Virtual Tour (VT), Informational Modeling (IM), and Augmented Reality (AR) for Visual Inspections (VI) and Structural Health Monitoring (SHM)

FINAL REPORT
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16. Abstract

Existing infrastructure in the U.S. is deteriorating; the symptoms of overdue maintenance and underinvestment are ever-present in our society (rated with D+ by American Society of Civil Engineers, ASCE). To ensure the safety of existing infrastructure, on-site life-time inspections and monitoring are required. While these methods yield a great deal of raw and analyzed data, current methods for their simple and intuitive management, (i.e., simple and intuitive integration, documentation, access, and visualization), are severely lacking and can lead to mismanagement of infrastructure resources. To enable both on- and off-site documenting and viewing of infrastructure a novel method was developed in this project, which combines image-based documentation, Virtual Tours (VT) and informational modeling (IM), and augmented reality (AR). A cross-platform, client-server system for creating, saving, and viewing annotations was designed and implemented. The strengths and weaknesses of this implementation were addressed, and the accuracy of the approach was evaluated. The findings of this work show the promise of VT/IM/AR as a useful framework for documenting the built environment and assisting access and visualization of data and metadata related to SHM and visual inspections. This work presents a prototype and includes the proof of concept and real-life application.

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This report is, in large parts, based on the published papers listed in References.

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Table of Contents

List of Figures

List of Tables

DESCRIPTION OF THE PROBLEM

Existing infrastructure in the U.S. is deteriorating; the symptoms of overdue maintenance and underinvestment are ever-present in our society (rated with D+ by American Society of Civil Engineers, ASCE). To ensure the safety of existing infrastructure, on-site life-time inspections and monitoring are required. While these methods yield a great deal of raw and analyzed data, current methods for their simple and intuitive management, (i.e., simple and intuitive integration, documentation, access, and visualization), are severely lacking and can lead to mismanagement of infrastructure resources. New technologies such as virtual and augmented reality, combined with informational modeling, have a great potential to overcome this issue.

Currently, there are three challenges with how the SHM and visual inspections (VI) data and metadata records are managed:

(1) The heterogeneous nature of the data and metadata (e.g., drawings, dynamic measurements, static measurements, photographs, camera streams, notes, etc.) makes it difficult to access and visualize.

(2) The size and geometry of infrastructure components (e.g., bridges) are large and frequently complex, which presents a challenge to directly correlate the data with metadata (e.g., sensor readings are not directly correlated with their position, results of data analysis with the location of the damage, etc.).

(3) A diverse audience consults the infrastructural data and metadata; the inspector, operator of monitoring system, evaluating engineer, and decision maker are frequently not the same person for an infrastructure project. They may have different backgrounds and needs in terms of documentation. Therefore, how they manage (register, update, consult, understand, and use) the documentation differs.

The above challenges raise problems in understanding and interpreting the data, and consequently in identifying and making optimal decisions.

APPROACH

We identified a need for a novel method and associated software that will enable effective correlation between heterogeneous datasets, intuitive access and visualization of data and metadata, and diverse audience to manage it. This method is based on Virtual Tours (VT), Informational Modeling (IM) and Augmented Reality (AR).

The VT component creates a platform that physically integrates data and metadata in an intuitive manner. It enables a user to virtually “walk” through a site and identify points of interest, and link collected, accessed, or visualized data and metadata to those points through IM. Points of interest can involve both very local data and metadata (e.g., related to cross-section) and global data and metadata (e.g., related to entire structure or part of it).

The IM component, coupled with the VT, is what enables direct access and visualization of data within the VT. Action is taken through “hotspots” – clickable icons that activate the access and visualization. Actions can be chosen from a large set of possibilities. For example, VI and SHM data (raw, processed, and/or analyzed) and metadata (sensor properties, geometry of structure, materials used, finite element simulation, etc.) can be accessed through remote connection to database and visualized in various formats (e.g., tables, graphs, images, etc.) at local and global scale, embedded within VT. While the VT and IM environments are a viable option for viewing and annotating the information management system off-site, they are not efficient or intuitive for on-site purposes. For this reason, the creation of an AR component is necessary.

The AR component is comprised of a sparse point cloud with the main purposes of documenting, integrating, and visualizing the data and meta-data during the on-site visit (e.g., inspection, assessment, NDE tests, etc.).

METHODOLOGY

The aim of this work was to create a method and associated software for integrating, documenting, accessing, and visualizing (i.e., managing) lifetime inspections and monitoring data and metadata of infrastructure using virtual tours (VT), informational modeling (IM), and augmented reality (AR). Validation of the method was performed on Streicker Bridge in Princeton, NJ.

The work contained three main tasks: (1) Generating VT/IM environments for off-site data management (2) Enabling on-site upgrades using AR, and (3) Validation, testing, and technology transition. These tasks are described below.

Task 1: Generating VT/IM environments for off-site data management

This task focused on VT/IM environments which are built with a cyber-physical user in mind and are flexible for any future updates in the needs of the users. This was done using the Unity Game engine. The spherical panoramas were embedded in the game engine using the GPS coordinates to geo-locate them. Annotations were facilitated within the VT/IM in a similar fashion to the preliminary version – through on-click conditionals. This enabled an environment creator to be more flexible than using the preliminary version since the annotations will be scriptable and not “out of the box.” As an outcome of this task, a framework on how VT/IM environments can be used as a tool for VI and SHM was created. A demonstration VT/IM environment was created and tested to ensure that it is flexible enough to meet the needs of a diverse user group.

Task 2: Enabling on-site upgrades using AR

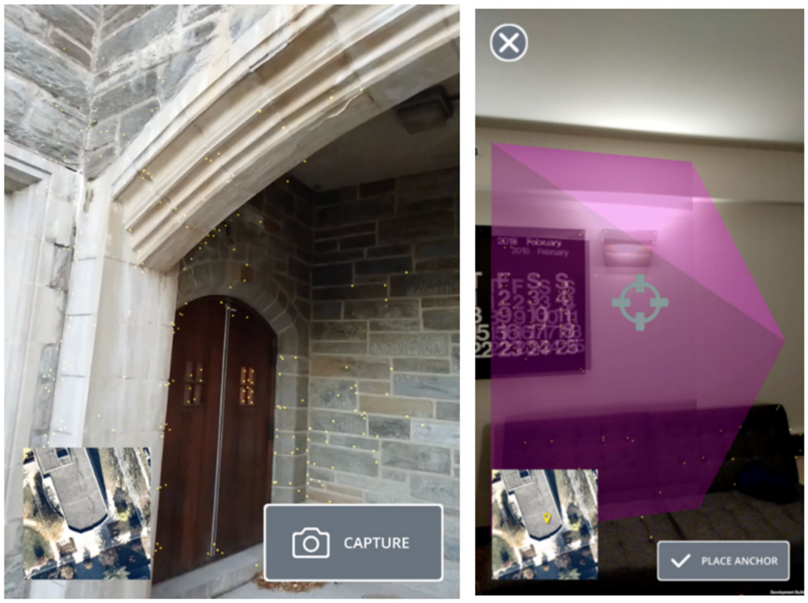
VT/IM method alone is limited in that (i) it is not able to update the VT/IM environment on-site and (ii) it does not allow a user to directly interact with the environment when they are on-site. Using the VT/IM alone, a user can open the VT and access data independent of the environment around them. If a user were to use this tool on-site, they should be able to interact with the data in a more intuitive and connected manner. Thus, it is necessary to create a method and associated software that would also be able to access previous data on-site through AR. By enabling an on-site user to visualize and interact with the data, this increased the accuracy, efficiency, and usability of the overall method. The real-time display of sensor data through AR enables infrastructure decisions at the site, instead that at the office. Similarly, the data and metadata collected in the field was programmed to be anchored in the field to provide cyber notes for inspectors across time and space, as opposed to purely cyber notes that are generally not linked to physical locations. As an outcome of this task, a formulation of how AR can be used for on-site VT/IM environment upgrades was established. A demonstration of VT/IM/AR was created and tested to ensure that it meets the needs of a diverse user group.

