Visualization of real-time displacement time history superimposed with dynamic experiments using wireless smart sensors and augmented reality

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Abstract: Wireless smart sensors (WSS) process field data and inform inspectors about the infrastructure health and safety. In bridge engineering, inspectors need reliable data about changes in displacements under loads to make correct decisions about repairs and replacements. Access to displacement information in the field and in real-time remains a challenge as inspectors do not see the data in real time. Displacement data from WSS in the field undergoes additional processing and is seen at a different location. If inspectors were able to see structural displacements in real-time at the locations of interest, they could conduct additional observations, creating a new, information-based, decision-making reality in the field. This paper develops a new, human-centered interface that provides inspectors with real-time access to actionable structural data during inspection and monitoring enhanced by augmented reality (AR). It summarizes and evaluates the development and validation of the new human-infrastructure interface in laboratory experiments. The experiments demonstrate that the interface that processes all calculations in the AR device accurately estimates dynamic displacements in comparison with the laser. Using this new AR interface tool, inspectors can observe and compare displacement data, share it across space and time, visualize displacements in time history, and understand structural deflection more accurately through a displacement time history visualization.

Keywords: wireless smart sensor; monitoring; augmented reality; displacement; acceleration; human-infrastructure interface

1 Introduction

Critical civil infrastructure components deteriorate with time due to wear and tear (Frangopol and Liu, 2007). Engineers need to inspect structures to establish that a damage has occurred and to accurately measure its deterioration. The information about damage must be precise, transmitted in real time and in a way that can be easily understood by inspectors (Chen and Ni, 2018a). In some structures, inspectors and managers use displacements and deflections to quantify their health and serviceability (Moreu et al., 2016). For example, AREMA (2014) recommends that timber bridges must be inspected “to determine evidence of excessive deflection, lateral movement, or longitudinal movement that may necessitate immediate closure of the structure to traffic.” Likewise, New York State Department of Transportation 2017 Bridge Inspection Manual states on page 254 that “when inspecting thru-girder shear splices in bridges, it is required to inspect for displacement of the connection, deformation of structural members, alignment and profile of members.” In practical terms, this means that inspectors and managers need to examine the data in their computers during train crossings and at the same time focus their attention and look at each element and the movement at the moment of crossing, so that they are able to continuously determine displacements and deflections in real time in the field by observing the effect of live loads on the structure with their own judgment without being distracted. So far, this issue has been problematic and has not received a suitable solution, though recently, a study by Wyckoff...
et al. (2022) showed that augmented reality (AR) successfully reduces human gaze distraction. In their work, they investigated human central vision, which constitutes an area of approximately 13 degrees around the area of fixation. The purpose of that work was to track human eyes so as to test human capacity to react and maintain awareness of reality with and without the application of AR tools. The results of the experiment demonstrated that while monitoring vibration data in AR, the participants’ gaze remained close to the primary area of focus and that they kept awareness of the vibration data while also maintaining the ability to use a handheld sensor to replicate the response of a sensor in focus. The participants’ performance was substantially better when they used an AR headset to monitor vibration data than when they saw the data on a separate screen; their work therefore indicates that when the data acquired from sensors is augmented, the inspector is able to concentrate better on the parts of interest in the structure, which gives more informed and reliable results.

Two types of sensors are currently applied to measure displacement: wired sensors (Casciati and Fuggini, 2011; Feng et al., 2015; Fukuda et al., 2013; Ribeiro et al., 2014) and wireless sensors (Casciati and Wu, 2013; Park et al., 2014; Shitong and Gang, 2019). Wired sensors include, for example, linear variable differential transformers (LVDT). LVDTs are robust sensors, with a very long life cycle, which can be used in harsh conditions and at high temperatures, but it can be challenging and costly to mount LVDTs to stationary reference points on large structures such as bridges which span big areas (Moreu et al., 2015). It is easier to install GPS sensors, whose modern variants have high measurement accuracy (Cranenbroeck, 2015), though sometimes not sufficient to identify minor displacements, such as those caused by train crossings on railway bridges (Chen and Ni, 2018b). Non-contact laser vibrometers often give satisfactory accuracy, but they cannot be used to measure large structures, as that would require applying high-intensity laser beams that endanger human health (Feng et al., 2015; Kohut et al., 2013; Nassif et al., 2005).

