AERIAL NONDESTRUCTIVE TESTING AND EVALUATION (aNDT&E)

GENDA CHEN*†, LIUJUN LI†, HAIBIN ZHANG†, ZHENHUA SHI†, AND BO SHANG†

ABSTRACT

Drones are increasingly used during routine inspections of bridges to improve data consistency, work efficiency, inspector safety, and cost effectiveness. Most drones, however, are operated manually within a visual line of sight and thus unable to inspect long-span bridges that are not completely visible to operators. In this paper, aerial nondestructive evaluation (aNDE) will be envisioned for elevated structures such as bridges, buildings, dams, nuclear power plants, and tunnels. To enable aerial nondestructive testing (aNDT), a human-robot system will be created to integrate haptic sensing and dexterous manipulation into a drone or a structural crawler in augmented/virtual reality (AR/VR) for beyond-visual-line-of-sight (BVLOS) inspection of bridges. Some of the technical challenges and potential solutions associated with aNDT&E will be presented. Example applications of the advanced technologies will be demonstrated in simulated bridge decks with stipulated conditions. The developed human-robot system can transform current on-site inspection to future tele-inspection, minimizing impact to traffic passing over the bridges. The automated tele-inspection can save as much as 75% in time and 95% in cost.

KEYWORDS: robotic platform, aerial nondestructive testing and evaluation, beyond-visual-line-of-sight inspection, augmented reality

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Introduction

In the United States, currently there are more than 617 000 bridges in the National Bridge Inventory. According to the 2021 American Society of Civil Engineers (ASCE) Infrastructure Report Card, more than 42% of the bridges were at least 50 years old (the design life for most existing highway bridges), and 7.5% of the bridges were considered structurally deficient or in "poor" condition (ASCE 2021). These structurally deficient bridges supported 178 million trips every day, a potential safety concern. Overall, the bridges were rated C, with A being excellent and F being a complete failure. Other types of elevated infrastructure, such as dams, levees, transits, and school buildings, are even worse in their existing conditions.

The current practice of visual inspection is required biennially. Bridge inspection often requires the use of heavy lifting and access equipment, thus increasing operation time and direct costs. When access to the inspected area must be made from bridge decks, the indirect costs associated with road closure multiply. In such a case, both travelers and inspectors are subject to a safety concern on high-volume highways. Moreover, visual inspection is quite subjective and often inconsistent (Moore et al. 2001). It is only capable of detecting damage when it has advanced to become visually apparent. It is thus of economic, psychological, and social importance to develop an alternative platform for faster, safer, cheaper, and more consistent bridge inspection with minimum impact on traffic flow.

In November 2012, a robot-assisted bridge inspection tool, referred to as RABIT, was developed as a product of the Federal Highway Administration (FHWA) Long-term Bridge Performance Program (LTBPP) and applied to survey bridge decks (Gucunski et al. 2013; La et al. 2013). The RABIT was equipped with six nondestructive evaluation (NDE) devices and cameras: (a) impact echo for delamination detection; (b) ultrasonic surface wave for concrete quality evaluation; (c) ground penetrating radar (GPR) for object mapping and deck deterioration assessment; (d) electrical resistivity for concrete corrosive environment characterization; and (e) two high-resolution, panoramic cameras for deck and surrounding area imaging.

To extend autonomous inspection from deck elements to an entire bridge, the INSPIRE University Transportation Center (UTC) led by Missouri University of Science and Technology (Missouri S&T) has been developing advanced technologies to aid in next-generation bridge inspection and maintenance. Once integrated, the overall system with the advanced technologies is referred to as Bridge Inspection Robot Deployment Systems (BIRDS). Specifically, structural crawlers, uncrewed aerial vehicles (UAVs), and multimodal uncrewed vehicles provide mobile platforms for in-depth inspection of bridges. For example, a multimodal uncrewed vehicle, called BridgeBot, combines the traversing capability of crawlers and the flying capability of UAVs into one system for bridge inspection. The BridgeBot can fly to the underside of a bridge deck, attach to a bridge girder, and provide an inspection platform for installed cameras to take high-resolution images from deficient areas as conventional visual inspection would do.

