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HUMAN-INFRASTRUCTURE INTERFACES (HII) ENABLED USING AUGMENTED REALITY (AR)

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HUMAN-INFRASTRUCTURE INTERFACES (HII) ENABLED USING AUGMENTED REALITY (AR)

by

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DEDICATION

To my parents Rabindra Maharjan and Dilkumari Maharjan.

To my fiancé Pratistha Sharma.

Thank you for your belief in me.

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ABSTRACT

The modern industrial society is built upon the productivity of advanced computing and agile machines assisting the human workforce to perform their tasks more effectively, accurately and efficiently. The industrial revolution termed as "Industry 4.0" is based on the intelligence of machines working with humans in a collaborative workspace. Contrarily, infrastructure management has relied on the human for making day to day decisions. New emerging technologies can assist during infrastructure inspections, to quantify structural condition with more objective data. However, today's’ owners agree in trusting the inspector's decision in the field over data collected with sensors. If data collected in the field would be accessible during the inspections, the inspector decisions would be improved with sensors. New research opportunities in the human-infrastructure interface would allow researchers to improve the human awareness of their surrounding environment during inspections. This MS thesis studies the role of Augmented Reality (AR) and sensor technology as tools to increase human awareness of infrastructure. The domains of interest of this research include both inspections and emergency scenarios where humans need fast information about their environment to save lives. The results of

this MS thesis research are the design, programming, and validation of two applications using AR headsets: AR-QR code scanning and AR-sensor connection. The two new programs facilitate the interface of humans with infrastructure, laying out a new scenario for technology enabling new research, tools, and testbeds for human-infrastructure interface research. The results of this MS thesis lay the foundation for future growth in the area of machine-assisted human-centered structure inspections, emergency management and human-machine collaboration using AR.

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CHAPTER 1. INTRODUCTION

1.1 Overview

American infrastructure is aging at a rapid rate, surpassing its intended design life. The American Society of Civil Engineers (ASCE) infrastructure report card assigns a D+ score to American Infrastructure (ASCE, 2017). This report states that almost four in ten bridges in the US are built over 50 years ago, and almost 10% of US bridges are structurally deficient. The conclusions of the ASCE report also states that the condition of American infrastructure is of national importance due to safety and economic reasons. One of the priorities to address and remedy the infrastructure problem in America is regular inspection of assets to better inform maintenance priorities and protect society of unsafe conditions (Spencer, Ruiz-Sandoval, & Kurata, 2004). In the US, highway bridges are inspected once every 24 months for Fracture Critical Members unless approved for 48 months by National Bridge Inspection Standard, Federal Highway Administration (FHWA, 2004) (Agdas, Rice, Martinez, & Lasa, 2015). Similarly, private infrastructure owners including railroad companies are mandated by federal agencies to keep track of the current state of infrastructure annually (FRA, 2010). Both public and private infrastructure stakeholders rely on human judgment to carry out inspection and monitoring structures. In all cases, the data is often collected by human inspector individually at the site and reported at the headquarters with all other inspection reports and reports from the past. The inspectors process this data using computer models and optimizing decisions, but they depend on the information collected in the field. As a result, when the information from the inspection ends in the decision-makers, there are challenges for them to take actions, as inspection reports are limited to the experience of the inspector, the quality of the report, and the database organization (Moreu and LaFave, 2012). It would be preferred if structural condition, inspector knowledge, machine capabilities, and the human decision could happen simultaneously at the same time and location.

Human capabilities could be increased with machine assistance during the inspection. accessing information faster and more accurately and being able to observe information from their past inspections across time while they are in the field. Overlaying data from the past in the last inspection and design information has been ranked as a top priority of inspectors (Maharjan, Agüero, Lippitt, & Moreu, 2019). These research studies barriers identified by inspectors to develop a new machine-assisted inspection coupled with visualization tool (AR) to enhance the profession of structural inspectors in the field. This research addresses the challenge of integrating available technologies such as low-cost wireless sensing technology, AR, and remote database, establishing a new reality in the area of Human-Infrastructure Interface (HII). This thesis has used Structure Health Monitoring (SHM) tasks as a testbed to implement the use of HII. **Figure 1** shows an overview of technology developed in the course of this thesis. These technologies are low-cost sensors and barcode scanner enabled remote database connected AR-enabled HMD for the study of proposed interface. The solutions presented in subsequent chapters discuss building an interface architecture as a basis to develop applications that can be implemented to solve current challenges of interface with infrastructure. The architecture also discusses the different components that make up the integrated solution for the field implementation. This interface architecture supports using technology for monitoring, inspection, repair and maintenance work with AR adding human inspectors in the loop for structure inspection.

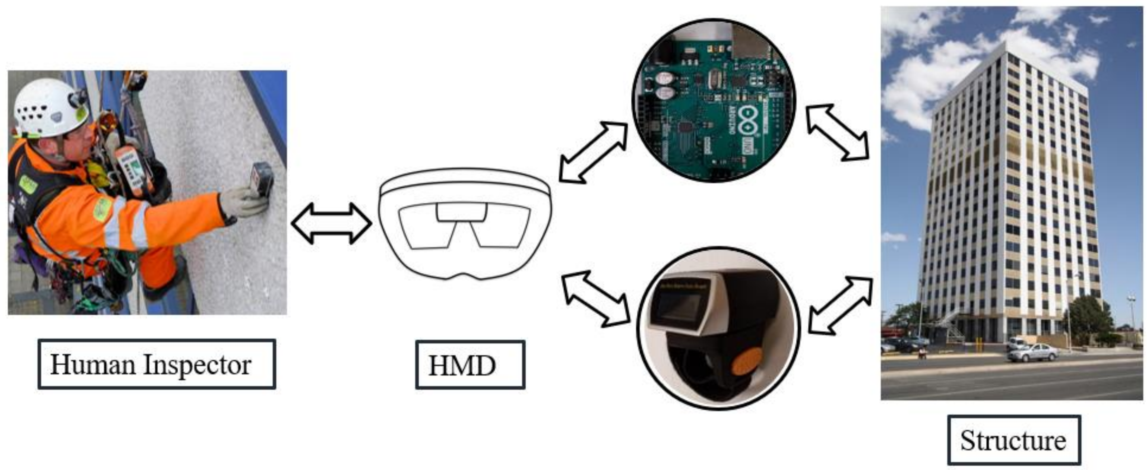


Figure 1. Study of HII using AR technology for structure inspection.

The work of this research is to develop AR-enabled interface architecture for human and structure interface. While acknowledging the fact that the primary task of an inspector is to inspect the structure, not use a wearable computer at the site, this research contributes to developing AR-enabled applications for human interface with structures by addressing the stated problem of quick access to information on-site environment. The AR technology helps to achieve the goal of computer-aided wearable technology without compromising inspectors' ability to conduct primary task which is an inspection. Secondly, using the interface architecture, AR applications designed and built considering inspector workflow at the site. The research presents the gaps in existing methods of conducting structure inspections as well as limitations that could be overcome by using proposed applications.

1.2 Scope of the Thesis

The author has conducted a literature review of relevant work in the area of structural inspection and monitoring, the importance of conducting structure inspection and current technologies available for structure inspections. The literature review also summarizes the past work in the area of HII and AR, highlighting its use in the emergency management system where real-time data monitoring is essential for monitoring the dynamic environment.

The author presents the novel interface architecture developed for HII applications. The components of the architecture are explained. The software and hardware components for developing the AR-enabled applications are also described in the thesis. Two AR applications using this architecture were designed, programmed, tested and validated. The first application discusses the AR-QR code application which allows facility inspectors to connect to remote server databases using a new web socket. The second application is the connection between AR and one sensor which allows the bridge inspector to stream real-time structural data.

Finally, the last chapter provides the conclusions of all the contributions of this research work. The author also provides prevalent limitations of the proposed technology and recommendations for overcoming those limitations for industry adoptions.

1.3 Outline of the Thesis

This section describes the content of this thesis. There are six chapters in total. Each chapter describes the work done by the author about the AR for HII applications.

Chapter 1 is the general introduction of the thesis work. It includes the motivation behind the work and overview of the thesis. The chapter also contains the scope of the thesis which describes the different aspects of the research.

Chapter 2 provides a literature review of relevant work done in the area of HII. This chapter provides the past researches in AR-enabled smart interface, use of currently available technologies for structure inspection applications. It also explores the state-of-art in the field of AR in structural inspection and monitoring. It highlights the current challenges faced in developing AR applications for HII and also talks about potential solutions for addressing those challenges. The use of previous research work in the use of AR for emergency management has been discussed.

Chapter 3 describes the framework for HII developed by the author to develop AR-enabled applications for structure inspection on-site environment. This chapter describes the different components of AR-enabled HII: application framework, solution architecture, and AR applications to rapidly access data of structures during the inspection. This section also describes the workflow for developing the framework and how other developers can follow the processes to deploy their application for structure inspection. The HII framework touches on the importance of human-centered design for AR applications. The interface between humans and computers as well as humans and the environment are studied for this research.

Chapter 4 summarizes the results of the two main applications developed using this framework are discussed in this chapter. The first application describes the connection between an AR device and a remote database using a handheld QR code scanner to visualize inspection reports. The second application explains the connection between AR and low-cost sensor units for visualization of strain data for real-time monitoring of a structure. The applications are demonstrated in a laboratory setting and with stakeholders. Feedback about AR and structural inspection needs were summarized and included in this chapter.

