track displacement inspection.

The research team is optimistic about the opportunity to pursue the AR inspection research. Also, they will update the currently developed software based on the deep understanding of railroad inspection's needs. The updating ideas obtained from meeting with domestic and international expert railroaders.

PRESENTATIONS, CONFERENCES AND PUBLICATIONS:

September 2021 _ 2nd ARMOR SMILab Symposium _ San Diego, California

The 2nd ARMOR /SMILab symposium was held under the conference "Mechanistic Machine Learning and Digital Twins for Computational Science, Engineering & Technology (MMLDT-CSET 2021)" at the University of California at San Diego. The research team presented the results of this research under the title "HumanMachine Interface Using Augmented Reality" (Figure 42). The audience was over 40 people. The main feedback was the scientific community's optimistic perspective of AR as a practical tool for railroad inspections.

Figure 44. MMLDT-CSET 2021 presentation in San Diego, (September 2021.)

January 2022 _ TRB Annual Meeting _ Washington, DC

The tall "New Bridge Inspection and Monitoring Using Human-Machine Interface" was presented at the bridge management committee of the Annual Meeting of the Transportation Research Board, January 9-13, 2022, Washington DC, US (Figure 43). The audience was over 70 people, and their main interests were on the actual interest of the railroad in the use of AR for inspections, in contrast with other transportation industries, which are currently interested in AR but have not yet tested in the field.

Figure 45. TRB 2022 presentation in Washington, DC (January 2022.)

June 2022 _ Scientific community presentation _ Orlando, Florida

The research team also had the chance to present the applicability of AR in railroad inspection to the scientific community at the 8th World Conference on Structural Control and Monitoring (8WCSCM) at the University of Central Florida (UCF) in June 2022. Many researchers and scientists joined that meeting to present their latest achievements regarding Structural Health Monitoring (SHM) and maintenance. The UNM team also presented the articles submitted to the conference about the developed AR inspection software. An in-person presentation for the people working at the edge of SHM technology was a unique experience for the research group. The idea and questions from other domestic and international SHM experts ignited newborn ideas in the research team to upgrade the AR inspection software developed. The future directions part of this report talks comprehensively about those ideas. Figure 44 shows photos of the conference.

Figure 46. 8WCSCM conference at Orlando, Florida (June 5-8th 2022).

August 2022 _ AREMA 2022 Conference and Expo _ Denver, Colorado

AREMA 2022 Conference & Expo in Denver (Aug 26-Aug31, 2022) was an excellent opportunity for the research team to meet expert railroaders and to test and present the augmented reality software developed by them. The attendees of this event were mostly experienced people in the railroad community or companies related to this billion-dollar industry.

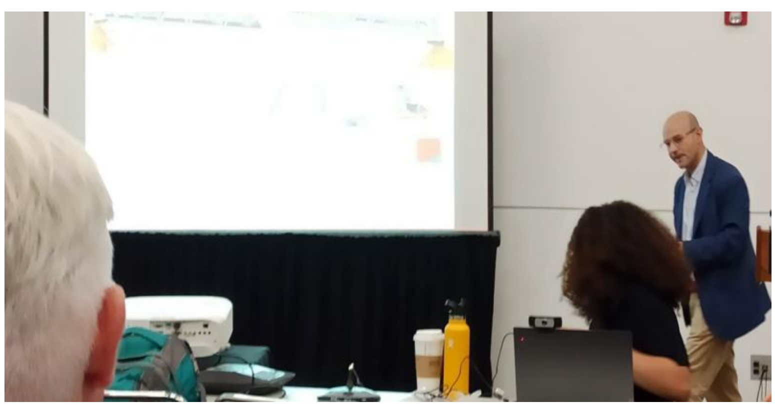


Figure 47. PI's presentation in AREMA 2022, Denver, Colorado.

This conference was a great opportunity for the research team to introduce the AR developed software to the railroad experienced people and experts. The research team planned an AR experiment using the AR measuring app for the experts. By doing so, the research group could not only measure their intent to use AR in the railroad inspection for measurements only but also provided an AR training opportunity for the railroaders. In the first step, the PI presented to the attendees the AR software developed in this group and asked them to join our experiment if they were interested. Figure 45 shows the PI's presenting for the experts at AREMA 2022 conference.