Task 3: Validation, testing, and technology transition

The VT/IM/AR method was validated using Streicker Bridge at Princeton University campus In the ending stages of validation, technology transition activities were performed in form of TRB webinar, presentations, and published papers. To test the efficiency of the proposed method, the VT/IM/AR environments was directly compared to comparable existing methods such as those based on simple images and drawings (2D methods) and more sophisticated Building Information Modeling (BIM – 3D method). The methods were compared in terms of time for preparation, size of data files necessary for storage, and the cost of implementing. This verified that the resulting method was cost-effective (i.e., efficient). To ensure that the proposed method was effective, the different methods outlined above were also be given to a group of beta testers accompanied by a survey. This survey showed that the environment can convey heterogeneous datasets for a large, complex structure to an audience consisting of students from a variety of backgrounds in classes taught by the PI.

Unity Game Engine was used for cross-platform development as it supports open-source programming for headsets, computers, web addresses, and mobile devices. By building the framework for the project in such a versatile manner, the goal was to not rule out any future users or capabilities of the program. Unity's ARInterface library was used to support the cross-platform AR features in this application. ARInterface is an abstraction over ARCore and ARKit which works with android and iOS devices to facilitate a broader application. ARInterface enables an application to perform estimation which involves predicting the position and rotation of the device in 3D space. This works by combining data from inertial sensors, including the built-in accelerometer and gyroscope, with visual tracking using the camera. As the user moves their device around the environment, ARInterface tracks the movement of key points in the scene to measure how long it is moving. These key points make up the raw point cloud (Figure 1A). The point cloud is composed of key feature points in a user's surroundings. This point cloud is critical to the current prototype's implementation as it provides interactive depth information about a space. This point cloud can be combined with a technique called raycasting to enable selection of certain points in space to place annotation on.

There are two types of annotation tools in the current prototype: image-based and point cloud-based annotations. The image-based annotations refer to annotations (in this prototype, drawing) directly on the flat image itself, while point cloud-based annotations refer to annotations made in the AR environment. Drawing was used as a prototype feature however the same scripts for augmenting, accessing, and storing data can be used to develop additional functionality. The simplest type of annotation is the ability to draw free form lines on the image itself. This component works by detecting when the user touches the image plane, and tracing the location of their movements on the surface of their tablet or mobile device. The component then plots the captured positions on the image and this is saved to a server. A more interesting type of annotation is the ability to draw directly on surfaces in the scene, even when the surface is not parallel with the image plane. For example, the user may find it more expressive to annotate the surface of a curved wall, a task which would not be possible on a flat image. This is made possible by leveraging the AR toolkit's raycasting feature to determine the geometry of locations in the scene.



A **B**

Figure 3: (A) Image showing the initial capture interface; the yellow dots are the point cloud. (B) Image showing the application reanchoring an image. The pink pyramid represents the relationship between the camera position and image plane in terms of position and pose [1].

Using this input, the user can draw lines directly on surfaces in the scene by moving their device around the area to capture the point cloud. Rather than moving the position of the user's mouse or touch input as with image-based annotations, the point cloud-based annotations use the AR raycasting tool to locate the coordinate on the screen. Connecting together multiple coordinates, the component captures the desired outline. Using the raycasted coordinates, the drawing can be rendered directly within the point cloud. However, to make these annotations visible on a desktop, projection back to the image plane was necessary. This transformation is performed by projecting a ray starting from the image's original camera location, through the image plane, and ending at the surface point in the scene. The intersection of this ray with the image plane provides the coordinates needed to render a drawing directly on the image. If the image is properly positioned, then the drawing on the image plane will appear to be located at the same spot as the drawing in the point cloud except flattened onto the image. This approach provides the benefit of being able to perform AR annotations that can also be viewed on a 2D screen off site.

While AR interface offers precise positional tracking, this method is subject to drift over time as it uses the relative positioning from one camera to the next as a basis. To minimize the adverse effects of this high-precision, yet low-accuracy method, the out-of-the box tracking with ARInterface has been augmented using GPS. As GPS utilizes an absolute location, it is not subject to drift over time as the AR methods are. However, a shortcoming of only relying on GPS data is that it is not precise. Thus, by combining the two methods, the adverse effects of each can be mitigated.

To combine the methods a Kalman filter was used to incorporate data from each source. Kalman filters are a statistical estimation technique for predicting the true state of an underlying system using a sequence of noisy output data. It is an optimal estimator as it is able to minimize the covariance of the predicted output even if the individual measurements are noisy. Kalman filters are composed of two main parts, the process update step and the measurement update step. For this application, the AR position was used as the process update step since the AR framework determines the position of the device using a relative calculation from one frame to the next. Then GPS is used as the measurement update step. Each GPS location update provides an “accuracy” parameter which represents the precision of this measurement as determined by the strength of the received signal.

There are five main tenants to SHM monitoring:

(1) defining the SHM plan.

(2) installing the SHM sensors.

(3) operating and maintaining the SHM system.

(4) managing data and metadata associated with a system.

(5) closing out of the SHM system (if applicable).

Our prototype in particular is useful for the documentation, organization, and visualization of the data and metadata associated with SHM systems (tenant 4). As visualization of SHM data is commonly a “bottleneck” for disparate parties collaborating on a SHM system, an application that facilitates organization of heterogenous data sets for both on and off-site viewing is a critical undertaking. While this work presents a very early prototype using only drawing annotations, it provides an understanding into how combining image-based and point cloud-based annotations could fill a gap in existing methods for visualizing SHM systems.