Chapter 5 summarizes this thesis and concludes this work. Mainly, the impact of AR in HII is discussed within the context of structural inspection and monitoring. It also points out the limitations of the study and ways to enhance the impact of AR-enabled HII research for structure inspections. This chapter also provides a recommendation for improving the work in HII while considering the human-centered design. The importance of overcoming hardware and software limitations is discussed to make this technology readily adopted in the industry.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

This chapter discusses the current and past studies of HII. The author presents the past work conducted to understand the critical aspects of the interrelationship between humans, infrastructures, and machines. Relevant works in AR technology is discussed in the context of structural inspection and monitoring. The next section includes a review of AR applications for indoor emergency management systems and smart buildings. Then the current work is outlined in the area of HII, including past research in Human Machine Interface (HMI) and human cognition.

2.2 Structural Inspection and Monitoring

Inspectors conduct structure inspections and monitoring to ensure the safety of the operations conducted on those structures and that of the people using or near them. Inspectors are required to conduct structural inspections and monitoring timely and routinely. This becomes even more demanding if the current state of infrastructure is in a compromised condition (Farrar & Worden, 2007). SHM is known as an engineering area developing technologies and algorithms for structural monitoring which can be also employed for inspection and maintenance (Fernando Moreu, Spencer, Foutch, & Scola, 2017). Conducting structure inspections and monitoring of decaying structures help inform the need for maintenance (Spencer et al., 2004). Structures that are more vulnerable to weather and adverse site conditions need a higher frequency of inspection and maintenance. More than one-third of the bridges are 50 years or older (**Figure 2**). Hence, the task of structure inspections become even more important to ensure the safety of structure as well as users.

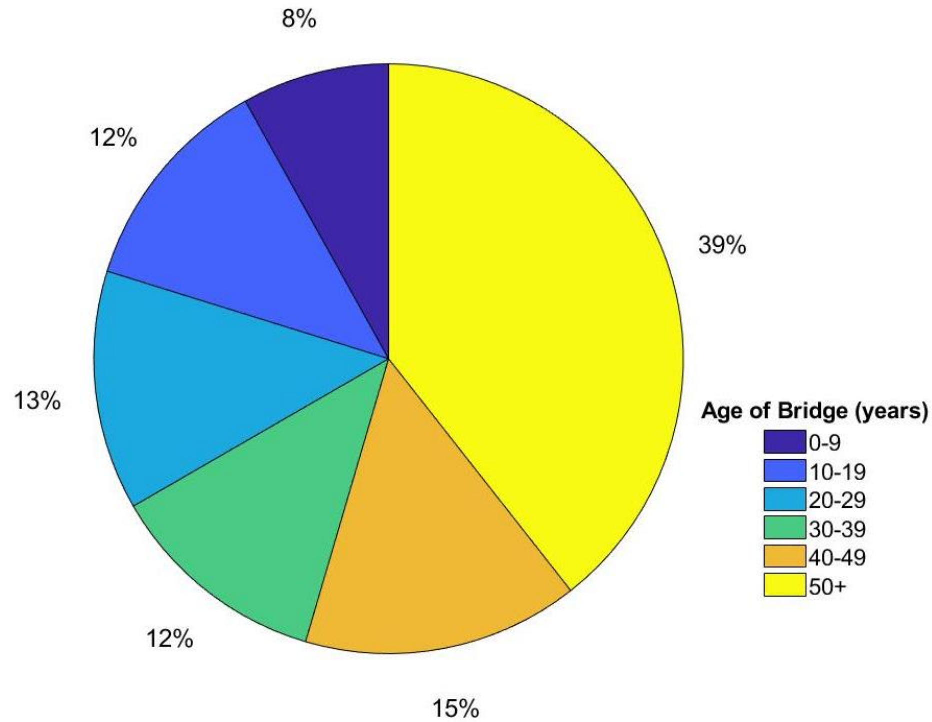


Figure 2. US bridges by age (ASCE, 2017).

Past researches have pointed out the importance of structure inspection and monitoring strategies to quantify if infrastructure complies with current standards (Spencer et al., 2004). It is also noted SHM can reduce the cost of periodic inspections mandated by federal regulations (Frangopol & Soliman, 2016). Additionally, structure inspections facilitate the monitoring of decaying infrastructure by obtaining objective data that can be used in making maintenance decisions (Otter, Joy, Jones, & Maal, 2012) (Glisic, Inaudi, & Casanova, 2009.)

Past researchers have described how using low-cost sensor networks can automatize structure inspection and monitoring tasks and decisions (Spencer, Ruiz-

Sandoval, & Kurata, 2004; Kim et al, 2007.) In the past, surveys have identified that the top interest of critical infrastructure managers is to obtain data in the field in real-time while conducting field inspections (Byers & Otter, 2006; Fernando Moreu & Lafave, 2012; F. Moreu et al., 2015.) Similarly, in 2018 the author conducted one workshop with railroad bridge managers to explore their top concern regarding structure inspection technologies (Maharjan et al., 2019). The results of this workshop identified that one of the challenges with structure inspection technologies is that they can't be interpreted in the field. As of today, owners still rely on inspectors to inform management decisions and are averse to data obtained by technology that cannot be validated/contrasted in the field (Fernando Moreu, Lippitt, Maharjan, Aguero, & Nasimi, 2018; Maharjan, Agüero, Lippitt, & Moreu, 2019). In conclusion, there is a general interest in new technology interfaces that can assists inspectors to better understand the structural condition while in the field.

Current technologies in infrastructure inspection

The most common method for inspection is considered visual inspection and remains the default method for bridge inspections (Agdas et al., 2015). Decision-makers find the visual inspection appealing because of the reliability it provides for the decision-makers to base their decisions (Agdas et al., 2015). The common method for conducting a visual inspection of the bridge structure is by a group of inspectors who travel to the site and record the visually available information (**Figure 3**). However, bridge inspectors and stakeholders have started using sensor-based technologies to record and inform decision-makers about the current state of the structures (Ozdagli, Gomez, Moreu, & Asce, 2017) (Kim et al, 2007) (Cho et al, 2010). Additionally, both industry and academia have expanded their interest in drone-based technologies for structure inspections (Dorafshan, Maguire, Hoffer, & Coopmans, 2017).

Figure 3. Visual bridge inspection carried out by bridge inspectors.

While visual inspection is the most common inspection method for the infrastructure industry, there is a growing interest in deploying other technologies such as distributed sensor networks and robotic inspection for infrastructure inspections. Two commonly used inspection technologies are addressed in **Table 1** to address their limitations and propose potential solutions. The visual inspection methods have limitations due to the likelihood of human-induced error that makes the inspection work either less efficient or more expensive (Agnisarman, Lopes, Chalil Madathil, Piratla, & Gramopadhye, 2019) (Agdas et al., 2015). The distributed sensor network systems are capable of data acquisition but lack in terms of informing the real-time condition of structures to human decision-makers (Alamdar, Kalantari, & Rajabifard, 2015). Hence, there is room for improvement in developing new technologies that can facilitate a human inspector to a level where the work can be performed with more accuracy, efficiency and, safety.

Table 1. Limitations and potential solutions for currently available infrastructure inspection technologies.

SN	Existing Solutions	Limitations	Potential Solutions	Addressed by this Research
1	Visual inspections	Likelihood of human-induced error	Real-time access to a database containing inspection reports and procedures	AR-enabled real-time access to a database containing inspection report PDFs was developed
2	Real-time sensors system	Not capable of providing objective data to change human behavior	Seamless connection between sensor networks and human decision-makers	AR connection to strain gauge sensor for visualizing of real-time data acquisition was developed

The researchers conducted a workshop to gain industry feedback for the AR applications developed for infrastructure inspection works. This workshop was conducted in collaboration with the New Mexico Department of Transportation (NMDOT) as part of validation and feedback for the AR applications and low-cost sensing technology for field implementation. The workshop allowed researchers to share their ongoing research as well as gain insight into existing challenges faced by field staff during inspection work. This feedback allowed the researchers to optimize the research effort in terms of making the results more applicable to field implementation. The scope of the workshop was to share ongoing research in the development of AR and low-cost technology to let the participants have hands-on experience in the technology. During the workshop, participants were asked to try the demo version of the AR applications developed for bridge inspections. According to NMDOT bridge inspection staff, real-time crack measurement and deformation calculation using sensors and AR could become helpful tool if developed for efficient inspection of structures.

2.3 AR in Structural Inspection and Monitoring

AR combines real and virtual environments (Azuma, 1995). Traditionally, people have relied on 2D graphical images to interpret information of the 3D world. AR can change this paradigm by allowing users to view real-world data in an intuitive 3D world. AR superimposes virtual objects on to real environment in the user's field of view. It acts as a medium that integrates sensor data, wearable technologies or Internet Of Things (IoT) devices (Regenbrecht, Baratoff, & Wilke, 2005) (Ballor et al., 2019). AR can display information without having to interpret complex data on-site environment thereby improving efficiency and reducing redundancy in data collection and management (Napolitano, Liu, Sun, & Glisic, 2019). This integration of these different technologies makes AR as a powerful visualizing technique for prompt decision making. Previous researches have highlighted the importance of new visualization techniques for structure inspection sensor data in the 3D environment (Napolitano, Blyth, & Glisic, 2018) (Sato, Sakamoto, & Shimada, 2015).

Some efforts are underway for using AR for enhanced bridge inspection work (Fernando Moreu, Bleck, Vemuganti, Rogers, & Mascarenas, 2017). Using the spatial mapping technology of Microsoft HMD, AR can be used for measuring the surface area of footpath and pavement (**Figure 4**). AR has also been used in the post-earthquake inspection of building (Kamat & El-Tawil, 2007). A comprehensive study can assist to identify and list the links between the human-computer interface for appropriate use of AR with human-centered activities related to infrastructure inspection.

