THE AMERICAN SOCIETY FOR NONDESTRUCTIVE TESTING

MATERIALS EVALUATION

TECHNICAL FOCUS

NDE OF TRANSPORTATION INFRASTRUCTURE

Aerial NDT&E

Underwater Inspection

Corrosion Mitigation

Condition Assessment

JANUARY 2023

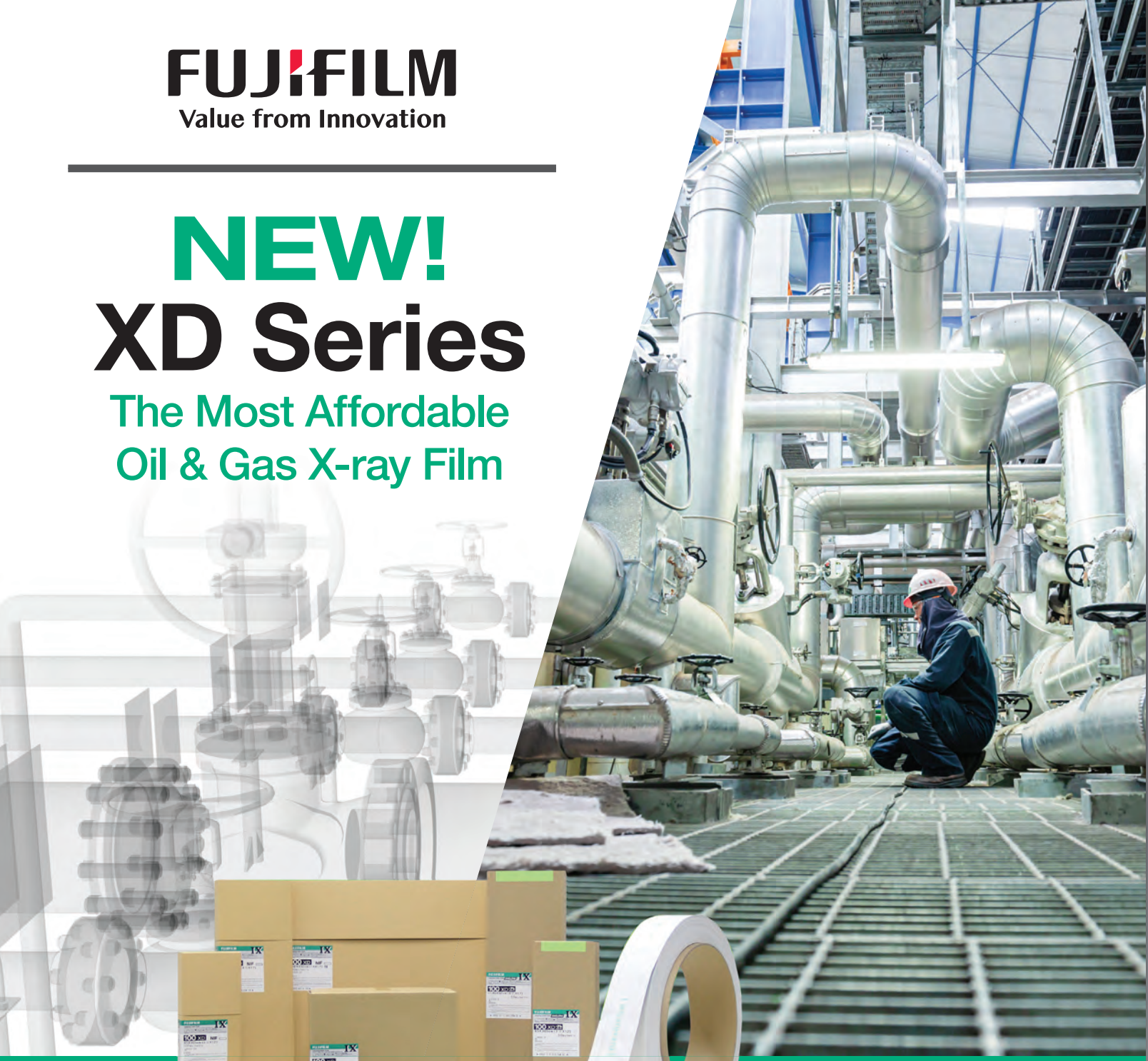
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ASNT 2022 IN REVIEW

YOUTUBE

ASNT 2022: The Annual Conference in Nashville, Tennessee, was one for the books. Enjoy this epic recap! [watch: 2 min]

LISTEN

THE WOMEN OF ASNT'S BOARD OF DIRECTORS

CHAT NDT WITH ASNT

2022 was a historic year for ASNT, with four women now serving on its Board of Directors. In this podcast episode, they share their experiences and advice. [listen: 58 min]

READ

GUEST BLOGGERS SHARE CONFERENCE EXPERIENCES

ASNT PULSE

Our guest bloggers share their personal experiences and favorite moments from ASNT 2022: The Annual Conference in Nashville, Tennessee. [read: 8 min]

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ASNT PRESENTS STATE OF SOCIETY

ASNT PULSE

The State of the Society was presented both in person and virtually during the Annual Meeting of the Members on 31 October 2022. [read: 5 min]

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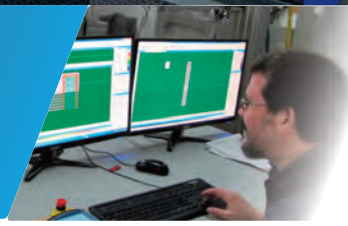


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ME

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HIGHWAY INFRASTRUCTURE INSPECTION



SREENIVAS ALAMPALLI PH.D., PE, MBA, F. ASNT
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It is a pleasure to share this focus issue on highway infrastructure inspection and evaluation with all of you. Highway bridges have been inspected using visual testing (VT) methods for more than 100 years, but the extent, frequency, personnel qualifications, and quality of these inspections have varied significantly depending on the owners. It should be noted that in bridge management terminology, the term "inspection" refers to (field) visual inspection of structures, which is equivalent to visual "testing" as used by ASNT. The word "testing" mostly refers to the use of NDT methods such as magnetic particle testing (MT), liquid penetrant testing (PT), and ultrasonic testing (UT), as well as to static and dynamic load testing.

The roots of current structured inspections mandated by Federal Highway Administration (FHWA) can be traced back to the collapse of the Ohio River Bridge (known as the "Silver Bridge") in 1967, which killed 46 people. This led to the establishment of the National Bridge Inspection Standards (NBIS) that defined structured inspection of publicly owned bridges nationwide, including inspection frequencies and qualifications. NBIS have been updated since then based on lessons learned from various failures–for example, the collapse of Schoharie Creek Bridge in New York State in 1988 led to underwater inspections at regular intervals. Until recently, the primary focus of these guidelines has been public safety by avoiding partial or full collapse of structures. Therefore, VT is predominantly used, with other methods used for local characterization of defects as further investigation based on inspectors' recommendations.

I consider the next decade to be a golden era for development and use of NDE technologies in highway infrastructure, including bridges.

The role of infrastructure in modern societies has changed from being a means to move people and goods from one place to another. Mobility, reliability, economic competitiveness, and security, in addition to safety, are expected by the public and consequently are important performance measures for owners in a resource-constrained environment. This shift in public expectations renewed emphasis on preservation and mobility-focused asset management, meaning finding deterioration and inspection methods that require low service interruptions becomes very important. Therefore, changes to NBIS in recent years have been focused on collecting data for effective and proactive asset management. This issue focuses on recent changes and developments in that direction. At the same time, ensuring quality during construction is also important, and there is renewed emphasis on QA/QC of construction using nondestructive testing methods.

This issue has five papers. The first by Alampalli, Jalinoos, and Ailaney discusses recent changes in NBIS in the direction of asset management and preservation focus. They also discuss recent changes in technologies associated with aboveground inspections and corrosion mitigation as a prelude to rest of the papers. Most failures are attributed to bridge scour; underwater inspections play

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a major role in mitigating these failures. The following paper by Severns discusses modern underwater inspections that are increasingly reliant upon new technologies and nondestructive testing methods beyond VT (such as UT, MT, and sonar in conjunction with remotely operated vehicles) to gain a broader picture of the asset and its condition, increasing efficiency while lowering risk in the process.

The quality of a completed structure starts with good quality control during construction, and thus the use of quality control during construction to adhere to design specifications is paramount for durability and preserving expected service life. Sanayei, Yuan, Moreu, and Alampalli discuss the use of these new technologies for ensuring construction quality and digital history for future management. They illustrate the use of these technologies through a study conducted using an RGBD camera.

While improving accuracy in the detection and characterization of deterioration and defects using NDE methods is essential, improving the speed of NDE data collection and interpretation—allowing economical periodical evaluation—has potential to yield tools for better bridge management. Gucunski et al. provide an overview of the current practice of bridge evaluation by NDE methods, recent efforts to improve the speed of NDE data collection through automation and robotics, and improved condition interpretation through advanced visualization and combined analysis of results of multiple NDE technologies. Similarly, use of advanced multi-sensor robotic platforms, such as uncrewed ground-based systems (UGS) and uncrewed water-based systems (UWS), are also being used increasingly for similar purposes. A futuristic view of using drone-based NDE for elevated structures (bridges, buildings, dams, power plants, tunnels, etc.) is discussed by Chen et al. These systems, including human-robot systems, have potential to transform bridge inspections in the future to minimize impact to traffic at bridge sites.

I consider the next decade to be a golden era for development and use of NDE technologies in highway infrastructure, including bridges, and am glad to share recent policy and technological changes with all of you. It was great working with ASNT Director of Publications Jill Ross and the authors in this issue. I thank them for their enthusiasm and hard work in bringing this issue to all of you, and I hope you enjoy reading the articles as much as we did in preparing them. We look forward to hearing your comments and opinions on these articles and on this topic in general. ME



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RESEARCH IN NONDESTRUCTIVE EVALUATION

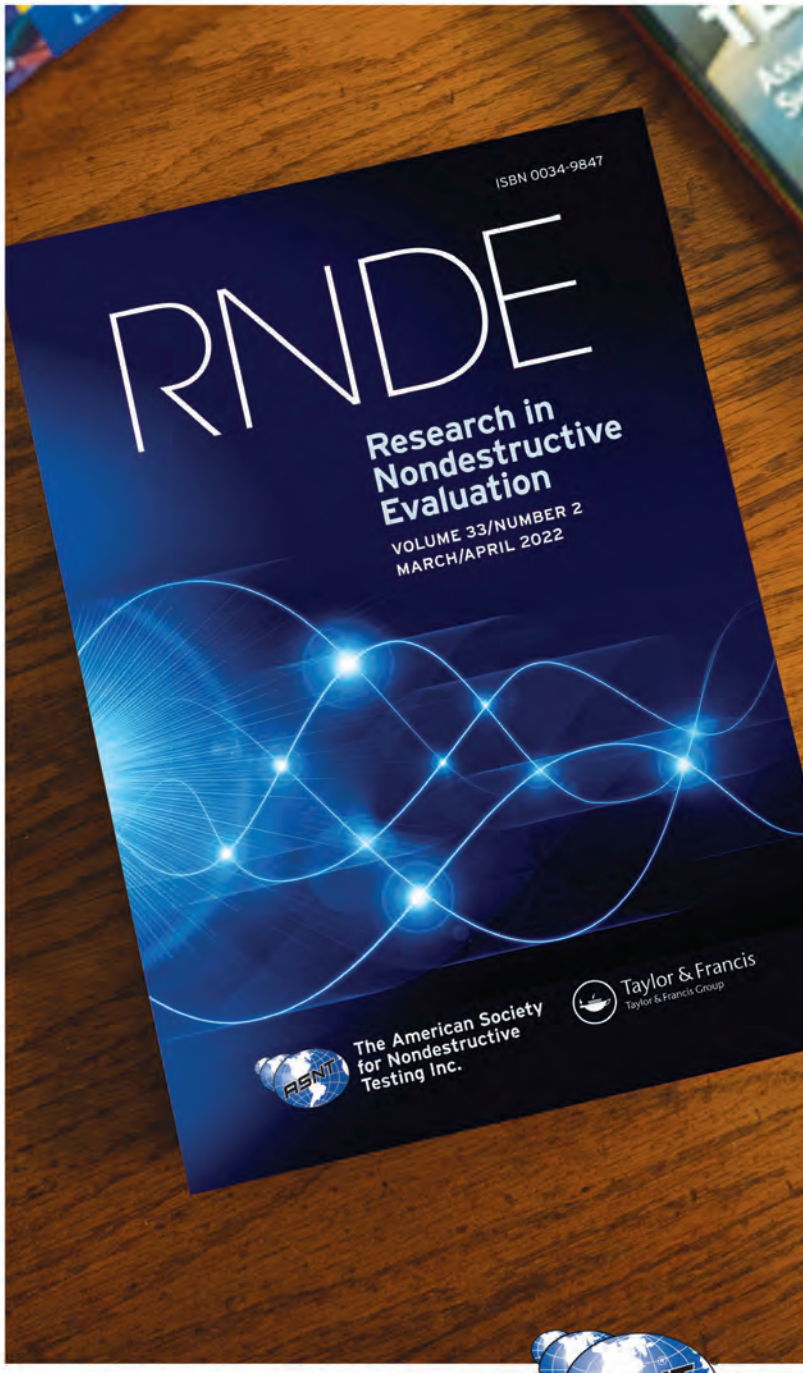
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RESEARCHER DEVELOPS NEW SENSOR THAT PROVIDES EARLY WARNING OF BRIDGE DAMAGE



A new prototype sensor that provides an early warning signal if a bridge is at risk of scour–the number-one cause of bridge collapse globally–has been developed by a Queen's University Belfast researcher.

Scour is erosion of riverbeds and banks, which can cause major bridge structural failure problems. **Dr. Myra Lydon** has been working on a sensor since 2021 to tackle the problem.

An initial prototype sensor has been developed in partnership with Somni Solutions Ltd. The project was funded by UK Research and Innovation's Impact Acceleration Accounts (IAA) and Invest NI has provided additional funding for market exploration.

Lydon explained the significance of the new sensor, saying, "In 2019 it was estimated that within the UK an average of 8.2 million passenger journeys are lost annually due to the risk of bridge scour, with an associated economic cost of £60 million."

Citing a 2009 catastrophic bridge failure in Malahide, County Dublin, where scour failure occurred suddenly, she added, "With scour, there is often no prior visible sign of distress to the structure. In Malahide, the bridge was inspected just weeks prior to its collapse and had passed inspection but then failed seconds after a full passenger train crossed. Thankfully, it narrowly avoided the catastrophe.

"It is vital that we protect our bridges and are able to detect scour before incidents like this take place. The sensor that we have developed detects changes in the riverbed prior to the damage occurring on the bridge. This can provide an early warning, which undoubtedly is safer and helps to prevent widespread bridge failures when we are faced with extreme climate events, such as flooding."

Initial laboratory and field trials have been completed, and Lydon is working with Kris Campbell Head from the Highway Structures Unit in the Northern Ireland Department for Infrastructure to identify a suitable bridge test site. The sensor will be installed along with other structural health monitoring equipment to ensure the safety of aging bridges.



Bridge scour–the erosion of riverbeds and banks–can cause major bridge structural failure problems.

TINY ROBOTS INSPIRED BY ORIGAMI HAVE POTENTIAL USES FOR MATERIALS TESTING

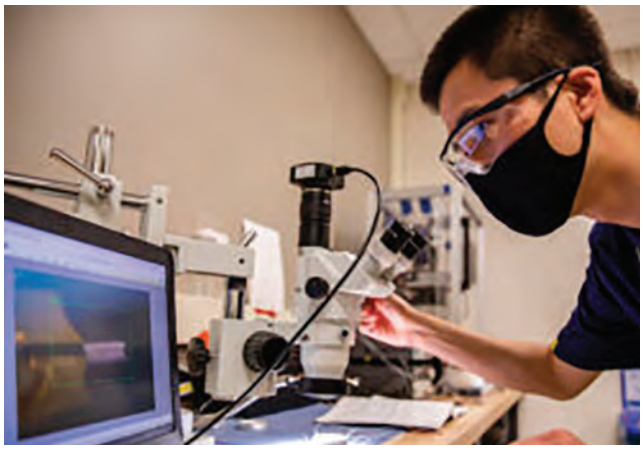
Origami principles can unlock the potential of the smallest robots, enhancing speed, agility, and control in machines no more than a centimeter in size. At University of Michigan, researchers have demonstrated that behavioral rules underpinning the Japanese art of folding can expand the capabilities of these machines, creating potential for greater use in fields as diverse as medical equipment, infrastructure sensing, and materials testing at a mass scale.

"We've come up with a new way to design, fabricate, and actuate microbots," said Evgueni Filipov, assistant professor of civil and environmental engineering. "We've been the first to bring advanced origami folding capabilities into one integrated microbot system."

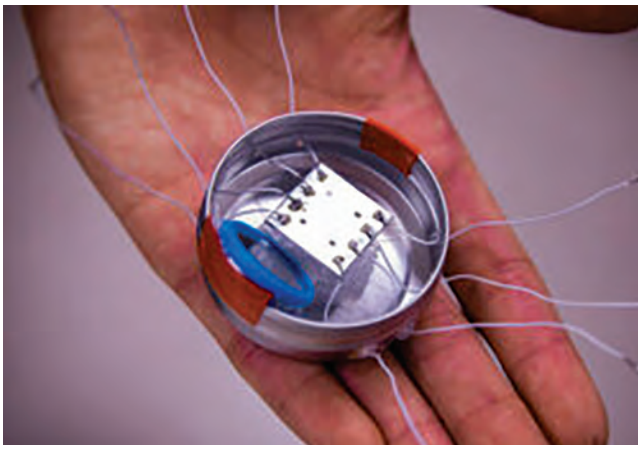
Their bots can form one shape, complete a task, then reconfigure into a second shape for an additional task, and so on.

The latest research from the team, which includes Kenn Oldham, a U-M professor of mechanical engineering, PhD student Yi Zhu, and graduate research assistant Mayur Birla, appeared in *Advanced Functional Materials*.

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Yi Zhu, Graduate Student Research Assistant for Civil and Environmental Engineering, tests a new generation of microrobotics inside Evgueni Filipov's lab at the University of Michigan.



A new generation of microrobotics is based on the principles of origami.

To date, most microbots have limited movements, which hampers their ability to perform useful tasks. To increase their range of motion, they need to be able to fold at large angles. U-M's team has created microbots that can fold as far as 90 degrees and more. Larger folds allow microbots to form more complex shapes. U-M's approach enables its microbots to complete their range of motion up to 80 times per second, a faster pace than most can operate.

Microbots using origami principles often require an outside stimulus to activate, such as heat inside a body or a magnetic field applied to the microbot. U-M's utilize a layer of gold and a layer of polymer that act as an onboard actuator–meaning no outside stimulus is needed.

While the microbots are currently controlled by a tether, eventually, an onboard battery and a microcontroller will apply an electric current in the systems.