FINDINGS

Virtual Tours (VT) and Informational Modelling (IM)

Streicker Bridge, a pedestrian bridge on Princeton University’s campus, is comprised of a deck-stiffened arch and four continuous curved girders termed “legs” throughout this paper. Between 2009 and 2010, the bridge was outfitted with discrete Fiber Bragg-Grating (FBG) long-gauge sensors and distributed Brillouin Time Domain Analysis sensors (BOTDA). In addition to these fiber-optic sensors, the bridge is also outfitted with FBG-based displacement sensors at the abutment of the southeast leg. More recently, the bridge was instrumented with several new sensor types called “sensing sheets”. Figure 2 shows the typology and layout of the sensors in plan and in section. In plan, the locations of the parallel sensors, prestressing tendon, sensing sheet, and the displacement sensor can be seen along the south section of the bridge. The cross section is taken at the location on the southeast leg with the sensing sheet.

Due to the complex 3D shape of the bridge (Fig. 3) and 3D topology of sensors, as well as the heterogenous typology and composition of the SHM system (Fig. 3), Streicker Bridge was a good candidate for testing the new 3D data visualization method based on VT/IM method. More details about SHM system on Streicker bridge can be found in Reference [2].

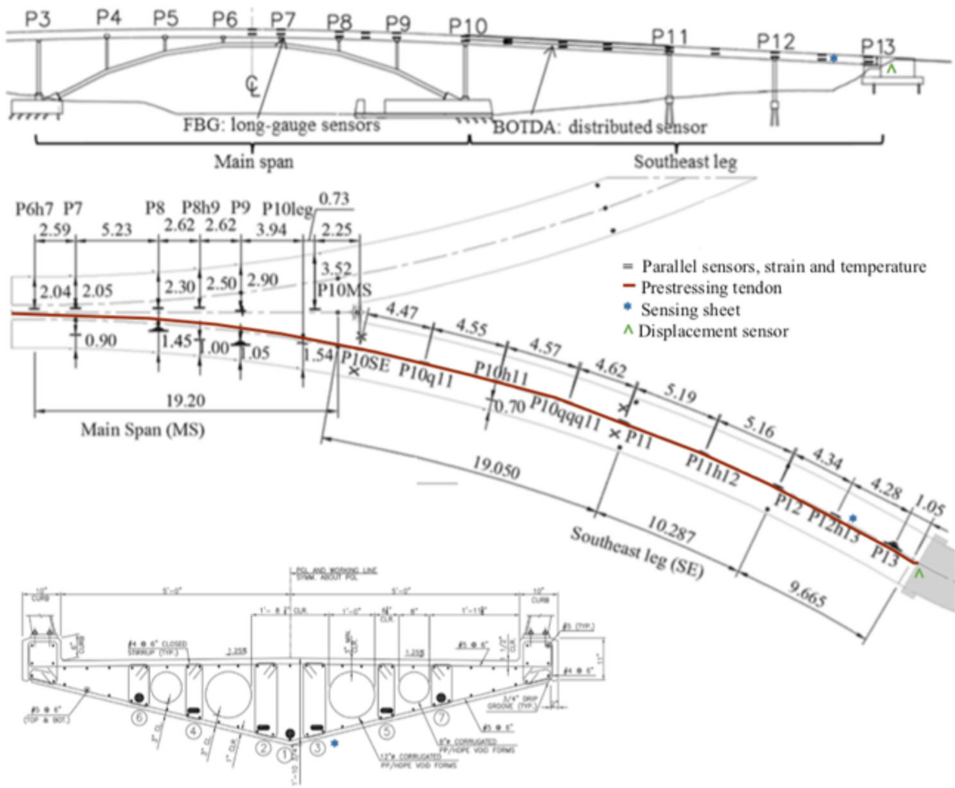


Figure 4: Location of sensors on Streicker Bridge in plan and section [2].

Figure 3: Complex 3D geometry of Streicker Bridge [3].

VT environment of Streicker Bridge was made in our preliminary research [3] using spherical imaging and Kolor Panotour Pro software. A customized interface was created using this software that enables a user to access embedded and/or internet-/ethernet-accessible SHM data and metadata in various formats – databases, image galleries, texts, graphs, etc. (e.g., formatted as PDF, jpg, etc.), and other items through what are called “hotspots.” A “hotspot” is an on-click conditional that allows a user to click on a certain part of the panorama, and a predefined event occurs. For example, if a user clicks on a strain sensor in the virtual environment, they can be brought to a database with the strain measurements. For this case study, the following was included in the VT/IM environment:

Metadata (structure)
- Technical images showing sensor location in cross-sectional, aerial, and side views
- Diagram showing the post-tensioning profile of South-East Leg.

Metadata (SHM system)
- Information box detailing the resolution, repeatability, typical gauge length, dynamic range, and maximum measured frequency of the strain sensors
- Legend showing various types of sensors
- Color-coding scheme that identifies function, malfunction, or disconnection of the sensors.

Data (raw)
- Databases connected to the strain sensors showing the raw strain data over time
- Databases connected to the sensing sheet showing the raw strain data for each strain sensor over time
- Databases connected to the displacement sensors showing the raw displacement data over time.

Data (analyzed)
- Graphs connected to the temperature sensors showing the relationship between temperature data and the time of day
- Diagrams showing curvature and displacement graphs for South-East Leg
- Diagram showing the pre-stressing force in South-East Leg.

To enable a user to visualize a 3D sensor network and communicate with others working on a project, an interactive interface was developed and applied. A user can navigate the virtual tour environment in three main ways.

(1) A user can interact with a built-in map, driven by Google maps; here a user can see the different viewpoints available, select one, and be transported virtually to this location on the bridge (see Figure 4)

(2) A user can use built in “scene-connectors” to virtually “walk” from one view of the bridge to another; if a user is on one part of the bridge deck, they can move to an adjacent position along the deck by clicking on the appropriate “hotspot” in the virtual environment (see Figure 4)

(3) Last, a user can select where to navigate to through a drop-down menu. This allows a user to navigate to a specific location without having to know where it is on a map. Figure 4 illustrates these means of navigating the VT/IM environment.

Each of the three modes of navigation serves a different purpose. The first mode enables a user who is familiar with the bridge and the surrounding topography a way to select the perspective they would like to view the bridge on a satellite map. The second mode enables a user to see how different parts of the virtual tour are connected—how what is happening above the bridge translates below and vice versa. The third mode enables a user who is not familiar with the bridge to navigate to specific parts of the bridge through a descriptive title given to each panorama as directed by another interested party. An example of this can be seen in Figure 4 where the user has selected to view the midspan.