Given the disadvantages of wired sensors, wireless sensors (WSS) have received prominence recently (Liu et al., 2016). Researchers have determined through tests that they have a better technological potential, which makes them strong alternatives to the traditional wired counterparts (Chen and Ni, 2018b). For example, WSS have a very short deployment time (Chintalapudi et al., 2006) and the application of WSS gives large cost reductions, as WSS are considerably cheaper than wired sensors (Cao and Liu, 2012). The lower cost of WSS makes it possible to install many more sensors in different areas of structures, which gives more reliable and systematic monitoring (Zhang and Li, 2005). However, although WSS provide robust data to inspectors, there is a strong need to make the received data more accessible and easier to process. Inspectors deploy sensor networks in an area of suspected damage to obtain displacement data (Dargie and Poellabauer, 2011). Sensors measure a phenomenon collectively and process the obtained raw data before it becomes transferred to the base station (Ayaz et al., 2018; Sim and Spencer Jr., 2009). Most of the currently used WSS provide the necessary amount of data remotely to inspectors located outside the area of collection. However, the large and heterogeneous strings of data provided by sensors may be confusing for inspectors, who then find it difficult to immediately process and visualize the received information (Chen and Ni, 2018b; Entezami et al., 2020; Limongelli and Çelebi, 2019). The lack of sufficiently explicit information necessitates laborious and time-consuming data processing in the office, which results in decision-making delays about the necessary structure maintenance and repair (Chang et al., 2003; Chen and Ni, 2018b; Chen, 2020; Cross et al., 2013; Louis and Dunston, 2018). Furthermore, the data processing performed by inspectors on site can be disrupted by the geometry and the size of the examined structures. Some components, especially in bridges, are big and complex, and pose a challenge for inspectors to correlate the data obtained from sensors with the part of the structure that needs to be investigated, the exact location of the damage, and the sensor placement (Glisic et al., 2014; Napolitano et al., 2019; Shahsavari et al., Silva et al., 2019). To address these challenges, the researchers propose the application of a new human-centered interface that provides visualization of real-time displacements under loads using an AR tool. The AR-based interface will help inspectors to obtain integrated, visualized, and understandable information about displacements in real time, so that they can perform objective judgments regarding damaged structures. By visualizing the displacements, inspectors will be able to determine the degree and severity of damage; whether the structural damage is still admissible, or near or over the limit.

AR has been used in engineering since the 1960’s (Sutherland, 1968), but it has become more relevant to industry and structure monitoring only recently, with the miniaturization of AR and improved computing and processing power (Egger and Masood, 2020). The applications of AR tools for monitoring purposes to date include, for example, Behzadan and Kamat’s (2011) development of an AR tool to create realistic virtual objects in animations of engineering processes. In Behzadan and Kamat’s experiment, these objects were displayed as independent entities in AR scenes, with a possibility of manipulating their orientation, position, and size in an animation. Other applications of AR tools include workflows for facility management (Bae et al., 2013; Wang et al., 2013), design (Broll et al., 2004; Thomas et al., 1999; Webster et al., 1996), and for inspection (Shin and Dunston, 2009, 2010). More recently, the AR solutions have been applied by, for example, Mascarenas et al. (2019), who created
a toolbox for the AR device application in the smart nuclear facility development. In Mascarenas et al.'s (2019) project, a nuclear facility was designed to be modeled in virtual domains, and subsequently it was augmented on the users' screen, giving the stakeholders access to the real-time operations taking place in the nuclear facility. Morales Garcia et al. (2017) have adopted the AR headset to perform smart inspections of infrastructure, focusing on the integration of thermal images. Hammad et al. (2005) created an AR tool that assisted inspectors in the assignment of condition ratings to bridge components and allowed them to interact with the georeferenced infrastructure model by providing real-time information about the inspectors' position and orientation. Mascarenas et al. (2014) developed a vibrohaptic system for Structural Health Monitoring (SHM), which interfaced the nervous system of human beings to the distributed network of sensors installed on a three-floor structure. This structure contained three bumpers that induced nonlinearity that were capable of simulating damage, with accelerometers located on every floor to estimate the structure responses to the excitations of the harmonic base. The measurements provided by the accelerometer were preprocessed, and their data were encoded as vibrotactile stimuli. The human participants were subsequently exposed to the vibrotactile stimuli and requested to describe the damage in the structure. Webster et al. (1996) developed an AR model to enhance architectural construction and renovation by supplying maintenance workers with information about hidden elements, such as electrical wiring, underground components, and buried utilities, in renovated buildings, reducing the possibility of causing accidental damage to structures.