Thermal and hyperspectral images are being developed to assess concrete delamination and steel corrosion of reinforced concrete (RC) bridges. Together with other technologies such as ground penetrating radar (GPR), they provide a suite of measurement tools and methods for the NDE of structural damage and deterioration conditions in RC and steel bridges. Innovative sensors such as UAV-based smart rocks for scour monitoring and integrated point and distributed optical fiber systems for strain and corrosion monitoring provide mission-critical data, such as the maximum scour depth, corrosion-induced steel mass loss, and live load-induced strains to normalize the NDE data taken over time at spatially distributed points.

This paper intends to provide an overview of a few advanced robotic platforms and their potentially supported NDE technologies. It is organized into five parts. After this introduction, a concept of field operation in augmented reality (AR) is first envisioned. It is then followed with supporting robotic platforms to make aerial NDE a possibility. Next, example NDE technologies suitable for installation on UAVs and robotic platforms are discussed. Finally, a few remarks are made to conclude this study and pose questions that warrant further investigations.

BVLOS Bridge Inspection via Augmented/Virtual Reality

The INSPIRE UTC has developed a mixed reality (MR) interface that can streamline inspection process, analysis, and documentation for seamless data uses from inspection to maintenance in bridge asset management via an automating access, visualization, comparison, and assessment, and to apply the MR interface in a beyond-visual-line-of-sight (BVLOS) NDE on flying and/or climbing robotic platforms.

Currently, Federal Aviation Administration (FAA) does not have any established regulations on the BVLOS operation of uncrewed aircraft systems (UAS). To meet increasing demand for broadening drone applications in various industries, including infrastructure construction, survey, surveillance, inspection, and maintenance, FAA formed an Aviation Rulemaking Committee (ARC) in 2021 to develop recommendations on the guidelines for BVLOS flights of UAS (ARC 2022). The ARC was represented by government organizations, different industries, and academia. It is thus expected that BVLOS inspection of infrastructure will likely be allowed in the years to come.

As bridges continue to deteriorate, biennial inspection becomes more critical and demanding than ever before. The current practice with visual inspection requires the presence of a crew of two inspectors at any bridge site with one for inspection and paperwork and the other for photographing bridge deterioration and areas of concern. In recent years, inspectors in some states are equipped with mobile tablets (with a flat-screen interface) in a 3D model-based data entry application (Brooks and Ahlborn 2017). The 3D model markup and rendering are often inaccurate and cannot be manipulated by the inspectors to record and visualize defects and element-level data (e.g., defect location). This shortcoming can be overcome with the aid of digital technologies in three forms. Virtual reality (VR) immerses users in a digital environment. Augmented reality (AR) could overlay digital objects onto the physical world by anchoring virtual objects to the real world. However, there is no interaction between the digital and physical elements. On the other hand, MR not only enables superposition of the two worlds but also allows the user to interact with the digital objects (Karaaslan et al. 2019). In bridge applications, MR allows inspectors to recognize their surroundings and digital contents to interact with the real bridge in three dimensions (Maharjan et al. 2021). Some of the recent AR/VR/MR development works are summarized in two review papers (Mascareñas et al. 2021; Xu and Moreu 2021).

An MR interface used in an app with a Microsoft AR headset, as illustrated in Figure 1, was recently developed by the INSPIRE UTC. The MR interface includes four main components: mixed reality, element inspection panel, function menu, and database. It will likely revolutionize the 3D data collection, storage, retrieval, and analysis (or general cloud-based data management) of an entire bridge as well as robot and sensor control through wireless communication. It will

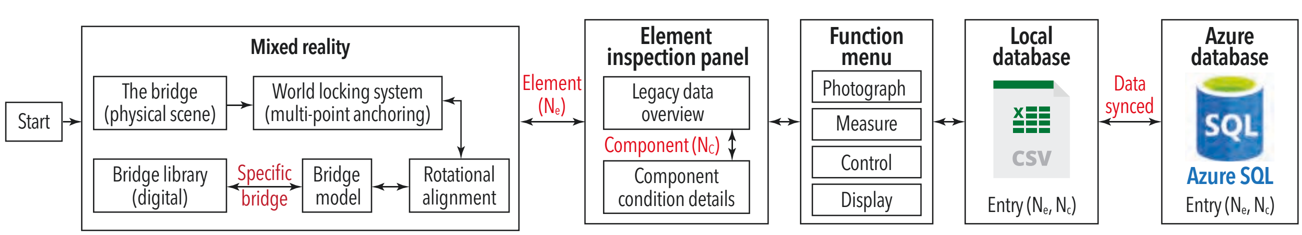

Figure 1. Bridge inspection app workflow: a mixed reality interface.