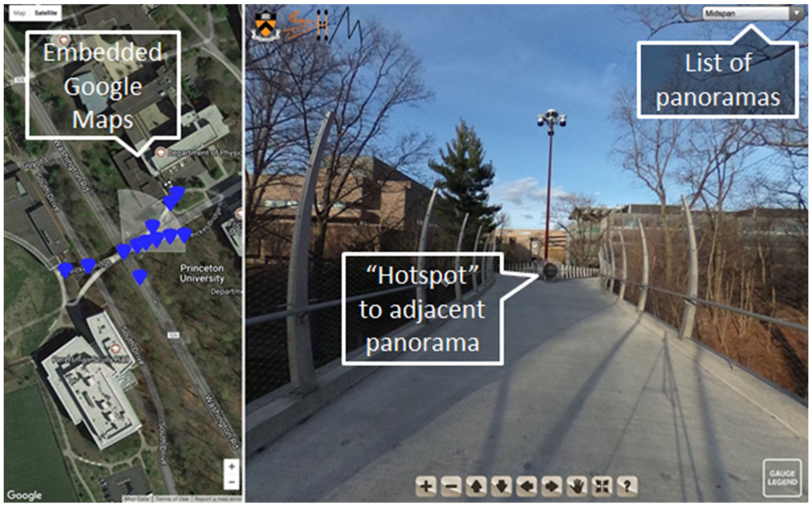


Figure 4: Virtual tour interface illustrating the different types of navigation: (1) embedded Google Maps, (2) "hotspot" connections to adjacent panoramas, and (3) drop-down menu with list of all panoramas of the bridge [3].

An advantage of using a VT/IM environment is interactive accessibility to information through "hotspots." It enables an SHM practitioner to click on a sensor in the virtual environment and be brought to a database of strain values. In the VT/IM environment, a user can access local, raw data (strain, temperature, displacement) and global, analyzed data (prestress force distribution, curvature distribution, deformed shape), and metadata relative to structure (technical drawings, prestressing scheme) or relative to SHM system (color coding of the sensors, specifications of the monitoring system). Some examples of how these hotspots were integrated into our virtual tour can be seen in Figure 5, which features hotspots for a temperature sensor and a strain sensor.

Figure 5: A) When a user hovers over a sensor, they can see its ID as well as what it is measuring. B) When a user clicks on the sensor they can access a database with time series [3].

The interactive legend in the bottom right corner of Figure 5A illustrates the type and the current state of each sensor (i.e., functioning, malfunctioning, disconnected). Figure 5B illustrates what happens when a user clicks on the sensor. Here, a user can access the database storing the time series of strain for this sensor and export it if desired. Examples of other objects that can be visualized such as thermal change over time, technical drawings, and strain sensor metadata can be seen in Figure 6.

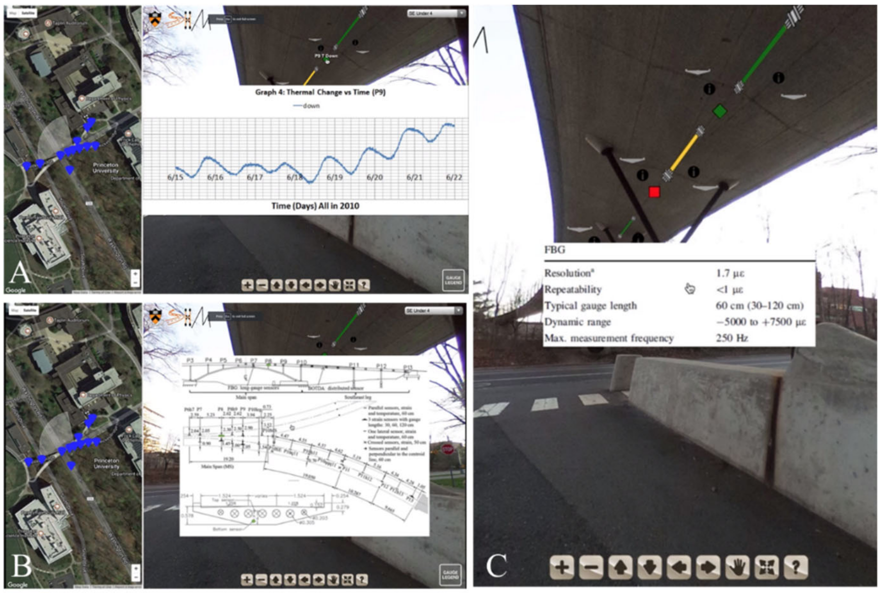


Figure 6: Examples of VT interactions showing (A) thermal change over time, (B) technical drawings, and (C) strain sensor metadata [3].

In the VT/IM environment, a viewer can virtually walk around, under, and on top of the structure by the means of navigation illustrated in Figure 4. On this tour, a user can see "hotspots" that can bring them to the positions where sensors are located on the bridge. A user can interact with these sensors to get further information about the sensors: the sensor ID, as well as the raw and analyzed data in databases where the data collected from the sensor is stored. To fully assess the performance of the method, a demonstration video showing a few different scenes of the bridge was prepared and can be found at the following link:

https://vimeo.com/234006206

To assess improvements in terms of ease of access to and visualization of SHM data and metadata, a short survey was conducted among graduate and undergraduate students at Princeton University. This method of evaluation has been utilized successfully in previous work to assess the performance of SHM visualization programs. While students understood basic civil engineering principles and participated in course on SHM, they lacked real-life experience in SHM and were unfamiliar with Streicker Bridge project. All this combined made them appropriate audience to evaluate the VT/IM environment. The three-minute-long video linked above and an accompanying short survey were sent to the students, so they could watch the video and write their feedback. A short description outlining the aims of the project was given at the beginning of the survey, but the SHM system presented in the video was not described. The survey comprised the following questions:

1) How easy was it to understand what the video shows?
2) Does the video help to understand the SHM system installed on the bridge?

3) Does the video help assess the behavior/functionality of the sensors on the bridge?

Each of the above-mentioned questions was scored on a linear scale from 1 to 5 where 1 indicated that the student did not understand and 5 indicated that the student completely understood. In addition to the numeric value assigned, the students were required to provide short paragraphs clarifying their answers. Furthermore, the students were asked if they had any other comments (positive or negative) about the video and if they had suggestions for improvements. The list of questions was brief to encourage student participation and they included both a numeric value to aid in quantification and open-ended description to catalyze critical thinking.

The validation criteria were set to 50% of positive feedback on questions 1-3 where a positive value is scored as a 4 or 5, a neutral value is scored as a 3, and a negative value is scored as a 1 or 2. This criterion accounts for both the inexperience of SHM students and lack of information given on the project.

Eleven students in total responded to the survey to validate the VT/IM environment. A graph of the responses can be seen in Figure 7, which indicates that all students found the virtual tour to be easy to understand. In examining the open-ended answers to the survey questions, it seems that only confusion about the video came when the user was taken below the bridge. It was indicated that if a different looking hotspot was used, one that indicated downward motion, that might have made it clearer to the viewer.