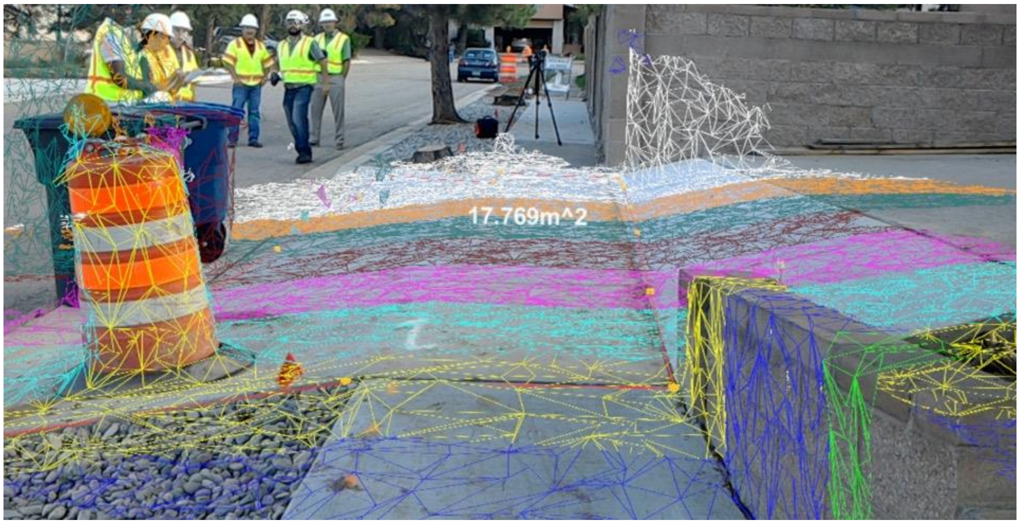


Figure 4. Footpath surface area measurement using AR spatial mapping technology (TRB, 2018).

Past studies have established the value of AR in various maintenance and inspection tasks (Palmarini, Erkoyuncu, Roy, & Torabmostaedi, 2018). AR applications have also been used in construction, aviation, design (**Figure 5**) and manufacturing industry to enhance the workers productivity (Ong, Yuan, & C Nee, 2008; Hincapie, Caponio, Rios, & Gonzalez Mendivil, 2011; Afonso, Santana, Afonso, Zanin, & Wernke, 2018).

Figure 5. Use of AR in aviation inspection and maintenance (Bellamy, 2017).

The use of low-cost sensors is also extensively studied in the IoT framework (Atzori, Iera, & Morabito, 2010; Kelly, Suryadevara, & Mukhopadhyay, 2013). However, to date, there are few practical combinations of sensors and AR enabling time-efficient, prompt information during structural inspections. It would be of interest to develop simple testbeds for humans to access data in real-time without the need of opening sensor databases or computers at the site during inspections of structures. This can have contributions to infrastructure managers, first responders, and humans in charge of assessing the condition of changing environments in real-time and against the clock.

The structure inspection industry relies on human expertise and swift problem-solving skills to navigate challenging built environment. To access information quickly in such an environment is critical to making timely decisions for maintenance of infrastructure. More specifically, the inefficiencies and delay in decision making caused in inspection workflow by not having access to information needs to be studied. Past studies have pointed out the constrains of building human and smart infrastructure systems when using wearable devices (Ogie, Perez, Dignum, & Dignum, 2017). It has also been noted the importance of building hands-free technology for site inspection due to constrains of movement within the work environment (Christian Bürgy James Garrett, 2002). However, the technology introduced for assisting the inspection worker should not interfere with carrying out the main task of inspection. This requires the interface of human and infrastructure to be pervasive rather than intrusive.

2.4 AR for Real-time Inspection During Emergency

Natural hazards like earthquakes, floods, hurricanes, terrorist attacks possess a threat to people. These hazardous situations are particularly detrimental because of their dynamic nature, which requires a dynamic response. The unpredictable nature of such events makes it additionally difficult to predict when the next sequence is going to occur. Even more dramatic is the case where humans die rescuing other people trapped in such unpredictable environments (Dearstyne, 2007). For instance, a terrorist attack in Twin Tower building on September 11, 2001, made the structure to collapse without any prior warning (Usmani & Chung, 2003.) People on the structure or in the surrounding environment would have survived if they had known the imminent collapse of the structure at the site. If sensors, infrastructure models, and human-centered framework would be explored as an integrated solution, real-time sensing technologies could inform human decisions while at the field.

The use of AR in firefighting is starting to commercialize with the advent of smart glasses. Private companies have tried to leverage the smart glass technology and integrate with firefighter helmet. To date, this technology has only been limited to visualization (such as thermal imagery) and not yet connected to smart sensing networks. **Figure 6** shows the use of thermal camera capturing imagery in dark, smoke-filled a room and displaying the image in the firefighter's helmet (Sam J . Cossman, Long, Haciomeroglu, & Ralston, 2019).

(a) (b)

Figure 6. AR-enabled Firefighter helmet called C-THRU produced by Qwake Technologies. (a) Normal Vision. (b) Augmented Vision (Sam J . Cossman et al., 2019).

Several algorithms have been developed to deal with the data acquired from these environmental sensors that are installed in the built environment. **Table 2** shows the different published research (ascending in date) that strives to address this topic. These technologies are designed for either first responders, command centers, building operator and building occupants. In this whole process, the building occupants are left out of the equation of emergency management. Human-centered systems can assist responders in the emergency management system (Lopez et al., 2015). As of today, there are limited uses of AR for field practical uses. If simple applications could enhance human access to information in real-time in the field, decisions could be faster, more accurate, and humans could identify their environment during emergencies more effectively. The use of AR-enabled real-time visualization of the state of structure could benefit emergency responders to make timely decisions and avoid catastrophic structural failure. This thesis attempts to build a framework for developing AR-enabled real-time data visualization using low-cost sensors along with smart building technology to assist emergency responders to take time-critical decisions.

Table 2. Summary of past researches for real-time data acquisition during emergency in indoor environment.

S.N	Authors	Proposed Technology	Key Findings	Target User	Review
1	(Jiang & Hong, 2004)	Ubiquities computing using wireless sensor and large display	Importance of accountability, assessment, resource allocation, and communication	Incident Command System (ICS)	The paper recommends using redundancy in a wireless communication system.
2	(Rueppel & Stuebbe, 2008)	A multi-method approach combining wireless LAN, Ultra-wideband, RFID.	GPS cannot be used indoor so multi-method tracking (various range) is necessary	Rescuers in complex structures like airports	The BIM-based approach is beneficial for complex buildings like airports to path navigation. However, it is not verified by field implementation.
3	(Filippoupolitis, Hey, Loukas, Gelenbe, & Timotheou, 2008)	Wireless sensor network system with Building Evacuation simulator for emergency response simulation	Augmenting the simulation with real sensor network increases the realism in the analysis	Building operators	Real-time evacuation using the proposed simulation is not accounted for using the first responders.
4	(Han & Ahn, 2011)	Cellphone base AR application utilizing cellphone's sensors and Imaged based machine learning	Timely evacuation can be achieved by recommending user with the shortest path based on a personal pedometry	End users carrying a personal cellphone	An end-user is required to take photographs during an emergency which might not be practical.
5	(Ni & Zhang, 2011)	Hybrid technology: RFID with an inertial navigation system and wireless sensor network	Reserve RFID technology can be used in post-disaster. RFID is cost-effective, yet it has drawbacks like interference	Public safety personnel	Tracking of Safety responders is presented. However, the visualization tool for tracking lacks explanation.
6	(Li, Becerik-Gerber, Krishnamachari, & Soibelman, 2014)	Environmental aware radiofrequency beacon deployment algorithm for Sequence-Based Localization	Even when ad-hoc sensor network is damaged, room-level accuracy can be maintained	Locating first responders and trapped occupants	Rendering BIM models can take significant computational power.
7	(Chen, Liu, & Wu., 2018)	IoT device using Grove Flame sensor integrated with BIM models to visualize fire	Real-time data integration of Fire Dynamic Simulator, BIM and IoT devices	Firefighters	The paper does not account for how real-time visualization is passed on to fire-fighters on the field.
8	(Al-Nabhan, Al-Aboody, Alim, & Islam, 2019)	IoT and cloud-based services	The proposed Emergency navigator can increase survival rate compared to another algorithm	Building occupants and First Responders	A cloud-based approach can handle computational power for real-time sensing.

2.5 Human-Infrastructure Interfaces (HII)

The conventional way of perceiving the environment by a human is sense such as sight, sound or touch. However, human perception solely relies on the human ability to see and detect the environment. In this context, Artificial Intelligence (AI) is an area in environment perception which utilizes the machine capability for the human-machine-environment interface. There are four main areas of AI for the smart environment: Pervasive-Ubiquitous computing, Human-Computer Interfaces, sensors, and Networks come together to form what the author refers to as Ambient Intelligence (AmI) (Carlos, Wrede, & Augusto, 2007). Such a network would have computational capabilities that can link perception through sensors with actuation based on human decisions. AmI emphasizes building a non-intrusive digital environment that supports the daily lives of people. Machines help humans to interface with their environment by improving accuracy and quality of life. HMI has also been explored in the area of sensory substitution for humans to replace lost sensory ability such as touch, sight and vestibular function (Bach-Y-Rita & Kercel, 2003). The use of robots for structure inspection is also gaining interest from academic and infrastructure industry practitioners (Lattanzi, Asce, & Miller, 2017). **Figure 7** shows one such example where bridge inspectors are using robots to inspect cables supporting the bridge.

Figure 7. Crawling robots are used in infrastructure inspection where human access is denied (Zasky, 2018).