"When current passes through the gold layer, it creates heat, and we use heat to control the motions of the microbot," Filipov said. "We drive the initial fold by heating the system, then we unfold by letting it cool down.

"To get something to fold and stay folded, we overheat the system. When we overheat, we can program the fold–change where it comes to rest."

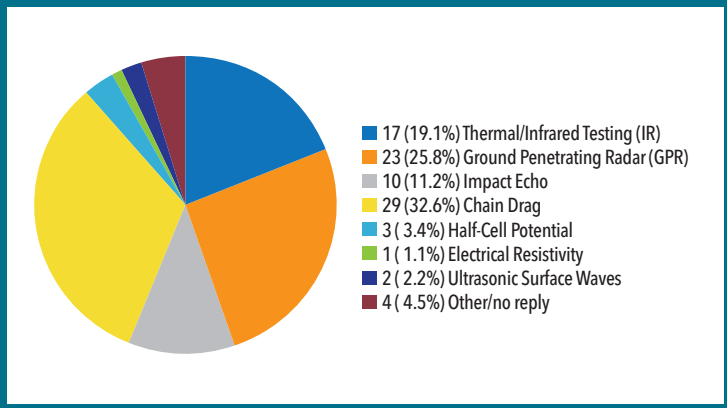
These capabilities allow microbots to function elastically and plastically–giving them the ability to recover their original shape.

The research was supported by the Defense Advanced Research Projects Agency and the U-M College of Engineering Dean's Fellowship.

DATAFACTS

NDE METHODS FOR BRIDGE INSPECTION

The Annual State Bridge Engineers Survey (2018)* conducted by the AASHTO Subcommittee on Bridges and Structures found that the most often recommended NDE methods for estimating delaminated areas for partial depth removal were chain drag (33%), ground penetrating radar (26%), and thermal/infrared testing (19%).



*based on 42 respondents; more than one method could be selected .

Source: Annual State Bridge Engineers Survey (2018), AASHTO Subcommittee on Bridges and Structures

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VISICONSULT ACQUIRES MAJORITY STAKE IN DIONDO

After reaching an initial agreement in July 2022, VisiConsult X-ray Systems & Solutions GmbH announced in November that it has completed its acquisition of a 51% majority stake in the CT specialist diondo GmbH. This strategic cooperation will significantly increase the capabilities of both companies.

Lennart Schulenburg, general manager of VisiConsult, said the combined products and services of the two companies would be greater than the sum of its parts: "For customers, bringing VisiConsult and diondo together means new opportunities to enhance operations. With our complementary product lines, customers can now widen the scope of what is possible. This is a perfect combination of world-class technology, automation, and AI capabilities."

NEW PREFIXES FOR EXTREME NUMBERS

The data boom has prompted the governors of the metric system to agree on new prefixes to describe the outrageously big and small. The prefixes ronna and quetta represent 1027 and 1030, and ronto and quecto signify 10–27 and 10–30. Earth weighs around one ronnagram, and an electron's mass is about one quectogram. Ronna and quetta might sound strange now, but so did giga and tera once, says metrologist Olivier Pellegrino. This is the first update to the prefix system since 1991, when zetta (1021), zepto (10–21), yotta (1024), and yocto (10–24) were added.

AIR FORCE RESEARCH LABORATORY DEBUTS RENOVATED CT LABORATORY

The Air Force Research Laboratory hosted an official tour of its recently renovated Computed Tomography (CT) Laboratory on 9 November. The lab, part of AFRL's Materials and Manufacturing Directorate, supports nondestructive testing of 3D-printed materials for the Defense Department's internal and external customer base.

The Accelerated Materials and Processing Solutions branch arranged the tour to highlight an extensive makeover of its facility, which included the installation of an additional CT machine and the construction of a brand-new suite to safely house the added equipment.

"The lab tour specifically highlighted how [materials and processing] lessons learned and the new Computed Tomography Lab are being applied to safely accelerate implementation of additive manufacturing technologies into emerging and future weapons systems," said Jeff Stricker, the Accelerated Materials and Processing Solutions branch chief.

The directorate also hosted a formal ribbon-cutting event in the Additive Manufacturing Laboratory to recognize the recent completion of major infrastructural improvements within both facilities under a shared funding source.

Senior Materials Engineer Steve Thompson from the Structural *Materials Evaluation* section oversaw the project from its inception in conjunction with Matthew Geis, a project engineer from the Engineering Services and Support branch.

"We're proud to bring this facility into the 21st century," said Thompson. "These changes will allow us to do our jobs better, and more efficiently."

The roughly $4.5 million, 6600-square-foot-facility renovation project was covered by Flex-4 funding and is slated to be completed by December 2022. The Department of Defense provides Flex-4 funds to enable unique research capabilities within its laboratories. Roughly $1 million in supplemental AFRL funding financed the additional computed tomography machine. ME

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NDE OF BRIDGES

Nondestructive testing and inspection of bridges have been historically limited to visual testing. However, lots of interesting solutions are being developed to determine key features of bridges such as concrete thickness, steel rebar conditions, corrosion, compressive strength, and chloride content. In this section, we discuss inspection of bridges using different techniques.

US7992449B1

METHOD FOR ASSESSMENT OF CABLE STRENGTH AND RESIDUAL LIFE

(Khaled M. Mahmoud)

This patent describes a statistical method for assessing condition and residual life span of bridge cables. The overall approach is based on random sampling of a few cable wires and mechanical testing to determine probability of defects in the wires, simulating stress strain curves to determine strain increment levels to reach ultimate elongation and hence remaining useful life. The approach utilizes a computational model to establish the distribution pattern of broken and cracked wires and applying the rate of changes to a time-dependent degradation prediction model to determine the remaining useful life.

US10620085B2

BRIDGE INSPECTION AND EVALUATION METHOD BASED ON IMPACT VIBRATION

(Jian Zhang, Qi Xia, Bo Zhang, and Shuanglin Guo)

This patent describes a low-cost and efficient technique for inspection of medium and small bridges utilizing impact vibration. A backward analysis based on impact of blocks is utilized to rapidly inspect bridges from the road network to find ones with bearing capacity shortage. A forward analysis based on progressive impact loading is performed to evaluate the bearing capacity of bridges in good safety conditions. This bridge bearing capacity is assessed using actual static deflections and residual deflections from a calculated static load at the displacement measurement points associated with cracks or other defects.

US9036861B2

METHOD AND SYSTEM FOR REMOTELY INSPECTING BRIDGES AND OTHER STRUCTURES

(Shen-En Chen, Edwin W. Hauser, Charles G. Boyle, and Meenu Natarajan)

This patent describes a low-cost invention based on spatially integrated small-format aerial photography for imaging bridge surfaces to supplement visual inspection. The camera, along with a GPS for geo-referencing instruments in the airplanes flying at about 304.8 m (1000 ft) above, allow detection of sub-inch cracks and joint openings on the bridge. A plurality of aerial photography image captures are processed and combined to create a composite image for automatically marking structural defects, followed by a rating technique to quantify the structural conditions of the bridge. ME

Patents Roundup *provides a review of recent patents of interest to the NDT community. If you've been granted a patent and would like to see it featured in an upcoming issue, please email Patents Editor Saptarshi Mukherjee at mukherjee5@llnl.gov.*

Editor's Note: *Patents Roundup reviews both issued patents and published patent applications. Issued patents are listed by patent number, typically separated by commas (e.g., US Patent 10,891,520) and published patent applications are listed with the year first, followed by an identification number (e.g., 2018/0261344). At times, published applications may be of more interest to our readers because they are published 18 months from the application date, whereas granted patents typically take much longer. However, please be aware of the provisional rights to a reasonable royalty under 35 U.S.C. 154(d) between the date of publication and the date the patent is issued.*

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SAVE THE DATE FOR RESEARCH SYMPOSIUM

The 31th Research Symposium will take place 26–29 June 2023 in Columbus, Ohio. Accepted presenters will have the opportunity to publish their work in a special Symposium edition of *Research in Nondestructive Evaluation*. For more details, go to asnt.org/events.

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ULTRASONIC INSPECTION SOLUTION



Waygate Technologies, a Baker Hughes business and provider of nondestructive testing (NDT) solutions for industrial inspection, introduces Krautkrämer SpotVision, a new phased array ultrasonic solution for spot weld inspection. Krautkrämer SpotVision was developed specifically for the requirements of spot weld inspection in the automotive industry. By using the inspection device (e.g., on chassis parts during the manufacturing process), car companies can reduce downtime while ensuring that their products meet high quality standards and product safety is guaranteed. The Krautkrämer SpotVision solution combines a new phased array probe with the latest software and the Krautkrämer Mentor UT flaw detector.

WAYGATE TECHNOLOGIES
BAKERHUGHES.COM/WAYGATE-TECHNOLOGIES

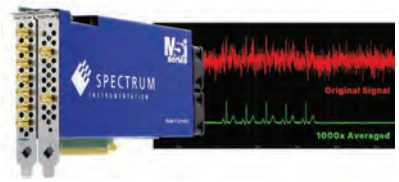
WIRELESS 3D SCANNER



Exact Metrology: A Division of In-Place Machining Company now offers the 2022 Artec Leo from Artec 3D. The NVIDIA Jetson TX2 processor in this new version runs at more than twice the power of its predecessor, while consuming less than 7.5 watts. Additionally, it's equipped with multi-core processing with the NIVIDIA Denver 2. This adds two cores and more horsepower to what's now a Heterogeneous Multi-Processor Architecture, with 2 GHz on each of the six cores. The 2022 Leo also features a new 3D scanning experience with a fresh new user interface and a screen that's easier to use.

EXACT METROLOGY: A DIVISION OF IN-PLACE MACHINING COMPANY
EXACTMETROLOGY.COM

DIGITIZER CARDS

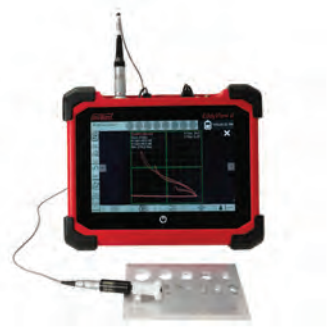


A new firmware option has been created by Spectrum Instrumentation that allows the company's high-speed M5i digitizer cards to perform onboard summation averaging. Averaging is a useful tool for reducing unwanted signal noise, while at the same time improving measurement resolution, dynamic range, and signal-to-noise ratio (SNR). The new option enables the M5i digitizers to perform the averaging function by utilizing advanced onboard Field Programmable Gate Array (FPGA) technology. The M5i series digitizers deliver real-time sampling at rates up to 6.4 GS/s with 12-bit resolution, and they can stream all the acquired data directly over the PCIe bus at 12.8 GB/s.

SPECTRUM INSTRUMENTATION GMBH
SPECTRUM-INSTRUMENTATION.COM

EDDY CURRENT FLAW DETECTOR

UniWest announces the new EddyView® II portable eddy current flaw detector. The EddyView II features a large 8 in. touchscreen display with gesture adjustments for key parameters such as gain and rotation, ability to drive conventional probes or array probes, an independent channel that monitors probe to part coupling (liftoff), and UniWest's signal performance with extremely low



signal-to-noise. The EddyView II also includes multi-frequency probe drive and signal mixing, digital conductivity and nonconductive coating thickness. It is compatible with UniWest's ECS-1S and JF-15 rotating bolt hole scanners.

UNIWEST
UNIWEST.COM

SPRAY FOAM DEPTH GAUGE

Paul N. Gardner USA introduces a new offering: The Depth Gauge. Used for measuring thickness of open and closed cell foam, this product allows commercial roofing contractors and spray polyurethane applicators to test the depth of the foam quickly and easily while being applied on a roof substrate. It is also designed for measuring the depth of fireproofing (spray fire resistive material)



to ensure consistent depth from one area to another. Constructed of sturdy plastic and weighing in at only 1 lb, this gauge can read depths up to 5.75 in. It has an easily adjustable stainless-steel pin and easy-to-read numbers.

THE PAUL N. GARDNER COMPANY INC.
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THE 13TH PRINCIPLE FOR DIGITAL TRANSFORMATION

Background

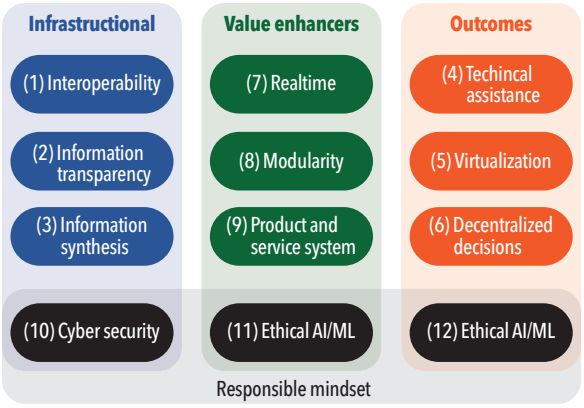
Digital transformation is at the core of the current industrial revolution. The nondestructive evaluation (NDE) sector has started embracing it under the broad theme of NDE 4.0. It is changing the value proposition of inspection processes from "an undesirable quality check" to a "much-needed source of data, information, and knowledge," from manufacturing to service life maintenance. The inspection community is at the stage where it has started exploring standards and preparing to create regulations. A precursor to such a disciplined or structured approach is a set of guiding principles that will enable proper development of technologies, products, and services, and enable infrastructure. This brief provides a structured model of 12 principles in three synergistic perspectives with a responsible foundation. They are designed to serve as a guide to meaningful development, deployment, and leveraging of the next generation of inspection systems, as well as creating, capturing, and distributing value from the data they generate.

Up Until Now

A 2019 paper published by Ripi Singh [1] mentioned four principles for NDE 4.0 derived from the Industry 4.0 context. The ICNDT Special Interest Group subsequently proposed eight principles as a part of NDE 4.0 deployment management guidance [2]. More recently, the authors had an extensive conversation on what is needed to help the community in absence of regulations and standards. The outcome is a list of 12 principles in a structured form, recently published in [3].

1. **Interoperability**: The ability of systems (assets, instruments, sensors, devices, inspection equipment) to connect and communicate with each other via the Internet of Industrial Things (IIoT).
2. **Information Transparency**: The ability of systems to share information (with semantic interoperability), facilitating interpretation, training, and visualization.
3. **Information Synthesis:** The ability of systems to synthesize information obtained from the materials, environment, and usage history, of several comparable assets and provide intelligent forecasting.
4. **Technical Assistance**: The ability of systems to assist with inspection automation, workflow management, decision-making, and traceability.
5. **Virtualization**: The ability of systems to create virtual models of themselves and of other assets in their environment that can facilitate the creation of digital twins, threads, and weaves.
6. **Decentralized Decisions**: The ability of systems to make decisions on their own and perform inspection tasks independently, and to seek human intervention in case of exceptions, interferences, or conflicting objectives.
7. **Real Time**: The ability of systems to generate and retrieve datasets in real time to support or substantiate decentralized decision-making processes.
8. **Modularity**: The ability of systems to flexibly adapt to different requirements by virtue of design characteristics.
9. **Product Service System (PSS)**: The ability to synergistically merge a specific set of products and services to create, capture, and distribute enhanced value for purpose.
10. **Cyber Security**: The ability of systems to protect themselves from disruption or misdirection and protect the data from theft, damage, or unauthorized disclosure.
11. **Ethics**: The ability of the systems to reduce bias, warn users when operating outside design parameters, and shut down before causing any harm.
12. **Sustainability**: The ability of systems to self-optimize energy consumption and data generation for sustainability.

The dozen NDE 4.0 principles



This list should not be treated as a compliance checklist but instead as a reference for awareness, education, and guidance applications. If you have something to add, please share with the authors. A follow-up may be published in a future issue of *Material Evaluation*.

***NDE Outlook** focuses on possibility thinking for NDT and NDE. Topics may include technology trends, research in progress, or calls to action. To contribute, please contact Associate Technical Editor Ripi Singh at ripi@inspiringnext.com.*

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Outlook – Application of These Principles

We see the following opportunities for the application of these principles in digitalization of inspection processes and digital transformation of inspection industry

- **Basis for Much More.** Profound transformation requires the community to revise governance and controls. These principles will form the basis for revisions to regulations, certifications, standards, conformance, and compliance requirements, as well as best practice recommendations.
- **Organizational Alignment.** As we are getting more and more dispersed globally–delegating authority and responsibility across cultures–it is important for managers to have clarity on what is acceptable and preferred. These principles make a useful leadership tool to keep the organization aligned and focused on meaningful actions.
- **Building a Strategic Roadmap.** Transformation requires a strategic roadmap that can handle higher levels of uncertainty, rapid obsolescence, multiple concurrent changes, and new skills. These principles help align various facets of organizational change, reduce conflict, validate the roadmap for purpose, and governance of its pursuit. In addition, these can help with assessment processes before and alignment after a merger/acquisition.
- **Developing New NDE Products and Services**. There will be times when it will be difficult to meet all of the desired requirements for the digitalized product and service system concurrently. In such situations, principles help make the right choices, prioritize the proper selection of alternatives, and reduce internal conflict.
- **Talent Development.** NDE is transitioning from a niche role as a quality control support instrument to an invaluable knowledge-generating process for creating value through substantial improvements in business sustainability, quality, and safety. These principles shape those instances and transform how we recruit and develop NDE practitioners in alignment with an NDE 4.0 roadmap.
- **Regular NDE Activity.** These principles enhance the value extracted from NDE 4.0 activities, be it in-production inspection on the shop floor or in-service inspection of a high-value asset.

Your Turn to Adopt and Adapt

When you look deeply, you will see the intent behind the organized structure to support the applications. These are focused on the responsible use of technology for a profound transformative purpose. With that in mind, you are welcome to tailor this set to your business situation, your supply chain, your customer expectations, and your desire to push innovation. You can even add some of your own to the mix. Dropping any one of them permanently is not advisable. ME

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1. Singh, Ripi. 2019. "The Next Revolution in Nondestructive Testing and Evaluation: What and How? " *Materials Evaluation* 77 (1): 45–50.

2. ICNDT-SIG-4.0-DMG-2-2022 NDE 4.0 Deployment Management – Guidance, Under review with ICNDT Expert panel.

3. Singh, Ripi, Ramon Fernandez, and Johannes Vrana. 2022. "Principles for Successful Deployment of NDE 4.0." Journal of Non Destructive Testing and Evaluation 19 (4): 28-34. Retrieved from http://jnde.isnt.in/index.php/JNDE/article/view/21

4. Singh, Ripi, and Ramon Fernandez, 2022. *NDE 4.0: How to Embrace and Thrive Now?* Independently published.

PARTICIPATE

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ASNT Certification Prep Courses are now offered both online and in person in Houston, Texas. The subject matter for all courses is derived from the training topics found in CP-105, Recommended Practice No. SNT-TC-1A, and CP-189. Courses have limited class sizes for optimal learning. ASNT Certification Prep Courses are considered Level III courses and are designed for those who are currently Level II or III and are looking to become an ASNT NDT Level III or to maintain their Level III status. To register, go to asnt.org > Learn > Refresher/Certification Prep Courses.

