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Enabling human–infrastructure interfaces for inspection using augmented reality

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Abstract

Decaying infrastructure maintenance cost allocation depends heavily on accurate and safe inspection in the field. New tools to conduct inspections can assist in prioritizing investments in maintenance and repairs. 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 is accessible during the inspections, the inspector decisions can 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 article studies the role of Augmented Reality (AR) technology as a tool to increase human awareness of infrastructure in their inspection work. The domains of interest of this research include both infrastructure inspections (emphasis on the collection of data of structures to inform management decisions) and emergency management (focus on the data collection of the environment to inform human actions). This article describes the use of a head-mounted device to access real-time data and information during their field inspection. The authors leverage the use of low-cost smart sensors and QR code scanners integrated with Augmented Reality applications for augmented human interface with the physical environment. This article presents a novel interface architecture for developing Augmented Reality–enabled inspection to assist the inspector's workflow in conducting infrastructure inspection works with two new applications and summarizes the results from various experiments. The main contributions of this work to computer-aided community are enabling inspectors to visualize data files from database and real-time data access using an Augmented Reality environment.

Keywords

Human–infrastructure interface, human-centered decision, low-cost sensing, augmented reality, infrastructure inspection

Introduction

Structure Health Monitoring (SHM) facilitates objective data acquisition of structural deterioration of infrastructures. The data can be used in making decisions for further maintenance intervention.[1] One of the main aspects of implementing SHM is the measurement and inspection of the current state of infrastructure.[2] Currently, these practices are carried out via visual inspection which is primarily performed by inspectors. In the past, surveys have identified that the main interest of critical infrastructure managers is to obtain data in the field in real-time while conducting inspections in the field.[3–5] A workshop conducted with railroad

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bridge managers in 2018 identified that the major challenge with implementing inspection technologies is that they cannot be interpreted in the field in real time while observing the structure.[6] As of today, infrastructure owners still rely on inspectors to inform management decisions and are averse to data obtained by technology that cannot be validated in the field with humans' experience.[7] Researchers have tried to address this challenge by developing innovative technology that can assist inspection on-site environment.[8,9] However, there has not been notable advancement in procedures for visualizing real-time sensor data and inspection databases to enhance the visual inspector's workflow in a site environment.

The integration of real-time sensing technology with visualization is essential for real-time infrastructure damage monitoring. For example, the implementation of Virtual Reality allows data presentation in an interactive and intuitive way, which may improve communication among different teams working on an SHM system over an extended period of time. This improvement may in turn lead to the optimization of funds and time devoted to a particular SHM project.[10] More substantial enhancements can be attained with a network of current sensing technology connected to a state-of-art visualization technology, such as AR. By analyzing real-time data, this technology could help the inspector make accurate, unbiased, time-critical decisions in the field. The integration of AR and Wireless Sensor Network (WSN) connection has been explored by the researchers for several applications ranging from environment monitoring[11] to indoor person localization.[12,13] Past researchers have developed tools for WSN visualization and troubleshooting.[14,15] Recently, researchers have studied various network architecture using the Wi-Fi module, Bluetooth module, and Zigbee module for visualizing WSNs with AR devices.[16] There has also been an effort for using AR to provide access to sensors and actuators for the Internet of Things (IoT) applications.[17] These studies have led to the importance of building an integrated network of sensors connected to a powerful visualization tool. However, little effort has been given to building AR-enabled data visualization from sensors to enable objective decision making at the site environment.

Critical environments such as natural hazards like earthquakes, floods, and hurricanes; man-made emergencies like a terrorist attack; and unforeseen events like structural collapse possess a threat to the lives of people. Humans die rescuing other people trapped in such an environment.[18] These hazardous situations are particularly detrimental because of their dynamic nature. It is often difficult to predict what the next sequence of events is going to occur given the unpredictable nature of such events and emergencies. For instance, a terrorist attack in Twin Tower building on 11 September 2001 caused the structure to collapse without any prior warning.[19] People on the structure or in the surrounding environment would have been better off had they known the state of the structure and its condition in real time. Table 1 shows the different research papers published (ascending in date) that strive to address emergency management. While these technologies are designed for either first responders, command centers, building operators, and building occupants, they still lack intuitive integration of dynamic site environments with emergency responders. The use of AR-enabled real-time visualization of the state of structure could benefit emergency responders to make a timely decision and avoid catastrophic structural failure.

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.[27] It has also been noted the importance of building hands-free technology for site inspection due to constrains of movement within the work environment.[28] 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.

The work of this article is to develop AR-enabled interface architecture for human and structure interaction. 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 interaction 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. Second, using the interface architecture, the authors designed and built AR applications considering inspector workflow at the site. This article presents the gaps in existing methods of conducting structure inspections as well as limitations that could be overcome by using proposed applications.

Table 1. Progressive development in an indoor emergency management system.

S.No.	Authors	Proposed technology	Key findings	Target user	Review
1	Jiang and Hong[20]	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 and Stuebbe[21]	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 et al.[22]	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 and Ahn[13]	Cellphone base AR application utilizing cellphone's sensors and Image-based machine learning	Timely evacuation can be achieved by recommending user with the shortest path based on a personal pedometry	End users carrying personal cellphone	An end-user is required to take photographs during an emergency which might not be practical.
5	Ni and Zhang[23]	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 et al.[24]	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 et al.[25]	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	This article does not account for how the real-time visualization is passed on to firefighters on the field.
8	Al-Nabhan et al.[26]	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.

AR: augmented reality.

Table 2. Limitations and potential solutions for currently available infrastructure inspection technologies.