Figure 2. Hand-free bridge inspection enabled by augmented reality.

provide an inspector with hands/voice-control robot operation following a flight mission plan, aNDT&E, and intraoperative hands-free access to complex data, real environments, and two-way communication. As an engine of the MR interface, the World Locking System (WLS) toolkit helps lock holograms in place as the user walks around so that "space pins" can be added to specific locations of the model to align perfectly with corresponding features in the physical bridge. The MR bridge environment imports a high-resolution 3D reconstructed and georeferenced bridge model at 5 cm/pixel from a laser scanner and stores and visualizes the metadata (such as past inspection reports and photos of discontinuities including size, shape, and location). The region of interest (ROI) discontinuities can be compared and annotated as needed by retrieving the historical inspection data and appending the current inspection data. A database is established to automate the bridge inspection and reporting process according to the 2019 AASHTO Manual for Bridge Element Inspection. Therefore, the bridge element field inspection efficiency and accuracy can be dramatically improved with the developed MR interface.

A point cloud model of the bridge on 10th Street in Rolla, Missouri, was established as shown in Figure 2 in SketchUp and Unity. The model texture and size were maintained. When the bridge was scaled 1:1 in Unity, it was the same size as the actual bridge. This allowed the bridge model to be overlaid over the actual bridge with virtual and physical features roughly aligned. The model was scaled, rotated, and repositioned in X, Y, Z directions either manually or by inputting an accurate desirable value to improve the accuracy of bridge alignment.

WLS and its space pin feature was implemented to align local features of the bridge. WLS used an alignment manager called the Frozen Engine to lock the world space. Space pins were added as small objects that could be individually positioned on physical objects at runtime, and then the Frozen Engine would adjust the view of the model to align. In this way, the bridge model was aligned more accurately and anchored perfectly with the real bridge for future revisits.

After the 3D bridge model was overlaid with the real bridge asset, the Photograph mode can capture the discontinuity areas and localize them correspondingly. The discontinuity pictures and their locations, preliminary bridge element category (subjected to later review and confirmation) and their service conditions were annotated as illustrated in Figure 2. The discontinuity metadata were saved to a .csv file together with the bridge inspection legacy data for cloud synchronization with the Azure SQL database.

The Measure mode allowed the user to select the start point and then raycast measurement points in sequence. The dimension measurement along specific surfaces was enabled for bridge element inspections. Similarly, the quantity measurement for certain discontinuity areas or volumes was done for each structural component or limit state in service.

The Control mode (to be developed) will enable the user to guide the navigation of robotic platform according to a predefined mission plan and execute an aNDT&E task. The user will closely coordinate these tasks with the UAV/robotic platform and an on-site safety worker through wireless communication. The task will not be directly executed at the UAV or robotic platform but teleoperated by the user through haptic sensing and dexterous manipulation (Kim 2021).

The Display mode allowed the discontinuity photo, the measured distance, and/or flight and test scenario to be visualized for further analysis. Besides the local database where information was fed directly from the application at runtime, an Azure cloud database based on SQL was accessible whenever any internet connection became available. This allowed the operator to work in a remote site, then synchronize the data collected locally to the cloud database. This practice is crucial to prevent data loss and allow data access anytime and anywhere.