AR tools may also provide inspectors with an opportunity to overlay obtained data on the structure and to correlate the observations with the timeline of the investigation. Such data overlay is possible regardless of whether inspectors are present on the field or work offline, which makes investigation less expensive and available for implementation at any time, irrespective of potential time constraints. The data overlay may also improve data management and ensure that the way all engineers document and process data is more uniform (Genaidy et al., 2002; Gino and Pisano, 2008; Karwowski, 2005). However, a serious problem with most of these AR applications is that they overlap existing information in databases, and since they do not process real-time data, inspectors cannot perform decisions using the information coming from sensors in real time.

This work proposes a new human-centered access technology to make structural data (real-time displacements under loads) actionable to inspectors using AR. The researchers develop a new AR interface that gives inspectors located in the field better access to the physical structure under investigation and improves their analysis of the received information by visualizing data coming from the WSS in a graphic form. Specifically, the new AR interface enables inspectors to establish the degree of displacements and deflections by monitoring the effect of loads on the structure in real time. It also allows inspectors to make quick, well-informed decisions on the basis of their best judgment. This paper provides a summary of the design, the development, and the validation of the new AR interface. The researchers conducted three experiments. The aim of the first experiment is to compare the displacements obtained in the AR headset with a mobile phone camera. The aim of the second experiment is to validate the accuracy of the displacements obtained in the AR headset. For this purpose, researchers put the sensor over a shake table, then apply a displacement to the shake table and compare the displacements obtained from the WSS with the displacements obtained from a laser. The goal of the third experiment is to show historical displacement data and compare it with current displacement data. Through these experiments researchers have demonstrated that the application of an AR tool significantly improves the human-infrastructure connection on field, facilitates on-site observations, and ensures reliable, real-time data transfer from WSS to databases. Moreover, these experiments indicate that the two systems, WSS and AR, can be successfully integrated.

2 Visualization of real-time displacements with dynamic experiments

2.1 State of the art: WSS

This section presents the low-cost, efficient wireless intelligent sensor (LEWIS 2) and describes its components. LEWIS 2 consists of sensor, a transceiver, a microcontroller, a power source, and external memory (Akyildiz et al., 2002). Figure 1 presents the basic components of the wireless sensors (Aguero et al., 2019), whereas Fig. 2 demonstrates the assembled LEWIS 2.

The equation used for the estimation of the reference-free displacements make uses of the data coming from LEWIS 2 that uses an accelerometer as the sensor and then applies finite impulse response (FIR) filters (Lee et al., 2010).

![Fig. 1 Basic components of wireless sensors and connections](image-url)
\[\Delta_d = \left(L^T L + \lambda^2 I\right)^{-1} L^T L \bar{\pi}(\Delta t)^2 = C \bar{\pi}(\Delta t)^2 \quad (1)\]
\[\lambda = 46.81 N^{-1.95} \quad (2)\]

where \(\Delta_d\) is the dynamic displacement, \(L\) is the diagonal weighting matrix, \(\lambda\) is the optimal regularization factor, \(I\) is the identity matrix, \(\bar{\pi}\) is the acceleration data, \(L_t\) is the integrator operator, \(\Delta t\) is the time increment, \(C\) is the coefficient matrix used for the reconstruction of displacement, and \(N\) is the number of data points that correspond to the finite time window.

Moreu et al. (2016), Ozdagli et al. (2017), Park et al. (2014, 2016), and Aguero et al. (2019) provided a demonstration of the FIR filter in the dynamic displacement estimation. The researchers validated the estimation of displacement from wireless sensors after applying the FIR filter and compared the results with those obtained from commercial sensors. These validations showed that wireless sensors are able to accurately reconstruct displacements of railroad bridges under service traffic, with root mean square (RMS) errors of less than 13.60% (Moreu et al., 2016), 12.00% (Ozdagli et al., 2017), 10.48% (Ozdagli et al., 2018), 4.00% (Park et al., 2016), and 10.11% (Aguero et al., 2019) and transmit the data in real-time wirelessly. However, these solutions lacked an interface between the transmitted data and the professional on the field that could improve access to the data. This type of interface was developed in the experiment reported in this paper.

Although displacement or acceleration visualization on AR is independent of the type of sensors and visualization of data from wireless or wired sensors is identical, the researchers want to develop an AR capability to perform computational analysis of the headset, so that inspectors can walk on the field and see multiple displacements from acceleration data when they are closer to the sensors. For this reason, it has to be a portable headset and a wireless sensor. The installation of a wired sensor on AR would not be possible, as there would be no way to provide power to such a sensor. Moreover, the researchers need to use a smart wireless sensor combiner with smart AR that allows signal processing, as they need the visualization of reference-free displacements from the sensor.