S.No.	Existing solutions	Limitations	Potential solutions	Addressed by this article
1	Visual inspections	Likelihood of human-induced error	Real-time access to a database containing inspection reports and procedures	Authors developed AR-enabled real-time access to a database containing inspection report PDFs
2	Real-time sensors system	Not capable of providing objective data to change human behavior	Seamless connection between sensor networks and human decision-makers	Authors developed AR connection to strain gauge sensor for visualizing of real-time data acquisition

AR: augmented reality.

Inspection industry implementation barriers

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. Authors have identified two commonly used inspection technologies and tried to address the rationale of this research in context to address their limitations (Table 2). 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.[29,30] 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.[31] 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.

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.

Human–infrastructure interfaces

The way human perceives the surrounding environment is evolving with the more computer-assisted perception being developed with human-centered interactions. Nakashima et al.[32] discussed the interrelationship between the environment as being part of an intelligent system in assisting the human decision-making process. The environment surrounding equipped with intelligent sensors which can detect and warn human without human intervention. Recent researches[33,34] highlight the 3-Dimensional User Interface (3DUI) for immersive interaction with the virtually reconstructed surrounding environment. However, the fundamental way of perceiving any surrounding environment or its components has not changed. Few kinds of researches in this area of human and infrastructure interactions have contributed to a lack of innovation in technologies that can assist in human decision making. In this article, the authors developed a new interface for humans and infrastructure incorporating the existing technology such as human–computer interaction (HCI), sensing technologies, and Augmented Reality.

Human–machine interfaces

Machines help humans to interface with their environment by improving accuracy and quality of life. Researchers use neurophysiological signals to develop neuro-prosthetics increasing brain–machine interfaces, augmenting the presence and interaction of injured individuals with their environment.[35,36] Another type of control system known as Myoelectric Control System (MCS) was used to develop an intuitive interface to assist amputees or disable people to control prosthetics based on the muscle contraction.[37,38] Human–Machine Interfaces (HMI) have also been explored in the area of sensory substitution for humans to replace lost sensory ability such as touch, sight, and vestibular function.[39] The study and research of human perception enabled by computer manipulation can change and overcome current frontiers to people's life and health. The symbiotic relationship between humans and machines can enhance safety and productivity in the next-generation manufacturing revolution. The protocol of establishing an interface with computers is gaining interest as humans become more open to using machines to do our day-to-day decisions. Researchers Bailenson[40] and Jofré et al.[41] 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 engage the user for immersive experience is one key area of interest for HMI research.

Human–environment interfaces

The human–environment interface relies on the ability of a human to perceive the surrounding environment. The conventional way of perceiving the environment is by human senses such as sight, sound, or touch. However, human perception solely relies on the human ability to see and detect the environment. It does not leverage the power of a machine to make an informed human decision. Artificial intelligence is an area in environment perception which utilizes the machine capability for human–environment interaction. There are three main areas of Artificial Intelligence for the smart environment: Pervasive-Ubiquitous computing, Human–Computer Interfaces, sensors, and Networks come together to form what author refers to as Ambient Intelligence (AmI).[42] 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–environment interface using sensors

The availability of sensing technology has facilitated technical innovation in environmental monitoring such as weather, air quality monitoring, indoor human movement, energy usage, thermostat, security systems, and many more. The distributed sensor network is believed to be the backbone of the IoT devices. When it is necessary to collect data and have the system process the information, humans have relied on sensing technology to accurately and efficiently do the job. Structure or infrastructure monitoring is carried out by a trained professional with some aid of technology. The interface between environment and machines is established by the use of sensing technology. The infrastructure inspection is one such area where usage of sensing technology is encouraged. Past researchers have also pointed out the use of low-cost sensor networks for automation in inspection work.[43] However, infrastructure inspection work relies heavily on human judgment to make decisions. Hence, the authors find this area appealing for researching on HII.

AR as a link between human, environment, and machines

AR has proved itself to be the most advanced technological innovation in terms of combining real and virtual environments.[44] 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 the IoT devices[45] and displays without having to interpret complex data analytics. This integration of these different technologies makes AR as a powerful visualizing technique for prompt decision making. Recently, researchers demonstrated quicker user awareness of their environment with AR.[46] While AR enables the users to interact with real-world structures using virtual environment, the real-time visualization of information is only the front-end application of the whole system. The information displayed through AR-enabled application requires the system to perform data acquisition using low-cost technology including, but not limited to, anomaly detection in data using machine learning techniques[47] and automated modal identification of structural system.[48] Some efforts are underway for using AR for enhanced bridge inspection work.[49] A comprehensive study would be required to know the links between HCI for appropriate use of AR and seamless integration with human-centered activities related to infrastructure inspection. This article addresses the challenge of integrating AR with available technologies such as wireless sensing technology and remote database for establishing a human–infrastructure interface. The authors of this article have identified structural inspection tasks as a testbed to implement the use of interfaces between inspectors and their environment with the help of computers.