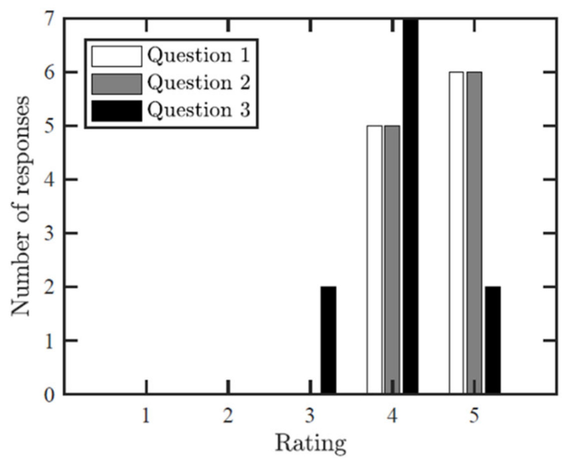


Figure 7: Bar chart reflecting answers to survey questions; the scale for each question was from 1-5 with 1 being the lowest [3].

Like the first question, in the second part of the survey all students claimed to understand the SHM system installed on the bridge without prior knowledge and in the open-ended section it was remarked that this system helped the users to gain perspective about how the sensors were related to the bridge and to each other.

Lastly, 9 students (81%) found the virtual tour useful for assessing the behavior/functionality of the sensors on the bridge (Question 3). The users found that the system provided good information about sensor typology and location, but more hotspots discussing the global behavior of the bridge should be added. This is something that future generators of VT/IM.

In the sections for “Other comments” and “Suggestions for improvements,” it was stated that the ability to move from between different viewpoints on the bridge was crucial to understanding the overall structure of the SHM system while it was somewhat overwhelming as a user since there was a lot to take in with each scene. Based on the survey feedbacks, VT/IM was improved and successfully applied within the scope of this project to Morris Island Lighthouse, see Figure 8. More details about VT/IM can be found in references [3-4].

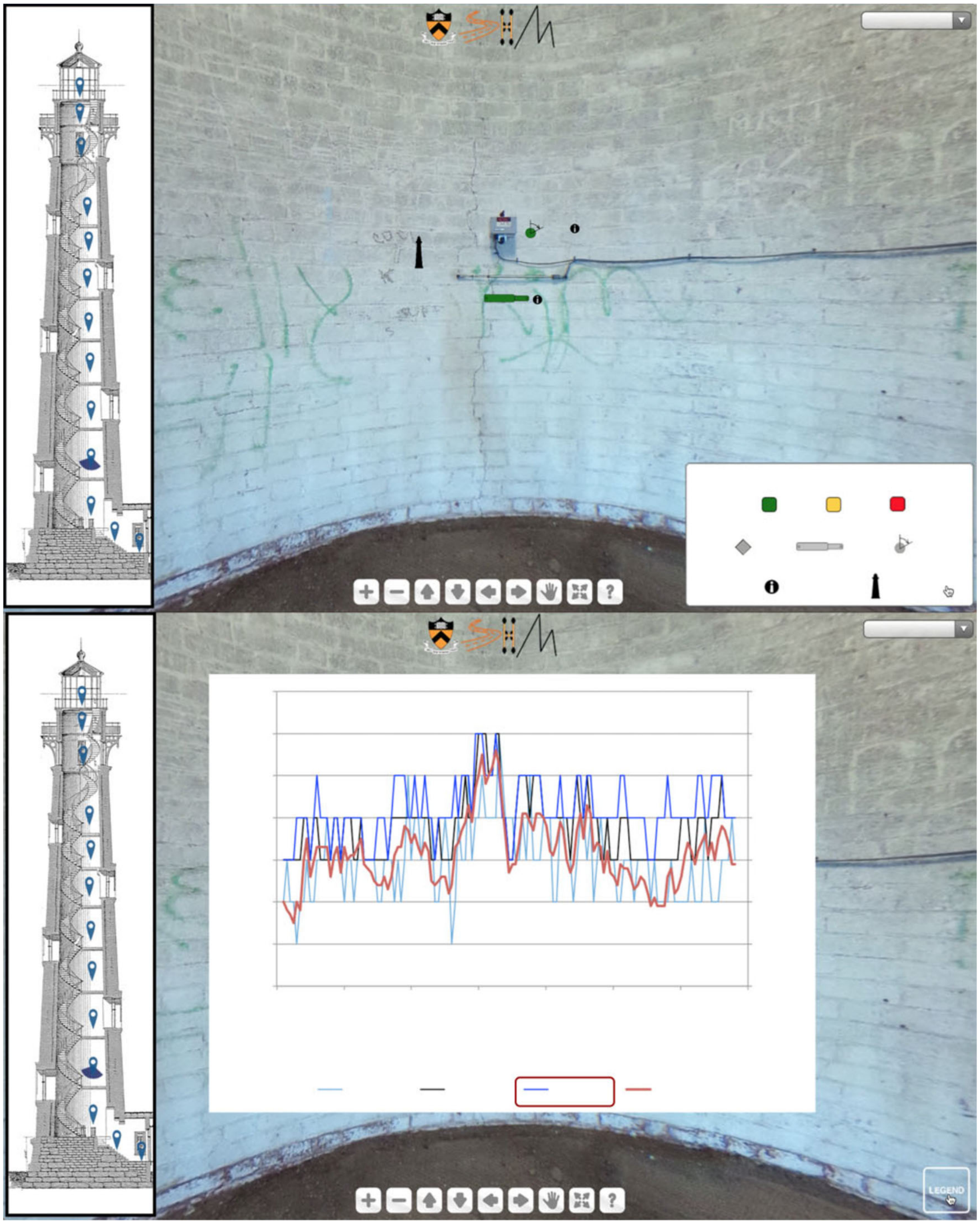


Figure 8. Screenshots of the VT/IM interface. Up: Interior view of sensor placement on a crack within the tower. Down: Data access associated with the afore mentioned sensor [4].

Augmented Reality (AR)

While creation of VT/IM models based on spherical imaging represents great advancement in data visualization and accessibility, it has limitation when it comes to any image-based update, as the entire structure would have to be rescanned, and not only the part of it that of interest. Similar applies when some annotations have to be added, especially off-site. Typically, these updates and annotations are performed during visual inspection of the structure. Approaches based on Augmented Reality (AR) can greatly help address this challenge.

There are two types of annotation tools: image-based and point cloud-based annotations. The image-based annotations refer to annotations directly on the flat image itself, while point cloud-based annotations refer to annotations made in the AR environment. Drawing was used as a prototype feature however the same scripts for augmenting, accessing, and storing data can be used to develop additional functionality.

The simplest type of annotation is the ability to draw free form lines on the image itself. This component works by detecting when the user touches the image plane, and tracing the location of their movements on the surface of their tablet or mobile device. The component then plots the captured positions on the image, and this is saved to a server.