### 2.2 The need of the interface

The main purpose of AR devices is to integrate actual objects with virtual holograms presented by computers in real time. AR tools fulfill this purpose by overlaying the visible attributes of real objects with their matching position on the computer display. When AR tools capture images from the sensors, the AR applications recognize the target, process the data, augment it with audio-visual information, and create illusions that make it possible for users to interpret real-world situations in greater detail. These additional synthetic overlays provide additional contextual data as well as the information that is unavailable otherwise to the user (Kalkofen et al., 2007; Kruijff et al., 2010). When inspectors use a laptop in the field, they put a laptop or a phone next to the bridge and they get distracted from the bridge element response. Furthermore, AR may enable a real-time interaction with objects and provide access to a precise three-dimensional representation of a structure (Schmalstieg and Höllerer, 2017).

AR comprises several technical subcomponents which use electronic devices to monitor the physical environment of the real world and to combine it with virtual elements.

The key elements which form an AR system are the following:

1. A device applied to capture images (for instance, a stereo, charge-coupled devices (CCD), or depth-sensing cameras).
2. A display applied to project the virtual data on the images received via the capturing tool. It is possible to distinguish two different technologies:
   - Video-mixed display—it gives a digital merge and provides a representation of the virtual and real data received with the camera on a display. The displayed images may show a limited field of vision and reduced resolutions.
   - Optical see-through display (for example, a projection-based system)—in this solution, the virtual data on the inspector’s field of view is superimposed by an optical projection system.
3. A processing unit which gives access to the virtual data that will be projected.
4. Activating elements that trigger display of the virtual information. These elements include, for example, sensor values from the accelerometer, GPS positions, QR (quick response) marker, images, gyroscopes, compasses, thermal sensors, and altimeters.

AR is a complex, novel technology that implements new solutions which juxtapose virtual and actual realities. The virtual reality is provided by sensory inputs generated by computers, which include images, video and sound effects. However, as the researchers...
pointed out earlier in this article, given the novelty of the AR technology, it has not been determined yet how the new AR solutions will impact the human-infrastructure interface, with potential unexpected challenges related to the human factors involved (see Hall et al. (2015) for an analysis of the AR solutions in railway environments).

2.3 New human-infrastructure interface for displacement visualization

2.3.1 Design

There are six stages in the AR interface development methodology that the researchers apply.

(a) Planning

This is the most important stage for the organization of the whole AR interface, which involves the completion of the following tasks:
- Identification of the AR interface that needs to be developed
- Drafting and creation of the AR interface plan

(b) Analysis

The purpose of the analysis stage is to address the inspectors′ needs and the requirements of end users. The collection of the inspectors′ requirements is the most important interface phase at this stage. These requirements are the functionalities that the AR interface under development must meet to be successful. Detailed requirements, such as a type of technological solutions applied in the AR interface implementation, are not determined at this stage.

(c) Design

The design stage determines the desired operations and required features of the AR interface. A flowchart was developed to clearly explain the AR interface and show the workflow of the system process, see Fig. 3. The flowchart indicates that when a user requires the visualization of the displacement data, the connection between the sensor and the AR device starts immediately, providing the inspector with the displacement data.

(d) Implementation

The development stage involves transformation of the flowchart from the previous phase into the actual AR interface. This stage includes the following two main activities:
- Database setup.
- Code development for the AR interface.

This stage is completed with the database creation and the development of the actual code so that the AR interface can be created following the provided specifications.

(e) Testing

The testing stage consists in the integration and deployment of all the pieces of the code in the testing

Fig. 3 Workflow of the new AR interface
environment. During the execution, the tester compares the actual results with the anticipated results, making sure that the AR interface operates as designed and expected. The tests need to be performed in a systematic and reliable way to ensure high quality software.

(f) Deployment

The deployment stage, also referred to as the delivery stage, involves AR interface exploitation in the real-life environment, often on the user’s premises, when the inspector starts operating the AR interface. During this stage, all the AR interface components and data become allocated in the production environment.

2.3.2 Real-time AR WSS displacement visualization

For a successful application of AR tools, it is necessary to consider a number of design principles of the system. For instance, it is crucial to determine the scope of AR functionality, so that it provides the amount of information that matches the user’s requirements. If the AR system provides too much data, the inspectors will not be capable of processing it or comprehending it, which may lead to confusion and human errors. Other restrictions that must be considered concern human learnability and efficiency of the amount of interactive data that an inspector can receive at a given time. The mechanism of the human-infrastructure interface is presented in Fig. 4, while Fig. 5 shows an example of an interface.