Researchers have studied if the relationship between humans and machines can enhance safety and productivity in manufacturing. Various mobile and virtual reality applications assisted human workers at their factories (Gorecky, Schmitt, Loskyll, & Zuhlke, 2014). **Figure 8** shows one such technology where AR is used in an industrial workspace to help human workers in the operation of equipment. The framework for HMI emphasized safety requirements where machines and humans share common workspace (Heinzmann & Zelinsky, 2003). The movement of machines such as robots should be easily predicted by humans and avoid the collision in the workspace. Past research (Prades et al, 2002) has also focused on implementing the interface of robots with AR spatial capture of the remote location. Recently, researchers demonstrated quicker user awareness of their environment with AR (Zolotas & Demiris, 2019). The study and research of human perception enabled by computer manipulation can overcome current frontiers between people and their nearby environment.

The protocol of establishing an interface with computers is gaining interest as humans become more open to using machines for day to day decisions. Researchers (Bailenson, 2018; Jofré, Rodriguez, Alvarado, Fernández, & Guerrero, 1999) predict that Non-Verbal Communication (NVC) with computers such as eye movement, gaze, gesture operated VR and AR head-sets would be of value in future. Natural User Interfaces (NUI) that engages the user for immersive experience is one key area of interest for HMI research.

Figure 8. AR applications developed in a hand-held tablet computer for smart factory applications (Gorecky, Schmitt, Loskyll, & Zühlke, 2014).

The way human perceives the surrounding environment is evolving with the more computer-assisted perception being developed with human-centered interfaces. However, the fundamental way of perceiving any surrounding environment or its components has not changed. It is a fundamental nature of human behavior to see, interpret and make decisions based on what they see, hear or feel of their surroundings. (Nakashima, Carlos, & Wrede, 2010) proposed an environment equipped with intelligent sensors which can detect and warn human without human intervention. In their work that they called intelligent systems, the environment assists the human decision-making process. Recent researches (Banic, 2014; Jackson, Jelke, & Brown, 2018) highlights the 3-Dimensional User Interface (3DUI) for immersive interface with the virtually reconstructed surrounding environment.

2.6 Summary

This chapter has provided the background required to explore further development in HII. In this chapter, state of art of previous work in inspection technologies, use of AR in structure inspection, different components of HII and its applicability to developing a framework for human interface with the environment is presented. It is now established that the current need for structure inspection requires technology that can integrate current sensing technologies and AR tools for augmenting inspector decisions in real-time. Based on this notion, the author developed an interface connecting humans with the environment for structure inspectors to have real-time access to information on the current state of the structure. The HII is further extended to be used in AR-emergency management and AR-collaborative machine applications which are presented in a later chapter of this thesis.

CHAPTER 3. AR INTERFACE FRAMEWORK FOR HII

3.1 Overview

This chapter outlines the AR as a main interface component of HII where humans, environment, and machines are integrated. Humans and computer systems interact with an interface that can understand both human commands and can interpret to computer/machine level language. This is done by technologies like natural language processing (voice recognition), touch screen or sensing human movement. The study of this connection between human and computer is broadly termed as Human-Computer Interaction. Another component of HII is the link between computers and the environment, sensing technologies such as distributed sensors networks are used to sense the state of environmental parameters. In this chapter, the use of QRs and strain gauge sensors to collect and transfer physical data to the user with machines (a computer as of today) is presented. The third link is a connection between humans and the environment which is established by perception. Currently, humans perceive the environment using their motor senses like vision, touch or hearing abilities. Combining these three connections with the help of AR, the author established the framework to develop HII applications. **Figure 9** shows the use of AR as the nexus of humans, computer and the environment. Here, the term environment implies infrastructures such as bridges, highways, buildings, airports represent the majority of the built environment. The computer enables the connection with models, databases, or information linked to the environment such as drawings, specifications, or properties. The human is the inspector collecting information of the environment, which now can interact and interface with real-time immersive access to the digital database linked to the structure in the field.

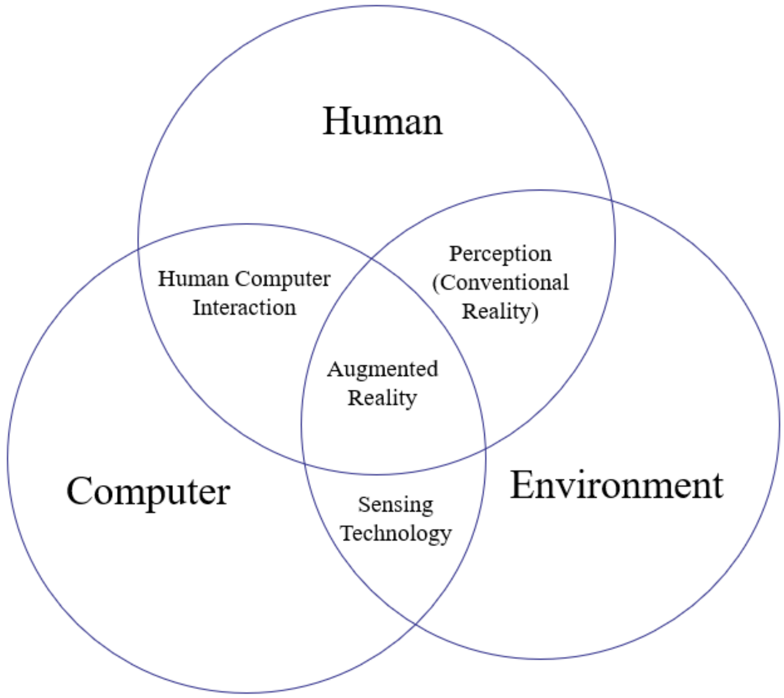


Figure 9. AR framework for interface with humans, computer and environment.

3.2 Methodology

The device used for this research is HoloLens, AR headset manufactured by Microsoft. HoloLens is an HMD capable of projecting virtual objects in a real environment in the users' field of view. The device runs on applications designed for Mixed Reality (MR) capability. Third-party software vendors can develop application and deploy in the HMD. HMD is built in such a way that humans can interact with different gestures. It can detect and track hand gestures, understand voice input commands and tracks the gaze of the user. The input/output peripherals of HMD like speakers, microphones, 3.5mm audio jack, brightness controls, and battery status LED indicator make the device more user-friendly. The HMD is the first untethered AR device by Microsoft hence it has powerful network connectivity. It operates with 802.11 wireless connectivity. It is also equipped with 4.1

Bluetooth and Micro-USB 2.0 for wired connection. The following section describes the hardware built of the device.

3.2.1 Hardware of HoloLens

The major hardware peripherals of HMD can be described in two sections: Optics and Sensors.

Optics

This HMD has see-through holographic lenses that enable to view virtual objects (**Figure 10**). It is also equipped with automatic pupillary distance calibration enabling the virtual objects to be correctly viewed by different users whose pupillary distance may be different. The HMD has a default application to make the calibration process easier for the user. The holographic resolution of HMD is 2.3 Million light points which equivalent to 2.5k radiant (light points per radian). A user can see holographic images in the lenses with the technology of light projection. However, when operated in daylight, the projected light may be dominated by the external light from the sun. This might cause a holographic image to appear faded.

Figure 10. Optical display of HoloLens.

Sensors

This HMD is equipped with various sensors to capture real-world environment data. It has 4 environments understanding RBG cameras, 4 microphones and each of the ambient light sensors, depth camera and Inertial Measurement Unit (IMU) sensor (**Figure 11**). The HMD is capable of taking 12 MP photos and captures High Definition Videos. The light sensor can detect the amount of natural light in the environment and adjust the rendering of the virtual objects when used for outdoor use. The IMU sensor detects the tilt and orientation of the head to render the virtual Holograms objects within the users' field of view. The microphones are placed in a strategic location in HMD to be able to capture human voice. The speakers are capable of producing a spatial sound that enhances the users' experience with multimedia applications.

Figure 11. Built-in sensors of HoloLens.

3.2.2 Software development for HoloLens

The Unity game engine, a cross-platform software development package was used to develop applications for Microsoft HMD. The application uses Visual Studio C# scripting to write codes, which is built into a solution file by Unity. The solution file is then deployed by Visual Studio to HMD. **Figure 12** shows the workflow for developing the application using Unity and Visual Studio.