Publications

The two following papers have been published so far in which the authors very appreciated the support of TRB for providing grant for their projects:

(1) Realtime conversion of cracks from pixel to engineering scale using Augmented Reality [23]

(2) Augmented Reality: Existing and Future Opportunities [24]

REFERENCES

[1] W. Wang, A. Zhang, K. C. P. Wang, A. F. Braham, and S. Qiu, "Pavement Crack Width Measurement Based on Laplace's Equation for Continuity and Unambiguity," *Computer-Aided Civil and Infrastructure Engineering*, vol. 33, no. 2, pp. 110–123, 2018, doi: 10.1111/mice.12319.

[2] R. S. Adhikari, O. Moselhi, and A. Bagchi, "Image-based retrieval of concrete crack properties for bridge inspection," *Automation in Construction*, vol. 39, pp. 180–194, Apr. 2014, doi: 10.1016/j.autcon.2013.06.011.

[3] J. F. Unsworth, *Design of Modern Steel Railway Bridges*. Boca Raton: CRC Press, 2010. doi: 10.1201/9781420082180.

[4] F. Moreu and J. M. LaFave, "Current Research Topics: Railroad Bridges and Structural Engineering," *Newmark Structural Engineering Laboratory Report Series 032*, Oct. 2012, Accessed: Feb. 27, 2023. [Online]. Available: https://hdl.handle.net/2142/34749

[5] American Railway Engineering and Maintenance-of-Way Association, Ed., *AREMA bridge inspection handbook*. Lanham, MD: American Railway Engineering and Maintenance-of-Way Association, 2008.

[6] E. Karaaslan, U. Bagci, and F. N. Catbas, "Artificial Intelligence Assisted Infrastructure Assessment using Mixed Reality Systems," *Transportation Research Record*, vol. 2673, no. 12, pp. 413–424, Dec. 2019, doi: 10.1177/0361198119839988.

[7] K. Krafka *et al.*, "Eye Tracking for Everyone." arXiv, Jun. 18, 2016. doi: 10.48550/arXiv.1606.05814.

[8] M. K. Tanenhaus and M. J. Spivey-Knowlton, "Eye-Tracking," *Language and Cognitive Processes*, vol. 11, no. 6, pp. 583–588, Dec. 1996, doi: 10.1080/016909696386971.

[9] H. Singh, "Human Eye Tracking and Related Issues: A Review," *International Journal of Scientific and Research Publications*, vol. 2, pp. 1–9, Sep. 2012.

[10] D. Ungureanu *et al.*, "HoloLens 2 Research Mode as a Tool for Computer Vision Research." arXiv, Aug. 25, 2020. doi: 10.48550/arXiv.2008.11239.

[11] "Microsoft HoloLens | Mixed Reality Technology for Business." https://www.microsoft.com/en-us/hololens (accessed Feb. 27, 2023).

[12] J. Xu, E. Wyckoff, J.-W. Hanson, F. Moreu, and D. Doyle, "Implementing augmented reality technology to measure structural changes across time." arXiv, Nov. 03, 2021. doi: 10.48550/arXiv.2111.02555.

[13] E. Wyckoff, M. Ball, and F. Moreu, "Real-Time Human Cognition of Nearby Vibrations Using Augmented Reality," in *Dynamics of Civil Structures, Volume 2*, Cham, 2022, pp. 139–145. doi: 10.1007/978-3-030-77143-0_14.

[14] D. H. Shin and P. S. Dunston, "Evaluation of Augmented Reality in steel column inspection," *Automation in Construction*, vol. 18, no. 2, pp. 118–129, Mar. 2009, doi: 10.1016/j.autcon.2008.05.007.