Figure 6 shows the way acceleration is demonstrated with the AR tool. The researchers deployed this application in Unity in order to obtain a graph of the information included in the database coming from the sensors, and they used C# to develop the source code of the application. The video capture in Fig. 6 shows that inspectors are able to receive visualizations of real-time changes of the acceleration, and in this way, they become informed of the dynamic nature of the structure. That data can be used to assess the health and condition of the structure, especially when it is combined with the knowledge of the environmental conditions and loading cases. According to inspectors, this technology could be applied to monitor the testing of live loads in quantitative manner in the field, with a potential additional field application of this framework in the future research (Moreu et al., 2019).

3 Hardware required for the AR-sensor application

3.1 The AR device

The AR headset used in this research is Microsoft HoloLens. It is a tool which allows interactions between a user in a mixed-reality environment and a computer. It has the form of a holographic computer that is attached to the user’s head. The AR headset is composed of the following parts and components:

1. A wide-screen, head-mounted, stereoscopic display (the resolution is 2k per eye, and the aspect ratio is 3:2). The display is equipped with holographic, colored lenses.

2. A depth camera (1 MP), coupled with additional four visible cameras and two infrared cameras. The sensors perform ambient light detection and environment sensing. The sensors receive input from the user with
an IMU that is equipped with an accelerometer, a magnetometer, and a gyroscope.

3. A set of five microphone channels with a system of integrated speakers, which make communication between the AR device and the user possible.

The AR headset contains a Holographic Processing Unit, with four GB of RAM. Furthermore, it is equipped with 64 GB of universal flash storage, and it supplies Bluetooth and Wi-Fi. The battery life is from two to three hours of active usage or maximum two weeks in the standby mode. The tool is not heavy (566 g) and is convenient to carry.

3.2 Advantages of the AR device

A remarkable benefit of the AR headset application in the process of collecting data is the ability to create holographic visualizations of data. The holographic visualizations generated by the AR device provide inspectors with data that complements the data they receive from the real world through their own senses. As a result, the AR headset produces an effect that mixes virtual and physical objects. This effect makes it possible for inspectors to interact with the received data and with the physical objects existing in reality, in their actual environment. The AR tool is equipped with powerful computing technology, which provides rapid visualization of complex information and enables reliable and quick task analysis. Furthermore, the AR headset is able to compute infrastructure, thanks to which inspectors can carry out physical operations and information analysis at the same time and within identical physical locations. Inspectors located in different areas can carry out a collaborative examination of the infrastructure concurrently in identical environments. They can also perform the same analysis in different scenarios, including routine infrastructure monitoring, as well as in disaster situations, when it is crucial to provide rapid representation of critical infrastructure.

3.3 The server

The server is a device whose function is to provide access to the sensor data in the Internet network via the AR device. The server used by researchers in this study is a Microsoft Surface laptop. The connection between AR and the sensors is presented in Fig. 7 (Aguero et al., 2020).

4 Software required for the AR-sensor application

The researchers made use of open-source software to support accessibility and affordability. The main exception was Unity 3D, for which it is necessary to receive a license. The features of Unity can be used free of charge, but this is not an open-source program.

4.1 Software in the sensor

The researchers performed the sensor programming using the Arduino Integrated Development Environment.

![Fig. 7 Connection between AR and sensors (Aguero et al., 2020)](image-url)
The Arduino platform is based on open-source software, and the environment is written in Java. It is possible to use this software with any Arduino board, which makes it easier to write the code and upload it to any Arduino-compatible board, as well as to any other vendor development boards when it is necessary to use third-party cores. In this way it is a very flexible solution.

4.2 Software in the server

The software installed on the server includes MySQL and Node.js. MySQL is an open-source database that is very popular worldwide due to its efficiency and accessibility. The role of Node.js is to execute the JavaScript code outside of the area the display programs. Node.js is supported on Microsoft Windows 10, Linux, macOS, and Windows Server 2008 (including subsequent versions). Node.js is primarily used to develop Web servers and other network programs, but it can also be used to create Web servers and JavaScript-based networking tools. The researchers wrote a script using Node.js in order to receive data from the sensor and store it in the database.

4.3 Software in the AR device

The researchers connected the AR headset to the server with an application developed in Unity. The researchers were in this way able to perform the projection of the data that was hosted in the database and transformed into displacements in the AR headset.