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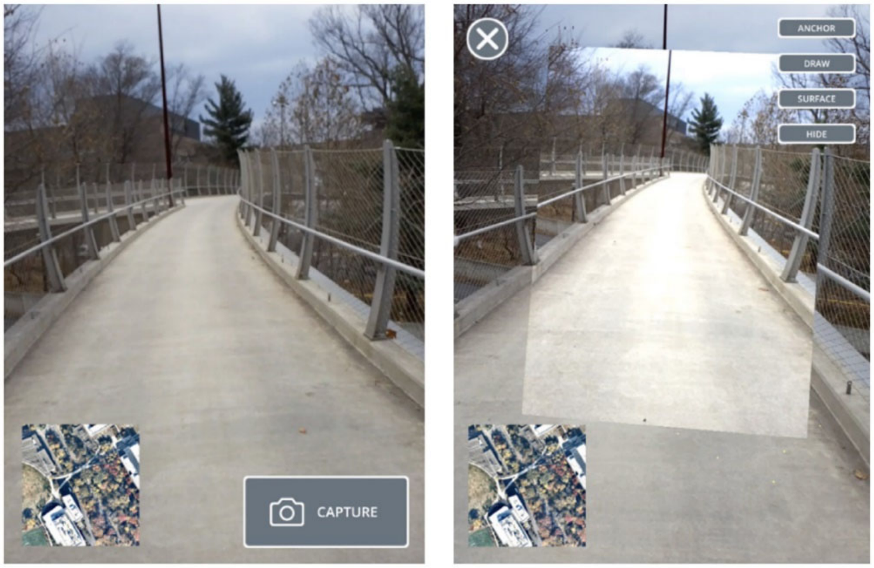
In contrast with VR environments or solely image-based environments, augmented reality operates as a layer within the space that a person occupies. Therefore, it is not as removed from the user as other approaches, and more care needs to be taken to ensure that proper design principles are accounted for. There are three main tenants of designing an interface for AR:

- Intentionality for how the real and digital worlds interact
- Flexible immersion levels
- Interfaces beyond the screen

These three tenants encourage a design approach which carefully considers the interaction between a user's screen and their physical space. As interacting with objects through a camera can be awkward, it is important to decide which components should sit on the screen and which objects should be in the real-world space. Additionally, it is important for the screen not to be covered in components and controls as this limits a user's field of view. This project uses these three tenants as the basis for its design principles.

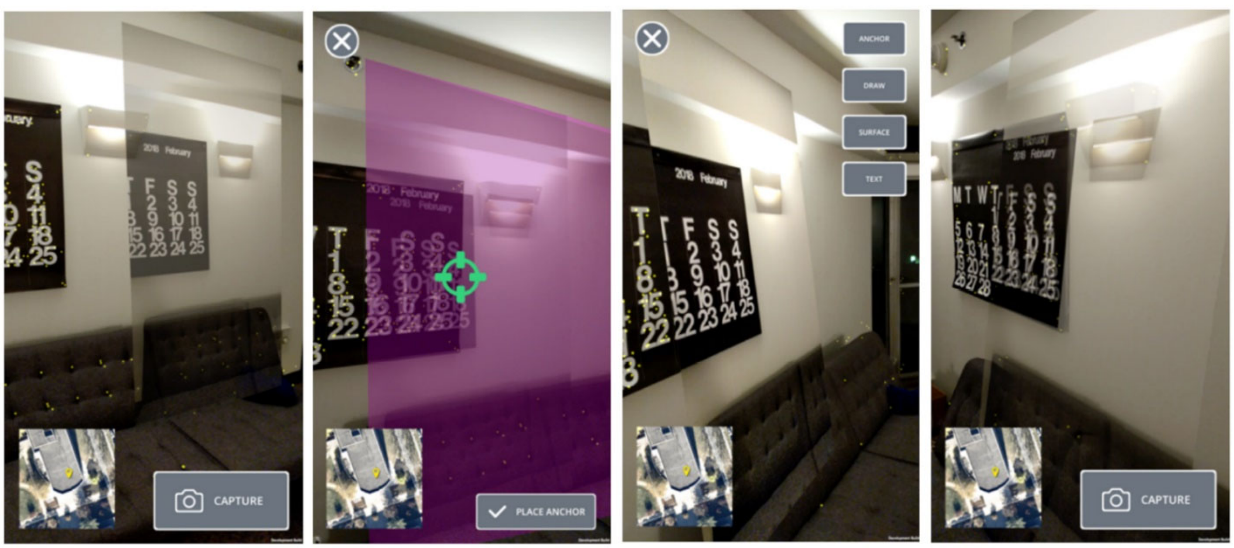
The initial interface for the prototype can be seen in Figure 9A. The application opens directly to the camera view and presents a user with a map preview and capture button. As previously described, pressing this capture button takes a photo using the camera and inserts it into the scene at a fixed distance from the camera position. As a user moves around the object, it can be seen that the image plane remains in place.

Tapping the image opens the annotation editing tools. The second interface can be seen in Figure 9B. Using the anchor tool, the user can move the image plane to affix it to an object or surface. Figure 10 shows this approach. At first, since the captured image is located a distance away from the wall, a strong parallax effect can be observed as a user moves around the scene (Figure 10A). Using the anchor tool, a spot on the wall can be selected to attach the image plane. The image pyramid (Figure 10B) provides a visual hint for how this sizing is a result of the camera's perspective. After anchoring the annotation, it can be seen that it now aligns with the wall and can now be viewed from multiple angles and positions (Figures 10C,D). Next, a point cloud-based annotation can be taken with the "Surface" button (Figure 9B). The AR framework is able to reliably detect the surface, as shown by the yellow dots indicating the point cloud. Even though the initial image was captured from an angle to the left of the wall, a user can still draw flat on the wall itself and view this drawing from multiple angles. Returning to the original image, it can be seen that this annotation was projected back onto the image plane for later viewing on a computer.



A B

Figure 9: (A) Initial interface for the prototype showing the geographic map and capture button. (B) Second interface for the prototype showing what happens after a user takes an image [1].



A B C D

Figure 10: (A) Illustration of image in the AR environment after capture, (B) Image showing the crosshairs turning green indicating there is a spot on the point cloud for this to align to, (C) Image showing alignment of image and AR environment from left angle, (D) Image showing alignment of image and AR environment from right angle [1].

Figure 11 illustrates the prototype developed in this project, being used to document and visualize part of the SHM system on Streicker Bridge. The first panel shows the capturing interface being directed at the sensing sheets under the southeast leg of the bridge. In the second panel, the captured image of these sensors can be seen along with the annotation interface. The third panel shows a user utilizing the point cloud-based annotation. The yellow dots representing the point cloud can be seen in the image as well as the pink annotation. The last panel depicts the annotation not only on the point cloud but also projected back onto the image. The main impetus for capturing images is to serve as a low-cost and low-effort visualization system while off site. The ability for the annotations to be projected between the images and the point cloud lessens the amount of documentation a user would have to do to enable both on- and off-site viewing.