[15] M. F. Agüero Injante, "VISUALIZATION OF REAL-TIME DISPLACEMENT TIME HISTORY SUPERIMPOSED WITH DYNAMIC EXPERIMENTS USING WIRELESS SMART SENSORS AND AUGMENTED REALITY," *Civil Engineering ETDs*, Dec. 2020, [Online]. Available: https://digitalrepository.unm.edu/ce_etds/252

[16] M. Hossain, J.-W. Hanson, and F. Moreu, "Real-Time Theoretical and Experimental Dynamic Mode Shapes for Structural Analysis Using Augmented Reality," in *Topics in Modal Analysis & Testing, Volume 8*, Cham, 2021, pp. 351–356. doi: 10.1007/978-3-030-47717-2_36.

[17] K. Malek, A. Mohammadkhorasani, and F. Moreu, "Methodology to integrate augmented reality and pattern recognition for crack detection," *Computer-Aided Civil and Infrastructure Engineering*, vol. n/a, no. n/a, doi: 10.1111/mice.12932.

[18] F. Moreu and K. Malek, "Bridge Cracks Monitoring: Detection, Measurement, and Comparison using Augmented Reality," *Transportation Consortium of South-Central States*, Aug. 2021, [Online]. Available: https://digitalcommons.lsu.edu/transet_pubs/125

[19] Y.-F. Liu, X. Nie, J.-S. Fan, and X.-G. Liu, "Image-based crack assessment of bridge piers using unmanned aerial vehicles and three-dimensional scene reconstruction," *Computer-Aided Civil and Infrastructure Engineering*, vol. 35, no. 5, pp. 511–529, 2020, doi: 10.1111/mice.12501.

[20] R. Mojidra, J. Li, A. Mohammadkhorasani, F. Moreu, C. Bennett, and W. Collins, “Vision-based fatigue crack detection using global motion compensation and video feature tracking,” *Earthq. Eng. Eng. Vib.*, Jan. 2023, doi: 10.1007/s11803-023-2156-1.
[21] “Google Maps,” *Google Maps*. https://www.google.com/maps (accessed Feb. 27, 2023).
[22] https://cornershop-immersion.com/en/ar-headsets/32-trimble-xr10-headset-microsoft-hololens-2.html
[23] K. Malek and F. Moreu, “Realtime conversion of cracks from pixel to engineering scale using Augmented Reality,” *Automation in Construction*, vol. 143, p. 104542, Nov. 2022, doi: 10.1016/j.autcon.2022.104542.
[24] F. Moreu, K. Malek, E. Wyckoff, and A. Mohammadkhorasani, “Augmented Reality: Existing Capabilities and Future Opportunities,” *TR News*, no. 340, Jul. 2022, Accessed: Sep. 12, 2022. [Online]. Available: https://trid.trb.org/view/2015255

APPENDIXES

Appendix A

I. BACKGROUND

Objective of this survey: What are the main aspects of railroad operations related to inspections that can be improved with new technologies?

Population: Railroad employees (field inspectors, track inspectors, bridge crew, rail, maintenance, etc.)

Background: We propose building an Augmented Reality (AR) technology that imparts higher situational awareness to human operators to support more enhanced decision making. This research will focus on the means and methods in AR headsets that increase situational awareness in dispatch, locomotive, and railroad environments. The proposed AR research will initially identify the ability of AR to increase human-machine interfaces while increasing safety. This collaboration will demonstrate the railroad technology in laboratory settings to receive feedback on railroad environments' validity.

II. GENERAL RAILROAD QUESTIONS

1. What is your role in the railroad industry?

a) Field inspectors
b) Track inspectors
c) Bridge crew
d) Rail
e) Mechanical
f) Signals
g) Maintenance
h) Others, please specify ___________________________________

2. What are your major safety concerns in your daily work for the railroad in your job? (1: not a frequent concern in my daily job; 5: a significant concern in my daily job)

a) Train conductor negligence
b) Train derailment
c) Improper maintenance of the tracks will cause unsafe situations
d) Cars, locomotives, traffic are my most serious concern about safety on my job
e) Faulty equipment (mechanical or any equipment)
f) Collision with another train, with car, bus, or truck trying to cross-train tracks
g) Bridge safety, structural safety
h) Tools mishandling myself or others near me
i) Tripping hazards
j) Spills (chemical) on the tracks or near the tracks
k) Faulty train crossings
l) Others (Please State, add more lines if needed)

i. ____
ii. ____
iii. ____

3. In your opinion, what are the leading causes of train accidents? (1: not a significant cause; 5: major cause and should be prioritized)