4.4 Sensor data to server

The researchers used the MySQL database to store the sensor data. This database contained the accelerations in \( x \), \( y \), and \( z \); the angular velocities in \( x \), \( y \), and \( z \); the field time; and the sensor ID.

4.5 Server data to AR device

The researchers made use of queries in PHP and SQL languages to access the data from the MySQL Database located in the Server. The experiment presented in this paper was an initial analysis of data visualizations, coming only from one sensor. In future work, the experiment can be easily expanded to a mesh of sensors.

4.6 Implementation of the AR interface

The researchers used Unity and visual studio with C# to develop the application and to graph the displacement information calculated from the accelerometer data stored in the database from the sensors, as shown in Fig. 8. The sensor sends information to the server through an XBee antenna. In order to receive the data coming from the sensor, the server has an Xbee antenna connected to an Xbee Explorer. Displacements were visualized in real-time, with a delay of approximately 2.5 seconds through the AR Headset.

The application receives the acceleration data coming from the wireless sensors and transforms this acceleration data into displacements, making use of an algorithm that will be explained in the following section.

4.7 Algorithm

The algorithm was developed by the researchers using C#. The algorithm requires acceleration data collected with a frequency of 300 Hz, which means 300 points per second, and all the data obtained from the sensor is stored in a database on the server. Then the AR device requests the data storage in the database and converts it into displacements, applying the algorithm showed in Fig. 9. In order to visualize the displacement in the AR device, it was required to resample the displacement from 300 Hz to 5 Hz. Finally, the user is able to visualize the displacement data. The number of points obtained as a displacement is exactly the same as the number of points of the acceleration data. The algorithm for the displacement calculation follows the equation showed in section 2.1. The program requests the acceleration from the server; the \( C \) matrix is predefined since the frequency of the sensor is known, then with the acceleration data and the \( C \) matrix, the researchers obtain the displacements. Once the displacements are obtained, they are displayed in a graph.

For the displacement calculations, the app installed in HoloLens makes a query to the acceleration data that is in the server. This query is made approximately every 0.5 seconds. In order to obtain the displacements with the acceleration data received from the query, the researchers applied the algorithm described earlier. Since

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![Diagram](image_url)
this application uses a fixed frequency, the researchers consider the C matrix as constant so the program does not need to recalculate the long matrix multiplications $\left( L^T L + \lambda^2 I \right)^{-1} L^T L_0$ continuously. This reduces the runtime down to approximately 1 second. Finally, once the researchers obtained the displacements, they plot this data as a collection of points and lines; this process takes 1 second, making the visualization delay a total of approximately 2.5 seconds. The complete algorithm for the displacement calculation from acceleration data was implemented in the AR device without the necessity of using an additional computer.

4.8 Code implementation for the interface

The user-server architecture for the human-infrastructure interface is displayed in Fig. 10. The communication between the user and the server is performed through the Internet. On the server side, a MySQL database is configured, a Node.js Script is developed to connect the sensor with the server and PHP Scripts have been written to send data from the server to the user. On the user side, the AR interface was developed in Unity 2018.4.14f1 and programmed in C#.

The code that the researchers have developed has some limitations at this stage. The main challenges that need to be addressed in the future are as follows:

- The code was tested in the new Microsoft HoloLens 2. To deploy the application in Microsoft HoloLens 1, it may be necessary to reduce the sampling rate of the graph that is being displayed, for example from 5 Hz to 3 Hz.
- In order to start the application properly, it is necessary to ensure that the table datalewis2 is empty. When it is empty, it means there is no data left from previous experiments and it is ready to perform a new experiment.
- The maximum number of data values that can be displayed at the same time with the current hardware is 100 points (5 Hz × 20 seconds).
- Because the communication between the server and the user is using the Internet via a wireless connection, the limitation of the application is related to the limitation of a wireless local area network: 150 feet or 46 m indoors, and 300 feet or 92 m outdoors.
- The internet protocol (IP) that the application uses should be updated when the application is used in a new Local Area Network (LAN).

5 Visualization of sensor data on the field

The interface consists of two sections, one called “current displacement” and the other one called “past displacements,” see Fig. 11. Each section is composed of an information area, which displays the time of the displacement and the maximum displacement, a graph area, which displays the time history of the displacement data, and the buttons area.