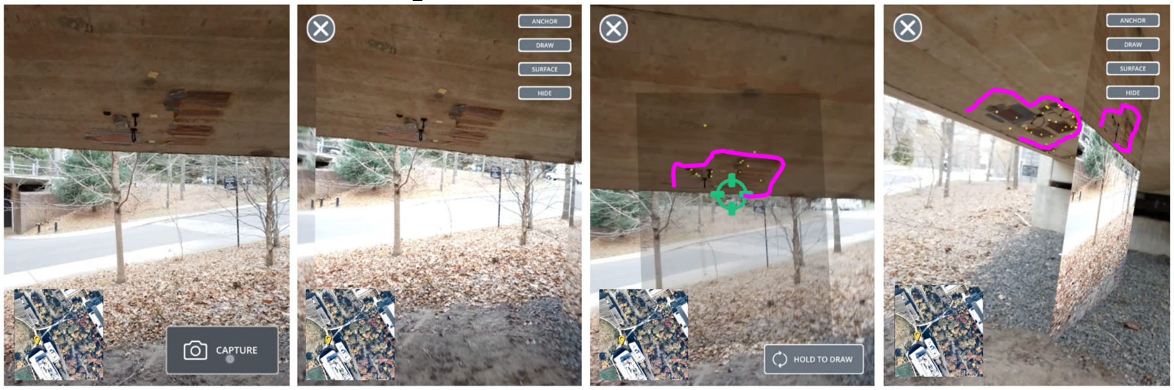


Figure 11: Sequence of user interacting with interface [1].

This is only one example of how this method could be applied to SHM systems. As a user defines what information is to be overlaid and where, it is highly flexible for various applications. For example, information can be related to a very local scale (e.g., the position of sensors in cross-section), regional scale (e.g., the position of sensors in a structural element such as a beam or cable), or global scale (e.g., the position of sensors over entire structure).

To evaluate the performance of the GPS and AR location tracking, alignment testing was performed at Streicker Bridge. This testing was performed during the day under clear skies. A user started from the east, walked under the bridge, crossed a road, returned to the east end of the bridge, and crossed the bridge to the west before exiting to the north toward the adjacent buildings. Figure 12 shows the locations returned by both AR and GPS positioning and the final aligned result.

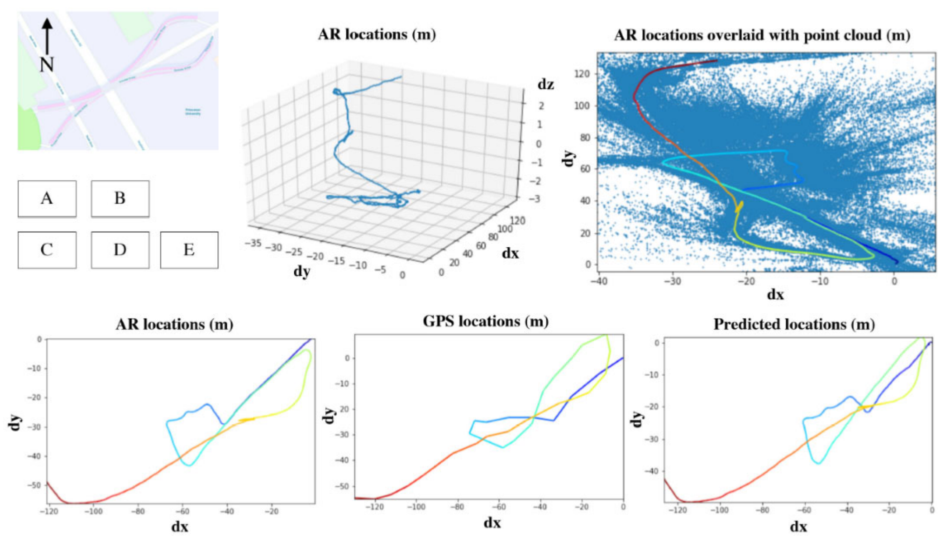


Figure 12: (A) 3D view of AR locations over the course of the user walking across the bridge, (B) AR locations overlaid on the point cloud, (C) AR locations projected into only x and y where color indicates time for comparison with other plots, (D) GPS locations, (E) predicted locations [1].

It can be seen that the AR-tracked position performs well at tracking when a user returns back to the same location. When the user walked back along the road to return to the end of the bridge, the AR position accurately retraces the original path. In comparison, the GPS locations wander significantly, and it is not clear from the GPS trace that the same path was traversed. It can also be seen that during the time when the user was under the bridge, which is the loop in the middle, GPS accuracy and update rate is low. This shows a significant advantage of AR tracking as it is able to continue tracking even when there is no clear view of the sky. The final predicted output is skewed as a result of inaccurate GPS data, especially during the loop under the bridge. However, when Figure 13 is considered, it can be seen how the accuracy actually converges to the correct location over time as the user approaches the end of the path. This is most likely due to the fact that the Kalman filter builds accuracy over time.

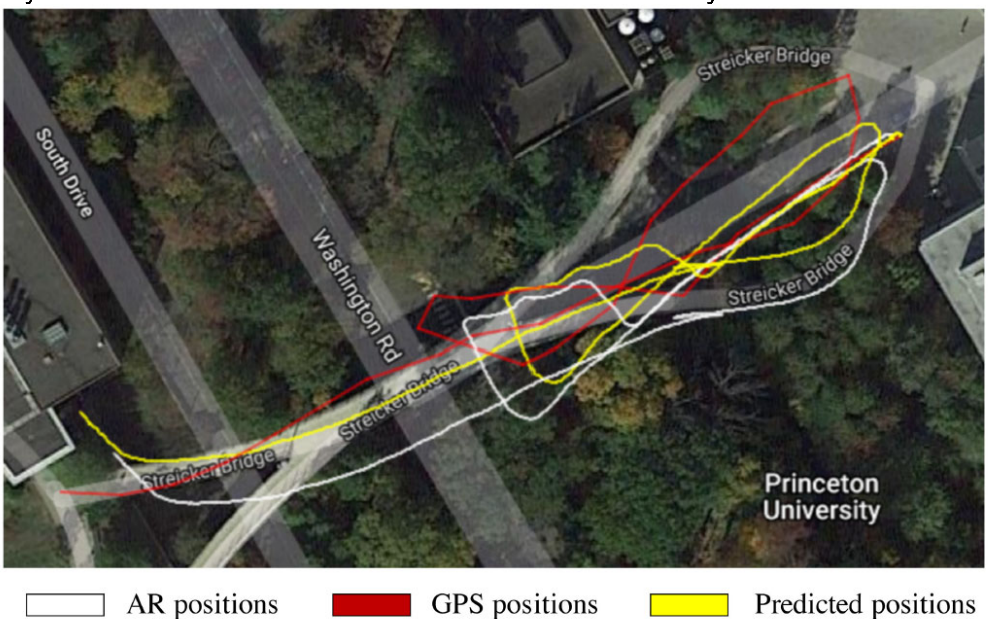


Figure 13: x and y positions of the user during the test according to AR, GPS, and predicted [1].