Figure 1 shows the use of AR as the nexus of humans, computer, and the environment. Here, the term Environment implying infrastructures such as bridges, highways, buildings, and airports represents the majority of the built environment. The solution presented in subsequent sections discusses building an interface as guiding rules to develop applications that can be implemented to solve the inspection tasks. The interface consists of different components that make up the integrated solution for the field implementation. This interface architecture supports the well-established technology for monitoring, inspection, repair, and maintenance work by adding humans in the loop. The authors presented the fundamental components of AR as a tool for inspections, both in hardware and

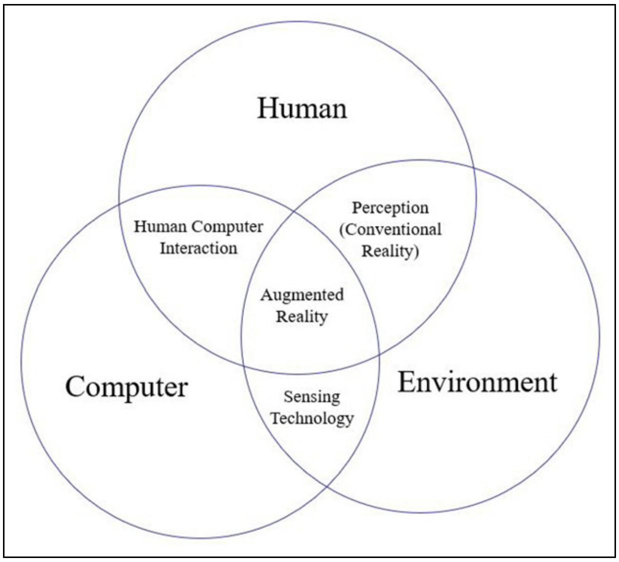

Figure 1. AR interaction with human, computer, and environment.

software contexts. The authors developed three new AR-based interfaces in the area of structural inspection, validated in the laboratory, and developed an architecture for human–infrastructure interfaces with AR. Finally, the authors added recommendations for future implementation of this technology for augmented human–infrastructure interfaces.

This article outlines the AR as a critical component of HII where humans, environment, and machines are three crucial components that integrate to make the interface possible. Humans and computers interact with an interface that can understand both human commands and can interpret to computer/machine level language. The other aspect is establishing a link between computers and the environment. Authors find the use of sensing technologies that sense the state of environmental parameters to be a valuable component in augmenting a human sense of environment. In the subsequent section, the authors describe each of the sections separately to make a case for AR as an enabling tool to link together the three main aspects of this interface.

AR enabling HII

The device used for this research is HoloLens, AR headset manufactured by Microsoft. HoloLens is a Head-Mounted Device (HMD) capable of projecting virtual objects in the 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 track the gaze of the user. The input/output peripherals of HMD like speakers, microphones, 3.5 mm 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.

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 us to view virtual objects. 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 is equivalent to 2.5k radiant (light points per radian).

Sensors. This HMD is equipped with various sensors to capture real-world environment data. It has four environments understanding RBG cameras and four microphones and each of ambient light sensors, a depth camera, and an Inertial Measurement Unit (IMU) sensor. 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. The total weight of the HMD used in this experiment is 579 g. The authors have used the device extensively during the course of several experiments, and based on the personal experience of the authors, there were no uncomfortable conditions due to weight of the device. It is worth mentioning that the newer HMD version has further decreased the potential discomfort that could be caused for extensive inspections.

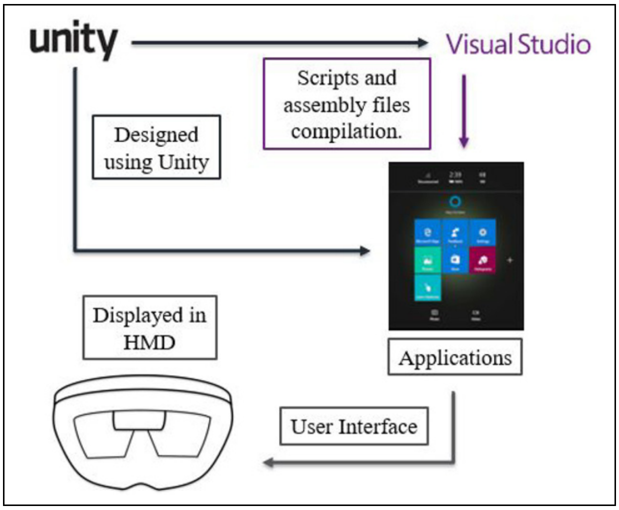

Figure 2. Workflow for developing AR applications.

Software development framework

The authors used the Unity game engine, a cross-platform software development package, to develop an application 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 2 shows the workflow for developing the application using Unity and Visual Studio.

The development of the application starts with the designing "Scenes" in Unity. These scenes later become the user interface for AR applications (Figure 3). 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, and toggle buttons. 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. This makes the Unity software agile for developers to adopt a component-based approach for developing AR applications.

The authors used Microsoft's Mixed Reality Tool Kit (MRTK) which uses inbuilt attributes like spatial mapping, voice, and gesture recognition to integrate into the applications. Additional critical components of AR application development such as input system, User Interface (UI) controls, gaze and gesture control, and 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