Robotic Platforms to Support aNDT&E

In current practices, a moving inspection platform that costs about US$1 million, as shown in Figure 3a, is often installed between girders in the superstructure of river-crossing bridges due to access needs during bridge inspection and maintenance. Mobile platforms such as structural crawlers on concrete/masonry walls (Yang et al. 2019) and steel members (Nguyen and La 2019) have recently been developed to support bridge inspection with advanced data-driven evaluation technologies based on aNDT. For example, a four-wheel magnetically attached structural crawler, as shown in Figure 3b, that can move along the surface of steel bridges was manufactured. The climbing robot measures 12 × 10 × 12 in. (30.5 × 25.4 × 30.5 cm) and weighs 40 lb with each battery good for approximately one hour. It is equipped with 2 GoPro cameras, a LiDAR, and an IMU. Its ground control station (GCS) has 16 channels with a control range of 2 km. It has a NUC i7 computer, a monitor, and a joystick. The crawler includes two independent channels of robot teleoperation and monitoring. A Dell Optiplex computer processes the data from the LiDAR and cameras and is then transferred to the GCS for live monitoring. For remote control, Rx receives commands from the operator via the GCS's joystick. An Arduino Mega processes these signals and then exports outputs to control the robot's motors and steering servos via power amplifiers.

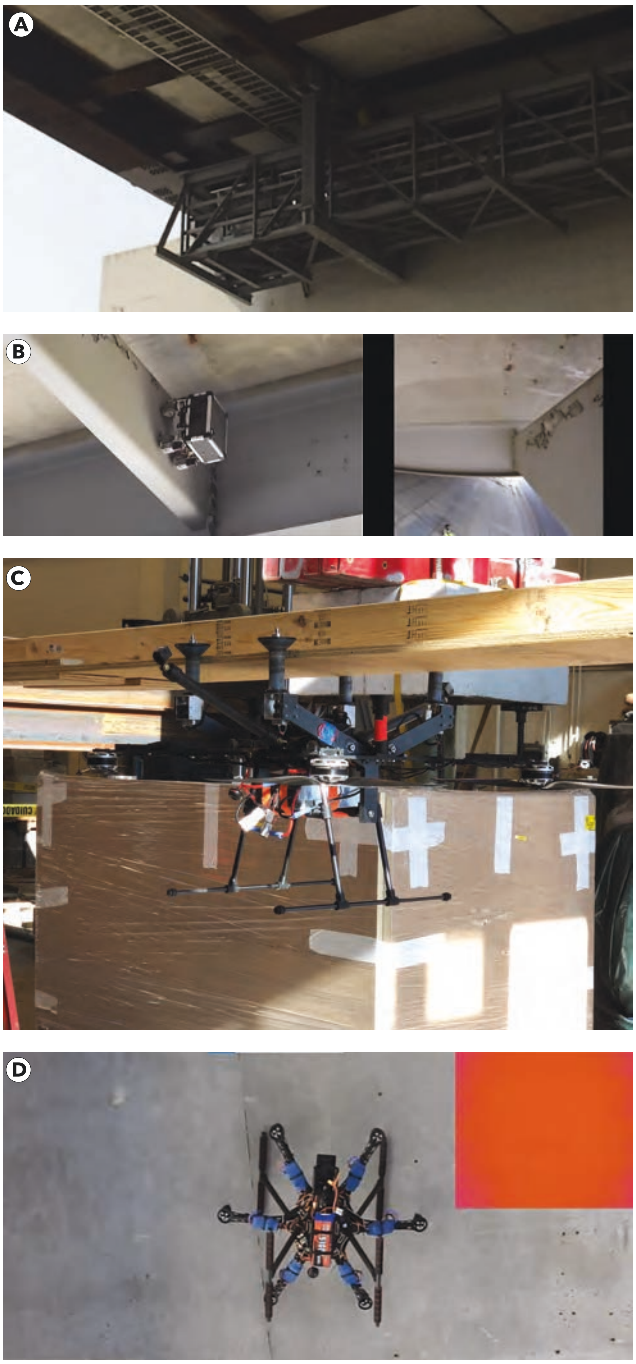

Figure 3. Bridge-attached platforms for close-in bridge inspection: (a) the moving platform in current practice; (b) the proposed structural crawler with four magnet wheels, which carries a RGB camera for visual inspection; (c) the proposed hybrid flying and traversing uncrewed vehicle (BridgeBot) attached to a wooden deck; and (d) the proposed ceiling UAV in contact with the deck, which carries a dual-sensor (thermal and optical) camera.