The current displacement section has the following options for the user (see Fig. 12):
- Display: Display the displacement of the structure at the current time.
- Stop: Stop displaying the displacements.
- Save: Save the current displacement data to be visualized later on.
- Delete: Remove the displacement data that has being visualized.
The past displacements section has the following options (see Fig. 13):
- Experiment: Show previous experiments
- Clear: Clear the data that is being visualized at the moment

6 Experiments and analysis

6.1 Set-up

The researchers attached the wireless smart sensor LEWIS 2 to the shake table, as shown in Fig. 14. The shake table utilized in the experiment is a Quanser Shake Table II. A Keyence laser IL600 with a range of 800 mm (400 mm back and forth) and an accuracy of 0.1 mm is installed to validate the displacements of the shake table obtained with LEWIS 2 and visualized from the AR device.

6.2 Signals

The researchers applied four different signals to the shake table, two sinusoidal signals with the details displayed in Table 1, and two train-crossing displacements recorded in Bluford Bridge by Moreu et al. (2015), with the details showed in Table 2.

The acceleration data from LEWIS 2 was collected at a frequency of 300 Hz, and the displacements collected from the Laser were collected at a frequency of 51200 Hz. The acceleration data from LEWIS 2 was converted into displacements in the AR device and was visualized in real-time, while the experiments were performed with a delay of 2.5 seconds, as shown in Fig. 15.

Moreu et al. (2014) argues that showing the time history is important because it reliably indicates the condition of the bridge. Moreover, recently Azim (2021) demonstrated that dynamic strain time-history responses that were obtained under baseline and unknown-state bridge conditions can be applied to obtain the magnitudes of differences in strain values between two successive time-steps.

6.3 Comparison

This work is the first step to perform computation of wireless sensors data in the headset by calculating (1) the time delay, (2) the accuracy of the amplitude, and (3) the frequency domain with the laser. The validation of the displacements obtained in the AR device after comparing them with the Laser is shown in Fig. 16. The root mean square (RMS) error was calculated following

| Signal number | Frequency (Hz) | Amplitude (mm) |
|---------------|----------------|----------------|
| S1            | 1              | 1              |
| S2            | 2              | 2              |

| Train number | Velocity km/h (mph) |
|--------------|---------------------|
| T1           | 24.9 (15.5)         |
| T2           | 31.1 (19.3)         |
the Eq. (3):

\[
E = \frac{\text{RMS}(\Delta_{\text{est}} - \Delta_{\text{meas}})}{\text{RMS}(\Delta_{\text{meas}})} \tag{3}
\]

where \(\Delta_{\text{est}}\) are the displacements estimated from LEWIS 2 and \(\Delta_{\text{meas}}\) are the displacements measured with the laser. The obtained RMS errors for displacements in time domain are displayed in Fig. 17.

Apart from the comparison of the displacement time in history, this paper also developed an analysis of the frequency history through the power spectrum density (PSD) of the displacements. Figure 18 shows the PSD of the displacements of LEWIS 2 using AR vs. the laser. The PSD were calculated in Matlab by means of Welch’s

![Fig. 15 Real-time displacement visualization from the human-infrastructure interface. (a) displacement from S1, (b) displacement from S2, (c) displacement from T1, (d) displacement from T2](image)

![Fig. 16 Comparison real-time displacement visualization vs laser. (a) displacement from S1, (b) displacement from S2, (c) displacement from T1, (d) displacement from T2](image)
method. Figure 18 presents the dominant frequencies in the range of 0–20 Hz, which take into consideration the field monitoring experience in bridges of other analyses (Moreu et al., 2014, 2015). The PSD of displacements obtained from LEWIS 2 are comparable to the PSD obtained from the laser. The sources of the error in the displacement estimation are due to data transmission losses between the Sensor and the Server through the Zigbee protocol; data transmission losses between the Server and the AR Device through the transmission control protocol combined with the internet protocol (TCP/IP), and due to the $C$ matrix static. The error estimation for this application is around 20%, which is a first contribution toward improved accuracy, and it is in line with the range of acceptable errors for SHM of railroad bridges between 10% and 20% (Moreu et al., 2015; Aguero et al., 2019). The experiment provides a first estimate of the displacement of railroad bridges in the field, with an approximate value that is more accurate than the visual observation of the inspector. This accuracy can be improved further by increasing the sampling rate of the sensor and by enhancing the protocol for communication between the sensor and the server from Zigbee to Wi-Fi.

To summarize, the results of the experiment presented in this section demonstrate that the displacements visualized with the AR device provide accurate estimates of the dynamic displacement. The new AR human-infrastructure interface gives comparable performance results to those produced by the commercial laser.