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IN SITU LASER ULTRASOUND-BASED RAYLEIGH WAVE PROCESS MONITORING OF DED-AM METALS

C. Bakre, T. Meyer, C. Jamieson, A.R. Nassar, E.W. Reutzel, and C.J. Lissenden

A laser ultrasound system is integrated into a directed energy deposition additive manufacturing (DED-AM) chamber to use Rayleigh waves for process monitoring in a noncontact layer-by-layer mode. Layers of Ti-6Al-4V are deposited and then interrogated with ultrasonic Rayleigh waves that are sensitive to flaws and material nonuniformities. The novel integrated material processing and monitoring system is described in detail. Process parameters are intentionally altered to create flaws and anomalies to demonstrate some capabilities of the monitoring system. The generation laser actuates either broadband pulses with a cylindrical lens or narrowband wave packets with a slit mask, which are received in through-transmission mode by a laser interferometer despite the inherent surface roughness. Flaws are detected through comparison to a reference state.

https://doi.org/10.1080/09349847.2022.2120652

TOWARDS IN SITU CHARACTERIZATION OF ADDITIVELY MANUFACTURED PARTS USING NONLINEAR RESONANCE ULTRASONIC SPECTROSCOPY

Prabhakaran Manogharan, Jacques Rivière, and Parisa Shokouhi

In this study, we investigate the feasibility of nonlinear resonance ultrasound spectroscopy (NRUS) for in-situ monitoring of additively manufactured (AM) parts, i.e., while they are still on the build plate. In NRUS, the test specimen is excited around one of its resonance frequencies with increasing driving amplitude. The linear shift in resonance frequency with the increasing driving amplitude is a measure of the constituent material's hysteretic nonlinearity (α). We conduct NRUS on test specimens glued to a thick plate. The specimens are excited using a piezoelectric transducer (PZT) adhered to the bottom of the plate. We measure the hysteretic nonlinearity parameters (α_f and α_Q) of several cylindrical AM specimens fabricated by laser powder bed fusion technique. The measured nonlinearity parameters for the specimens on the build plate are compared to those measured without the build plate. We observe a systematic decrease in the measured nonlinearity when the specimens are tested on the build plate. An analytical study demonstrates that we measure the weighted average nonlinearity of the specimen and build plate, which itself has a lower nonlinearity. Despite the observed difference, the measured nonlinearity parameters of the specimens with and without the build plate are highly correlated.

https://doi.org/10.1080/09349847.2022.2103219

ULTRASONIC NONDESTRUCTIVE EVALUATION OF ADDITIVELY MANUFACTURED PHOTOPOLYMERS

Luz D. Sotelo, Amelia O. Vignola, Celeste A. Brown, Kaushik Sampath, and Matthew D. Guild

Advanced applications of polymer additive manufacturing (AM) require knowledge of the material acoustic and complex elastic properties. Recently, ultrasound nondestructive evaluation (NDE) methods have been applied to the understanding of AM polymers manufactured with a variety of methods. Nonetheless, the available information is still limited to a few materials and frequency ranges, and knowledge of shear acoustic properties and complex elastic properties of AM polymers is lacking. In this study, ultrasound measurements of compressional and shear phase velocity and attenuation are used to experimentally determine the complex elastic properties of 14 AM photopolymers manufactured using PolyJet systems. The results provided in this paper are expected to aid in the design of advanced polymer AM structures and highlight the value of ultrasound NDE for the characterization of AM polymers.

https://doi.org/10.1080/09349847.2022.2151058 ME



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ASTM E2105-00(2016): STANDARD PRACTICE FOR GENERAL TECHNIQUES OF THERMOGRAVIMETRIC ANALYSIS (TGA) COUPLED WITH INFRARED ANALYSIS (TGA/IR)

Thermogravimetric analyses are used for assessment of the thermo-mechanical properties of certain materials. Material characterization, which is defined as the process of measuring and determining the physical, chemical, mechanical, and microstructural properties of materials, has many overlaps with nondestructive testing (NDT) techniques. In other words, in addition to inspection applications, NDT techniques in many cases are applicable for material characterization or can be integrated into a material characterization technique for a more comprehensive assessment and provide extra information. ASTM E2105-00(2016) provides an overview and guideline for the process and machinery involved to achieve thermogravimetric analysis (TGA) results and experiment with different materials. The scope of the standard practice involves several features that provide the overall use and expectations of the analysis. The practice covers general techniques that provide qualitative analyses of samples by using the thermogravimetric analysis coupled with infrared spectroscopy. The use of these two methods is usually named as TGA/IR, which is a great example of materials characterization assisted by nondestructive evaluation methods. A sample of material that undergoes this process is heated in a thermogravimetric furnace at a predetermined temperature profile and typically undergoes through one or more weight losses. Following the weight loss process, the samples are analyzed using infrared spectroscopy to determine the chemical composition and identity. Some thermal analysis instruments are designed to perform both thermogravimetric analysis and differential scanning calorimetry simultaneously. The instrument used for this analysis is called a simultaneous thermal analyzer (STA). The final scope includes the use of values in SI units, regarded as standard. No other units of measurement are included in the standard practice.

The newest version, released in 2016, gives feedback about certain changes in the analysis. The previous limitations of different spectroscopy analyses were modified in the new version of the standard, adding several analyses such as mass spectroscopy. Modifications such as the choice of infrared detectors were added to the standard, explaining how TGA/IR detectors, such as mercury-cadmium-telluride and deuterated triglycine sulfate are used in these analyses. General techniques were modified as well, such as the techniques in evolved gas trapping. These are the means for collecting TGA/IR data. The gas is collected from the furnace in discrete aliquots, which are then analyzed. The overall application of the standard is to provide general guidelines for the practice of thermogravimetry coupled with infrared spectrometric detection and analysis. The practice assumes that the thermogravimetry involved in the practice is proper and well-used.

Applications lie in the areas of manufacturing engineering and material characterization. It is important to address the importance of these methods to understand the overall chemical composition of materials and samples. The use of thermogravimetry in samples will allow the user to understand the chemistry behind the process and get knowledge of how materials change at certain temperatures.

STANDARDS EDITOR
Hossein Taheri, PhD: Georgia Southern University, Statesboro, GA; htaheri@georgiasouthern.edu

REFERENCES

ASTM. 2016. ASTM E 2105-00(2016): *Standard Practice for General Techniques of Thermogravimetric Analysis (TGA) Coupled with Infrared Analysis*. ASTM International, West Conshohocken, PA.

AMERICAN NATIONAL DRAFT STANDARDS

PROJECT INITIATION

ANSI procedures require notification by ANSI-accredited standards developers of the initiation and scope of activities expected to result in new or revised American National Standards. The following is a list of proposed actions and new standards that have been received recently from accredited standards developers. To view information about additional standards for which a project initiation notification has been submitted, and to search approved American National Standards, please visit ansi.org, which is a database of standards information. Note that this database is not exhaustive.

- **BSR/EIA 364-02D-2012 (R202x),** *Air Leakage Test Procedure for Electrical Connectors.* This is a reaffirmation of ANSI/EIA 364-02D-2012 (R2017). This standard establishes a method to determine the integrity of the seal of the shell, insert, and contact interfaces in an electrical connector.

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- **BSR/IEEE 1936.1-202x,** *Standard for Drone Applications Framework.* This is a new standard. The standard establishes a framework for support of drone applications. It specifies drone application classes and application scenarios and the required application execution environments.
- **BSR/IEEE 1937.6-202x,** *Standard for Unmanned Aerial Vehicle (UAV) Light Detection and Ranging (LiDAR) Remote Sensing Operation.* This is a new standard. This standard specifies the operational methods and data management for Unmanned Aerial Vehicle Light Detection and Ranging (LiDAR) remote sensing applications.
- **BSR/ASTM WK82917-202x,** *New Specification for Mechanical Couplings and Fittings for use with AWWA C906 & ASTM F714 Polyethylene pipes.* This is a new standard. Develop and issue a performance standard (similar to ASTM F1948) for use with AWWA C906/ASTM F714 Polyethylene pipe. Scope may include "Seal Only" (Category 2) mechanical fittings to be used in absence of axial loading or in presence of some supplemental axial loading provided external to the fitting.
- **BSR HPS N13.6-202x,** *Occupational Radiation Exposure Records.* This is a revision and redesignation of ANSI N13.6-2010 (R2019). The N13.6 standard provides guidance for radiological facility operators for implementing an occupational radiological exposure records program. It sets forth acceptable techniques for the generation, administration, and retention of occupational radiation exposure records and supporting documentation. The standard applies to all facilities that have personnel who are monitored for exposure to radiation or radioactive material.

CALL FOR COMMENT ON PROPOSALS LISTED

The public comment period has passed for the following draft American National Standards, which are currently in review.

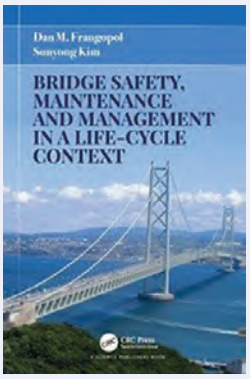
- **BSR/AWS D9.1/D9.1M-202x,** *Sheet Metal Welding Code.* This is a revision of ANSI/AWS D9.1/D9.1M-2018. This code covers the arc and braze welding requirements for nonstructural sheet metal fabrications using the commonly welded metals available in sheet form. Requirements and limitations governing procedure and performance qualification are presented, and workmanship and inspection standards are supplied. The informative annexes provide useful information on materials and processes.
- **BSR/AWS B2.4-202x,** *Specification for Welding Procedure and Performance Qualification for Thermoplastics.* This is a revision of ANSI/AWS B2.4-2020-AMD1. This specification provides the requirements for qualification of welding procedure specifications and welders for manual, semi-automatic, mechanized, and automatic welding. The welding processes included are electrofusion, hot gas, socket fusion, butt contact fusion, infrared, extrusion welding, flow fusion welding, and solvent cement welding. Base materials, filler materials, qualification variables, and testing requirements are also included.
- **BSR/ASME B89.1.13-2013 (R202x),** *Micrometers.* This is a reaffirmation of ANSI/ASME B89.1.13-2013. This Standard is intended to provide the essential requirements for micrometers as a basis for mutual understanding between manufacturers and consumers. Outside, inside, and depth micrometers are described in the Standard.
- **BSR/NSF 14-202x (i125r1),** *Plastics Piping System Components and Related Materials.* This is a revision of ANSI/NSF 14-2021. The physical, performance, and health effects requirements in this standard apply to thermoplastic and thermoset plastic piping system components including, but not limited to, pipes, fittings, valves, joining materials, gaskets, and appurtenances.
- **INCITS/ISO/IEC 23053:2022 [202x],** *Framework for Artificial Intelligence (AI) Systems Using Machine Learning (ML).* This is an identical national adoption of ISO/IEC 23053:2022. Establishes an Artificial Intelligence (AI) and Machine Learning (ML) framework for describing a generic AI system using ML technology. The framework describes the system components and their functions in the AI ecosystem. This document is applicable to all types and sizes of organizations, including public and private companies, government entities, and not-for-profit organizations, that are implementing or using AI systems.
- **BSR/ASME PTC 47.1-2017 (R202x),** *Performance Test Code for the Cryogenic Air Separation Unit of an IGCC Power Plant.* This is a reaffirmation of ANSI/ASME PTC 47.1-2017. The object of this code is to provide uniform test methods and procedures for conducting performance tests of air separation units (ASUs) supplying products to a gasification block and/or power block within an integrated gasification combined cycle (IGCC) facility. This Code applies to ASUs of any size, in either a single-train or multitrain configuration. It can be used to measure the performance of an ASU in its normal operating condition, with all equipment in a new, clean, and fully functional condition.
- **BSR/ASME BPVC Section IX-202x,** *Welding, Brazing and Fusing Qualifications.* This is a revision of ANSI/ASME BPVC Section IX-2021. Section IX of the ASME Boiler and Pressure Vessel Code relates to the qualification of welders, welding operators, brazers, brazing operators, and fusing operators, and the procedures employed in welding, brazing, or plastic fusing in accordance with the ASME Boiler and Pressure Vessel Code and the ASME B31 Code for Pressure Piping.
- **BSR/ASME PTC 19.22-2007 (R202x),** *Performance Test Code on Data Acquisition Systems.* This is a reaffirmation of ANSI/ASME PTC 19.22-2007 (R2017). This Code provides guidance for design, selection, and application of the data acquisition systems used in ASME Code Performance Tests. This Code provides descriptions of the various data acquisition system architectures and information on determining system uncertainties and to assist in selecting and applying these data acquisition systems.

ISO DRAFT INTERNATIONAL STANDARDS

The following are standards that the International Organization for Standardization (ISO) is considering for approval. The proposals have received substantial support within the technical committee that developed them and are now being circulated to ISO members

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BRIDGE SAFETY, MAINTENANCE, AND MANAGEMENT



CRC Press has published **Bridge Safety, Maintenance and Management in a Life-Cycle Context** by Dan M. Frangopol and Sunyong Kim. This book addresses important concepts and approaches developed recently on bridge safety, maintenance, and management in a life-cycle context. Bridge life-cycle performance and cost analysis, prediction, optimization, and decision-making under uncertainty are discussed. The major topics include bridge safety and service life prediction; bridge inspection and structural health monitoring; bridge maintenance; life-cycle bridge and bridge network management; optimum life-cycle bridge management planning; resilience and sustainability of bridges and bridge networks under hazards; and bridge management considering climate change. By providing practical applications of the presented concepts and approaches, this book can help students, researchers, practitioners, infrastructure owners and managers, and transportation officials to build up their knowledge of life-cycle bridge performance and cost management at both project level and network level under various deteriorating mechanisms, hazards, and climate change effects.

ROUTELEDGE.COM

STANDARDS UPDATE FROM P. 19

for comment and vote. Readers interested in reviewing or commenting on these standards should order copies from ANSI.

- **ISO/DIS 22974,** *Petroleum and natural gas industry - Pipeline transportation systems - Pipeline integrity assessment specification*
- **ISO/DIS 3444,** *Stainless steel wire ropes*
- **ISO/DIS 23665,** *Unmanned aircraft systems - Training for personnel involved in UAS operations*
- **ISO/DIS 5668,** *Corrosion of metals and alloys - Guidelines for corrosion testing in simulated environment of deep-sea water*
- **ISO/FDIS 23669,** *Corrosion of metals and alloys - Requirements for localised corrosion and environmentally assisted cracking testing of additively manufactured metals and alloys*
- **ISO/DIS 19901-3,** *Petroleum and natural gas industries - Specific requirements for offshore structures - Part 3: Topsides structure*
- **ISO/DTS FDIS 24399,** *Thermoplastic pipes for the conveyance of fluids - Inspection of polyethylene butt fusion joints using time of flight diffraction testing*
- **ISO/DIS 15613,** *Specification and qualification of welding procedures for metallic materials - Qualification based on a preproduction welding test*
- **ISO/DIS 15614-11,** *Specification and qualification of welding procedures for metallic materials - Welding procedure test Part 11: Electron and laser beam welding*
- **ISO/ASTM DIS 52910,** *Additive manufacturing - Design Requirements, guidelines and recommendations*
- **ISO/DIS 8529-3,** *Neutron reference radiation fields - Part 3: Calibration of area and personal dosemeters and determination of their response as a function of neutron energy and angle of incidence*
- **ISO/FDIS 11745,** *Brazing for aerospace applications - Qualification test for brazers and brazing operators - Brazing of metallic components*
- **ISO/DIS 3834-6,** *Quality requirements for fusion welding of metallic materials - Part 6: Guidelines on implementing ISO 3834*
- **ISO/ASTM DIS 52939,** *Additive Manufacturing for construction Qualification principles - Structural and infrastructure elements*
- **ISO/DIS 11611,** *Protective clothing for use in welding and allied processes*
- **ISO/DIS 18279,** *Brazing - Imperfections in brazed joints*
- **ISO/DIS 4773,** *Non-destructive testing - Ultrasonic guided wave testing using the phased array technique*
- **ISO/DIS 10534-2,** *Acoustics - Determination of acoustic properties in impedance tubes - Part 2: Two-microphone technique for normal sound absorption coefficient and normal surface impedance*
- **ISO/FDIS 5156,** *Corrosion of metals and alloys - Corrosion test method for disinfectant - Total immersion method*
- **ISO/DIS 11623.2,** *Gas cylinders - Composite cylinders and tubes - Periodic inspection and testing*
- **ISO/DIS 1089,** *Resistance welding equipment - Electrode taper fits for spot welding equipment – Dimensions*
- **ISO/DIS 19735,** *Corrosion of metals and alloys - Corrosivity of atmospheres - Mapping areas of increased risk of corrosion*
- **ISO/DIS 20956,** *Radiological protection - Low dose rate calibration of instruments for environmental and area monitoring*
- **ISO/DIS 24426,** *Radiological protection - Format of input data for the statistical description of dose records of individuals monitored for occupational exposure to ionizing radiation*
- **ISO/DIS 24588,** *Protective clothing - Personal protective ensembles for use against chemical, biological, radiological, and nuclear (CBRN) agents - Classification, performance requirements and test methods*
- **ISO/DIS 3882,** *Metallic and other inorganic coatings - Review of methods of measurement of thickness* ME

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2023

International Conference on Nondestructive Evaluation of Concrete in Nuclear Applications
25–27 January, Helsinki/Espoo, Finland
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Pipeline Pigging and Integrity Management Conference and Exhibition
6–10 February, Houston, TX
ppimconference.com

NDTMA Annual Conference
7–9 February, Las Vegas, NV
ndtma.org

12th International Conference on Industrial Computed Tomography
27 February–2 March, Furth Germany
iis.fraunhofer.de

16th Asia Pacific Conference for Non-Destructive Testing
28 February–3 March, Melbourne, Australia
apcndt2023.com.au

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International Congress of the Foundry Industry
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8th Middle East NDT Conference & Exhibition
12–15 March, Manama, Bahrain
mendt.co

NASCC: The Steel Conference
12–14 April, Charlotte, NC
nascc.aisc.org

Japan Radiology Congress
13–16 April, Yokohama, Japan
radiology.jp

Digital Imaging for NDT
9–11 May, New Orleans, LA
asnt.org/events

35th Control: International Trade Fair for Quality Assurance
9–12 May, Stuttgart, Germany
control-messe.de

COFREND Days
6–8 June, Marseille, France
cofrend2023.com

art'23: 14th International Conference on Non-destructive Investigations and Microanalysis for the Diagnostics and Conservation of Cultural and Environmental Heritage
14–16 June, Brescia, Italy
aipnd.it

31st Research Symposium
26–30 June, Columbus, OH
asnt.org/events

Oil & Gas Pipeline Leak Detection Congress 2023
27–28 June, Houston, TX
pipeline-leak-detection-congress-usa.com

NDE in Nuclear 2023
27–29 June, Sheffield, UK
snetp.eu

13th ECNDT
3–7 July, Lisbon, Portugal
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European Congress of Radiology
5–9 July, Vienna, Austria
myesr.org/congress