The structural crawler in Figure 3b is mostly applicable to large areas with little or no obstacles. Transverse climbing of the crawler around an I-shaped beam or girder is not a trivial task. A climbing robot may have an insufficient footprint or inappropriate orientation to make a safe turn from the inner to outer face of a flange of I-beams or girders. In addition, the unexpected disengagement of a climbing robot from its attached steel bridge may be a safety concern for passengers on underpass highways or over rivers. Therefore, innovative UAVs that can interact with a bridge deck for its enhanced inspection and maintenance were recently proposed. Two example vehicles are presented and demonstrated in Figures 3c and 3d. (Note that Figure 3c is still in laboratory test stage and Figure 3d was tested on an actual bridge.) Additionally, more recent generations of the structural crawlers described in Nguyen et al. (2021) and Otsuki et al. (2022) improved mobility around acute angles.

Figure 3c shows an uncrewed multimodal vehicle, called BridgeBot, that was driven by four propellers in a flying mode and by four DC motors in a traversing mode. Both actuation systems were powered by batteries. The mechanics of train wheels and beam trolleys were followed to allow the inspection vehicle to be attached to the edge of an I-beam bottom flange. The four clamping wheels were 3D printed and coated with urethane to promote a higher coefficient of friction against the beam. Each wheel was independently driven by an electric DC motor. As shown in Figure 3c, the BridgeBot can mimic the operation of a traditional inspection platform as shown in Figure 3a. The uncrewed vehicle will be used to facilitate the I-girder bridge inspection and deploy structural crawlers, such as shown in Figure 3b, on the bottom flange of bridge girders. The uncrewed vehicle and the structural crawlers will allow the inspection and local maintenance of more than 90% of the bridges in the National Bridge Inventory. The uncrewed vehicle can fly in air and traverse along a girder with an effective vehicle-bridge engagement mechanism for a smooth transition from flying to traversing mode, or vice versa. Design criteria of the hybrid vehicle include, but are not limited to, the following:

- In the flying mode, the vehicle is stable with necessary positioning precision and navigation guidance in a GPS-denied environment.
- In the traversing mode, the vehicle with necessary positioning precision moves at a constant speed to provide a stable station for various measurements.

- In the transition period between the flying and traversing modes, the vehicle engages with a girder safely and efficiently.
- Overall, the hybrid vehicle must have the required payload for measurement devices and structural crawlers to be deployed, and the required flight time for local maintenance or complete inspection of one bridge.

The uncrewed multimodal vehicle was successfully tested to demonstrate its flying and traversing functions and its system performance. First, the vehicle as a drone flew to the underside of a simulated wooden bridge girder. Once directly underneath the girder, the vehicle grabbed the bottom flange of the girder with a specifically designed roller clamping system and then traversed the bridge at a constant speed. Finally, the vehicle simply detached from the bridge as it encountered any obstacles and flew to the next area of interest. The overall performance of the vehicle met the design requirements. However, the vehicle system could be improved by stiffening several components to avoid any potential vibration during landing that would cause damage (Reven et al. 2019).

Figure 3d shows a ceiling UAV that is in direct contact with the ceiling of a room for close-distance (<10 in. [<25.4 cm]) inspection. The ceiling UAV is a hexacopter that is installed with a dual-sensor (thermal and optical) camera. The main difference of the ceiling UAV from a conventional hexacopter is the addition of a top frame to make the hexacopter in firm contact with the ceiling. The top frame is composed of two 10 in. (25.4 cm) wide legs 14 in. (35.5 cm) apart.

Once in position against the building ceiling as shown in Figure 3d, the UAV enabled consistent imaging of the ceiling at a known standoff distance and thus provided high-quality thermal and RGB images as illustrated in Figure 3d. As the UAV approached the underside of a building ceiling, the required throttle to maintain a certain speed was reduced exponentially (Jiao et al. 2021). Therefore, moving the UAV along the building ceiling or a bridge deck is also energy-efficient in practice.

Both the hybrid uncrewed vehicle in Figure 3c and the ceiling UAV in Figure 3d can be used to support various NDE methods, such as active thermography and GPR. The capability of the active thermography and GPR for the detection of subsurface defects is demonstrated using embedded defects in reinforced concrete (RC) bridge decks in the following section.