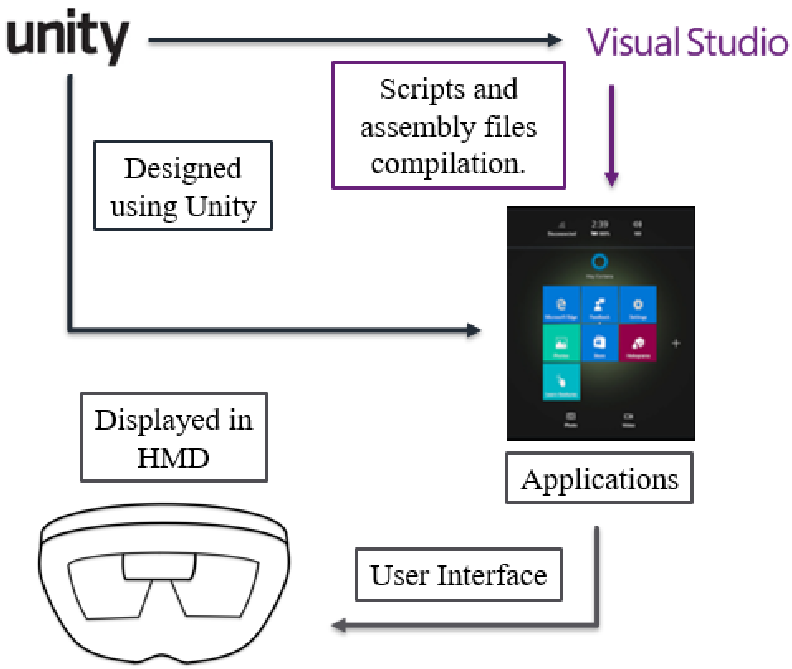
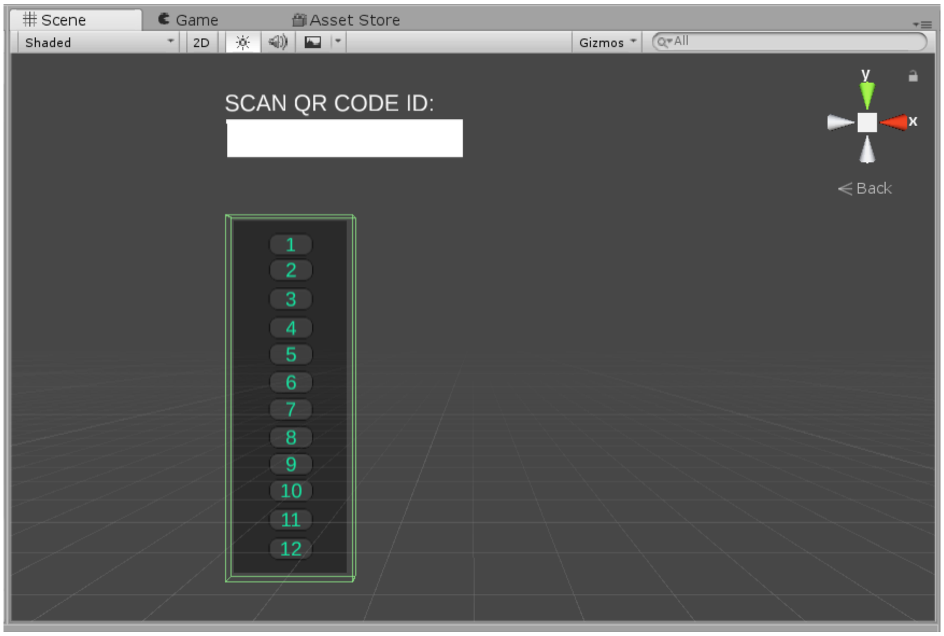
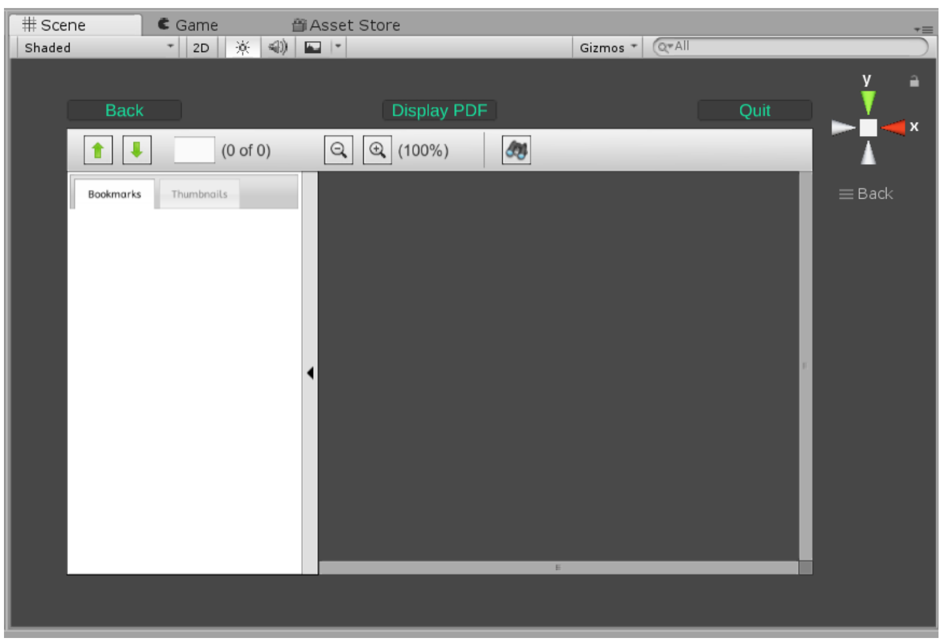


Figure 12. Workflow for developing AR applications.

The development of the application starts with the designing "Scenes" in Unity. These scenes later become the user interface for AR applications (**Figure 13**). The scene contains objects the user needs to see while interacting with the application. The scenes are composed of "GameObjects" which contain 3D holograms, interactable buttons, input fields, slider bars, toggle buttons and such. These GameObjects are assigned with C# script called "Components" which provides an attribute to the objects. The scenes can have multiple GameObjects arranged in a hierarchy (**Figure 14**). This makes the Unity software agile for developers to adopt a component-based approach for developing AR applications.



(a)



(b)

Figure 13. Scenes in Unity before deployment (a) A sample of a scene with an input field and buttons (b) A sample of a scene to display PDF files.

Microsoft's Mixed Reality Tool Kit (MRTK) was used to integrate inbuilt attributes like spatial mapping, voice and gesture recognition into the applications. Additional critical components of AR application development such as input system, User Interface (UI) controls, gaze and gesture control, spatial awareness is also built with the MRTK. This toolkit makes the workflow easier by providing basic building blocks for Unity applications and can be implemented in a wide variety of devices including HoloLens. In this research, two main applications are presented to leverage the use of AR in the domain of human-infrastructure interface. The first application uses the connection of AR with physical assets using unique QR codes whereas the second application uses the connection of AR with the physical environment with the help of embedded sensors such as strain gauge. These applications are discussed in detail in subsequent sections.

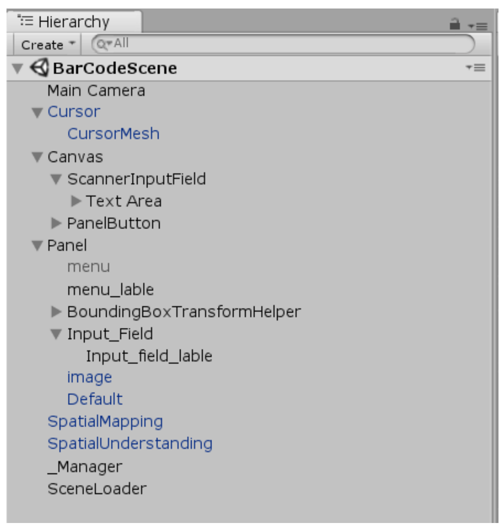


Figure 14. Hierarchy of GameObjects in Unity Software development platform.

Based on the requirement of the AR application, the developer can add components/attributes to the GameObjects. For instance, in one of the applications where the user requires to view the linked asset (PDF document) at all moments while conducting an inspection, the GameObject that displays the PDF has a “Tag-Along ” component. This reference tracks the gesture of the inspector and allows the GameObject to float around within the user's field of view. Additionally, it also contains "Gaze and Gesture Manager" to allow the inspector to interact with the GameObject.

3.2.3 AR-Database Connection

The author developed a new AR-Database Connection, to enable inspectors to access databases in an auditing scenario. This section describes the architecture that enables the communication of the site environment object (i.e. observed feature of interest to the inspector) with a database with information of that feature that is made available instantly to the human. **Figure 15** shows the architecture components.

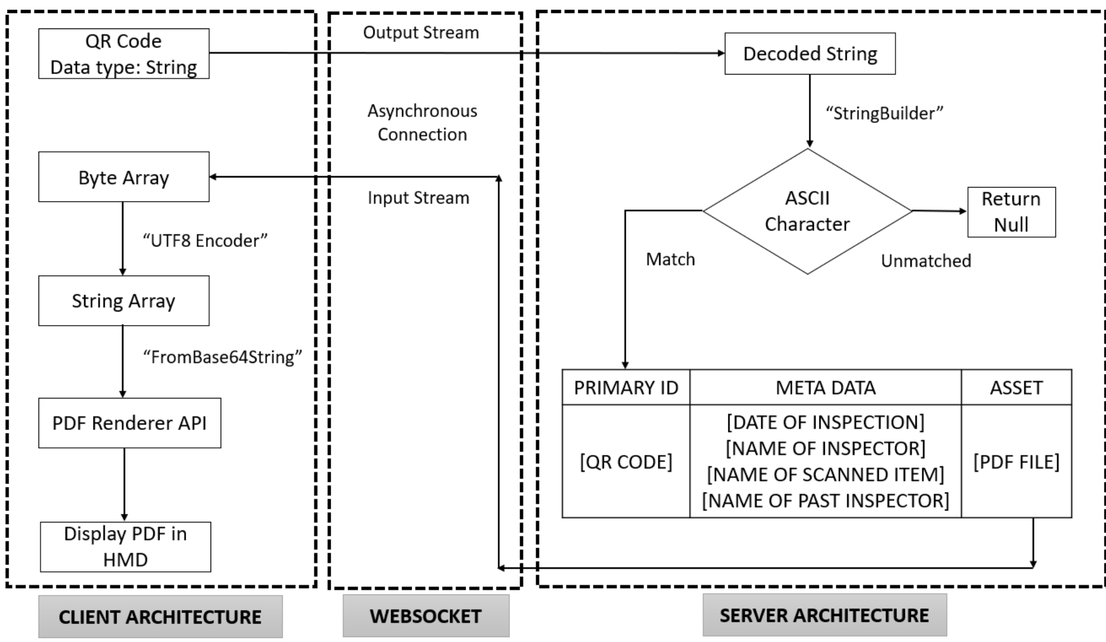


Figure 15. Components of WebSocket connection for Client and Server Architecture.

The following section discusses the components in creating and deploying a remote database server connection.