17th International Symposium on Nondestructive Characterization of Materials
15–17 August, Dübendorf, Switzerland
asnt.org/events

60th Annual British Conference on NDT
12–14 September, Northampton, UK
bindt.org

National Pavement Preservation Conference
18–21 September, Indianapolis, IN
tsp2pavement.pavementpreservation.org

FCTM-ESOPE
26–27 September, Paris, France
fctm-esope.com

ASNT 2023: The Annual Conference
23–26 October, Houston, TX
asnt.org/events

4th Asia-Oceania Conference on Neutron Scattering
18–23 November, Dongguan, China
aonsa.org/aocns

World Nuclear Expo
28–30 November, Villepinte, France
world-nuclear-exhibition.com

2024

NASCC: The Steel Conference
20–22 March, San Antonio, TX
nascc.aisc.org

20th WCNDT
27 May–31 May, Incheon, Korea
20thwcndt.com

ASNTONLINE

ASNT Virtual Section Meeting*
11 JANUARY
Topic: Converting between Clock Positions, Degrees, and Metric or Imperial Measurements Using Standard Equations or Microsoft Excel
Speaker: Jeffrey Browning
Time: 3:00 to 4:00 p.m. (ET)

ASNT NDT Level III Liquid Penetrant Testing (PT) Refresher Course
12-13 JANUARY
Time: 8:00 a.m. to 5:00 p.m. (ET)
Deadline to register/transfer/cancel: 29 December

ASNT NDT Level III Radiographic Testing (RT) Refresher Course
17-19 JANUARY
Time: 8:00 a.m. to 5:00 p.m. (ET)
Deadline to register/transfer/cancel: 4 January

Membership Mondays*
23 JANUARY
Topic: New Digital ME
Time: 7:00 a.m. and 4:00 p.m. (ET)

ASNT Learn Webinar*
25 JANUARY
Topic: Bridge Inspection and Evaluation: Current Status and Where We Are Heading
Speaker: Sreenivas Alampalli, PhD, PE
Time: 3:00 p.m. (ET)

ASNT Rewind*
1 FEBRUARY 2023
Time: TBA (two sessions)

ASNT NDT Level III Basic Refresher Course
13-17 FEBRUARY
Time: 8:00 a.m. to 5:00 p.m. (ET)
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BRIDGE INSPECTION

Progression of Bridge Inspection Toward Preservation and Corrosion Mitigation for Improving Asset Management

BY SREENIVAS ALAMPALLI, FRANK JALINOOS, AND RAJ AILANEY

The primary intent of bridge inspection is safety. Thus, the focus during the initial development of bridge inspection guidelines, including National Bridge Inspection Standards (NBIS), was on making sure structures are safe for the traveling public. NBIS are mandated by federal statute at 23 U.S.C. 144 and implemented under 23 CFR 650 subpart C. Most changes since the inception of NBIS have been due to failures, but recently the focus has shifted to include bridge/asset management. As such, there has been an increased emphasis on using inspection data for bridge management purposes and on preservation to make sure these structures are not only safe but also can be maintained cost-effectively to minimize life cycle costs. This requires shifting the focus from predominantly visual inspection to supplementing visual inspections with advanced technologies. In this paper, the authors discuss the changes that have occurred since their 2009 *Materials Evaluation* article.

Introduction

During his inaugural speech on 20 January 2009, US President Barack Obama commented on infrastructure, "We will build the roads and bridges, the electrical grids and digital lines that feed our commerce and bind us together." This quote clearly illustrates that the role of infrastructure in modern societies is multifaceted (Alampalli 2019). Bridges and highway infrastructure are not viewed as just a means to move people and goods from one place to another, but as the backbone of a thriving society. Mobility, reliability, economic competitiveness, and security, in addition to safety, are important performance measures for owners in a resource-constrained environment. This shift in public expectations encourages the use of advanced inspection technologies to maintain uninterrupted mobility (see Figure 1). It also calls for preservation-focused bridge management, in which the focus is finding deterioration at early stages and addressing it proactively through cost-effective preservation/maintenance to avoid costly repairs and rehabilitation.

Over several decades, the Federal Highway Administration's (FHWA) Highway Bridge Replacement and Rehabilitation Program (HBRRP), later known as the Highway Bridge Program (HBP), was the primary source of federal funding for bridges. The HBP afforded

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Figure 1. Augmenting routine bridge inspections using a drone instead of an under-bridge inspection unit to improve mobility.

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state departments of transportation (DOTs) discretion to use funds not only for bridge rehabilitation and replacement, but also for a broad array of preventive maintenance activities. Having a "worst-first" approach to bridge management by focusing only on replacing poor bridges while ignoring the maintenance needs of good and fair condition bridges is inefficient and cost-prohibitive in the long term. Bridge owners have taken advantage of the flexibilities in the HBP and have maintained their inventory in good to fair condition under constrained resources. The Moving Ahead for Progress in the 21st Century Act (MAP-21) and the Fixing America's Surface Transportation (FAST) Act recognized preservation as a vital component of achieving and sustaining a desired state of good repair of highway facilities.

The purpose of data from bridge inspection programs required by the NBIS is safety, but this purpose has also adapted over the years to include bridge management (NBIS 2022). NBIS are mandated by federal statute at 23 U.S.C. 144 and implemented under 23 CFR 650 subpart C. This requires augmenting visual inspection with advanced technologies such as nondestructive evaluation (NDE) methods, corrosion analysis, and engineering structural health concepts to implement objective decision-making processes for asset management (FHWA 2017).

National Bridge Inspection Standards (NBIS)

The inception of systematic bridge inspections in the United States can be attributed to the collapse of the Ohio River Bridge (known as the "Silver Bridge") between Point Pleasant, West Virginia, and Gallipolis, Ohio, which killed 46 people. This failure led to the establishment of the NBIS that include inspection frequencies and qualifications (23 CFR 650.309, 650.311). Given the primary focus of NBIS establishment is safety (i.e., avoiding bridge failures) of bridge structures longer than 6 m (20 ft), NBIS were modified several times, mostly after notable bridge failures. For example, the failure of the Mianus River Bridge led to fracture-critical inspections, and the Schoharie Creek Bridge failure led to underwater bridge inspections with established intervals.

Alampalli and Jalinoos (2009) and Ettouney and Alampalli (2011a, 2011b) discussed evolution of NBIS until 2004 which became effective in January 2005. They described the major provisions of NBIS in effect at that time, including inspection types and personnel qualifications, and then elaborated on the use of inspection data and NDE/NDT technologies. This section describes changes to NBIS since then.

AASHTO's Manual of Bridge Evaluation (MBE) serves as a standard and provides uniformity in the procedures and policies for determining the physical condition, maintenance needs, and load capacity of the nation's highway bridges. Changes made to NBIS in 2009 incorporated the MBE, 1st Edition, 2008 by reference, as FHWA felt that MBE aids bridge owners at all phases of bridge inspection and evaluation (NBIS 2009).

MAP-21 included a requirement for each state and appropriate federal agency to report element-level bridge inspection data to the Secretary, as each bridge is inspected, for all highway bridges on the National Highway System (NHS) (Title 23 U.S.C 144(d)(2).). To meet this requirement, FHWA asked state agencies to collect element-level data during all inspections of NHS bridges performed after 1 October 2014 (FHWA 2013). FHWA also issued the "Specification for the National Bridge Inventory Bridge Elements" (FHWA 2014) to provide the framework for bridge owners to collect and report element-level data to the FHWA. These data have to be collected in addition to other inventory data owners have already been collecting as per the Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges (Coding Guide). All states now collect these data, which provides consistency and uniformity across the country. This is also meant to allow better data-driven performance-based decisions for bridge management. Some states like New York have shifted to element-level inspection of all bridges (both NHS and non-NHS) to maintain uniformity across the state.

The latest revision to NBIS as part of the rule-making process was published on 6 May 2022 (NBIS 2022), and key revisions are noted here. This regulation requires inspection of bridges on all public roads, on and off federal-aid highways, including tribally and federally owned bridges, and private bridges connected on each end by a public road (23 CFR 650.303). This revision redefined fracture critical member to nonredundant steel tension member, NSTM (23 CFR 650.305). It also requires the bridge inspection organizations to maintain a registry of nationally certified bridge inspectors (23 CFR 650.307). Even though there are several changes, the major shift in the regulations is toward the risk-based inspection interval. NBIS addresses the inspection frequency in two ways: (a) permissible inspection intervals for bridges based on the bridge component conditions to allow for extended routine inspection intervals up to 48 months, and 72 months for underwater inspections (23 CFR 650.311); and (b) more rigorous methods

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based on the consideration of condition and other factors that will allow for routine, underwater, and nonredundant steel tension member inspections that would allow some inspection intervals to be up to 72 months (23 CFR 650.311). The regulation requires written reports to FHWA of critical findings identified during inspections and provides minimum criteria for what a critical finding is, to maintain national consistency (23 CFR 650.313).

The rule also introduced "Specifications for the National Bridge Inventory, SNBI" (23 CFR 650.317) (FHWA 2022a) to replace the "Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges (Coding Guide)" introduced in 1995 (FHWA 1992). This is a major change including an expansion of component-level ratings to include bridge railings and their transitions, bearings, joints, channel, channel protection, and scour besides deck, superstructure, substructure, culvert, and channel. A larger set of data is collected not only ensuring highway bridge safety but other considerations, including oversight of the National Bridge Inspection Program; reporting to Congress; emergency response; administering a risk-based, data-driven, performance management program; the National Performance Management Measures for Assessing Bridge Condition regulation (National 2017); and providing quality data through clarity and ease of use (FHWA 2022a).

Full implementation of these changes is expected by Calendar Year 2028 (FHWA 2022b) due to time required to modify relevant software used by bridge owners, development of federal metrics and data-collection mechanisms, development of regulation and policy changes in owner agencies, and so on. These changes to NBIS will not only continue the focus on improving safety but will move toward quality data collection for making better bridge management decisions, and thus supporting the asset management requirements.

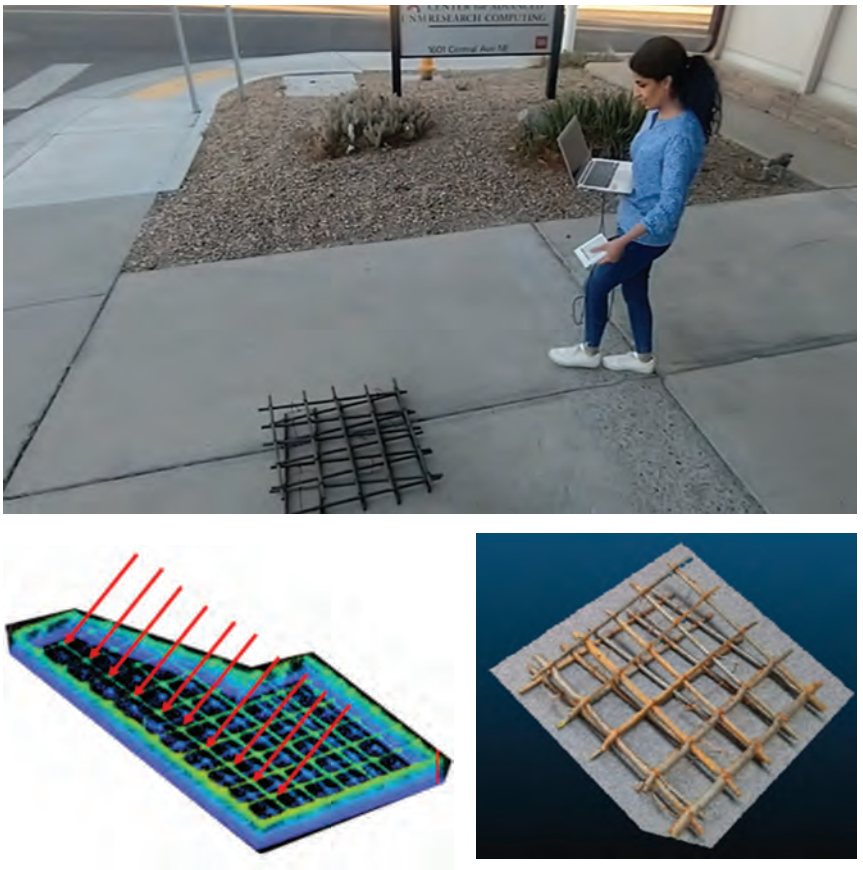
Role of Advanced Technologies in Bridge Inspection

As noted earlier, the public expects not only safe bridges, but also reliability and uninterrupted mobility. This may be accomplished by supplementing visual inspections with advanced NDE and structural monitoring technologies as well as uncrewed aerial systems (UAS) or robotic techniques so that bridge inspection does not require bridge closures that affect the mobility of the traveling public. These methods, combined with risk-based inspection intervals, will likely become prevalent soon, especially with the implementation of the new NBIS.

These advanced technologies have a big role to play in the coming years. Augmenting bridge inspections through these methods has the potential to improve durability and minimize life cycle costs. The most practical of these systems are being used by owners during "in-depth" or "special" inspections or implemented for long-term monitoring. Some examples of advanced systems that are discussed in this special issue include the following:

- Inspection during and before opening to traffic is very important in ensuring durability and maintaining expected service life. The use of light detection and ranging (LiDAR), augmented reality, and technology fusion for data visualization of inspection data plays a major role. Sanei et al. (2023) summarize available technologies for quality control of reinforced concrete structures during construction and focuses on using Red Blue Green Depth (RGBD) cameras for this purpose (see Figure 2).
- In recent years, the use of UAS has been introduced to improve data consistency, work efficiency, inspector safety, and cost-effectiveness during routine inspections. Advanced multisensor robotic platforms, such as ground-based systems (UGS) and uncrewed water-based systems (UWS), are also being used increasingly

Figure 2. Use of RGBD camera for construction inspection.



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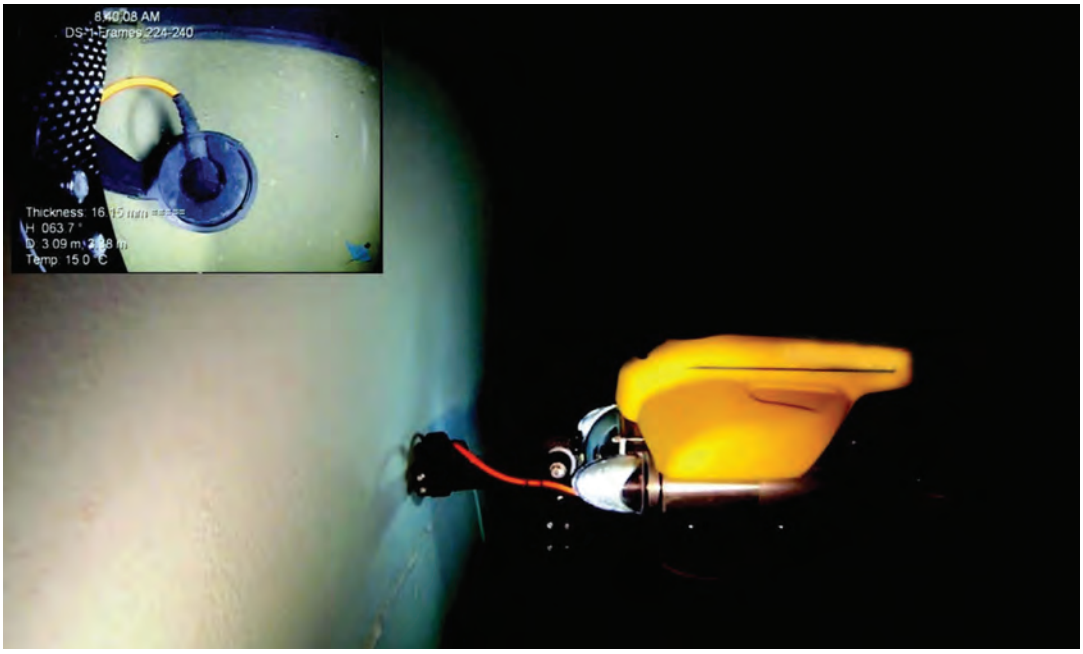


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Figure 3. Climbing robot with NDE capabilities assisting with bridge inspection.

for similar purposes. A futuristic view of using UAS-based NDE for elevated structures (bridges, buildings, dams, power plants, tunnels, etc.) is discussed in detail by Chen et al. (2023). These systems, including human-robot systems, have the potential to transform bridge inspections in the future to minimize impacts to traffic at bridge sites (see Figure 3).

- Similarly, modern underwater inspections are increasingly reliant upon new technologies and nondestructive testing methods beyond visual inspection (see Figure 4). These technologies are used in conjunction with conventional diving inspection to gain a broader overall picture of the asset and its condition, increasing efficiency while lowering risk in the process. Severns (2023) discusses the more modern underwater inspection approach, emphasizing the modern NDT technologies utilized as well as their benefit to the process.
- Improving the accuracy in the detection and characterization of deterioration and defects using NDE methods is essential for the condition assessment of reinforced concrete bridge elements. At the same time, improving the speed of NDE data collection and interpretation—allowing economical periodical evaluation—will enable capturing of deterioration processes and defect formation leading to the development of more realistic deterioration, predictive, and life cycle cost models. Ultimately, those will lead to better bridge management. Gucunski et al. (2023) provide an overview of the current practice of bridge evaluation by NDE methods, recent efforts to improve the speed of NDE data collection through automation and robotics, and improved condition interpretation through advanced visualization and combined analysis of results of multiple NDE technologies.
- Deployment of large-scale wired and wireless sensor networks for bridge structural monitoring (SM) is also being accepted by more and more owners. Augmented by use of artificial intelligence (AI) and deep learning for data analysis,



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Figure 4. Underwater ultrasonic inspection of steel using remotely operated vehicle.

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Figure 5. Processed historical InSar Satellite data (20 708 distinct radar scatters) detecting no settlement at Merrimac Memorial Bridge Tunnel.

these technologies can be useful, especially for complex structures. Remote sensing using satellite-based technologies for system-wide monitoring of the structural assets as a first level of monitoring is also perceived to play a major role as the cost associated with satellites becomes affordable (see Figure 5).

Early-Age Preservation Activities

A bridge preservation program consists of performing cost-effective cyclical and condition-based preventive maintenance (PM) activities that seek to prolong the service life of bridges and delay the need for rehabilitation or replacement. PM activities, as part of the bridge preservation program, can extend the service life of a bridge when it is in good or fair condition. In Figure 6, the leftmost line represents a service life of a bridge without PM and the rightmost line represents the same bridge with both early-age and NDE-based cyclical and condition-based (blue vertical line) PM activities applied when the bridge elements are in good and fair condition. The comparison shows the longevity of a bridge's service life in a bridge preservation program.

The need for collecting early-stage NDE data using advanced multi-sensor systems is discussed for bridge preservation decision-making (Jalinoos et al. 2010a, 2010b). In the next section, field NDE data examples from a reinforced concrete bridge, specifically bridge decks, are included to demonstrate a data-driven tool that can lead to bridge preservation decision-making.