a) Human Error

  i. Engineer distraction
  ii. Excessive speed
  iii. Failure to timely brake

b) Lack of Signals

c) Lack of Money (Please state the areas needed more money) ______________________

d) Track and Roadbed Malfunctions

e) Mechanical Failure

f) Others (Please State, add more lines if needed)

i. ____

ii. ____

iii. ____

4. Which function do you think is most helpful to make the railroad industry safer? (1: not helpful at all; 5: very helpful)

a) A reminder of obstacles when you walk and work

b) A reminder when you are distracted

c) A highlight of the rails or other railroad like track elements

d) A virtual display of train information (distance, velocity, etc.) to inform humans

e) Crew safety with partners' views. Someone near you to protect you

f) Sound signals

g) Visual signals

h) Others (Please State, add more lines if needed)

i. ____

ii. ____

iii. ____

III. SOFTWARE EXPECTATIONS

5. Have you tried a Virtual Reality (VR) training system?

a) Yes, very frequently. Specify the VR system you ever used_________________________

b) Once or twice and quit. Reason______________________________

c) Never tried

6. Have you tried an Augmented Reality (AR) headset (wearable devices)?

a) Yes, very frequently. Specify the AR system you ever used__________________________

b) Once or twice and quit. Reason_______________________________

c) Never tried

7. Rate the barriers for field adoption of AR headsets (1: not a barrier; 5: severe barrier)

a) Comfort/Weight

b) Complex interface, I would never learn how to use it

c) Too fragile and not suitable for outdoors

d) management indicates the equipment is too costly to use even if it is useful at times
e) Safety while wearing it with real dangers (tripping hazards)
f) "False positive" messages
g) Others (Please State, add more lines if needed)
i. ____
ii. ____
iii. ____

8. AR Railroad Safety is in the concept phase for now. Any feedback and suggestion are welcomed and valued!
a) Suggestion 1: _____________________________________
b) Suggestion 2: _____________________________________

IV. FUTURE INTERACTION TO DEVELOP A USEFUL TOOL FOR YOU

9. How would you like to interact with us in the future (Circle the one that best work for you. You can choose more than one)
a) Zoom conference (live) and we share screen, and you observe and tell us what you think
b) We record a video, and you look at it at your own time, and later we call you, and you tell us what you think
c) We record a video, you look at it at your own time, and you fill up a survey about that video that you email us
d) Any other suggestion: ________________________________

10. Are you interested in participating in the first experiment to test your interests in "Human-Machine Interfaces of New Technologies and the Railroad"? The experiments are going to take place in the next couple of months. It will take you about 30 minutes.
a) Yes
b) No, I am not interested
c) Only under these circumstances: _____________________________

11. Are you interested in participating in the alpha version experiments after the development of the AR Railroad Safety application? The experiments are going to take place during March-April 2021.
a) Yes
b) Only if you develop the ____________________function/s (as listed in Question 4)
c) I want, but the schedule does not work for me
d) No, I am not interested

12. Are you interested in participating in the beta version field experiments of the AR Railroad Safety application? The field experiments are going to take place during May-July 2021.
a) Yes
b) Only if you develop the ____________________function/s (as listed in Question 4)
c) I want, but the schedule does not work for me
d) No, I am not interested

Appendix B

1. Visitor Feedback Survey

I BACKGROUND

Objective of this survey: What are the main aspects of railroad bridge operations related to inspections that can be improved with new technologies?
Population: Railroad engineers, railroad leaders, and other railroad professionals (field inspectors, track inspectors, bridge crew, rail, maintenance, etc.)

Background: We presented several tools developed based Augmented Reality (AR) technology that imparts higher situational awareness to human operators to support more enhanced decision making. This research will focus on the means and methods in AR headsets that increase situational awareness in railroad bridge environments. The proposed AR research will initially identify the ability of AR to increase human-machine interfaces while increasing safety. This collaboration will demonstrate the railroad technology in laboratory settings to receive feedback on railroad environments' validity.