HMD

The HMD is equipped to collect information from the site environment with its inbuilt sensors. To input data into the AR application, a user can use voice recognition, hand gesture for the virtual keyboard of HMD or use Human Interface Device (HID) such as a QR code scanner. The scanned text (QR code) is saved in a GameObject that references to the "InputField" component.

WebSocket

WebSocket protocol enables bidirectional communication between client and server (Fette & Melnikov, 2011). It establishes a persistent asynchronous connection which is ideal for creating real-time applications (Pimentel & Nickerson, 2012). The asynchronous connection makes the WebSocket protocol ideal for data requests and listening for client-server architecture due to its event-driven nature. WebSocket protocol was used for the interface to enable remote connection to a server and real-time visualization of data. The interface uses the "StreamSocket" object to connect to the host (server) using a unique port number. The "InputStream: and "OutputStream" attributes of this object were used to read and write data to host respectively. In the interface architecture developed for infrastructure auditing, there are three main tasks involved in data transfer through WebSocket.

i. Sending Data to Server

The scanned QR code is recorded as a string in the buffer memory. "DataWriter" command is executed to send the string to the server through WebSocket.

ii. Structured Query in Database

This was done by using Relational Database from Microsoft's Access software. This database contains the QR codes as a primary key for searching. Once the scanned string is received, it is stored in temporary buffer memory using “Stream.Read”. The string is in parsed form hence it needs to be appended into one character using the “StringBuilder” function. If the database contains scanned item, then the server application updates the metadata information about the inspector as well as extract the PDF file from the database. The PDF file is saved into a string array before converting it into ASCII Encoded byte array. Using the “Stream.Write” attribute of the network stream, the encoded byte array is transferred through WebSocket.

iii. Receiving Data from Server

Back to the client-side, the “InputStream” attribute is used for reading the byte array which is temporarily saved in the buffer. The byte array is then converted into a string array using UTF8 Encoding. The “FromBase64String” decoding is used for converting this string into a PDF file that is displayed by PDF Renderer in the AR device.

Server Application

The server application is also developed using the .NET framework in C# environment. The server application runs on the remote server which contains the database. This application has mainly two purposes: establish a WebSocket connection with a client and perform a structured query in a database system. The database located in the primary memory of servers such as hard drives. The database contains Primary ID (QR code) which is used for the query, Meta Data contains information about the inspector and scanned items, Inspection Assets (PDF File).

3.3 Framework for AR Enabled HII Application

The solution presented in this section discusses building a framework as guiding rules to develop applications that can be implemented to solve the inspection tasks on-site environment. The framework also discusses the different components that make up the integrated solution for field implementation. This framework supports the well-established belief of using inspection and monitoring work by adding humans in the loop. In this thesis AR-based interfaces in the area of structural inspection was developed and validated in the laboratory using a new framework for HII with AR.

3.3.1 Components of Framework

The framework consists of three assets linked together in a system. The three assets are human inspector, remote server computer and database access (**Figure 16**). The human inspector relies on client-side AR application to access the information from the system. The server-side application is running remotely in a terminal that holds the database which is programmed in MS Access, a type of Relational Database Management System (RDBMS). This type of SQL database is robust in data integrity whereas it lacks flexibility. For this research, this database system worked without requiring extensive database know-how. The server computer has an application to establish a LAN connection with HMD in real-time using TCP web socket connection. The database is built within the server computer giving access to the inspector for viewing, appending or modifying inspection information as they become available. The connection between database and server is established using Object Linked & Embedding (OLE) Database Management System which is an API designed by Microsoft for accessing data in a relational format (Blakeley, 1997).

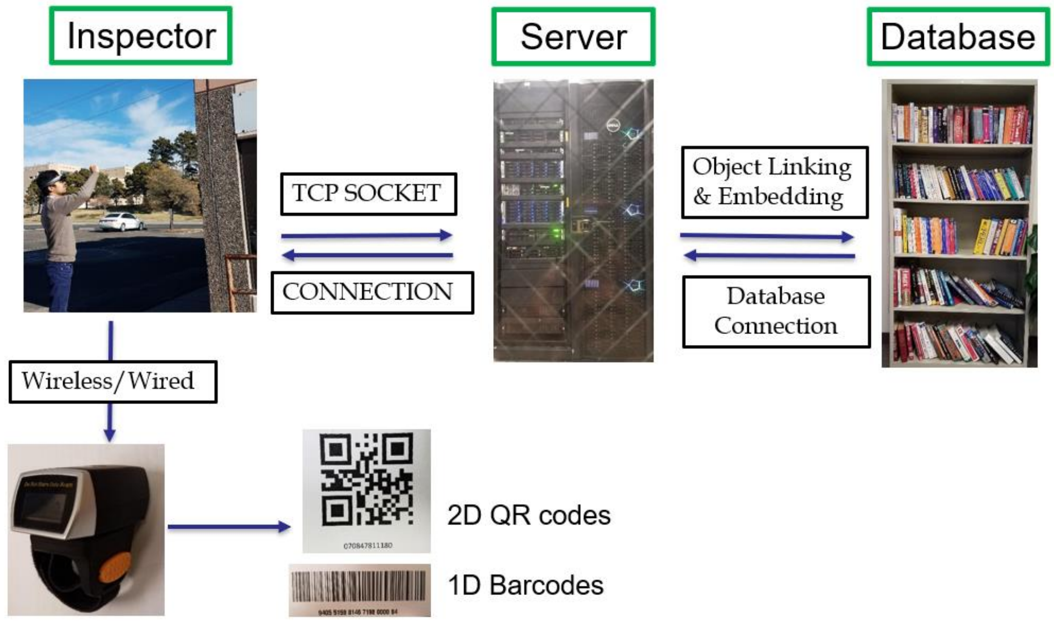


Figure 16. AR-enabled a framework for HII applications.

Additionally, this framework allows the inspector to add third-party devices such as a QR code scanner using wireless Bluetooth connection for scanning of QR codes to connect to HMD. Specifically, for this research QR code scanner device is used for handheld input devices instead of typing the text by the inspector. This helps to improve the efficiency of the inspection workflow. The external device is supported with the operating system built within the HMD hence requires no programming in developers' part.

3.3.2 User Interface in AR Framework

The framework consists of the integration of the three assets through QR-code scanning and AR for smart inspection tasks for infrastructure auditing. Infrastructure auditing refers to keeping track of inspection reports, maintenance history, inspector information and updating database with new inspections. **Figure 17** summarizes the three dimensions interlinked with the framework. The three dimensions refer to the human interface with

AR and remote databases. The flowchart shows the sequence of various steps followed by an inspector to access the remote database using an AR device. The following section illustrates those steps one by one.

1. At the start of the AR application, a login page is popped up in the user's field of view. This is created using 3D Hologram, a district feature of Microsoft's HMD. The user is asked to put credentials in a login page. Each user is given unique id and when the id matches with the id in the database, the user is granted access to other features of the application.
2. Once the credentials are verified, the user now can use the QR-code scanner device. This scanner device is used for identifying the 2D marker placed for each of the infrastructure assets. The application asks the user to scan a QR code. Each asset has a unique id which is also stored in the relational database.
3. After successfully scanning the QR code, it is displayed in HMD. The user can activate the transfer of QR code (a numerical value) by voice command. The voice command feature is originated from Microsoft's keyword library built within the HMD. Several keywords were used for using voice command. For instance, “SEND” for sending the QR code id to the database, “CLEAR” to clear the input field, “SHOW USER” to show the currently signed in the user name, “RESTART” to restart the application.
4. The QR code value is then transferred to the server computer using a TCP web socket. The server application is also designed and deployed using Visual Studio.
5. The server application identifies this code and performs a structured query in the database. If the QR code string is matched with any of the database fields, then a

PDF file is transferred to the AR application using web sockets. In the meantime, the database also updates the metadata related to the search such as date of last scanned, name of the user to last scan the file, number of times the files have been scanned. This feature for recording metadata for each scanned item was introduced because it is often the case when more than one person is responsible for conducting an inspection and updating the database.

6. This PDF file is transferred as a stream of data in web sockets. Once the file is received by the AR application, a third party application is used for displaying the PDF content in HMD. "PDF Renderer" (PAROXE, 2015) as the third-party application was used for displaying the PDFs.
7. The inspector can view the PDFs hands-free in AR HMD. This PDF is not saved locally in the HMD memory; hence it can only be accessed through scanning the unique QR code. This feature provides an extra layer of security for viewing the files.
8. After this, the inspector has options to end the program or continue to scan other QR codes. A simple hand gesture or voice-activated command can restart the application.