Corrosion of Bridges

Steel-reinforced concrete bridges endure exposure to corrosive materials and environments such as deicing salts and salt water. Unmitigated, these materials accelerate corrosion and significantly reduce service life. The corrosion process begins once the flow of ions from anodes to cathodes has reached a threshold as to destroy the protective oxide film on the rebar. The expansion of corrosive products leads to micro- and macro-cracking of the concrete, delamination, and ultimately bridge deck spalling. Clearly, the ability to characterize a corrosive environment, measure metal corrosion and broken strands, and detect delamination/deterioration is essential in describing concrete member conditions. Due to significant resources spent fixing bridge decks and the value in preserving the superstructure members under them, there have been considerable NDE research and implementation efforts regarding bridge decks during the last decade. Hence, this section describes some of these efforts related to bridge decks. It should be noted

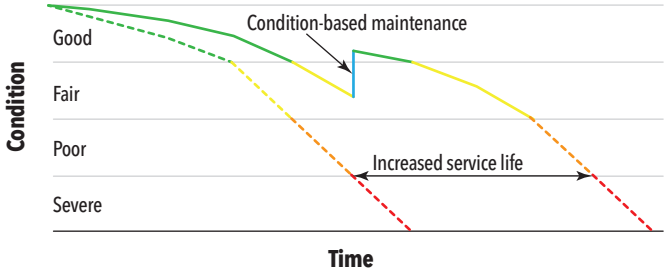


Figure 6. A comparison of bridge condition over time with and without bridge preservation (FHWA 2018).

Legend
Solid-colored lines = with preservation (cyclical and condition-based maintenance)
Dashed-colored lines = without preservation

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TABLE 1
NDE techniques and their application in bridge deck deterioration detection

Corrosion State	NDE Method	Defect/Deterioration
Early-Stage Corrosion	Half-Cell Potential (HCP)	Probability of active rebar corrosion
	Electrical Resistivity (ER)	Likelihood and severity of corrosive environment
	Ground Penetrating Radar (GPR)	Detection of deterioration caused by corrosion and moisture, and rebar cover depth/thickness
Late-Stage Damage - Delamination	Ultrasonic Surface Waves (USW)	Measurement of degradation of elastic moduli
	Impact Echo (IE)	Deck delamination detection and characterization
	Thermal/Infrared Testing (IR)	Shallow delamination detection

that these technologies are equally applicable to other concrete members with metal reinforcement.

Table 1 highlights NDE techniques that have applicability for the detection of defects and deterioration in bridge decks. To successfully track the early-age corrosion progression, NDE techniques such as electrical resistivity (ER), half-cell potential (HCP), and ground-penetrating radar (GPR) are typically used. For later phases of corrosion to end of service life physical damage, ultrasonic surface waves (USWs), impact echo (IE), and thermal/infrared (IR) imaging are commonly used. To assess the service life of the bridge deck, it will be of interest to be able to assess the condition of a bridge deck at all stages of deterioration.

With recent advancements in robotic technology, however, there has been a shift toward the development of automated bridge data collection systems which include automation in data processing for near real-time results. Some of these multi-sensor platforms can be deployed at traffic speeds such as GPR, IRT, and sounding/chain drag systems for deck scanning. For higher-resolution, more in-depth evaluation, the deck is closed for traffic and other systems such as ER, HCP, USW, and IE surveys are used. The robotic systems allow for several times faster data collection time than deploying individual NDE tools—thus decreasing lane closure time and traffic congestion. The multi-sensor systems also allow for the acquisition of large physically independent datasets to increase the reliability of the results and reduce false calls.

DEVELOPMENT OF NDE STACK

Given the complex nature of the corrosion process, it is imperative to collect data from a suite of NDE technologies in order to ensure consistency among different technologies. To accomplish this, the use of "NDE Stack" plot is described herein, where multiple NDE contour plots are organized in a sequential manner. As shown in Figure 7, initially a set of contour maps is used to study the deck's corrosive environment starting with rebar concrete cover depth (obtained from the GPR data); ER and HCP to assess corrosion rate and activity, respectively; and GPR for the corrosive environment. This group is followed by contour maps indicative of concrete physical damage, starting with USW indicating changes in concrete elastic moduli and concrete quality and IE, which is indicative of delaminated areas.

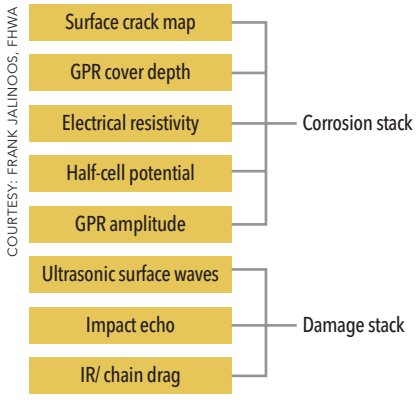


Figure 7. Proposed NDE stack template.

The two corrosion and damage stack groups are summarized as follows:

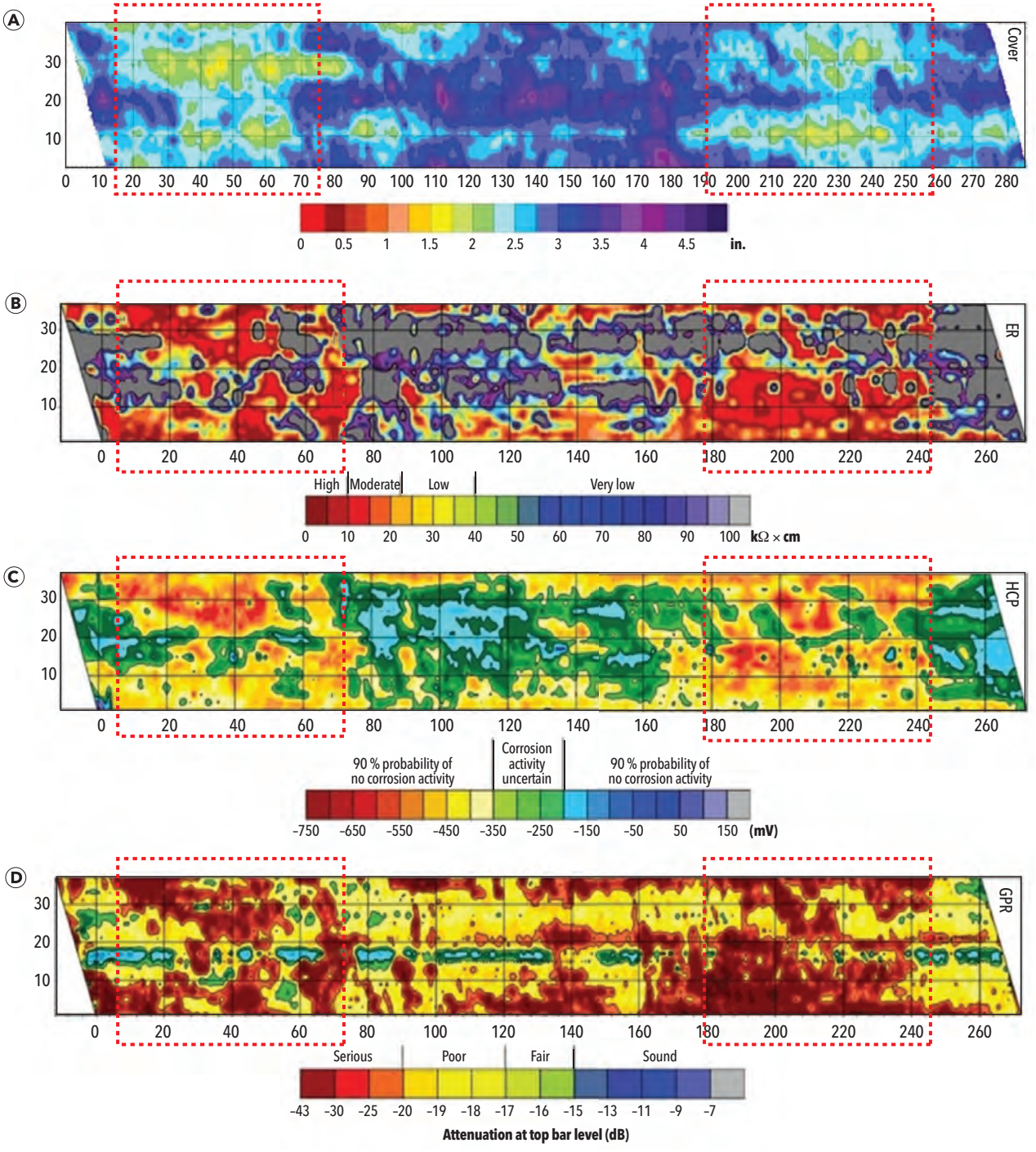
- **Corrosion Stack**: The two principal methods for corrosion assessment include ER and HCP, with ER evaluating the corrosive environment and HCP assessing the probability of active corrosion. The GPR (both cover depth and depth-corrected amplitude) can identify the corrosive environment and the presence of moisture. Areas where GPR indicates low concrete cover depth are good candidates for increased corrosion activity. The

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corrosion stack is particularly useful for characterizing cyclic or condition-based bridge preservation activity—especially useful for bridges with a National Bridge Inventory (NBI) rating between 7 and 9 (bridges in "good" condition).

- **Damage Stack**: IE is the primary NDE technique for the detection and characterization of deck delamination. USW provides a quantitative assessment through the measurement of concrete modulus and is an indicator of concrete quality. It sometimes indicates delaminated areas as well. The damage stack is useful for characterizing the extent of condition-based preservation activity—especially useful for bridges with an NBI rating of 5 or 6 ("fair" bridges).

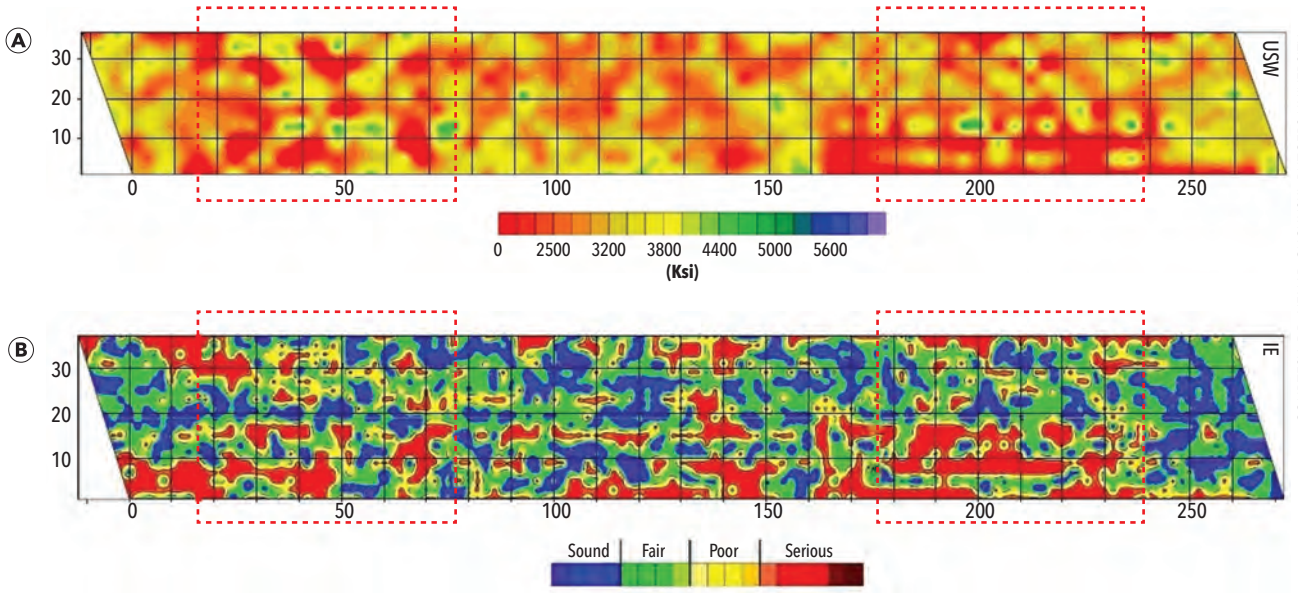
Figures 8 and 9 demonstrate a sample of an NDE stack from a bridge in the Mid-Atlantic cluster obtained through the FHWA Long-Term Bridge Performance (LTBP) program (Gucunski et al. 2016; Kim et al. 2019). As a part of the QC/QA process, it is important to ensure all NDE results are consistent and follow reasonable correlation across different



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Figure 8. Comparative assessment of NDE technologies on corrosion stack: (a) GPR cover depth; (b) ER; (c) HCP; (d) GPR amplitude.

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Figure 9. Comparative assessment of NDE technologies on damage stack: (a) USW; (b) IE.

test methods. The results indicate that ER, GPR, and HCP generally correlate in defective zones (shown in the broken rectangle), showing the onset of the corrosion activity (Figure 8). The same conclusion is observed for the correlation between the IE and USW contours for the damage phase (Figure 9). Such strong correlation between multiple NDE techniques confirms the improved reliability of complementary NDE technologies to monitor the progression of corrosion leading to damage in a bridge deck. The above correlation between defective zones provides for a qualitative assessment of condition; a more rigorous, statistically based condition evaluation of the deck is presented in Babanajad and Jalinoos (2022).

Several efforts are underway from FHWA, which is currently working with nine state transportation agencies to determine the feasibility and cost-benefit of incorporating NDE and SM methods into bridge deck preservation strategies. Adoption of NDE/SM information should complement data-driven decision-making systems in the selection of various preservation actions. This ongoing effort includes investigating and documenting the conventional NDE/SM technologies that are currently being used; quantifying the value of NDE/SM using return on investment methodology; and developing a model that relates NDE/SM results to the structure's condition and quantifies the associated return on investment for each maintenance and preservation strategy. In addition, FHWA and Iowa DOT led an initiative to develop the framework for a bridge deck preservation portal (BDPP) intended to be widely available to engineers across the nation and widely applicable but tailorable to bridge-specific scenarios the engineers encounter. The BDPP framework (ElBatanouny et al. 2020) provides a systematic approach for predicting changes to bridge deck service life by combining physical characteristics, condition assessments, and user preferences/constraints with the application of specific bridge deck maintenance actions. When completed, the developed cloud-based tool will be hosted on the FHWA's InfoBridge website (https://infobridge.fhwa.dot.gov/).

Conclusion

Despite the obvious advantages, deployment of multiple complementary NDE technologies still has not gained widespread use for informed maintenance and replacement decision-making. This is attributed to the following factors:

- **Reliability of advanced technologies**: Technological advancement has been rapid while there are few studies available on their reliability. Many NDE technologies have been well proven for local defect characterization, but their use in large-scale components is still not very clear. The standardization of methods, measurement inconsistency among multiple NDE technologies, lack of temporal and spatial correlations for multiple datasets, lack of repeatability between multiple vendor technologies, reliability of a given method, reporting requirements, and different measurement resolution limit the capabilities of many NDE techniques in being integrated into routine practice. More work is underway to address these areas.
- **Cost-effectiveness**: Cost-effectiveness has been a major issue in implementing advanced technologies. New technologies should provide value to owners. To augment them with routine visual

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inspections, these technologies should replace some components of the visual inspections or reduce the time of inspections to offset the additional costs. Most advanced technologies are not yet at that stage, and there has been little focus from technology developers on this aspect.

- **Education**: Most college undergraduate students entering the workforce still do not have a formal introduction to new technologies while in school due to given educational requirements and a limit of how many courses/technologies can fit beyond fulfilling engineering fundamentals.
- **Exposure and training**: There are limited trainings available for owner agencies as part of continuing education to improve the current workforce in these technologies. There is little focus by technology developers and academic institutions in this area.
- **Procurement**: Many bridge owners do not have in-house technical staff that can keep up with technological advances and develop procurement specifications due to wide array of manufacturers and vendors offering similar equipment and services but with different features. The typical procurement methods used by owners for design and construction of bridges also may not be suitable for procurement of developing technologies. The burden of longtime maintenance and fear of obsolescence also hampers the use of new technologies. Some technologies such as SM have high breakeven periods, and thus is hard for owners to justify their use due to resources needed that outweigh immediate needs.

Given the challenges in implementing new technologies, FHWA and other transportation agencies have striven to improve their accessibility and know-how for the underutilized technologies. FHWA developed the Bridge Inspectors NDE Showcase (BINS) program (Jalinoos 2009). The purpose of the showcase is to familiarize bridge inspectors with various portable technician-driven NDE technologies such as ultrasonic testing, eddy current, ground penetrating radar, impact echo, and infrared thermography. Further, FHWA developed a companion NDE web manual as an aid for the bridge community for selecting suitable NDE technology solutions for different engineering problems (Jalinoos 2008). The NDE web manual has since been expanded into the InfoTechnology web portal (FHWA 2022c) which, besides the bridge module, now includes tunnels and pavements and will soon include structural monitoring and underground utilities modules. Finally, for geotechnical disciplines—including concerns about foundations and subsurface characterization—FHWA has developed the geophysical manual (Wightman et al. 2004); now hosted by the subsurface committee of the Deep Foundation Institute (DFI). FHWA is also working on developing procurement guidance as well as technical resources at its research and resource centers.