II GENERAL RAILROAD QUESTIONS

1. What is your role in the railroad industry?

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   d) Rail
   e) Mechanical
   f) Signals
   g) Maintenance
   h) Others, please specify ___________________________________

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   b) Train derailment
   c) Improper maintenance of the tracks will cause unsafe situations
   d) Cars, locomotives, traffic are my most serious concern about safety on my job
   e) Faulty equipment (mechanical or any equipment)
   f) Collision with another train, with car, bus, or truck trying to cross-train tracks
   g) Bridge safety, structural safety
   h) Tools mishandling myself or others near me
   i) Tripping hazards
   j) Spills (chemical) on the tracks or near the tracks
   k) Faulty train crossings
   l) Others (Please State, add more lines if needed)
      i. ____
      ii. ____
      iii. ____

3. In your opinion, what are the leading causes of train accidents? (1: not a significant cause; 5: major cause and should be prioritized)

   a) Human Error
   b) Engineer distraction
   c) Excessive speed
   d) Failure to timely brake
   e) Lack of signals
   f) Lack of money (Please state the areas needed more money) ______________________
   g) Track and Roadbed Malfunctions
   h) Mechanical Failure
   i) Others (Please State, add more lines if needed)
      i. ____
      ii. ____
      iii. ____

4. Which function do you think is most helpful to make the railroad industry safer? (1: not helpful at all; 5: very helpful)

   a) A reminder of obstacles when you walk and work
   b) A reminder when you are distracted
   c) A highlight of the rails or other railroad like track elements
   d) A virtual display of train information (distance, velocity, etc.) to inform humans
   e) Crew safety with partners' views. Someone near you to protect you
   f) Sound signals
   g) Visual signals
   h) Others (Please State, add more lines if needed)
      i. ____
      ii. ____
      iii. ____

III AR TOOL EVALUATION

Table 1: AR technology evaluation for railroad industry

	Strongly Disagree 1	2	3	4	Strongly Agree 5	Comment to Improve This Aspect
Current AR headsets are potentially an effective tool for enhancing railroad operations and railroad infrastructure						
Future generations of AR headsets have the potential to play a significant role to transform the railroad operations and improve railroad infrastructure						
Communicative capabilities of AR headsets can improve communication and data sharing within railroad workforce in the field						
Handsfree mobility and wireless capabilities of AR headsets can facilitate the use of information technology (IT) for bridge operations						
AR can improve safety of railroad infrastructure and railroad operations for example by reducing the human error						
AR can increase the speed of railroad inspection						
AR can ease the process of railroad human inspection						
AR technology has the potential to reduce the cost of railroad industry for example by improving the overall condition of railroad inspection						

Table 2: Eye-tracking evaluation for railroad industry

	Strongly Disagree 1	2	3	4	Strongly Agree 5	Comment to Improve this Aspect
Eye-tracking tool can be an effective tool for enhancing railroad operations and railroad infrastructure						
Eye-tracking tool can increase the objectivity of railroad field inspection						
Eye-tracking tool can improve safety of railroad infrastructure and railroad operations for example by reducing the human error						
Eye-tracking tool can increase the speed of railroad inspection						
Eye-tracking tool can ease the process of railroad human inspection						
Eye-tracking tool has the potential to reduce the cost of railroad industry						

Table 3: Measurement tool evaluation for railroad industry

	Strongly Disagree 1	2	3	4	Strongly Agree 5	Comment to Improve this Aspect
Measurement tool can be an effective tool for enhancing railroad operations and railroad infrastructure						
Measurement tool can increase the objectivity of railroad field inspection						
Measurement tool can improve safety of railroad infrastructure and railroad operations for example by reducing the human error						
Measurement tool can increase the speed of railroad inspection						
Measurement tool can ease the process of railroad human inspection						
Measurement tool has the potential to reduce the cost of railroad industry						

Table 4: Microcrack detection tool evaluation for railroad industry

	Strongly Disagree 1	2	3	4	Strongly Agree 5	Comment to Improve this Aspect
Microcrack detection tool can be an effective tool for enhancing railroad operations and railroad infrastructure						
Microcrack detection tool can increase the objectivity of railroad field inspection						
Microcrack detection tool can improve safety of railroad infrastructure and railroad operations for example by reducing the human error						
Microcrack detection tool can increase the speed of railroad inspection						
Microcrack detection tool can ease the process of railroad human inspection						
Microcrack detection tool has the potential to reduce the cost of railroad industry						