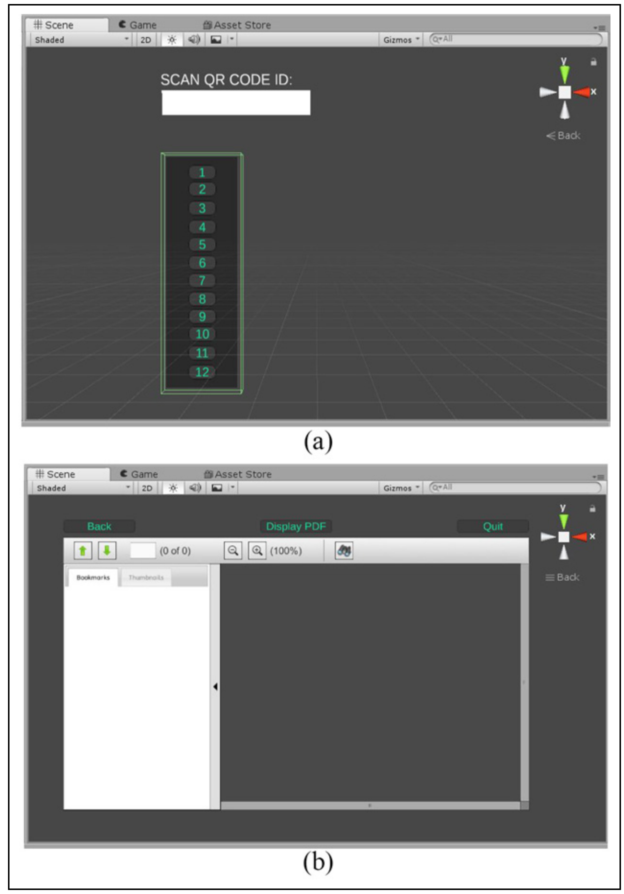

Figure 3. Scene samples before deployment in Unity: (a) a sample of a scene with an input field and buttons and (b) a sample of a scene to display PDF files.

HoloLens. In this research, the authors have presented two main applications 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.

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. In addition, it also contains "Gaze and Gesture Manager" to allow the inspector to interact with the GameObject.

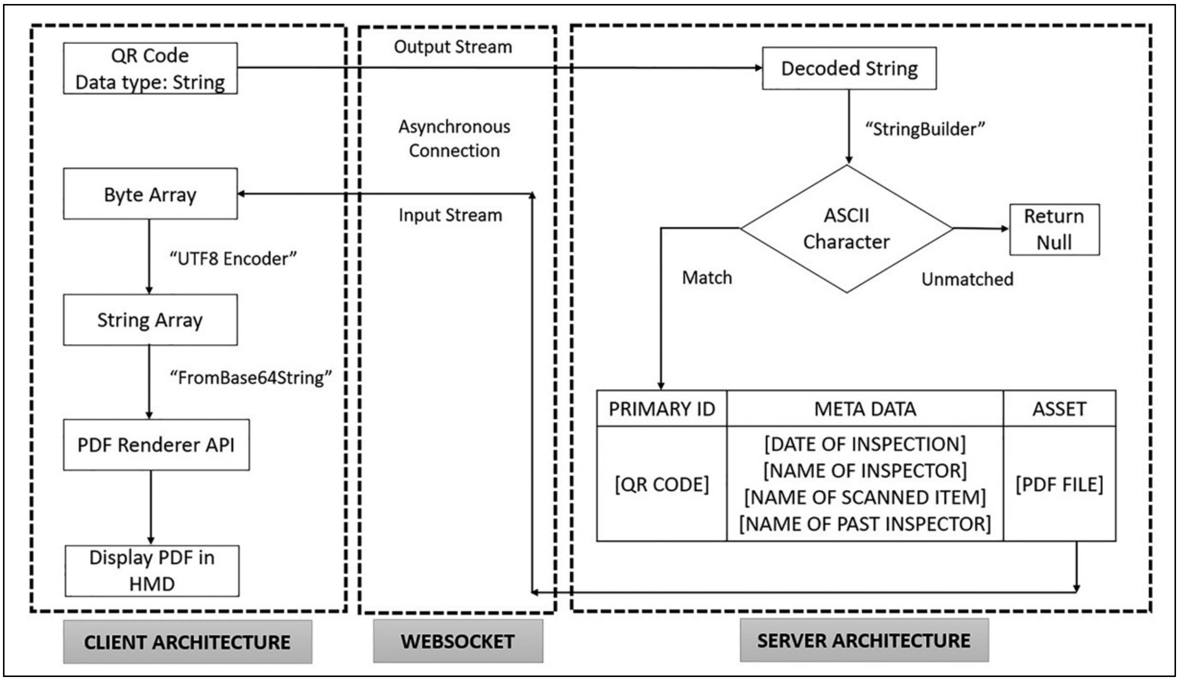

Figure 4. Components of WebSocket connection for Client and Server Architecture.

AR-database connection

The authors have 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 4 shows the architecture components.

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.[50] It establishes a persistent asynchronous connection which is ideal for creating real-time applications.[51] The asynchronous connection makes the WebSocket protocol ideal for data requests and listening for client-server architecture due to its event-driven nature. The authors used WebSocket protocol to design 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.

1. *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.
2. *Structured Query in Database*. The author built a Relational Database using 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