Finally, in September 2021, the Government Accountability Office (GAO) in its report, *Highway Bridges: Federal Highway Administration Could Better Assist States with Information on Corrosion Practices* (GAo-21-104249), recommended that FHWA to include activities in ongoing bridge preservation efforts. Examples of such bridge preservation efforts include peer exchanges and case studies that focus on addressing the challenges states face with determining the circumstances under which specific corrosion practices and materials are most effective. As such, FHWA plans to conduct two regional peer exchanges. The first peer exchange will include representative midwestern and northeastern states, which have environments with arid conditions or that experience frequent freeze/thaw cycles and use deicing chemicals on their highway bridges. The second peer exchange will include representative southeast and western states which have environments that experience freeze/thaw cycles and/or have highway bridges that are exposed to a saltwater environment. These peer exchanges will focus on the states' practices and materials used that mitigate bridge corrosion. Based on these shared experiences and lessons learned, FHWA will publish case studies and/or communicate the findings to states to improve their bridge preservation programs. ME

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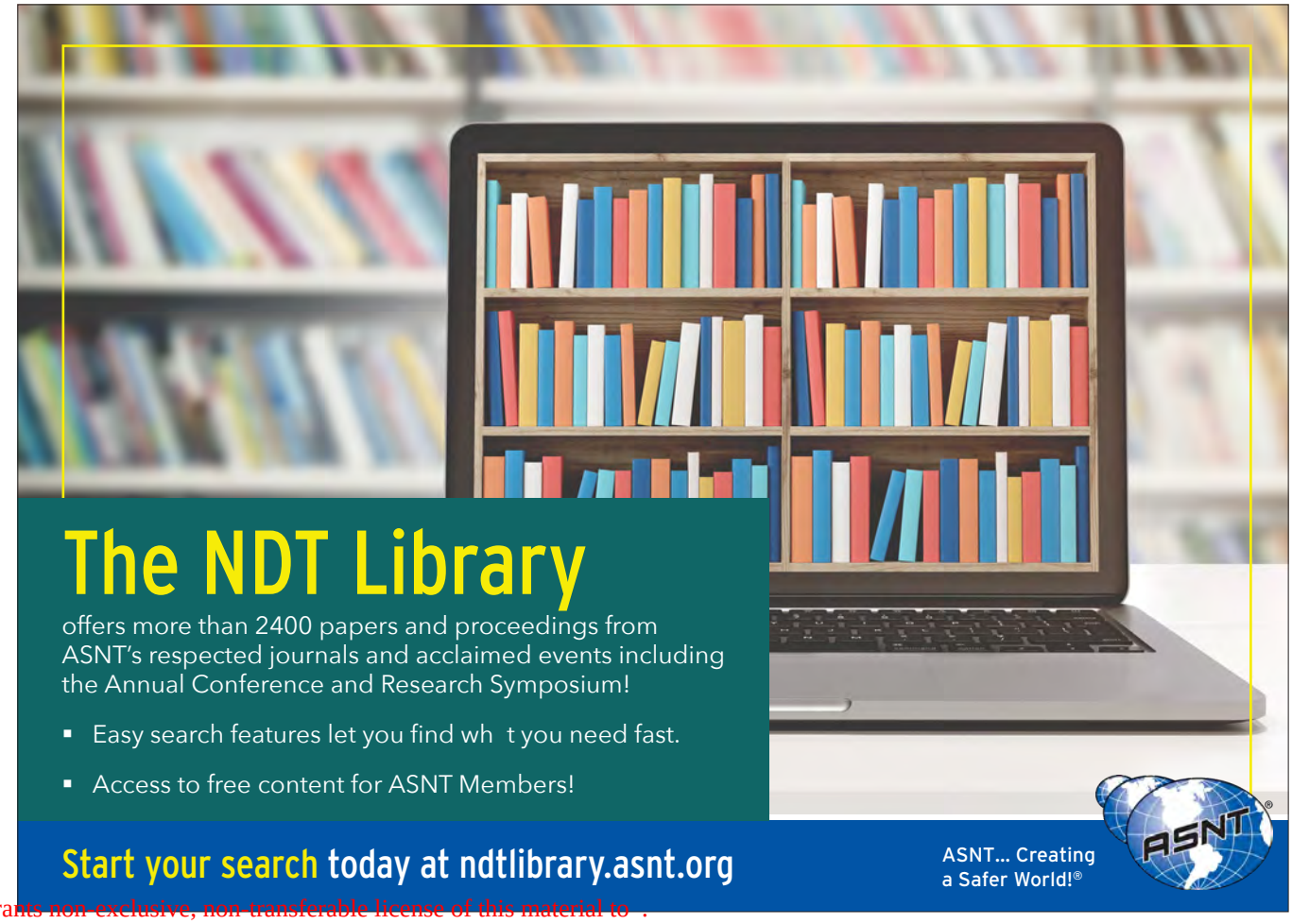
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UNDERWATER INSPECTION OF HIGHWAY BRIDGES – RECENT TRENDS AND TECHNOLOGIES

BY DAVE SEVERNS, P.E.

Underwater engineering evaluations of transportation assets have historically relied largely upon conventional, crewed commercial diving operations, using visual testing (VT) and tactile examination methods to detect surface discontinuities and evaluate site conditions. In practical application, this approach alone is often found to be suboptimal, due to multiple challenges inherent in conducting inspections in the underwater environment. Modern underwater inspections are increasingly reliant upon new technologies, and nondestructive testing methods beyond VT are used during conventional diving inspection to gain a broader picture of the asset and its condition, increasing efficiency while lowering risk in the process. Underwater engineering inspectors today employ traditional nondestructive technologies, including VT, ultrasonic testing (UT), and magnetic particle testing (MT) techniques, in concert with acoustic (sonar) imaging techniques and remotely operated vehicles (ROVs) to obtain more detailed information about the asset and adjacent waterway conditions. This approach enhances the inspection's safety and efficiency and reduces risk to the bridge owner and end user. This article discusses today's underwater bridge inspection approach, emphasizing the NDT technologies utilized and their benefits.

Introduction

As transportation assets within the United States continue to age, the need to manage their performance and ensure their safety becomes increasingly important. This is especially true for the nation's bridges, which rely on periodic safety inspections to assess condition and determine needs for maintenance, repair, and eventual replacement. Bridge safety inspections are mandated by federal regulation, falling under the jurisdiction of various federal agencies including Federal Highway Administration (FHWA), US Department of Defense, Bureau of Reclamation, Bureau of Indian Affairs, US Forest Service, and others. According to 2021 National Bridge Inventory (NBI) data, there are approximately 500 000 bridges in the United States that span waterways. Of those, nearly 30 000 bridges exhibit submerged substructure elements that require stand-alone underwater bridge inspection. This article will discuss the historical state of practice regarding conducting regularly scheduled National Bridge Inspection Standards (NBIS) underwater bridge inspections, including their use of NDT techniques, as well as a newer, more innovative approach marrying conventional, commercial diving techniques with more advanced nondestructive technologies, including sonar imaging and remotely operated vehicles (ROVs). Some example procedures employed in this enhanced work approach will be presented, along with their advantages.

Historical Inspection Approach

Underwater engineering evaluations of bridge assets have historically involved conventional diving operations, using visual testing (VT) and tactile examination methods to detect surface discontinuities and evaluate site conditions. Underwater inspections are required on a maximum 60-month inspection interval for all highway bridges in the United States, as per 23CFR650 National Bridge Inspection Standards (NBIS), with oversight provided principally by the FHWA as well as individual bridge owner-agencies. Aided by high-intensity underwater lamps and small hand tools to facilitate cleaning and rudimentary measurement, the formally accepted inspection practice is for the inspection team to conduct a "Level I" "swim by" cursory inspection of the asset, in conjunction with a "Level II" hands-on, tactile examination of the asset elements, involving the localized removal of biofouling to expose the element surface. Unless otherwise scoped, the use of specialized testing to evaluate material properties or identify subsurface conditions has typically been conducted on an as-needed basis, as a "Level III" detailed, or "in-depth" inspection.

The water body spanned by the bridge is also typically evaluated during the underwater inspection, to evaluate both geomorphologic aspects (the shape and physical characteristics of the waterway) as well as to detect scour (erosion of the banks and underwater channel bed caused by flowing water). Waterway inspection procedures during a typical NBIS underwater bridge inspection rely on VT, in conjunction with a conventional echo-sounding fathometer, to chart channel bottom profiles both along the exterior edges of the bridge as well as adjacent to individual substructure units. Channel bottom depth data is post-processed and converted into elevations, which, in turn, can be compared to past data as

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well as analytical data identifying critical bridge foundation elevations raising structural concerns.

Trusted NDT Technologies

Since the 1960s, transportation assets have been evaluated by divers using a combination of NDT devices that migrated inland largely from the offshore oil and gas fields, combined with modified "topside" (above water) NDT testing equipment and a few improvised pieces of gear. In addition to VT using ubiquitous handheld or helmet-mounted high-definition photographic and video cameras, measuring devices (usually wooden folding rulers) and clear water boxes (used to aid still photography in murky waters), inland diver inspectors conduct underwater structural inspections using a small variety of hand-held NDT devices.

Ultrasonic Testing (UT)

Other than VT, select UT methods are by far the most common NDT technology employed during underwater bridge inspections to identify, locate, and size discontinuities in steel, timber, and concrete members. The equipment used underwater comes in two varieties: modified topside ultrasonic equipment, typically consisting of a transducer connected with a long cable to a conventional topside UT scope; or a self-contained, water-tight unit handheld by the diver (see Figure 1). In the former instance, the diver manipulates a straight-beam or angle-beam transducer underwater while readings are taken from a topside technician who controls the UT instrument in a clear, benign



Figure 1. Underwater-capable UTT unit with long transducer cable.



Figure 2. Diver held UTT unit. Note display visible to diver.

environment. More common today is self-contained equipment built specifically for use underwater (see Figure 2).

Ultrasonic thickness testing (UTT) is the most common UT technique employed during underwater bridge inspections. It is commonly used to obtain thickness measurements in steel members. The member to be tested is cleaned to establish a clean, smooth surface, and measurements are obtained in predetermined locations. For substructure supports using steel piles or columns, section measurements are typically obtained in the splash zone, at the mudline, and near the midpoint of the water column. The results are typically archived in a matrix format, for ease of comparison to future measurements taken in the same areas. From this, deterioration rates may be established. Section thickness data of concern is evaluated analytically and appropriate actions are taken, which might include corrosion mitigation measures, structural repairs, or, in extreme instances, modifications to loading of the element(s) until repair or replacement actions are effected. UTT equipment used in the field is almost exclusively of the self-contained variety.

Ultrasonic angle-beam testing using shear waves (such as shear wave and phased array ultrasonic testing) is conducted on a very limited scale (primarily during in-depth, Level III inspections) on submerged bridge members for the inspection of welds, crack detection, and for sizing of discontinuities. While both single-element and multi-element phased array systems have been adapted for use underwater, the latter equipment type is seldom used during underwater bridge inspections. Unlike UTT, angle-beam testing in the inland environment is usually conducted using a topside scope, and the diver is merely manipulating the transducer, due to limitations introduced by water turbidity.

Magnetic Particle Testing (MT)

MT plays a diminished role in underwater bridge inspection as compared to its use in the offshore underwater inspection industry. Diver-manipulated yoke systems are at times used, but principally only during Level III inspections in clear, calm waters, where the powdered metallic filings can be applied and indications can be seen by the diver (see Figure 3). Unfortunately, these conditions are not often experienced in the inland environment.



Figure 3. Underwater MT system, with diver-held yoke and lamp.

Other NDT Methods

Other NDT methods and techniques are available to the underwater bridge inspection team for testing of steel members. Techniques such as acoustic emission testing (AE), time of flight diffraction (TOFD), and underwater pulsed eddy current (PEC), while in use in the offshore inspection arena, have not readily advanced into the inland bridge inspection industry. Underwater PEC in particular holds promise, considering that the technology is specifically designed to detect corrosion hidden under marine growth or coatings. Steel wall thickness can thus be measured

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without time-consuming surface preparation in piles, caissons, and the like.

With respect to the underwater inspection of concrete, several commercially available testing instruments have successfully been modified and tested for underwater use. Conventional rebar locators, operating to detect a magnetic flux disturbance caused by an embedded ferrous object, may be used underwater to locate and size rebar, as well as to measure the amount of concrete cover. Rebound devices (also known as the "Schmidt hammer") that evaluate the compressive strength of concrete have also been successfully modified to operate underwater. UT methods are also available to estimate compressive strength and detect hidden discontinuities in concrete members. While easily operated by the diver, working in concert with trained above water testing technicians, each of these technologies has to date seen limited use in the underwater inspection of in-service bridge assets.

A More Innovative Approach

The historical VT-biased, "hands-on" approach to conducting underwater bridge inspection described above has been developed to detect discontinuities and evaluate conditions with relative celerity and reasonable levels of inspection quality. In practical application, however, this approach is often found to be suboptimal, due to the multiple challenges inherent in conducting inspections in the underwater environment. As with inspection work conducted in dry environments, underwater VT examines only the exterior surface of the asset's elements. Additionally, while diver-operated NDT test methods are helpful, the risk factors lying within the underwater environment—minimal visibility, extreme cold, submerged drift and debris, stubborn biofouling, chemical and biological pollution, vessel traffic, dangerous aquatic animals, inspection time limitations imposed upon the dive team by physiologic restrictions to diving at depth, coupled with a nationwide lack of divers themselves—introduce physical barriers and psychological restrictions precluding a thorough inspection of the asset. This being the case, the NBIS in 23CFR650.305 ("Definitions") defines an underwater inspection as one involving wading, diving, or "other appropriate techniques."

Consequently, modern underwater bridge inspections are increasingly reliant upon marrying new technologies and NDT methods with conventional, crewed diving inspection to gain a broader overall picture of the asset and its condition, increasing efficiency while lowering risk in the process. Underwater engineering inspectors today utilize traditional VT and handheld UT and MT techniques, in concert with acoustic imaging techniques as well as NDT-capable ROVs, to obtain more detailed information about the asset's elements as well as the bridge site at a more macroscopic level.

Acoustic Imaging (Sonar) Inspection

Sonar technology plays an ever-increasing role in today's underwater bridge inspection procedures, both to increase inspector safety and improve inspection quality. Sidescan, sector-scan, multibeam, and real-time volumetric imaging sonar systems each play a role, and all have the ability to "see" underwater when little or no visibility exists to the human eye. While a sonar unit cannot remove marine growth, reliably detect hairline cracks, or thoroughly measure the penetration depth of foundation undermining at a bridge pier, it can outperform a diver in many other areas, including the measurement of local scour holes (in clear water conditions), in assessing opening widths and heights of scour voids under bridge foundation elements, in visualizing debris accumulations and other hazards adjacent to a bridge pier, and in the ability to assess the sizeable areas of streambed situated out and away from the pier face. Considering that the number-one cause of bridge failure worldwide is scour (and not those superficial, hairline cracks), and considering that most bridges span waterways exhibiting adverse conditions (deep, turbid, debris-laden, and/or swift water), one can make a strong case for mandating sonar assessments in certain inspection scenarios.

To assist in the assessment of sonar technology during underwater bridge inspections, on 14 June 2018, the FHWA released Technical Report FHWA-HIF-18-049, *Underwater Inspection of Bridge Substructures Using Imaging Technology*, which evaluated various sonar imaging technologies and compared their performance in real-world bridge inspection tests to conventional data collection using divers. As per the report's abstract, the study determined that:

- Sonar technology is capable of identifying larger-scale characteristics of interest such as scour holes, debris, and moderate to large size voids and protrusions. It is more limited in identifying small-scale cracks or features hidden by marine growth.
- Sonar is particularly effective in adverse conditions where limitations on diver bottom time exist, such as deep water, and conditions where diver safety or mobility is of particular concern including swift currents or turbid water. In all environments, including those with adverse conditions, sonar technology is useful for identifying macro features quickly.
- Sonar technologies can be used to inspect underwater structural elements where divers cannot work effectively, to guide divers for a closer look, or to provide independent inspection insights. Sonar can also be effective in covering large areas quickly.

The study reported two overall conclusions:

- "Sonar inspections have not demonstrated the ability to identify some smaller scale elements of substructure condition that may be important in assessing the bridge and recommending maintenance."
- "Sonar technologies offer significant opportunities for improving underwater bridge inspections, especially in adverse environments or to inspect extensive areas."

In summary, the study found that sonar cannot replace diver inspectors, but can yield an improved process when

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conducted in combination with traditional diving inspection.

Depending upon the technology of choice, sonar equipment uses a remotely controlled sonar head that is either hard-mounted, pole-mounted in a boat, towed, or even affixed to an autonomous watercraft. The newest technologies even provide "live" data capture, offering a 3D display in real time. Each sonar technology has its own advantages, as highlighted in the following.

Sidescan Sonar

A tried-and-true technology with offshore origins, sidescan sonar employs a towed or otherwise transported "fish" that continually moves through the water while scanning the channel bottom off to both of its sides. This technology yields processed data images with excellent resolution, readily revealing areas of local scour, pier foundation exposure, and accumulated drift and debris better than a diver can envision. One recent and unique adaptation of sidescan has been its integration into small autonomous watercraft, which can be deployed to gather bridge scour data adjacent to bridge piers during flooding conditions, before divers can safely access the bridge site (see Figure 4). Such systems are currently in use with several state DOT agencies and other service providers to help engineers make public safety decisions during emergency situations. (As an example, Figure 13 displays a typical data output screen from an autonomous vehicle system using sidescan sonar.)

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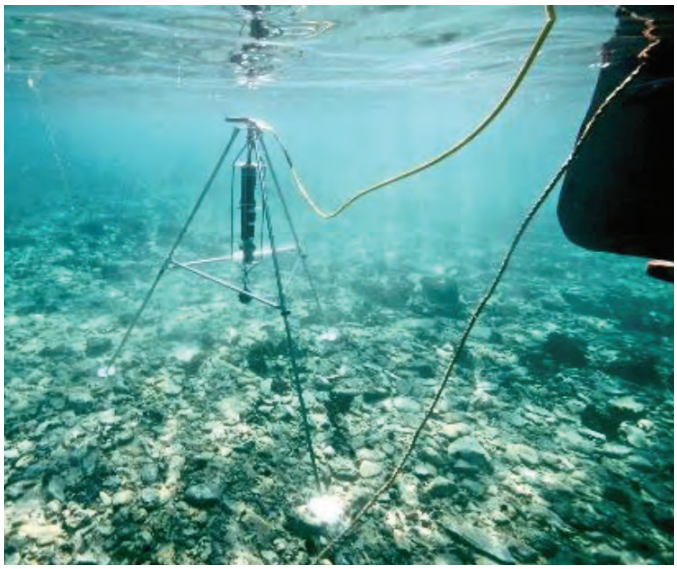


Figure 5. Sector scan sonar head deployed in a tripod on channel bottom.

Sector-Scan Sonar

Another established and valuable technology, sector scan employs a rotating head containing one or more sonar transducers, which is rotated in staccato fashion via a stepper motor, to gather image data of up to 360° from a single static deployment. Mounting of the scanning sonar head is quite flexible, as it may be rigidly mounted, attached to a pole for boat use, or deployed hanging vertically from a tripod which is lowered to the channel bottom. Tripod deployment of a sector-scan sonar head is illustrated in Figure 5. Individual scans can typically be completed in a few seconds, and output data of the site is displayed in either

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Figure 4. Autonomous vessel equipped with sidescan sonar evaluates a bridge.

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Figure 6. Post-processed sector scan image, showing elevation view of pier.

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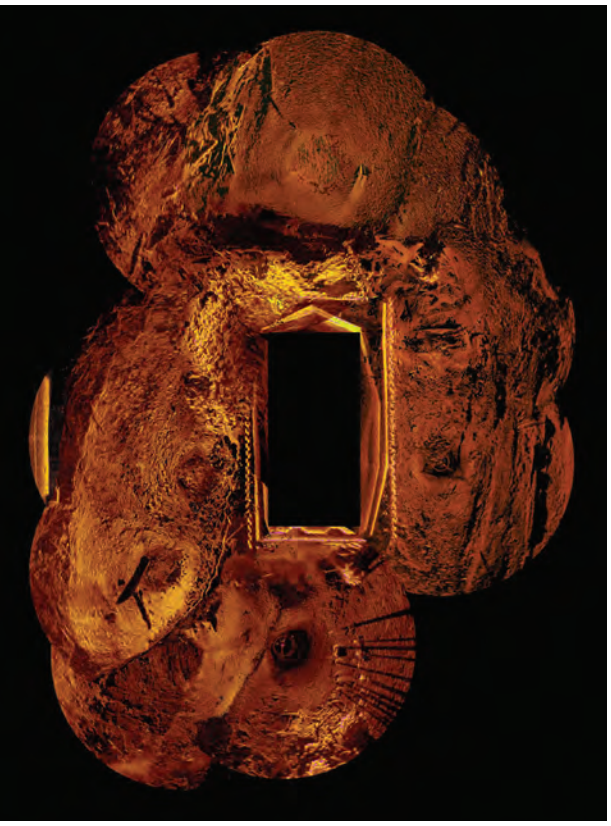


Figure 7. Plan view mosaic of channel bottom surrounding bridge pier using sector scan.

plan or elevation view. Figure 6 illustrates an elevation view output image. Multiple plan view images can be post-processed as mosaics to cover large areas of concern (see Figure 7), while elevation scans of individual bridge piers can be post-processed to show image views combining above- and below-water portions of a bridge pier as though they were a single photograph (see Figures 6 and 11 for reference). Scanning sonar software allows image data to be interrogated in real time, so as to calculate distances and dimensions of elements or defects and display them directly on the output images without the need for additional post-processing.