Example NDE Methods Appropriate for Deployment on Robots

A 6 × 3.75 ft (1.8 × 1.1 m) RC bridge deck 8 in. (20 cm) thick with embedded defects mimicking delamination in application was designed and cast to test the effectiveness of various NDE methods for defect detection. Two types of delamination with different dimensions embedded into the RC deck were designated as small and large delamination. All delamination was simulated using a combination of foam strips, each measuring 6 in. (15 cm) and 2 in. (5 cm) in length and width. The width of each strip is equal to the thickness of commercially available foam boards, which is 2 in. (5 cm). The length of each strip is equal to the length of a small plastic board, which is 6 in. (15 cm), to support the foam strips during concrete casting. Each small delamination consists of two strips side by side so that its dimension is 6 × 4 in. (15 × 10 cm). Each large delamination is composed of eight strips side by side in pattern to a total dimension of approximately 12 × 10 in. (30.5 × 25 cm) after the gap between the two strips has been taken into account.

Small and large delamination objects were supported on 6 × 6 × 5/64 in. (15 × 15 × 0.8 cm) and 12 × 12 × 5/64 in. (30 × 30 × 0.8 cm) plastic boards, respectively. Each plastic board was embedded at two depths, 1.0 and 1.5 in. (2.5 and 3.8 cm) from the top and bottom concrete surface, respectively. This depth scenario represents the concrete cover used in different RC members in bridges.

The RC deck was heated at the delamination area by a 1 × 4 ft (0.3 × 1.2 m) trip heater for 10 min from both the top and bottom concrete surfaces, respectively. The heater was then removed so the data could be collected for 20 min during the cooling phase. Figures 4a–4d present the infrared images of the delamination area at 20 min of cooling. The concrete surface immediately above the embedded delamination is hotter than its surrounding area. The thicker the delamination, the more the accumulation of heat and thus the higher the concrete surface temperature as indicated in Figure 4a through 4d when cooling inside the Highbay Laboratory at Missouri S&T. The passive thermography under sunlight from a drone at approximately 50 ft (15.2 m) above the concrete deck is presented in Figure 4e. Note that passive thermography was applied to field inspection (Sakagami 2015). In comparison with Figure 4a through 4d, passive thermography remains effective in detecting the large delamination areas but less effective for the small delamination areas in four RC decks.

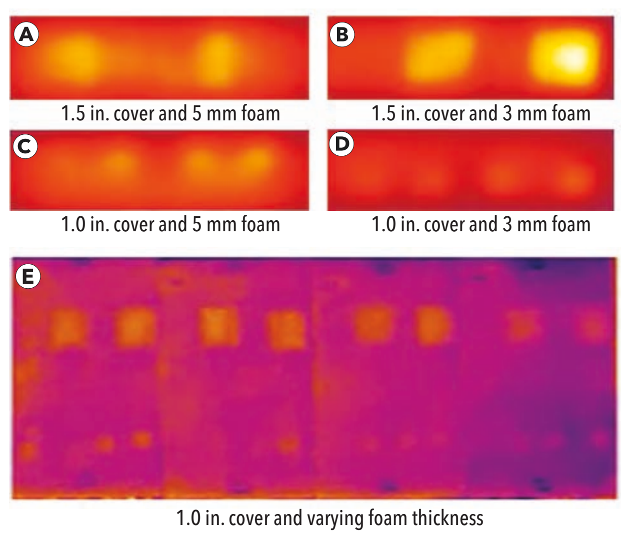

Figure 4. Thermal images of delamination with varying concrete covers and foam depths: (a) 1.5 in. (3.8 cm) cover and 5 mm foam; (b) 1.5 in. (3.8 cm) cover and 3 mm foam; (c) 1 in. (2.5 cm) cover and 5 mm foam; (d) 1 in. (2.5 cm) cover and 3 mm foam; (e) 1 in. (2.5 cm) cover and varying foam thickness.