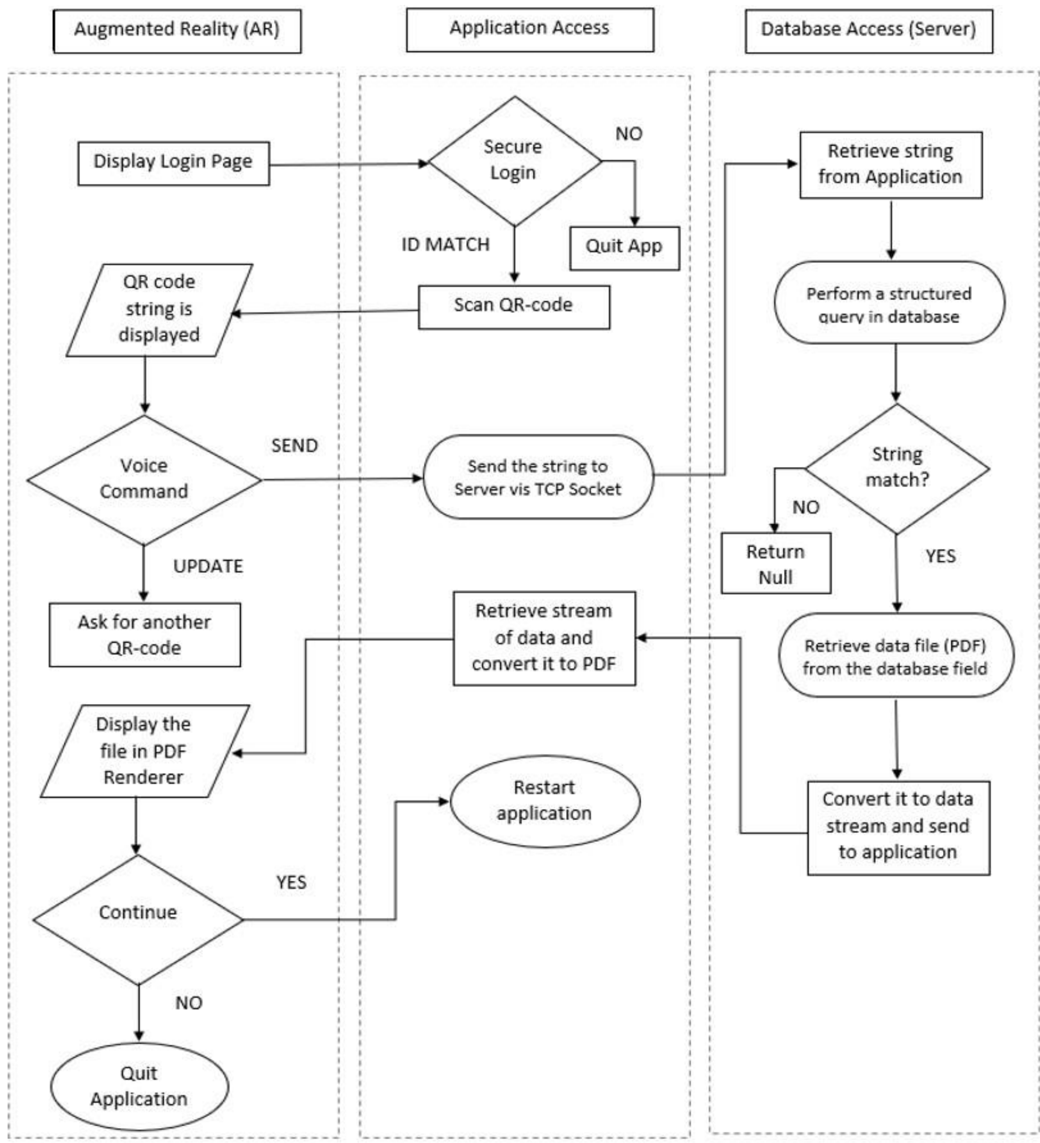


Figure 17. A flowchart showing three assets linked to QR-code scanner application in the framework of AR, application access and database server.

3.4 Summary

This chapter demonstrated a novel framework for developing AR-enabled HII for inspection and monitoring operations of structures. The key idea of developing the framework is to build a platform where site inspectors can have real-time access to data for their inspection tasks using remote database and low-cost sensors. The components of this framework such as database access or web socket connection, however, do not necessarily indicate the highest attainable efficiency in terms of computation or memory allocation. Thus, the research attempts to study only the connection made in the framework for AR-enabled infrastructure inspection using low-cost sensors and a remote server. The author utilized this framework as the basis for developing technologies for structure inspectors. Existing technologies such as low-cost sensing technology, and AR tools were deployed to build the framework. Moreover, the AR framework developed in this chapter can be used by other developers can build and deploy AR applications to make the infrastructure maintenance work more productive.

CHAPTER 4. HII APPLICATIONS

4.1 HII Applications

Researchers demonstrated the applicability of AR in HII by creating two AR applications. The applications follow a similar workflow as depicted in **Figure 12**. Third party software asset such as PDF Renderer (PAROXE, 2015) was to display PDFs within the applications. The first application presents the AR interface for physical assets using QR-code. The second application presented in the following section demonstrates the connection of AR with sensing technology.

4.2 AR-QR code Application

The use of markers for tracking AR has been used for the past two decades (Nakagawa, Sano, & Nakatani, 1999) (Schwald & De Laval, 2003) (Kan, Teng, & Chou, 2009). A type of unique barcode is used in the real environment to be able to be identified by the AR device. The marker is used for estimating the object distance, pose estimation, head tilt, and orientation. Other researchers have used various types of technology like speech, vision sensor-based tracking and object identification (Klinker, Reicher, & Brugge, 2000) (Goose, Sudarsky, Zhang, & Navab, 2003). These technologies employ advanced tools such as machine learning and object recognition (Azuma, 1995). Maintenance of critical facilities such as aviation, nuclear, plant, mechanical industry using AR has been established in past researches (Hincapie et al., 2011) (Martínez, Laukkanen, & Mattila, 2014) (Palmarini et al., 2018). As of today, AR applications are not designed to assist the inspector in real-time to access data that can inform their decisions. Real-time, seamless

AR interface with data fully enables inspectors during their fieldwork but has not been realized to date.

To test the hypothesis of AR-enabled inspection of critical facilities, an AR application was developed to establish communication between the server and physical assets using a QR-code scanner. The communication is established using TCP/IP, a web socket protocol. This socket enables two-way communication between server and HMD. Each physical asset (in this case, cannister) is provided with a unique QR code. These QR codes linked with the database as ID to access files in the database. The Safety Data Sheet (SDS files) were used in PDF format linked to the database. In critical facilities such as nuclear storage, each container needs to be tracked to maintain up to date information in handling. Using this application, an inspector can view the material handling procedures as SDS in real-time by accessing PDF files through the server. **Figure 17** shows the demonstration of the AR application's user interface which allows the inspector to scan the QR code of canisters and obtain critical information to assess its state.

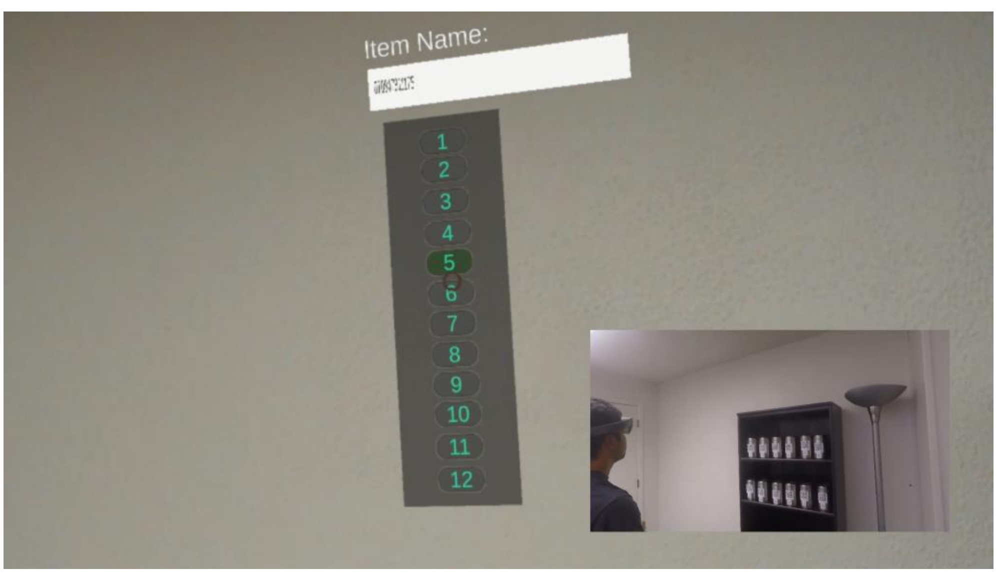


Figure 18. The user interfaces in HoloLens for indicating each sensor in the network.

The UI is controlled by hand gestures and voice commands making the application more intuitive and immersive (**Figure 19**). This application has been successfully demonstrated in a smart inspection of a nuclear facility in previous research contributed by the author (Mascareñas et al, 2019).

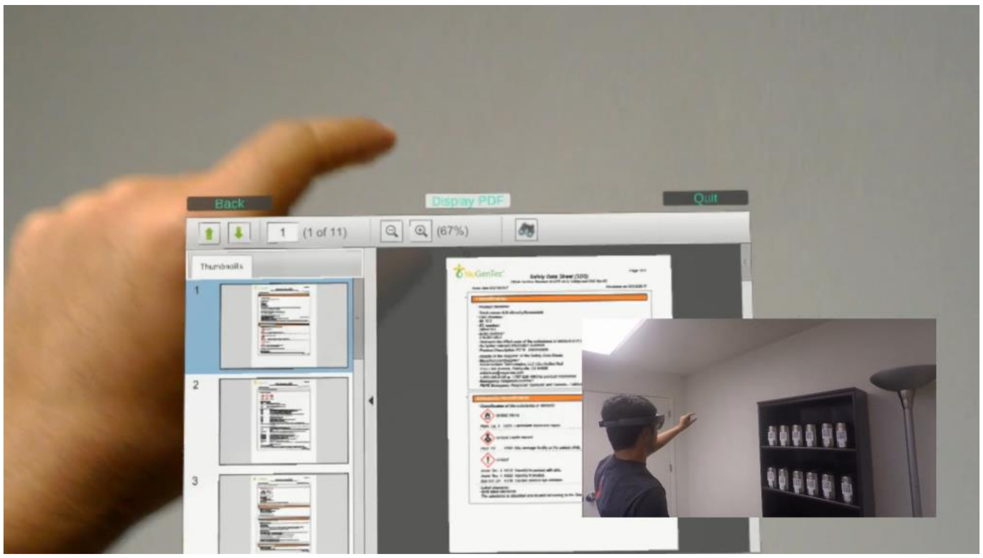


Figure 19. The information on the inspection is transferred through the socket to the inspector during the audition.