Sector scanning sonar has been used during underwater bridge inspections for many years and plays a fundamental role in the industry today, for both diver safety and inspection data acquisition. For example, prior to deploying an inspection diver, multiple plan view scans can be taken around the perimeter of a pier to quickly establish "safe zones" for subsequent diver deployment in areas free of drift and debris. Additionally, the angular range of the scan can be narrowed to focus in on a specific "swath" or area of concern. Thus, the sonar can be operated once the diver has entered the water to track them in real time as they conduct the inspection. Several state DOT agencies require acoustic imaging of bridge substructure elements as a part of their underwater bridge inspection procedure, and post-processed sector scan images are a common deliverable for those owners.

Multibeam Sonar

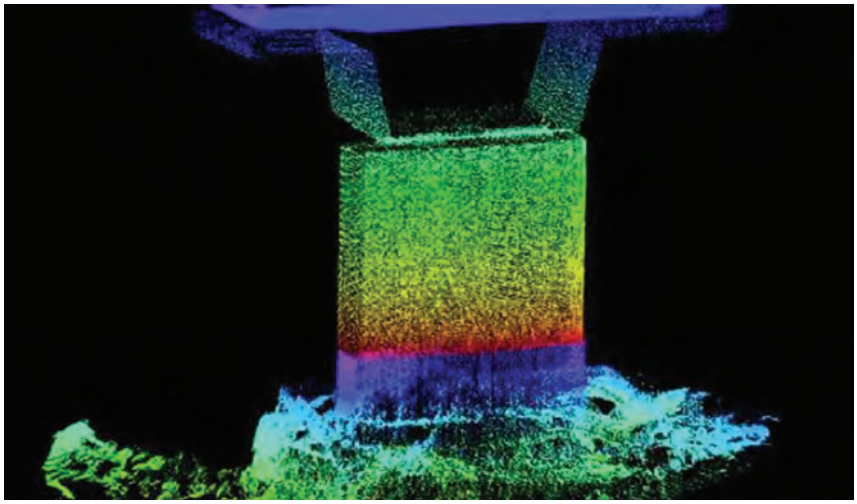
Unlike single beam sonar, which uses just one transducer to map the channel bottom, a multibeam sonar sends out multiple, simultaneous sonar beams from multiple transducers in a fan-shaped pattern. This covers the space both directly under the inspection boat and out to each side. Multibeam sonars interrogate the channel bottom and also collect returns from features that reflect sound in the water column. Water column backscatter data can be used to reveal objects in the water column, including the bridge substructure. Computers on the inspection boat collect and post-process the data to create colorful two- or three-dimensional bathymetric (water depth) maps as well as sonar images of the substructure elements (see Figure 8). As with sector scan, multibeam sonar is frequently used in the underwater bridge inspection industry due to its efficiency and data quality. Multibeam sonar is also used for obtaining bathymetry used for hydraulic modeling, such as SRH-2D modeling, as currently promoted by FHWA.

Volumetric 3D Imaging Sonar

Volumetric 3D imaging sonar is one of the newest, most high-tech sonar technologies available, yielding high-accuracy, high-resolution data images displayed in real time. This technology provides instantaneous 3D images, producing detailed GPS-referenced underwater scans in real time, with comprehensive measurement capability (see Figure 9). This technology also allows for monitoring moving objects underwater in real time (like watching a "sonar movie"), thus allowing monitoring of a diver at work in zero-visibility water. Another key advantage of volumetric 3D sonar is that it offers a more intuitive operation and significantly reduced post-processing time as compared to competing sonar technologies. As with multibeam sonar, volumetric 3D imaging sonar can also be used as an integral part of a hydrographic survey system.

ROV Inspection

Underwater ROV inspection also has roots in the deep-water offshore oil and gas industry. Over the years, however, ROVs have been developed that are



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Figure 8. Multibeam image of bridge pier, showing bottom topography.

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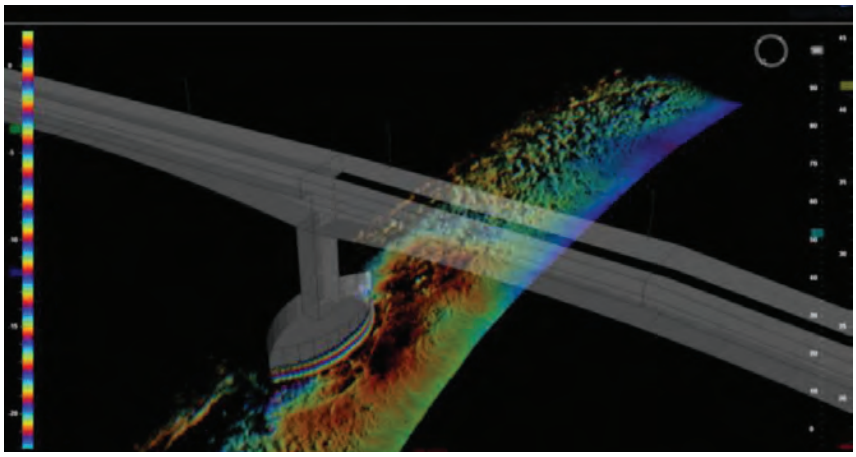


Figure 9. Volumetric 3D sonar image of bridge pier.

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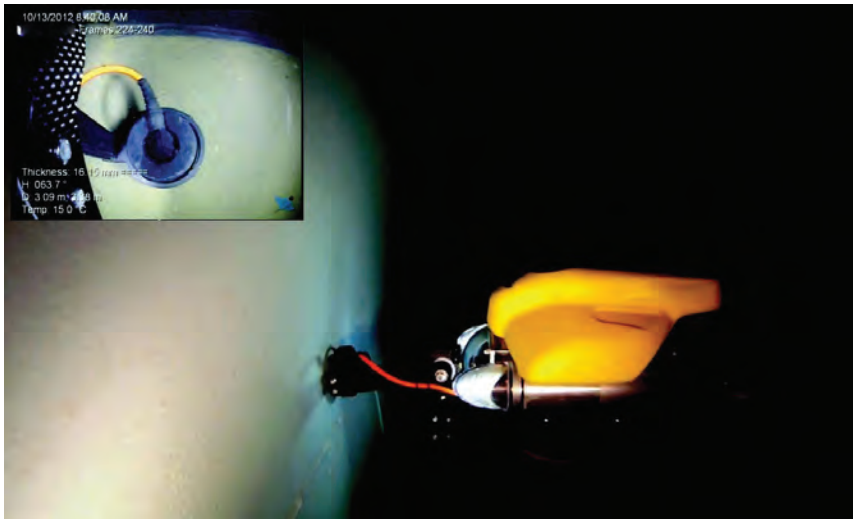


Figure 10. ROV with mounted UTT transducer.



Figure 11. Drift at pier foundation easily detected using sector scanner sonar.

lighter, more agile, and easier and less expensive to own and operate. While early inland-oriented units were primarily "flying photo/video cameras" with limited mobility, today's inspection ROVs are capable of operating against river flow velocities commonly experienced during underwater bridge inspections and employ multiple thrusters oriented to yaw the vehicle into proper position to inspect the element. Today's ROVs are smaller (some less than 12 in. [30.5. cm] in diameter to fit into confined spaces) and offer integral mounting of a sonar imaging head or UTT transducer (see Figure 10). As such, ROVs can be used in lieu of crewed commercial diving for select inspection operations, such as working in polluted waters, or in conjunction with convention diving operations.

Modern Inspection Procedures

A few scenarios illustrate the benefits of integrating imaging sonar and/or ROVs with conventional diving-based inspection:

- A sector-scanning, multibeam, or volumetric 3D sonar system or sonar-enabled ROV can be used by a dive team to preview piers to evaluate potential hazards, such as drift/debris accumulations, prior to deploying a diver (see Figure 11). This significantly increases inspection efficiency and enhances safety by allowing the dive team to preplan the inspection of each individual bridge pier. Using the appropriate technology, this "pre-inspection sonar scan" can be quickly accomplished as a first step in the inspection process.
- This same sonar system or ROV could then be used to monitor divers' progress and help ensure diver safety during the inspection. With adequate water clarity, the ROV could also provide video of the inspection. This "over-the-shoulder supervision" approach is common practice offshore and allows topside personnel to collaborate with and direct the diver.
- Sonar and ROVs can be used to help evaluate confined spaces, such as areas of foundation undermining,

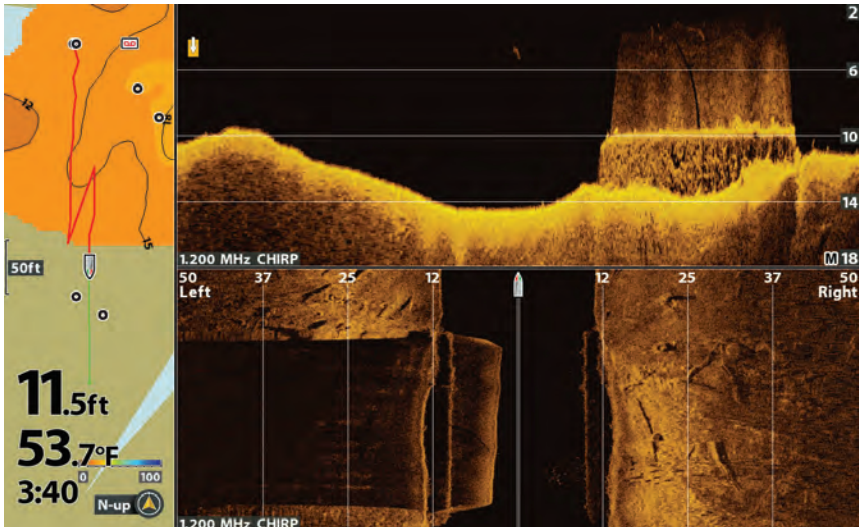
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which by regulation require a minimum five-person dive team to inspect. Considering that underwater inspections are often conducted by an OSHA-compliant, three-person minimum dive team, this approach could help determine the need to revisit only a specific area with a larger crew, rather than staffing the entire inspection with a larger crew. For longer bridges, this may prove especially beneficial.



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Figure 12. Sonar attached to bucket truck, to evaluate scour during flood conditions.



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Figure 13. Sidescan sonar output from an autonomous vessel during flood conditions.

- Both sonar and ROV technologies may be used during emergencies such as flood events to provide first-response or even mid-event scour assessment (see Figures 12 and 13). The aforementioned autonomous vessel assessment using sidescan sonar provides valuable assistance to the bridge engineer and owner. Similarly, boat-mounted sonar equipment can be deployed immediately after high-flow events or after impact events, to identify damage before a dive team can arrive onsite.

ME

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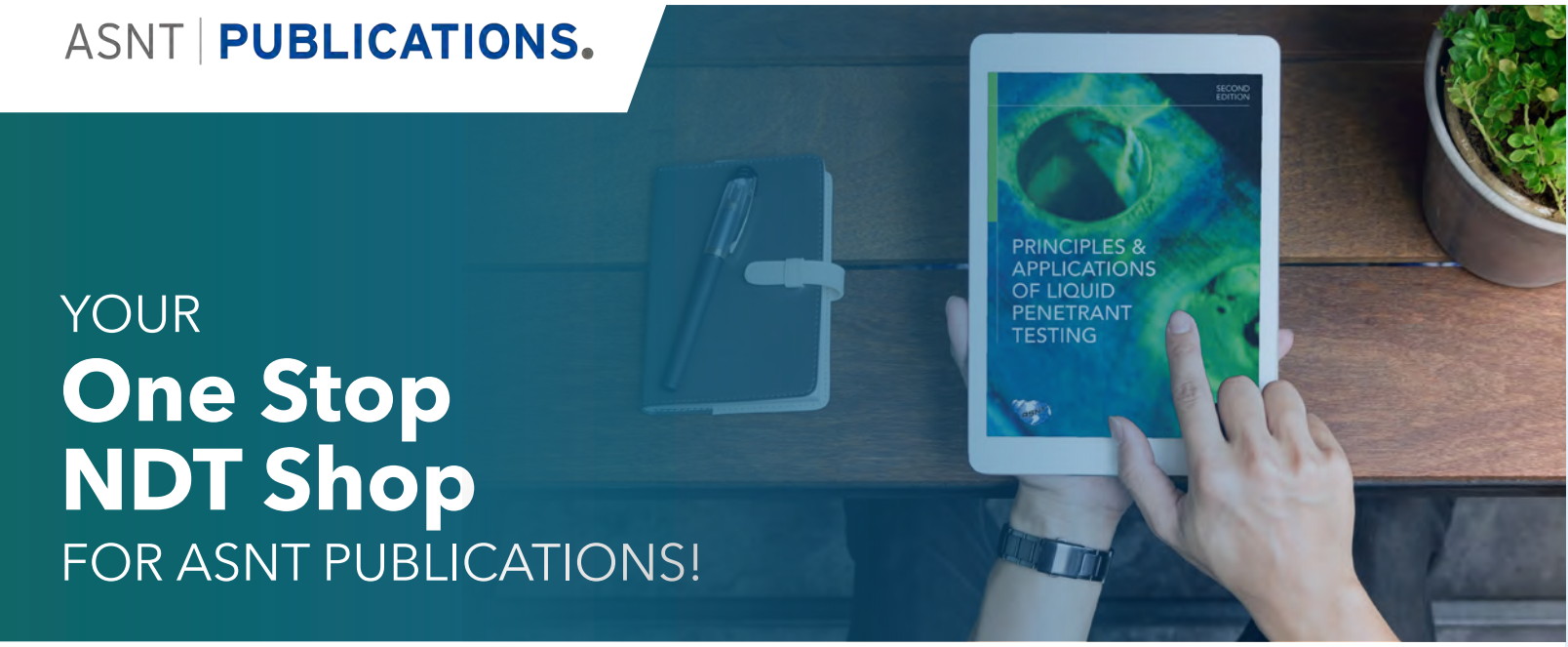
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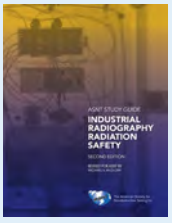
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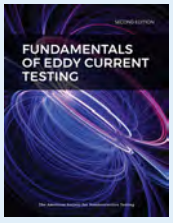
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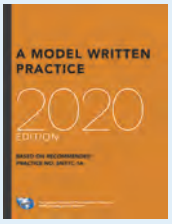
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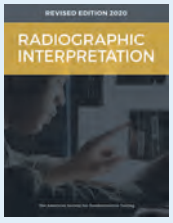
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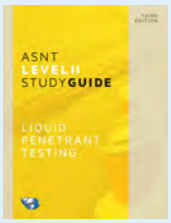


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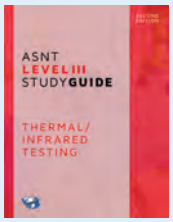
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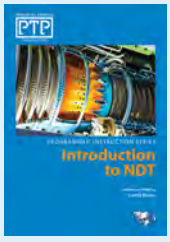
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AUTOMATED GEOMETRIC QUALITY INSPECTION OF REBAR LAYOUT USING RGBD DATA

MAHSA SANEI*, XINXING YUAN†, FERNANDO MOREU‡, AND SREENIVAS ALAMPALLI§

ABSTRACT

Quality control and quality assurance during construction is vital to ensure the structure is built as designed and durable. For reinforced concrete (RC) structures, rebar diameter, spacing, and concrete cover depth are critical in ensuring that the structure is designed for adequate strength and can maintain its service life without unplanned interventions. Once the rebar is laid out in the field, construction inspectors do the required quality control to ensure that the constructed rebar mat matches the design documents. The checks are made at finite points and thus can be improved with currently available technologies such as LiDAR, augmented reality (AR), and uncrewed aerial vehicles (UAVs). This paper summarizes the available technologies for such an effort and focuses on using Red Blue Green Depth (RGBD) cameras as a quality control tool for construction inspection of RC structures such as buildings and bridges. A study conducted using an RGBD camera for estimating rebar diameter is presented in this paper. Results show that RGBD cameras have a very high potential as a low-cost, efficient tool for quality control of RC structures during construction. RGBD cameras can potentially augment current visual inspections in assuring the structures are built as per design drawings, meeting the appropriate specifications with acceptable accuracy.

KEYWORDS: RGBD camera, 3D scanning, structural health monitoring, construction inspection, quality control

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Introduction

Recent initiatives for automated quantification of inspection and monitoring have demonstrated the promise for efficient management of construction projects (Zucchi 2015). The automated quantification system increases the data collection quality and enables real-time data processing for managers (Gucunski et al. 2015). The concept of e-construction, which calls for gathering, examining, authorizing, and disseminating highway construction contract documents without the use of paper, has also been gaining attention among owners. To design processes and store documentation in a paper-based system, a substantial amount of time and money is required (Cawley and Duval n.d.). This arrangement is quickly becoming outdated in an age of immediate communication, on-the-go information access, and a tech workforce. One advantage of using an automated quantification inspection platform is that it can also provide a permanent record of the construction throughout the service life of the structure. It would not be possible or easy to record this information manually. As a result, engineers can interpret the recorded inspection data, compare it at a different stage, incorporate it into the project design and schedule, and make informed decisions (Kopsida et al. 2015).

Most of the quality control methods used on construction sites are not good at recognizing defects early in the construction or maintenance stage. This is due to the data collection at a certain time and location (Almadhoun et al. 2016). Therefore, these new technologies allow inspectors to monitor the status of the structure as construction progresses. They generate appropriate digital data that describe the as-built condition when the data was collected (Memarzadeh and Pozzi 2016). To perform quality control, this digital data must be compared to the project's quality requirements derived from specific design and construction specifications. Also, the result of past inspections can be overlaid with the newly captured data to see how the structure condition has changed with time (Wang et al. 2015). To date, the efforts in automation in construction inspection enable inspectors to compare data collected during construction as a reference for long-term structural inspection and maintenance (Boukamp and Akinci 2007). It would be of value if in addition to the long-term structural construction inspection, the human in the loop can have access to the data at the site during the inspection.