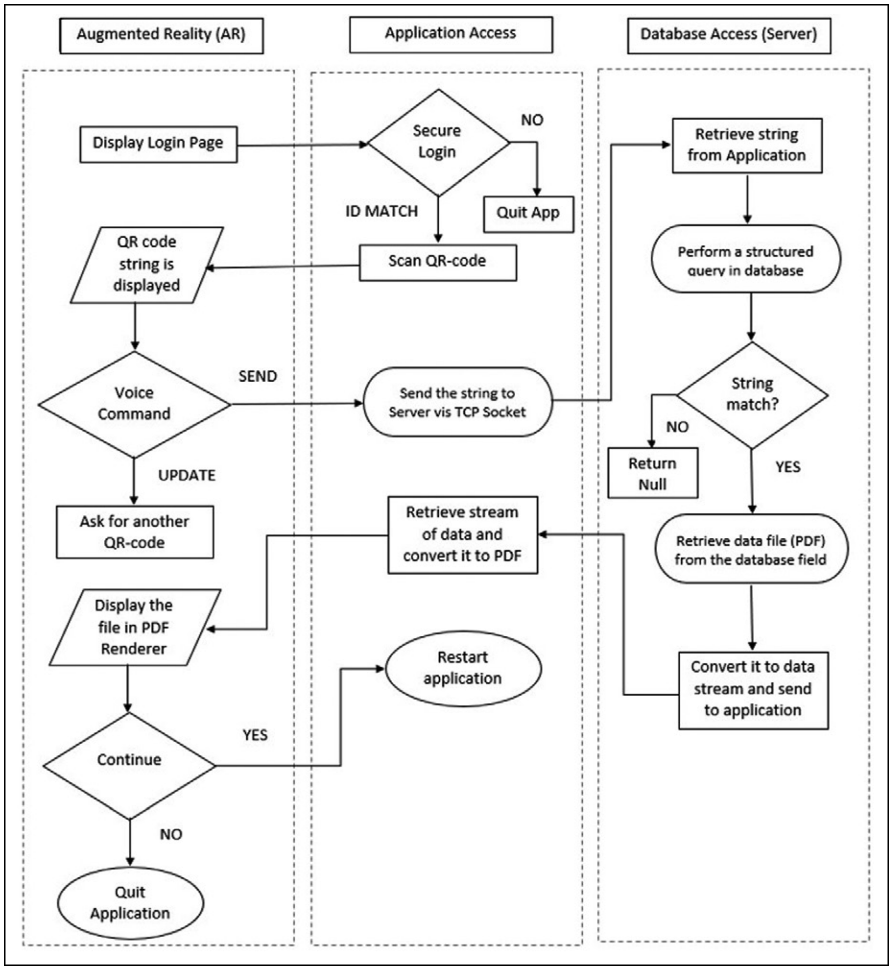

Figure 5. Flowchart showing three assets linked to the QR code scanner application.

network stream, the encoded byte array is transferred through WebSocket.

3. *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, and Meta Data contains information about the inspector and scanned items, Inspection Assets (PDF File).

Framework for AR-enabled infrastructure auditing

Infrastructure auditing refers to keeping track of inspection reports, maintenance history, inspector information, and updating database with new inspections. Figure 5 summarizes the three dimensions of interface interlinked within the architecture. 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 the AR device. The following section explains the steps:

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. The authors have used several keywords 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, and "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. The authors have used "PDF Renderer"[52] as the third-party application to display 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.

HII applications

Researchers demonstrated the applicability of AR in HII by creating two AR applications. The first application presents the AR interface for physical assets using QR code. This research project used a third-party software assets called PDF Renderer[52] to display PDFs within the application. The second application presented in the following section demonstrates the connection of AR with sensing technology. These applications have been developed for inspection works, data visualization through remote connection, or database query using QR as discussed in this article. The HII interface leverages the AR component in the application that can be utilized directly by the end users such as DOT officials, inspectors, or companies to implement in their workflow.

AR-QR code application

The use of markers for tracking AR has been used for the past two decades.[53–55] 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.[56,57] These technologies employ advanced tools such as machine learning and object recognition.[44] Maintenance of critical facilities such as aviation, nuclear plant, and mechanical industry using AR has been established in past researches.[58–60] 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, authors developed an AR application 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 authors have used the Safety Data Sheet (SDS files) 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 such as SDS in real time by accessing PDF files through the server. The transmission speed depends on the Internet connection in the area where the data are being

Figure 6. Twelve canisters were placed in a shelf with a unique identification QR code that was scanned using a QR code scanner.

accessed. Our experiments showed that the delay between the data transmitted and data displayed is less than 1 s.

This section shows two of multiple experiments conducted using AR-QR code application. Figure 6 shows the set of 12 canisters in a shelf. Without making a physical contact with the canisters, using simple hand gestures, the inspector was able to scan the QR code, establish wireless connection to the server, send the QR code for database query, and obtain PDF file into the HMD. Figure 7 shows the set of 12 rows of data in the database which is stored in the remote server computer. This database also contains the information of user and number of scanning operation performed to each of the canisters. In the first experiment, one of 12 canisters (Number 5 canister in this case) is scanned and displayed the result in the HMD (Figure 8). In the second experiment, number 11 canister was scanned, and results were displayed in the HMD (Figure 9).

The UI is controlled by hand gestures and voice commands making the application more intuitive and immersive. This application has been successfully demonstrated in a smart inspection of a nuclear facility in previous research by the same authors Mascareñas et al.[61] The results of these experiments are as follows:

1. The new interface enabled the inspector to access the specifications of cannisters by scanning their QR code without contacting the cannister. When the QR code was scanned, the access to data was under 1 s.
2. The inspector was able to quickly read each of the cannister's specifications from a set of 12 cannisters. The PDFs of the specifications were originated from a database which was updated and the inspector could access the information remotely. The research team chose 12 cannisters to demonstrate the scalability of this result to a larger number of cannisters for full implementation.
3. The interface enabled the inspector to conduct the reading of any cannister in any order, accessing the information of each database that is accessed by the AR HMD in very short time (a few seconds in between readings of two different cannisters.)

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 authors established the use of AR-enabled applications for a human–infrastructure interface.
2. This application allows agility in conduction of hazardous environment by allowing the inspector to view (hands-free) the critical information in the form of PDFs.