Table 5: Concrete crack characterization tool evaluation for railroad industry

	Strongly Disagree 1	2	3	4	Strongly Agree 5	Comment to Improve this Aspect
Concrete crack characterization tool can be an effective tool for enhancing railroad operations and railroad infrastructure						
Concrete crack characterization tool can increase the objectivity of railroad field inspection						
Concrete crack characterization tool can improve safety of railroad infrastructure and railroad operations for example by reducing the human error						
Concrete crack characterization tool can increase the speed of railroad inspection						
Concrete crack characterization tool can ease the process of railroad human inspection						
Microcrack detection tool Concrete crack characterization tool has the potential to reduce the cost of railroad industry						

2. Experiment form

Email: **University of New Mexico**

You are given a 12 ft tape measurer	Pre					Post				
	1	2	3	4	5	1	2	3	4	5
Q1: Concern about measuring distances in the floor and safety? (1 lowest-5 highest)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Q2: Concern about safety when giving attention to the measurement (1 lowest-5 highest)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Q3: Is contact with what is being measured a concern? (1 lowest-5 highest)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Q4: Is measuring vertical distances of concern? (1 lowest-5 highest)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Q5: Is measuring distances 10 ft from the floor a concern (1 lowest-5 highest)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Q6: Please write below, which one do you prefer? Tape measure or Augmented Realty (AR)? (1 lowest-5 highest) Pre: …………………….. & Post:………………………..	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Volunteer's First and Last Name: **Fernando Moreu, P.E, PhD**

Email: **University of New Mexico**

You are given a 12 ft tape measurer	Pre					Post				
	1	2	3	4	5	1	2	3	4	5
Q1: Concern about measuring distances in the floor and safety? (1 lowest-5 highest)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Q2: Concern about safety when giving attention to the measurement (1 lowest-5 highest)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Q3: Is contact with what is being measured a concern? (1 lowest-5 highest)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Q4: Is measuring vertical distances of concern? (1 lowest-5 highest)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Q5: Is measuring distances 10 ft from the floor a concern (1 lowest-5 highest)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Q6: Please write below, which one do you prefer? Tape measure or Augmented Realty (AR)? (1 lowest-5 highest) Pre: …………………….. & Post:………………………..	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

3. Consent form

Aug 2022

Augmenting Reality for Safer Inspections of Railroad Infrastructure and Operations

Consent to Participate in Research

Purpose of the research: You are being asked to participate in a research project conducted by Dr. Fernando Moreu (principal investigator), Dr. Victor Law, and research assistant Saiqa Mustari Susmita, Ali Mohammadkhorasani and Aaron Cowan, from the Department of Civil, Construction, and Environmental Engineering (CCEE) at the University of New Mexico (UNM). This project is funded by the Transportation research Board (TRB). This study aims to use augmented reality (AR) technology to increase railroader safety when conducting field inspections. You are being asked to join because the research requires you to provide your individual opinions about AR technology and railroader safety. You do not need to be familiar with the AR devices before this study.

This consent form contains important information about this project and what to expect if you decide to participate. Please read the information carefully. Feel free to ask questions before making your decision to participate. **Your participation in this research study is totally voluntary**.

What you will do in the project: You are asked to take part in two survey and two interviews.

- In the survey, you are asked to fill in a questionnaire about your expectations of AR technology. The survey will be sent to you by email, and you are asked to send the completed questionnaire back by email. The estimated time to finish the questionnaire is **15 min**.
- In the first interview, you are asked to conduct a field inspection. Two researchers will conduct a shadow interview, ask questions about safety during your inspection, and record a video while doing that. The first interview will be conducted in the inspection field. The duration depends on the inspection time, approximately **0.5~2 hours**. There will be two researchers and one participant in total in the same open area at the same time.
- In the second interview, you will try the AR application designed by the research group with a Microsoft HoloLens 2 device and provide feedback and comments. The second interview will be conducted in the Structural Engineering and Materials Lab. The exact address is 210 University Blvd NE, Albuquerque, NM 87106. The estimated duration of the second interview is **0.5 hours**. There will be one researcher and one participant in total in the same room at the same time.
- You will be asked to complete another survey in which you are asked to fill in a questionnaire about your expectations of AR technology. The survey will be sent to you by email, and you are asked to send the completed questionnaire back by email. The estimated time to finish the questionnaire is **15 min**.