More details regarding AR part of the project can be found in Reference [1]

CONCLUSIONS

This work identified the current gap in methods for accessing and visualization of SHM and visual inspection data, in particular when the topological complexity of an SHM system and monitored structure calls for 3D visualization, but creating 3D model (e.g., BIM) is out of the broader scope of the project. It was found that the method proposed in this work, which is based on VT/IM/AR, could be an efficient means of addressing the above challenge.

Using VT/IM, a user can first document their structure using spherical panoramas and connect adjacent views to ease 3D understanding of the structure. To augment the communication process, images, informational text, and data files can be directly linked to the environment and accessed by the user. This enables a user to quickly familiarize themselves with the structure and the SHM system, understand where the data is coming from on the structure, and see how results of data analysis relate to the structure. This in turn can help them identify and diagnose unusual behaviors. Effectiveness and efficiency of VT/IM were successfully tested on Streicker Bridge and evaluated through a survey and comparison with roughly made 3D model. The VT/IM method opens new doors and transforms current practices in SHM data visualization which is vital to the overall process of monitoring. However, it feature limitations when it comes to on- and off-site upgrades such new sensor installations and visual inspection annotations with information about damage, changes in geometry, observations, etc.

To enable both on- and off-site documenting and viewing of infrastructure a novel method was developed in this project, which combines image-based documentation and augmented reality. A cross-platform, client-server system for creating, saving, and viewing annotations was designed and implemented. The strengths and weaknesses of this implementation were addressed, and the accuracy of the approach was evaluated. The findings of this work show the promise of using a combination of image-based an augmented reality as a useful framework for documenting the built environment and assisting access and visualization of data and metadata related to SHM and visual inspections. This work presents a prototype platform for data and metadata visualization, i.e., it includes the proof of concept in controlled settings. Application of this method was performed using Stricker Bridge as the case study.

Two limitations of the methods are noticed, and they require future studies. To enable on-site annotations, it is necessary to accurately ascertain the position of the user. Although a user's position was able to be determined to a reasonable degree of precision, the current localization approach is still limited in its ability to accurately relocalize a user across sessions. GPS data is subject to both random noise and systematic error, so the resulting alignment offset between sessions may be insufficiently accurate. One promising future approach could be to leverage the point cloud data collected to build a rough, server-side 3D model of the scene. When a separate session is started, the point cloud data from this session can then be compared with the previous one to determine their offset. Techniques designed for point cloud registration could prove successful in this area. Second limitation of this method was the use of 2D images for off-site viewing. As addressed above, multiple 2D images often cannot efficiently describe complex geometries. While this work mainly was to explore frameworks for on and off-site use, this limitation should be the subject of a future work.

Performed research contributes to the following USDOT's strategic goals and research priorities:

Primary contributions:

- A1: Long Term Infrastructure performance
- B1: Innovative transit asset management
- D2: Innovative condition monitoring and condition/performance data integration for better asset management
- E1: Advances in robotics, sensors, and navigation systems to improve inspection, monitoring, and maintenance of lifeline infrastructure.

Secondary contributions:

- A2: Construction automation, Data integration from design to constructional and asset management
- B2: Asset management training & technical support
- B3: Innovative asset improvement technologies.

Proposed research contributes to the following UTC's strategic goals and research priorities:

- G1: Application of new materials and technologies
- G2: Cyber and communications security; Condition monitoring, remote sensing and use of GPS
- G3: Asset management and performance management
- G4: Data accessibility and security Analytical tools; G6: System response to disruptive events/resilience to disasters.

The following products and outreach activities resulted from the research:

Journal papers:

1. Napolitano, R., Liu, Z., Sun, C., Glisic, B. (2019). "Combination of Image-Based Documentation and Augmented Reality for Structural Health Monitoring and Building Pathology*," Frontiers in Built Environment*, 8:50 (14 pp).
   https://doi.org/10.3389/fbuil.2019.00050

2. Blyth, A., Napolitano, R., Glisic, B. (2019). "Documentation, Structural Health Monitoring, and Numerical Modeling for Damage Assessment of the Morris Island Lighthouse under Environmental Loading," *Philosophical Transactions A*, 377: 20190002 (19pp).
   https://royalsocietypublishing.org/doi/full/10.1098/rsta.2019.0002

Conference papers and presentations:

1. Blyth, A., Napolitano, R., Glisic, B. (2019). SHM in Action Event: "Method and associated software for integrating, accessing, and visualizing heterogeneous SHM data and metadata of structures using virtual environments," *International Workshop on Structural Health Monitoring, IWSHM2019,* Stanford University, September 2019.

2. Napolitano, R., Moshirfar, A., Liu, Z., Glisic, B. (2019). "Virtual Tours and Augmented Reality for Direct Data Integration, *IABSE Congress (International Association for Bridge and Structural Engineers)*, September 4-6, New York, NY.

3. Blyth, A., Napolitano, R., Glisic, B. (2019). "Structural health monitoring in workflows for preservation engineering," *SHMII-8 (International Society for Structural Health Monitoring of Intelligent Infrastructure),* August 4-7, St. Louis, MO.

4. Napolitano, R., Moshirfar, A., Liu, Z., Glisic, B. (2019). "Combining image-based documentation and augmented reality to create a cyber physical system for the built environment," *ASCE – EMI Conference*, June 18-21, Pasadena, CA.

5. Napolitano, R., Liu, Z., Sun, B., Glisic, B. (2019). "Augmented and virtual reality environments for structural health monitoring," *Structures Congress*, April 24-27, Orlando, FL.

6. Glisic, B. (2019). "Augmented Reality for Structural Inspection and Management," *New York State Department of Transportation (NYSDOT) 2019 Bridge Inspectors Meeting*, March 26, Albany, NY.

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9. Napolitano, R. , Glisic, B. (2019). “SHM-based Virtual and Augmented Reality for Visual Inspection and Nondestructive Evaluation,” *TRB Webinar: Augmented Reality for Structural Inspections, Transportation Research Board of National Academies*, November 29, 2018.

Website(s) or other Internet site(s):

Source code: *github.com/rkn2/arshm-release*

TRB webinar: *http://www.trb.org/Main/Blurbs/178486.aspx*

Course modules:

In Princeton University graduate course ”CEE537 Structural Health Monitoring,” starting with Fall 2020.

In Princeton University undergraduate course “HUM 417 / ART 408 / CEE 415 / HLS 417 Historical Structures: Ancient Architecture's Materials, Construction and Engineering,” starting in Fall 2022.

RECOMMENDATIONS

New technologies, such as VT/IM/AR, have great potential to facilitate integration of VI and SHM data and metadata, and provide for intuitive and comprehensive data and metadata visualization and accessibility. It is, therefore recommended to:

1. Make the potential users more and more familiar with new technologies, e.g., by providing starter kits and demonstrators for specific technologies

2. Provide more detailed education via university courses and short courses for practitioners

3. Continue research on VT/IM/AR and create more applications, with accent to translation to practice

4. Keep pace with technological developments in order to identify, combine, and implement other technologies for data and metadata integration, visualization, and accessibility, such as BIM and Digital Twins.

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