ID	BottleName	Scanned	ScanDate	Location	PastUser	Amount	CurrentUser	Files
070847811171	Acetone	☐			Dilendra	0	Dilendra	Package
070847811172	Isopropyl alcohol	☑	9/30/2018		Dilendra	2	Dilendra	Package
070847811173	Sodium hydroxide	☑	10/1/2018		Dilendra	6	Dilendra	Package
070847811174	Hydrogen Peroxide	☑	10/1/2018		Dilendra	6	Dilendra	Package
070847811175	Dimenthylformamdie	☑	10/1/2018		Dilendra	10	Dilendra	Package
070847811176	Ferric Ammonium	☑	10/1/2018		Dilendra	5	Dilendra	Package
070847811177	Methyl pyrrolidone	☑	9/30/2018		Dilendra	1	Dilendra	Package
070847811178	Piperdine	☑	9/29/2018		Dilendra	1	Dilendra	Package
070847811179	Sulfuric Acid	☑	10/1/2018		Dilendra	3	Dilendra	Package
070847811180	Trifluoroacetic Acid	☑	9/30/2018		Dilendra	3	Dilendra	Package
070847811181	Aerosol	☑	10/1/2018		Dilendra	7	Dilendra	Package
070847811182	Tangerine Essential	☑	10/1/2018		Dilendra	3	Dilendra	Package

Figure 7. A Microsoft Access database containing Safety Data Sheets specification for each of 12 canisters with unique ID numbers.

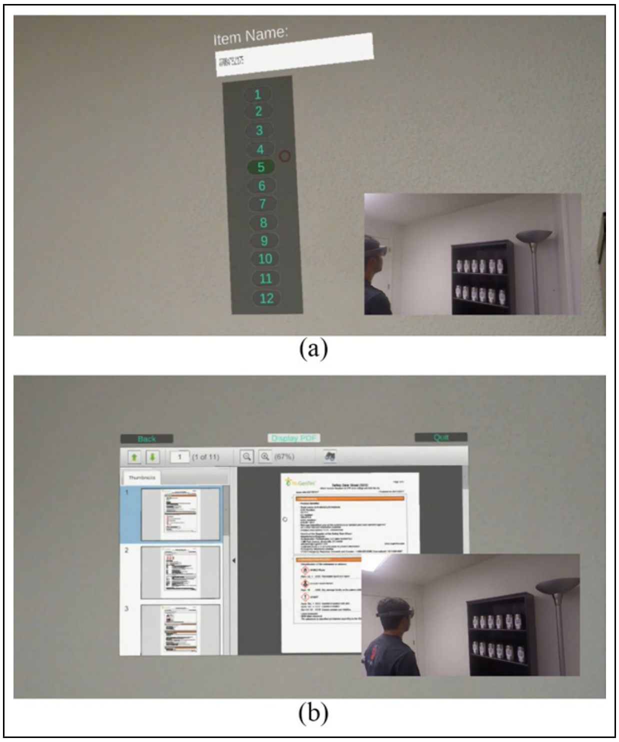

Figure 8. AR-QR code scanner result from first scan: (a) Canister #5 is scanned and (b) subsequently its respective PDF is displayed in HMD.

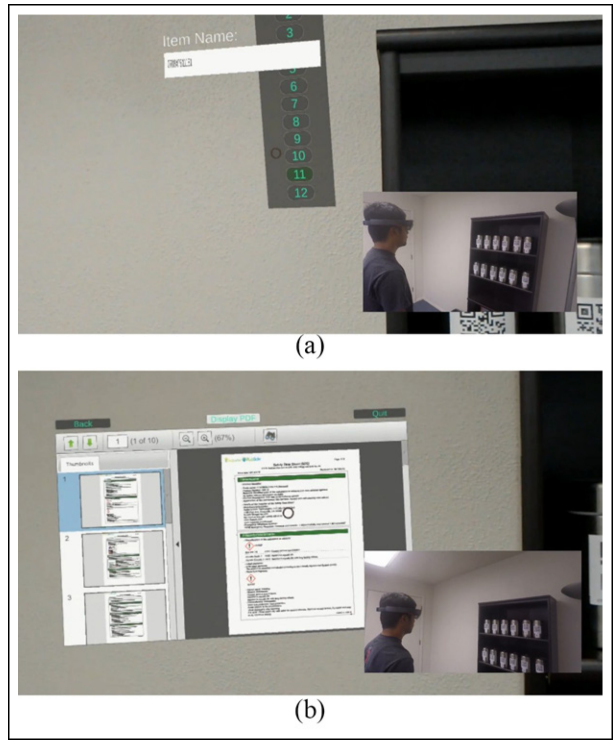

Figure 9. AR-QR code scanner result from second scan: (a) Canister #11 is scanned and (b) subsequently its respective PDF is displayed in HMD.

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 authors propose the use of AR-enabled inspection work. The AR HMD device was connected with a low-cost stain sensor to preview the strain data in real-time. The user/inspector can visualize the graphical strain data that are streamed by the SQL database via the Local Area Network (LAN). This can also be connected by the Internet if the data need to view from a remote location.

Low-cost strain gauge sensors. The authors 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 3.3 V 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 with the change in strain of the specimen to which it is attached. Using a calibration factor, the authors computed the strain in the samples.[62] The precision of strain gauge sensor used in this experiment was about 87% accurate in strain measurement.