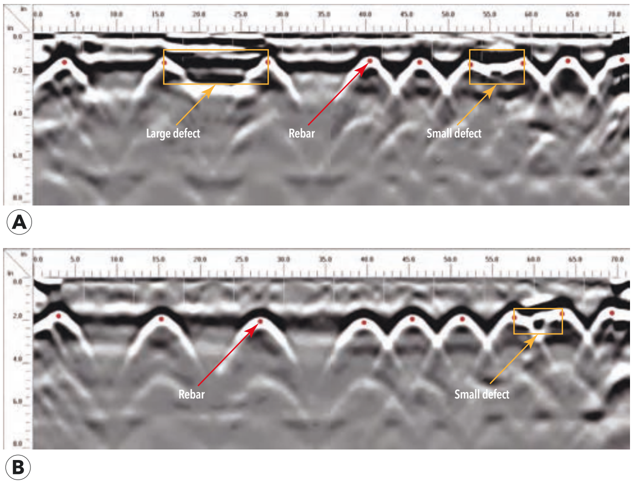

Figure 5. Line scans of GPR on the top and bottom surfaces of the concrete deck: (a) top surface with 1 in. (2.5 cm) concrete cover; (b) bottom surface with 1.5 in. (3.8 cm) concrete cover.

This technology will be implemented in a ceiling drone as demonstrated in Figure 3d.

Figures 5a and 5b show two example GPR scan lines from the top side (1 in. concrete cover) and bottom side (1.5 in. concrete cover) of the RC deck, respectively. The locations of the two scan lines in Figures 5a and 5b were aligned well to ensure that the same cross section was scanned and highlighted. Small and large defects (yellow rectangles) and rebar (red dots) locations near the test surface (1 in. from the top side and 1.5 in. from the bottom side) can be clearly seen regardless of the top and bottom sides of the deck. The defects away from the test surface cannot be identified reliably. The GPR is effective in detecting shallow defects or near-surface features and difficult in detecting deep defects due to electromagnetic wave signal loss through thick heterogeneous concrete and shallow rebar.

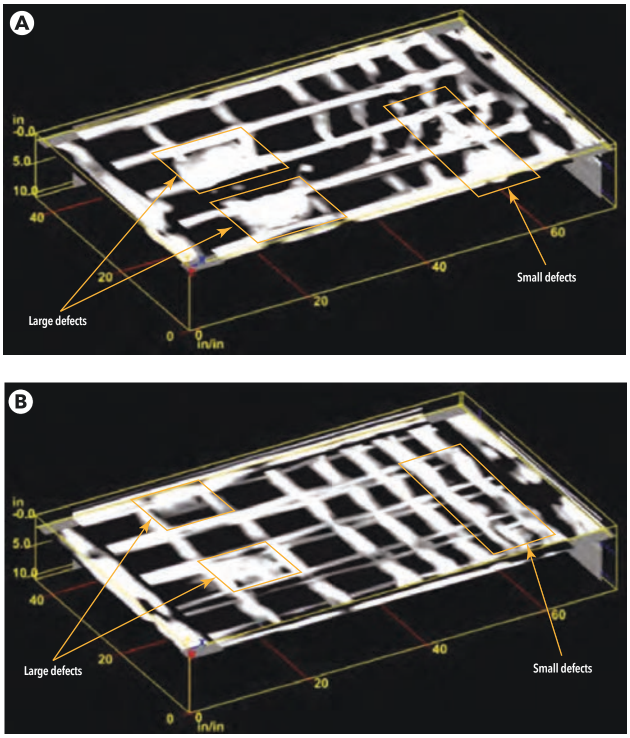

Figure 6. Isotropic view of GPR results from the concrete deck: (a) top surface with 1 in. (2.5 cm) concrete cover; (b) bottom surface with 1.5 in. (3.8 cm) concrete cover.

Figure 6 shows the 3D model of GPR results scanned from the top and bottom side of the RC deck. A total of 33 scan lines on each side of the concrete deck were collected. Since the large defects were placed at different elevations (two close to the top and the other two close to the bottom), the alternate locations of large defects identified verified that GPR can detect shallow defects. Defects that were buried deep or too small may not be identifiable. Note that a foam strip is not the best representation for delamination associated with corrosion effects; it does not include the corrosion objects that makes concrete more conductive and thus GPR signal more attenuating. The net result is the reduced resolution for detecting small/large defects indicated in Figures 5 and 6 under realistic field conditions. GPR will be implemented on a robot that will move in a two-dimensional plan following predetermined gridlines. Results will be summarized in a future report.