The results have shown that it is possible to visualize displacements in real time with a delay of 2.5 seconds in the AR device, with an error of less than 20% in time domain. The largest error in time domain was 19.96% for $T_1$; the other three errors are under 13%. The RMS errors for displacements in frequency domain are summarized in Fig. 17. The results have shown that the maximum error in frequency domain was 6.43% for $T_1$; the other three errors are under 3%, see Fig. 19. The results shown in this research are accurate for field sensing of dynamic displacements under different loads that are currently not available in the field.

### 6.4 Time machine for temporal displacements

The developed interface is able to show historical displacements visualized previously, so in this way it is possible to make a comparison between two displacements. The graph in the upper part of Fig. 20 is the current displacement, and the graph in the lower part is the historical displacement. In Fig. 20, the researchers can observe that the current displacement has a maximum value of 5.98 mm and the past displacement has a maximum value of 3.90 mm.

### 6.5 Future work

The experiments presented in this paper are an initial analysis of data visualizations, coming exclusively from one sensor. In future work, the researchers may expand the experiment to a mesh network of sensors. However,
during the AR headset application to a mesh network of sensors, the researchers pasted a quick response (QR) code to every sensor. In this way, every QR code became associated with the ID linked to each sensor, and the inspector can choose a sensor for scanning with the QR code reader. Afterwards, the AR tool will automatically identify the sensor with its respective ID. The method of QR-ID pairing enables filtering the relevant data coming from the database, providing only the information that corresponds to the sensor selected by the inspector (Kan et al., 2009; Mascarenas et al., 2019).

In order to receive additional feedback, the future work on this project will include benchmarking the new human-infrastructure interface for measuring displacements of different structures. The field testing could then be performed on a real bridge under different loads events.

In the next step of this research, the implementation of the new interface will be performed with a more advanced sensor LEWIS 5, which improves the wireless data transmission in comparison with the currently used LEWIS 2 sensor.

The general purpose of the research presented in this paper was to determine whether the HoloLens could compute the displacements and how to establish potential time delays and amplitude or frequency errors.

Additionally, it would be valuable to quantify live loads crossing the structure using strain gauges attached to the structural elements and a finite element model (Ozdagli et al., 2017). Therefore, a suitable solution might be to install strain gauges on the bridge and obtain strain that occurs during a train crossing, then inspectors can see bridge weight in motion. This framework would be of value so the inspector could also observe with AR assistance the projection of shear and moment diagrams on the bridge under crossing events. HoloLens could then be used to assist inspectors in their observation of these diagrams in real time, but this would require the development of an algorithm in the HoloLens that includes a connection between a finite element model of the structure and the strain data. The work developed in this paper is a first step toward real time computation on the HoloLens and future work in this area developing finite element and model integration with data in HoloLens such an algorithm in the future work.

7 Conclusions

This paper developed a new interface for measuring displacement calculated from the accelerometer data, which is obtained with a wireless smart sensor LEWIS 2. The crucial component of the interface is the AR headset HoloLens 2 from Microsoft, which allows the calculation and the visualization of the displacements in real time. The researchers conducted an experiment where they validated the displacements observed in the interface, using LEWIS 2 and a laser, and obtained errors in the displacement calculation of less than 20%, and the maximum error of 6.50% in frequency domain in comparison with the laser.

The results of the experiment have shown that the AR interface developed in this paper improves the inspectors’ ability to analyze the displacement data provided by the WSS in the field. It allows inspectors to have better access to both the physical structure under investigation and the observed displacement data that can be monitored live in a transparent, practical, and realistic way. By using the AR interface, inspectors can interact with the real world directly hands free, enhance their understanding of the physical behavior of structures, and quantify this behavior in real time. They can monitor the augmented information, determine the degree of displacements and deflections by examining the effect of loads on the structure in real time and compare the obtained data across time and space, modifying their decisions in real time if necessary. In this way they can also contextualize the data information with the behavior of the structure and establish whether the structure undergoes too much movement using with their own judgment.

More generally, the AR interface developed in this paper strongly improves SHM procedures. It enhances the inspectors’ capacity to implement required, well-informed decisions about structure maintenance, to precisely assess potential risks or on-site damage,
as well as to establish the accumulation of defects which grow in time. This leads to more accurate and quicker observations of displacement and subsequent prioritization of necessary infrastructure maintenance decisions. The AR tool also ensures appropriate documentations of performed inspections with high quality data, which may reduce the variability observed in inspections performed manually.

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