AR connection to sensor. The strain gauge sensor is built to record and perform 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 are transferred using LAN to the HMD using a Wi-Fi connection or a hotspot connection for a remote location. For a hotspot located in outdoor environment with 2.4 GHz bandwidth, the maximum distance covered is approximately 300 ft. The HMD accesses the online database and displays it in its web browser. The different components of this demonstration are shown in Figure 10. The research team conducted multiple experiments using both a local server and also using a

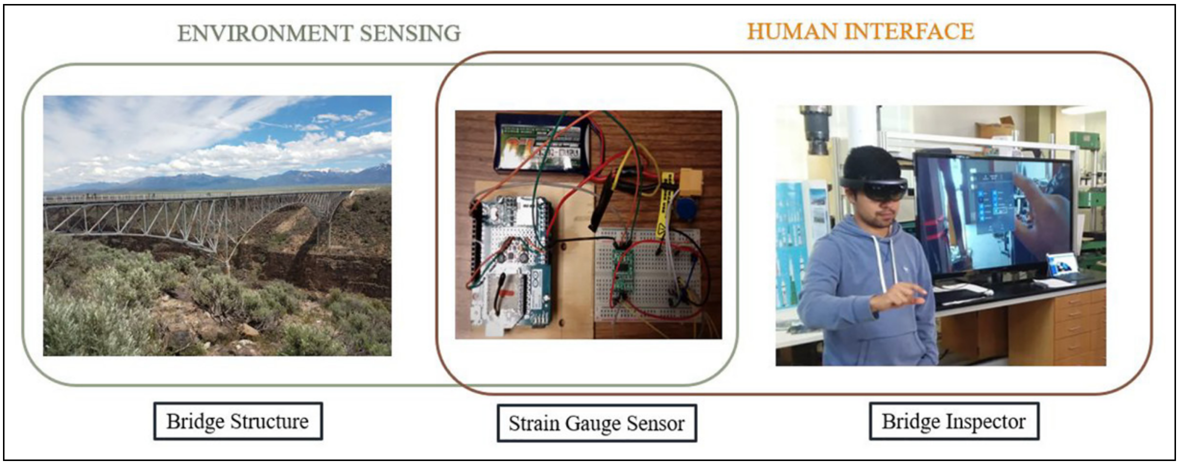

Figure 10. AR-enabled structure monitoring using a low-cost strain sensor.

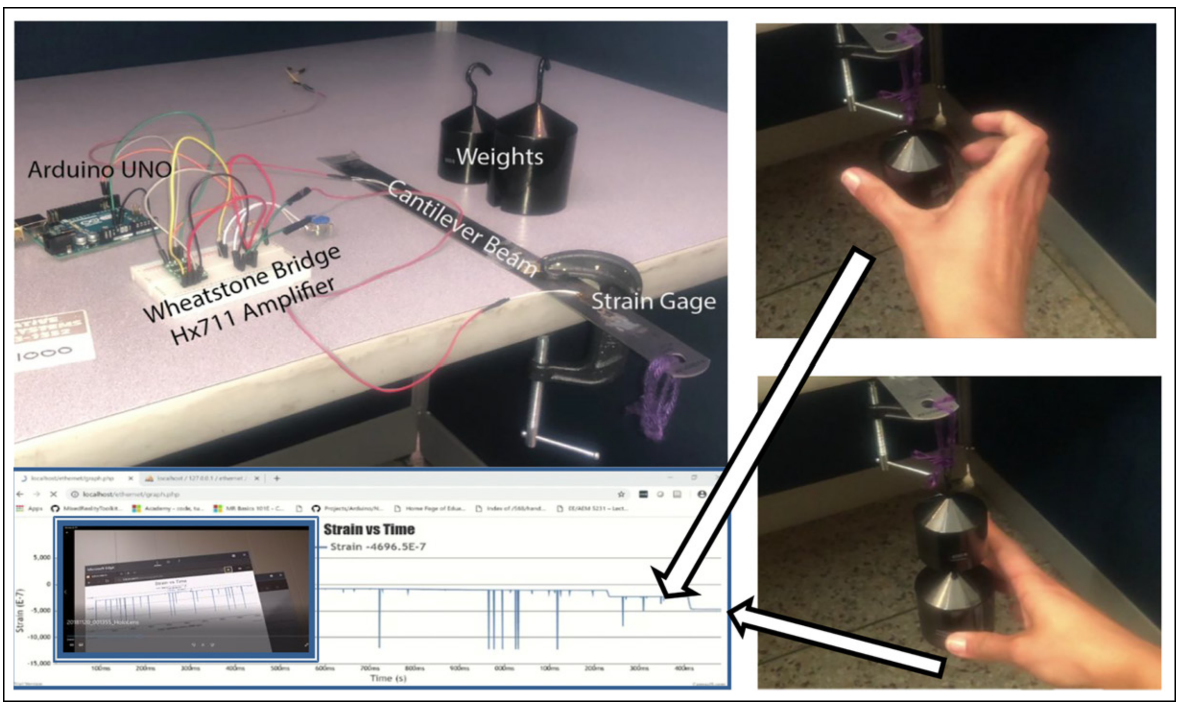

Figure 11. AR-strain gauge experiment (from top left, clockwise): experiment setup; loading cantilever beam with two different weights to check strain results; server view in the computer, and detail of the AR view with AR headset.

portable hotspot, in order to replicate real situations in the field where the transmission of data is limited. The experiments of data collection were conducted in various locations to validate the reliability of the hotspot outside of laboratory environments.