Concluding Remarks

The average age of America's bridges (numbering more than 617 000) is approximately 45 years based on ASCE (2021) and rapidly approaching the end of their 50-year design life. As they continue to deteriorate, the aging bridges require more effective and reliable inspections and more frequent maintenance to ensure safety and serviceability. Current practices require a biennial visual inspection of bridges and is only capable of detecting damage when it has advanced to become visually apparent. As a result, there is a rising demand for aNDT and aNDE tools to assess the condition of bridges both qualitatively and quantitatively, thus improving bridge asset management decision-making. GPR and infrared imaging as two potential NDE tools in aNDT&E were demonstrated to be successful in detecting subsurface defects in RC bridge decks.

The proposed MR interface and robotic platforms will accelerate the use of the proposed app with MR devices, such as HoloLens 2, in the bridge element inspection field to improve the quality of visual inspection (Moore et al. 2001) and condition state assessment for preventative maintenance workflow. The developed MR interface can assist in bridge inspection education, communication, and operative planning in the years to come. The feasibility of a few key robotic platforms and NDE techniques to be installed on the robotic platforms has been demonstrated for their potential applications in tele-inspection and tele-maintenance in the future.

While the potential of the different robotic technologies presented to augment routine inspection is very high, the more involved hands-on in-depth and special inspections still warrant transformative studies. The robotic platforms and associated NDE technologies presented in this paper require further field validations at bridge sites.

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ANNOUNCING NEW AND IMPROVED ASNT 9712 CERTIFICATION PROGRAM

We are pleased to announce the release of ASNT 9712, our new program for the qualification and certification of NDT personnel to the international standard ISO 9712. ASNT 9712 will comply with the 2021 edition of the international standard.

This is an important milestone for the Society. The ASNT 9712 program will be the centerpiece for ASNT's international growth and influence, beginning with India, where the program will be offered through ASNT India Private Ltd. in Chennai once the company opens its doors in January. Expansions to other regions of the globe are being planned for 2023 and beyond. The ASNT 9712 program specifically implements the ASNT Strategic Plan for 2022–2026, including Pillar 1 to improve and expand the certification program, Pillar 2 to improve the value of membership, and Pillar 5 to expand into new regions.

The ASNT 9712 program will be the centerpiece for ASNT's international growth and influence

With the launch of the ASNT 9712 program, the ACCP program, including the name and brand, is being sunset. However, ACCP certifications previously issued will remain in effect through their expiration date, after which time certificate holders will be required to apply and qualify for the ASNT 9712 credential.

The ACCP program has been around since the mid-1990s, but for various reasons never gained widespread acceptance in the international community. Our 75th anniversary publication *From Vision to Mission: ASNT 1941 to 2016* provides a detailed history of the struggles the international community experienced in establishing personnel qualification standards, and the challenges ASNT faced in fielding a certification program which would comply with the international standard and be widely respected and adopted. I encourage you to read that part of our history to understand the relevance and importance of the new ASNT 9712 program.

The ASNT Board of Directors recognized these challenges, as well as shifts in the international NDT community, and in 2016 directed the redevelopment of the ACCP program. Through the efforts of many staff and volunteers, the new ASNT 9712 program is now ready for release with credentials in ultrasonic testing (UT), magnetic particle testing (MT), liquid penetrant testing (PT), and radiographic testing (RT). Exams in other methods and techniques will be coming out in 2023 and beyond.

The first exam location in the US for ASNT 9712 will be the ASNT Houston office, beginning by the end of the first quarter of fiscal year 2023. Additional sites, as well as mobile testing locations, will be established soon.

I encourage you to watch ASNT's certification website (asntcertification.org), *Materials Evaluation*, and emails for further information on the ASNT 9712 program.

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MEMBER PERK! READ ASNT'S HISTORY BOOK ONLINE FOR FREE.