The key contributions of this work can be summarized in the following points:

1. The application demonstrated the connection of the AR-enabled QR-code tag of structures (physical assets) with associated PDFs (digital assets). The author established the use of AR-enabled applications for a human-infrastructure interface.
2. This application allows agility in conduction hazardous environment by allowing the inspector to view (hands-free) the critical information in the form of PDFs.

4.3 AR-Sensor Application

Building inspection requires inspectors to visit the site and assess the damage. To date, the building inspector has relied on visual inspection with minimal or no assist in modern technology. More time spent on those vulnerable structures increases the risk of injury for the inspectors. To address this problem, the use of AR-enabled inspection work can be utilized. The AR HMD was connected with a low-cost stain sensor to view the strain data in real-time. The user/inspector can visualize the graphical strain data that is streamed by the SQL database via the Local Area Network (LAN). This can also be connected by the internet if the data needs to view from a remote location.

4.3.1 Low-Cost Strain Gauge Sensors

The author built a low-cost strain sensor using off the shelf parts that are easy to fabricate and utilizes simple code for running the application. Currently, the sensor uses 3.3V power to operate, however, this can be replaced by a battery and solar panel to be able to deploy in structures that are not easily accessible in a post-disaster situation. The sensor uses the Wheatstone half-bridge configuration to convert the resistance value to the voltages. The voltage is then amplified using the HX711 amplifier which is then recorded by the Arduino board. The change in voltage reading is correlated to the change in strain of the specimen to which it is attached. Using a calibration factor, the strain in the samples were computed.

4.3.2 AR Connection to Sensor

The strain gauge sensor is built to record, and wireless transfer the data stream. It uses the Xbee wireless module (transmitter and receiver) to transfer the data from the sensor to the server. The server is a remote computer set up to receive a data stream from Xbee and transfer the data to online SQL database access by a web browser. The data is transferred using Local Area Network (LAN) to the HMD using a Wi-Fi connection. The HMD accesses the online database and displays it in its web browser. The different components of this demonstration are shown in **Figure 20**.

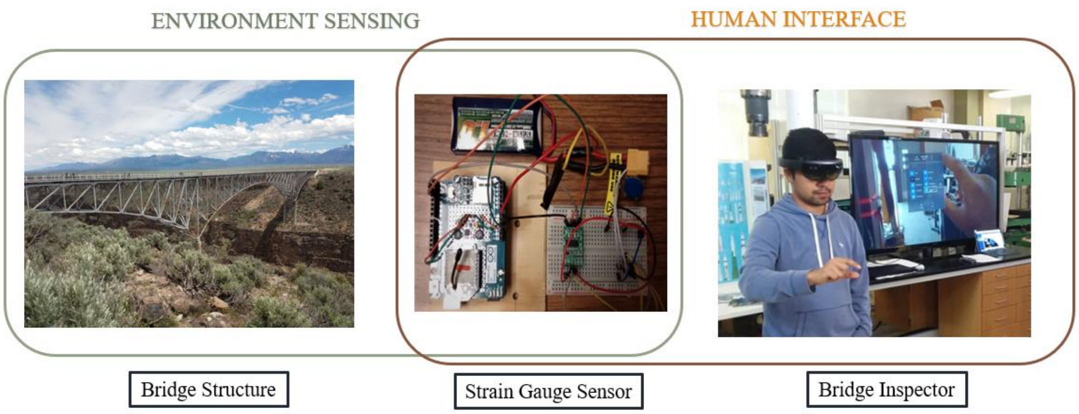


Figure 20. AR-enabled structure monitoring using a low-cost strain sensor

The key contribution of this work can be summarized as follows:

1. Visualization of real-time data such as the strain of one structure in the inspector's field of view. As the state of environment changes, it is updated in near real-time. This new capability enables the inspector to make a real-time decision based on changes in their surrounding environment.
2. Physical prototype enabling human-infrastructure interface by the integration of low-cost sensors and AR technology inbuilt structure.
3. The connection of low-cost strain gauge with the AR device was successfully configured. This application allows the inspector to view the near real-time strain data without having to access the sensor or perform data processing. The strain versus time graph is displayed in the HMD during structure inspection work which was not possible before.

4. The bridge inspectors highlighted the importance of using hands-free technology such as AR-enabled real-time visualization of data in day to day inspection and management of infrastructure.

This application is designed to be part of a broader application suite that can augment human decision based on environmental data, which can contribute to important domains such as emergency responders, evacuation brigades, military and rescue teams in adverse, real-time changing structures.

4.4 Conclusions

The contributions of this research are two AR applications: AR-database connection using QR codes and AR-Sensor connection. Using these two new AR developments, a new interface for structure inspection was developed on which other developers can build and deploy AR applications to make the infrastructure maintenance work more productive. Existing technologies such as low-cost sensing technology, and AR tools can be leveraged to develop the interface and deploy AR applications. The applications are built for field inspectors to help them conduct the structure inspection works and also for emergency scenarios where the fast interface between the human and critical infrastructure can save lives. The future work envisioned by the author involves making the AR application used in the field and validating aspects such as the safety of inspectors, new decisions and scenarios enabled by AR in the field.

CHAPTER 5. CONCLUSION

This thesis has provided the framework to use AR and sensors during structure inspections. The domain of this HII research is in structure inspection & monitoring and critical infrastructure inventory auditing. HMD was used for deploying these applications.

5.1 HII Conclusions

The thesis provided the interlink between humans, machines, and the environment using sensing technology and AR. The author investigated the human interface with other aspects like environment and machines. The major contribution of this thesis is the framework for deploying AR-enabled applications. The research considered the importance of building human-centered technology for assisting human field inspectors. Using this framework, the task of structure inspection was enhanced by enabling inspectors to access real-time data during their field auditing activities, in an immersive environment enabled by AR.

The results from a workshop conducted with stakeholders were analyzed to gain their perspective in the context of structural inspections. The author demonstrated various AR applications and low-cost sensing technology to NMDOT bridge inspection crew. NMDOT bridge engineers expressed interest in AR if it would be possible to develop a comprehensive application. They indicated that the potential use of this technology would be practical in their inspection activities if there could be one integrated application that integrates all tasks, instead of using multiple AR tasks. Their main concerns were safety and reliability to make this technology practical for their structural inspections.

The results shown in this thesis enable the research community to design, program, and test new AR applications connecting datasets to the user in a new immersive environment. More specifically, Chapter 4 summarized the steps to develop a socket connection between the sensor data or digital repository in the environment with the human using the HMD. This thesis demonstrated two context-aware AR applications for field applications. Using both the socket connection architecture of this chapter, new AR applications can be now developed for other HII domains, including, but not limited to: field emergency sensing, human-robot real-time interaction and new human-centered smart buildings.

5.2 Recommendations

While this thesis attempts to address the problem of HII with innovative tools such as AR and low-cost sensors, there are inherent risks and shortcomings. The adoption of AR technology in day to day use is uncertain given its current state of the hardware, as pointed out by stakeholders and bridge inspection experts. Based on the work conducted in this thesis and the interaction with industry, the following factors will accelerate the implementation of AR technology in the area of structural inspections: (i) improvement in hardware; (ii) decrease in overall size and weight; (iii) increase in processing capacity; and (iv) cost reduction for owners.

Based on the two applications developed by the author of this thesis, it is recommended that AR applications are designed with a human-centered approach. The digital security and privacy should also be considered while using such technology, including but not limited to critical infrastructure, nuclear facilities, energy grids, and government facilities sensitive to cyber-attack. The access to critical data should be protected using multilayer authentication and a stringent firewall system. Cybersecurity is indeed a concern for advancing HII using AR.

In the context of the structural inspection increasing the productivity of workers along with industry safety standards will facilitate the adoption of AR technology. Further research work will establish the safety of the HMD, including the impact of such a device on user cognition. The device may also cause a distraction for users, so further studies in safety of AR applications for structure inspections are required, involving both laboratory and field implementation. Preliminary trials were conducted in laboratory settings to inform the future design of safety testing (**Figure 21**).

Figure 21. Preliminary conceptual image informing the design of experiments using AR.

The author believes a partnership with industry will benefit the adoption of this technology. Further collaboration with is necessary for implementing AR tools for HII for understanding their needs and concerns. More specifically, exploring both public owners (DOTs) and private owners (railroads) specific priorities and barriers for implementation will contribute to research advancement in the area of HII and AR for structural inspections.

5.3 Publications

The results of this research are either published or in the process of publication in journals and conference proceedings.

a. Journal Publications

Mascarenas, D., Harden, T.; Morales., J; Boardman, B.; Sosebee, E.; Blackhart, C.; Cattaneo, A.; Krebs, M.; Tockstein, M.; Dasari, S.; Green, A.; Moreu, F.; **Maharjan, D.**; Aguero, M.; Fernandez, R.; Trujillo, J.; Wysong, A., (2019), Augmented Reality for Enabling Smart Nuclear Infrastructure. Frontiers (Published)

Maharjan, D.; Agüero, M.; Mascarenas, D.; Fierro, R.; Moreu, F., (2019), Enabling Human-Infrastructure Interfaces using Augmented Reality (AR), (Under Review)

Maharjan, D.; Wyckoff, E.; Zhu, C.; Moreu, F., (2019), Monitoring Human Induced Floor Vibrations for Quantifying Dance Moves. Frontiers (Under Review)

Agüero, M.; **Maharjan, D.**; Rodriguez, M.; Moreu, F., (2019) Framework for Remote Sensing and Augmented Reality (Under Review)

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