Figure 11 shows the setup of the various experiments. As shown in the top left corner, the setup allowed the researchers to test and validate the strain sensing with known weights and loads. The bottom left corner shows the interface with the server and the view with the AR headset of strain. The research team optimized the interface of the strain view. The AR-Sensor application was tested in five different experiments. The strain sensor was subjected to five different loading conditions. Figure 12 shows data from two experiments obtained from the strain gauge sensors. Similar graphs

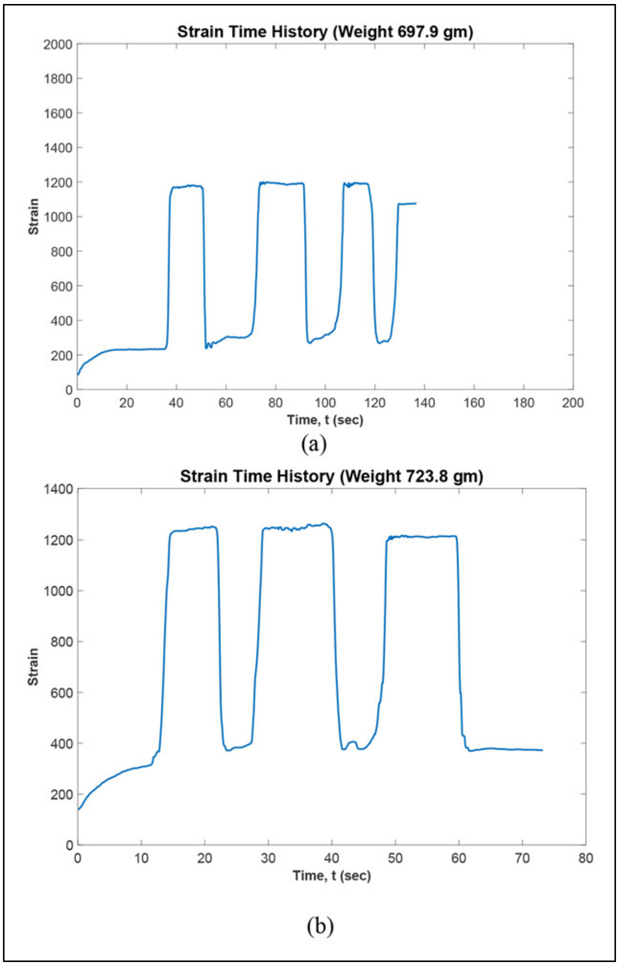

Figure 12. Two examples of time history data collected in the server from the strain gauge sensor: (a) experiment 3 and (b) experiment 4.

were displayed on inspector's HMD making a real time connection with the sensor. In the figure, each peak and trough represent a cycle of loading and unloading. For the purpose of this experiment, in order to reduce the likelihood of inaccurate data, average strain values were computed from multiple cycles of loading and unloading. For example, in Figure 10 (b), three cycles of loading were conducted. The average difference between peak and trough of these cycles give the observed strain in the test specimen. Similarly, the strain values were then obtained for each respective weight.

During a bridge inspection, the inspector will carry the portable hotspot that provides the Internet access to the area around the bridge. The size and weight of the portable hotspot fit in the AR HMD case and can fit in a small-size pocket. The data from a strain sensor can be streamed to the HMD via this portable hotspot. Since the data are available online, it will be possible to store the strain gauge data into the database using the hotspot.

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 authors successfully demonstrated the connection of low-cost strain gauge with the AR device. 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 system ensures high accuracy and reliability of data accessed from HMD, with no data loss occurring during the transmission,[62] for the results of strain data connection. In their experiment, the research team connected the AR HMD with a structure in a few minutes, enabling the inspector to visualize real-time strain in the AR HMD while loading the structure. The AR HMD display was compared with regular interface to ensure that both readings captured the same strain.
5. 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 section provides the comparison of data received from the sensor and datapoints transmitted through the server. Table 3 shows, for given five experiments, more than 95% of datapoints were accurately transferred. The erroneous datapoints might have been due to faulty connection or unregulated power supply of the sensor. No datapoints were lost during the transmission from sensor to the server. The authors believe that, with the accuracy of more than 95%, the strain gauge sensor is able to precisely capture the structural phenomena of the test specimen.

During the experiments, the authors noted that using AR HMD has not created discomfort in the researcher during the experiment, even if the data collection required extensive time wearing the HMD. Even this was not the scope of this research, future work includes human factors associated with using AR HMD to quantify comfort, safety, and trust.

Table 3. Data transmission accuracy of strain gauge sensor.

Experiment	Time (s)	Sampling rate (counts/s)	Estimate number of datapoints	Data point from the sensor	Erroneous points received	Accuracy (%)
1	183.8	10	1838	1838	40	97.8
2	191.2	10	1912	1912	25	98.7
3	136.7	10	1367	1367	43	96.9
4	73.2	10	732	732	17	97.7
5	174.8	10	1748	1748	48	97.3

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.

Conclusion

This article developed an AR-enabled human–infrastructure interface for inspection and monitoring structures. The authors utilized the novel concept of HII as the basis for developing AR-enabled technologies. This article built and validated a new human–machine interaction through the development of an AR application where the inspector is assisted by machine (AR HMD device) in the decision-making the process. The results showed that the inspector can use AR for infrastructure inspection with key information of interest that can be visualized hands-free during the inspection, which was not possible without AR. More specifically, this article developed two new uses of existing technology with AR: sensor-AR connection and QR code-AR connection. Using these two new AR developments, the authors developed a new interface for structure inspection on which other developers can build and deploy AR applications to make the infrastructure maintenance work more productive. The authors leveraged existing technologies such as low-cost sensing technology and AR tools 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 authors involves making the AR application used in the field and validating aspects such as safety of inspectors, new decisions and scenarios enabled by AR in the field, and characterization of protocols for human use of AR during inspections and emergencies informed by stakeholders, infrastructure owners and managers, and first responders with experience in human–environment interfaces.

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