Microsoft HoloLens 2 is a pair of AR glasses developed and manufactured by Microsoft Corporation. The physical pictures of a Microsoft HoloLens 2 device are shown as follows:

Risks: There are minor risks of stress, emotional distress, and inconvenience associated with participating in this research study. Also, minor risks of contracting COVID-19 due to research being conducted in person.

Benefits: There will be no direct benefit from participating in this research. However, it is hoped that the information gained will help improve railroader safety.

Confidentiality of your information: The research data will only be used for research purposes. We will protect all your personal information. Your name will not be used in any published reports about this project. Note that the researchers are not prevented from taking steps, including reporting to authorities, to prevent your or others' serious harm.

Note that you will be asked to take a video recording to explain your safety operations during field inspections. We will try not to record your face during the video recording. If your face were recorded, we would use mosaics to protect your identity.

Data Management and Confidentiality: The research data are collected in both digital and hard copy formats. As soon as the project ends, the personal data will be destroyed. The paper records will be stored in a locked file cabinet in the Center for Advanced Research Computing (CARC). Only the PI (Fernando Moreu) will have the keys to the locker. The electronic records are stored on a password-protected computer. The computer will be in CARC. Identifiers are stored separately from the consent forms and project data. The PI (Fernando Moreu) will take responsibility for the safety of the identifiers. When transferring the data, a secure domain will be used to send the files in encrypted form. After the research is done (Dec 31, 2022), your data can be maintained and used for future research.

The University of New Mexico Institutional Review Board (IRB) oversees human research, and the study sponsor, may be permitted to access your records.

Use of your information for future research: Your information collected for this project will be maintained and used for future research. Any identifiable information like your name will be removed.

Payment: No direct payment is provided.

Right to withdraw from the research: Your participation in this research is entirely voluntary. You can skip any questions if you feel uncomfortable during the survey and interviews. You have the right to withdraw your participation at any point without penalty during the survey and interviews. If you decide to withdraw your participation, all the information regarding you will be destroyed and not used in research.

COVID-19 Protection: If COVID-19 related public health restrictions are reimposed and participants in the study have not completed participation, previous and new guidelines will be followed. At the very least the previous health guidelines will be maintained which include but are not only limited to only you and two researcher (three people in total) in the same lab room during all your stay at the same time. You must wear a mask to meet current UNM guidelines. Also, social distancing, of 6 feet, must be followed when possible. We will also provide deposable masks before you enter the lab. You will be asked to sterilize your hands with nowash alcohol hand sanitizer and measure your forehead temperature before entering the lab. The devices will be sterilized with alcohol wipes after each participant's use. You will be asked to wear disposable gloves to operate the devices. We will constantly contact the lab manager to ensure the lab is safe during the COVID to conduct research and follow all the lab directions.
If you have any questions, concerns, or complaints about the research, please contact:

If you have questions regarding your rights as a research participant or about what you should do in case of any harm to you, or if you want to obtain information or offer input, please contact the IRB. IRB is a group of people from UNM and the community who provide independent oversight of safety and ethical issues related to research involving people:

CONSENT

You are deciding whether to participate in this research. Your signature below indicates that you have read this form (or the form was read to you), and all questions have been answered to your satisfaction. By signing this consent form, you will not waive any of your legal rights as a research participant. A copy of this consent form will be provided to you.

I agree to participate in this research.

________________________________ ____

Name of Adult Participant Signature of Adult Participant Date

Researcher Signature (to be completed at the time of informed consent)

I have explained the research to you and answered all of your questions. I believe that you understand the information described in this consent form and freely consents to participate.

________________________________ ____

Name of Research Team Member Signature of Research Team Member Date

Contact: **Fernando Moreu**, Ph.D., P.E.
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