This paper outlines the proposed objective quality control methodology for practical implementation in reinforced concrete (RC) structures' construction inspections that take advantage of low-cost automated global assessment technology

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to improve construction quality. The focus is not on replacing construction inspectors but on enhancing their ability to conduct global assessments quickly and in a thorough fashion by combining low-cost technologies available in the market with an artificial intelligence framework. Specifically, this paper emphasizes using new low-cost technology to obtain the rebar size in reinforced concrete construction. This study in conjunction with work of other researchers in rebar spacing and cover estimation can automatize the rebar geometric inspection. It can also be used as a general concept for inspection automation, where the collection of the data and its analysis can eventually inform the projected strength of the structure in real time. This also facilitates moving towards e-construction, where quality construction is achieved using a paperless format while also creating a permanent record.

Technology for Structure Inspection

Traditional infrastructure inspections are performed by qualified inspectors who physically go to the field and perform inspections (Newman and Jain 1995). In the industrial, commercial, and civil sectors of the construction industry, the application of automation technologies has attracted attention in recent years. These technologies, such as uncrewed aerial vehicles (UAVs) or drones (Kuo et al. 2016), LiDAR (Wood and Mohammadi 2015), augmented reality (AR) (Wang et al. 2019), and RGBD cameras (Wójcik and Żarski 2021) are being used for collecting 3D geometric information for inspection, renovation, and retrofit projects.

Researchers use UAVs to reconstruct a 3D image of the structure using a camera and remote sensor (Chen et al. 2019; Perry et al. 2020; Ayele et al. 2020). UAVs can be used in areas that are hard to access, but they have a limitation of payload equipment, vibration, environmental condition, and cost. LiDAR is another instrument that researchers consider an inspection tool, and it has been used to automatically evaluate the rebar spacing before pouring concrete (Yuan et al. 2021a). In another study, they proposed a platform for mounting the LiDAR on the UAV to detect discontinuities of the structure (Nasrollahi et al. 2018). Despite the high accuracy of collected data from the LiDAR, it requires an expert to be familiar with the technology. Also, the setup time in the field is, in general, a concern for construction managers and structural engineers who need a quick quality control/quality assurance method to inform them in a short time on the rebar quality. AR is another new technology that has recently attracted researchers' attention. There are studies in which the authors used the AR-BIM platform for inspection of the bridge and locating defects (John Samuel et al. 2022). Also, the application of AR in infrastructure inspection and its capability have been examined in the past (Mascareñas et al. 2021). The rapid development of low-cost RGBD sensors has attracted the attention of researchers in various scientific and technological fields due to the advantages they offer. The RGBD sensor includes a color sensor and a depth sensor that captures color information and depth data by measuring the time between emitted and reflected light bouncing back to the visor (time of flight). An RGBD camera was used in the literature to detect the position of a target and its orientation on a bridge that was identified as damaged (Ivanovic et al. 2021). Additionally, other important factors such as spacing and cover of the rebar need to be controlled before pouring the concrete. A group of researchers used an RGBD camera to obtain the rebar spacing and cover in a rebar cage automatically to demonstrate the capability of a low-cost approach to assist in quantifying the quality of rebar placement. This method was tested on a rebar cage to calculate the spacing and the result was validated with tape measurement (Yuan et al. 2021b). In addition to the capability of measuring rebar spacing and clearance, it would be of value to explore if the proposed methodology would be able to measure the rebar diameter automatically.

Each of these instruments has advantages and disadvantages that make the engineer and owner use them based on the project's specifications. However, there are important factors to consider for all inspectors as they can enhance the speed, cost, and quality of the inspection. Handheld, portable, low-cost instruments are among those capabilities that are worth considering.

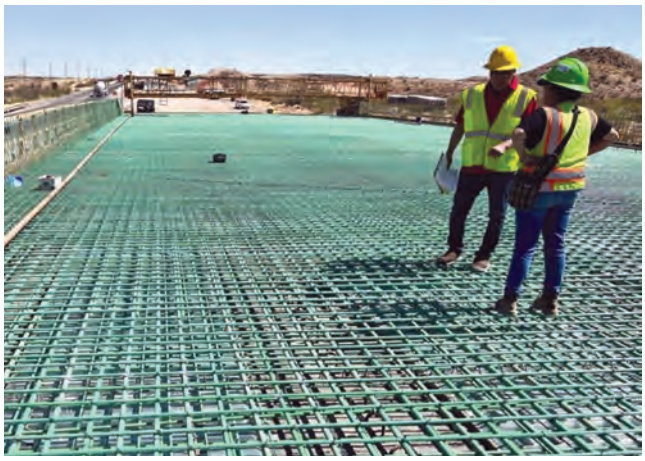
Inspection Industry Standards

For more than a century, reinforced concrete has dominated the global construction industry, even though RC structures are frequently subject to a variety of deterioration and damage owing to various exposure factors. As a result, the requirements of the building standards necessitate somewhat frequent inspections in many countries (Masoumi et al. 2013). The emphasis of the proposed method is on the inspection of rebar in RC structures, such as buildings or bridges. Rebar placement has a significant impact on the quality of RC structures (Qi et al. 2014). Rebar defects in concrete structures can induce structural collapse, uneven strength capacity, and serious concrete degradation (Cusson 2009). Incorrect rebar placement or insufficient concrete cover might decrease structural strength. One of the main issues limiting the durability of old RC structures is the rebar corrosion brought on when the concrete cover is not sufficient (Wilkie and Dyer 2022). Due to this, the concrete structure becomes less durable and is more susceptible to chemical attacks (Chemrouk 2015). RC structures benefit from accurate rebar arrangements for the duration of their lives (Słowik 2019; Concrete Construction 2005). Rebar construction errors can be reduced to a minimum to avoid costly repairs, task deferrals, flaws in structural strength, and even save structures from collapsing.

Current Inspections Limitations

Figure 1 shows the labor during rebar placement at a bridge deck construction project. Projects of this size can take several days to weeks for rebar placement. In tight construction schedules recognizing issues with placement as the project progresses is important in assuring that issues are addressed as soon as possible. Early detection of errors can accelerate construction.

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Figure 1. Rebar mat inspection on a big bridge deck construction site.

It is important to acquire geometric data for infrastructure management (Concrete Construction 2005). The present method for collecting geometric structure data for inspection of the structure relies on manual data collection methods, which require time and could be prone to error (Rens et al. 1997). Inspectors that are close to the hard-to-reach parts of the bridge (Kuang et al. 2009) may face safety issues, making the data collection process cumbersome and time-consuming (Sanford et al. 1999). Furthermore, the instrumentation can take measurements only in discrete and sparsely populated areas. In addition, most of the collected data is recorded in the form of paper-based or written files without any support, so the process of interpreting and retrieving geometric information requires a large amount of data transmission work to be done manually by a human (Estes and Frangopol 2003). Therefore, it would be advantageous to record the final location of reinforcement as a future document to be accessible if needed during the service life. This would become a permanent record of the field. When a forensic investigation is needed, a potentially effective tool for measuring concrete cover after construction could be ground penetrating radar (GPR), which uses penetrating wave. Researchers and companies use GPR to measure the actual cover, spacing, and bar diameter (Tosti and Ferrante 2020). Not only are GPR and other means expensive and only justified in specific cases, but also it is not always possible to use them due to traffic or other functionality restraints (De Souza et al. 2004). The cost of not knowing the actual quality of the structure will translate into negative consequences both in cost and safety (BrÜhwiler 2009).

Hence, an automated way of quantifying reinforcement in structures such as bridge decks using innovative technologies coupled with artificial intelligence (advanced processing and decision-making concepts) is agreed to be useful for construction quality (Akinci et al. 2006). The proposed method can inform the inspector of the reinforcement during construction and become a permanent record of the quality that can be accessed in the future.

Methodology

This section describes the technical capabilities of the Azure Kinect camera in relation to data collection, as well as examples of RGBD applications used in the past. Subsequently, the capability of using RGBD cameras for creating 3D point cloud data for rebar inspection is explained.

RGBD Camera

The RGBD camera is a color-depth camera that has the potential of reconstructing the 3D shape of an object. There are different types of RGBD cameras that can be used for this study. In 2020, Microsoft launched the third generation of Kinect, called Azure Kinect, with time of flight technology. This sensor is offered at a relatively low price (currently less than US$1000) but offers practical performance and depth accuracy. 3D scanning and measurement capabilities bring low-cost Kinect sensors to a wider range of applications such as gesture recognition (Ren et al. 2013; Patsadu et al. 2012; Biswas and Basu 2011), AR (Ren et al. 2013; Ma et al. 2013; Vera et al. 2011), robot navigation (Correa et al. 2012), and the construction of the building (El-laithy et al. 2012). Figure 2 shows the RGBD camera that is used in this study.

Figure 2 shows Microsoft's newest sensor technology that is incorporated into the Kinect hardware, which is a single USB-connected device. The camera dimensions and weight are 103 × 39 × 126 mm and 440 g, respectively. This RGBD camera

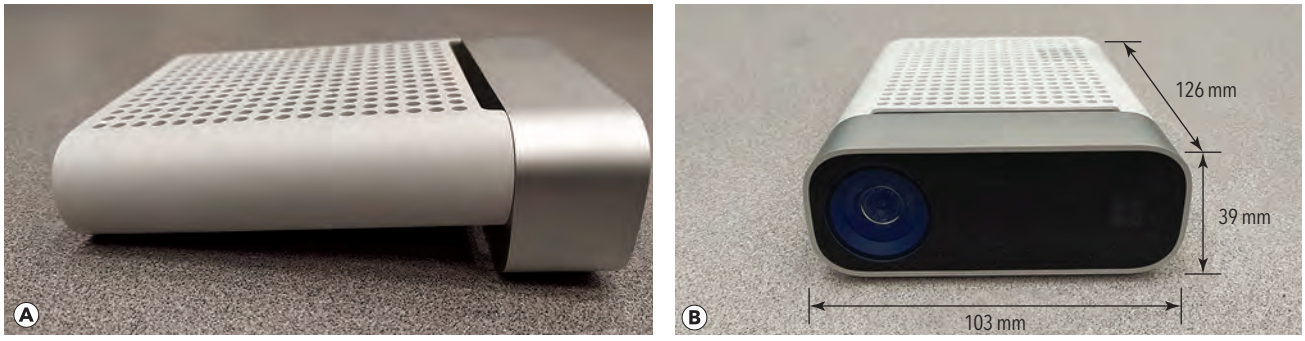


Figure 2. Azure Kinect camera: (a) front view; (b) lateral view.

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includes a 1-megapixel time of flight depth sensor that provides different modes of scanning. Different fields of view (FOV), resolution, and operating ranges can be selected to optimize the application. Table 1 summarizes the modes that this camera can support. The FOV, resolution, and functioning range are the features of interest for the automatic geometric measurement proposed in this paper.

As can be seen in Table 1, as the functioning range increases, the resolution will decrease. However, as long as the camera records a video in the functioning range mentioned in Table 1, the picture would be of good quality and the camera can detect the depth.

TABLE 1
Comparison of camera modes

Mode	Field of view	Resolution	Functioning range (m)
NFOV unbinned	75 × 65	640 × 576	0.5–3.86
NFOV 2 × 2 binned	75 × 65	320 × 288	0.5–5.46
WFOV unbinned	120 × 120	1024 × 1024	0.25–2.21
WFOV 2 × 2 binned	120 × 120	512 × 512	0.25–2.88

The RGBD camera also has a 12-megapixel color camera with a maximum resolution of 3840 × 2160 that can be used with 0, 5, 15, and 30 FPS frame rates. Additionally, an inertial measurement unit (IMU) is embedded in the camera that consists of an accelerometer and a gyroscope that can be utilized for sensor orientation and spatial tracking.

The mentioned camera contains a developer kit that uses artificial intelligence (AI) sensors to develop computer vision and speech model applications. This developer includes a cross-platform that can read data from the RGBD camera. The software development kit enables users to develop their own applications. Furthermore, the recorded data can be analyzed in other software such as MATLAB. In the next sections, the authors propose to use MATLAB to analyze the 3D point cloud data that has been generated by the RGBD camera.

RGBD Camera for Rebar Inspection

Instead of visual inspection as the conventional approach, the RGBD camera can be used to scan the entire rebar of the structure. In this regard, the authors present an algorithm to measure the diameter of the rebar in RC structures. So, instead of the inspector doing all the measurements with a tape or caliper, the RGBD camera can be an alternative for visual inspection of the rebar. This can also be accomplished at a distance, which can increase safety during the inspection, as can be seen in Figure 3. The process of data collection starts by connecting the camera to a computer, then a video is recorded by walking around the object and scanning it. The recorded video is imported to software such as MATLAB or CloudCompare to generate the 3D point cloud data. At the

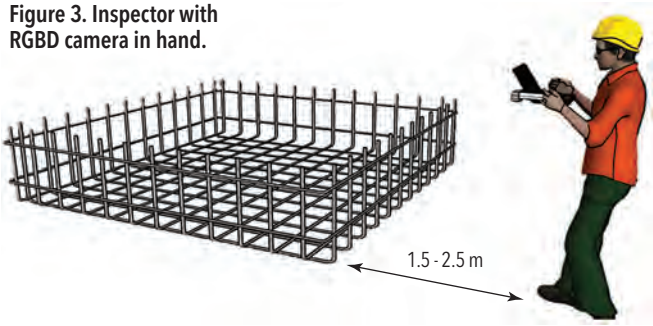


Figure 3. Inspector with RGBD camera in hand.

construction site, the camera needs to be plugged into a power bank. The inspecting crew can estimate the size/area to inspect based on the power bank capacity. The authors successfully tested using camera using a regular portable power bank at a construction site. The structure consisted of three 16 ft (4.9 m) tall walls with an approximate length of 50 ft (15.2 m). Future research efforts include the testing of longer reinforced cages in civil engineering infrastructure under construction (such as bridge decks, industrial slabs, and parking garages).

Further analysis can be applied to the data to get the required information from the rebar before pouring the concrete; for example, spacing, diameter, and elevation (cover). However, to estimate the cover from the generated 3D point cloud data before the construction, the space between the outer edge of the rebar and the ground or mold should be calculated, which can be done at any point where the inspector is willing to measure the spacing, so the camera and the algorithm can detect the cover even if it is uneven.

The algorithm measures the diameter of the rebar using a Pratt fitting circle algorithm (Chernov 2022). To have an accurate fitting implementation, all points in single rebar that are perpendicular to its orientation should be projected to a plane, and then the algorithm should be executed.

Experimental Setup

The experiments presented in the next section aim to evaluate the potential application of an RGBD sensor approach for rebar size placement inspection.

Rebar Selection

Rebar diameter increases by 1/8 in. (3.175 mm) in the United States. To get the nominal diameter in inches, the bar size should multiply by 1/8 (i.e., #4 rebar diameter is 0.5 in. [4 × 0.125 in.]). The purpose of this experiment is to recognize rebar #3 between four rebars of a different size (#4). Figure 4 shows a comparison between a #3 and #4 bar. #3 and #4 bars are 3/8 in. or 0.375 in. (9.525 mm) and 4/8 in., or 0.5 in. (12.7 mm) diameter, respectively. Although the diameter difference is 33.33% between a #3 and #4, the site conditions and the natural distance between the human and the case makes it a difficult task to catch a change in diameter of only 1/8 in. (3.175 mm). Figure 5 shows the different views in a sequence of increasing distances. Researchers chose a longer #3 rebar to illustrate better and track the differences between the two sizes

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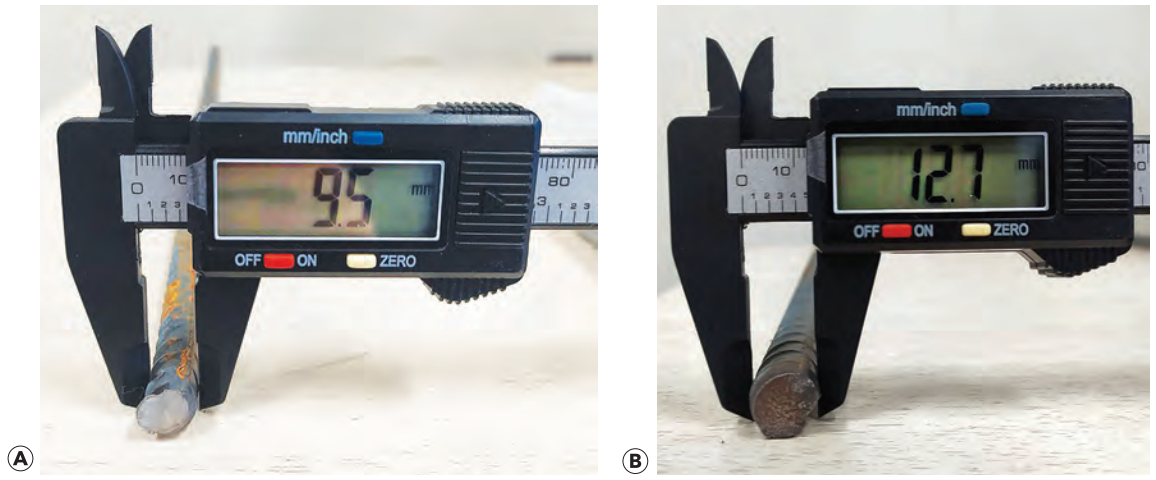


Figure 4. Caliber measurement of rebar diameters: (a) rebar #3; (b) rebar #4.

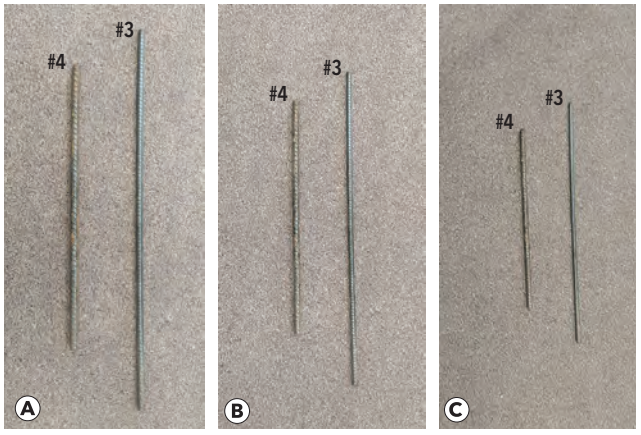


Figure 5. Distance comparison of rebar #3 and #4: (a) 2 ft (0.6 m); (b) 4 ft (1.2 m); (c) 6 ft (1.8 m).

of rebar from a distance. Human eyes, in general, may miss the two sizes from a quick inspection. The longer #3 rebar will be easily noticed from a distance to demonstrate the ability of the algorithm to detect the different diameters in various layouts. The research team laid out two bars and showed the different views from three different distances: 2 ft, 4 ft, and 6 ft (0.6 m, 1.2 m, and 1.8 m). From a human vision perspective, it is possible to see the difference in the first two cases of 2 ft and 4 ft; however, it is not so obvious for 6 ft.

Automated Geometric Quality Inspection Layout

The authors designed three different setups to implement the algorithm and test the level of accuracy using an RGBD camera. The researcher collected the data by holding the RGBD camera at a distance of approximately 4 ft (1.2 m), as it

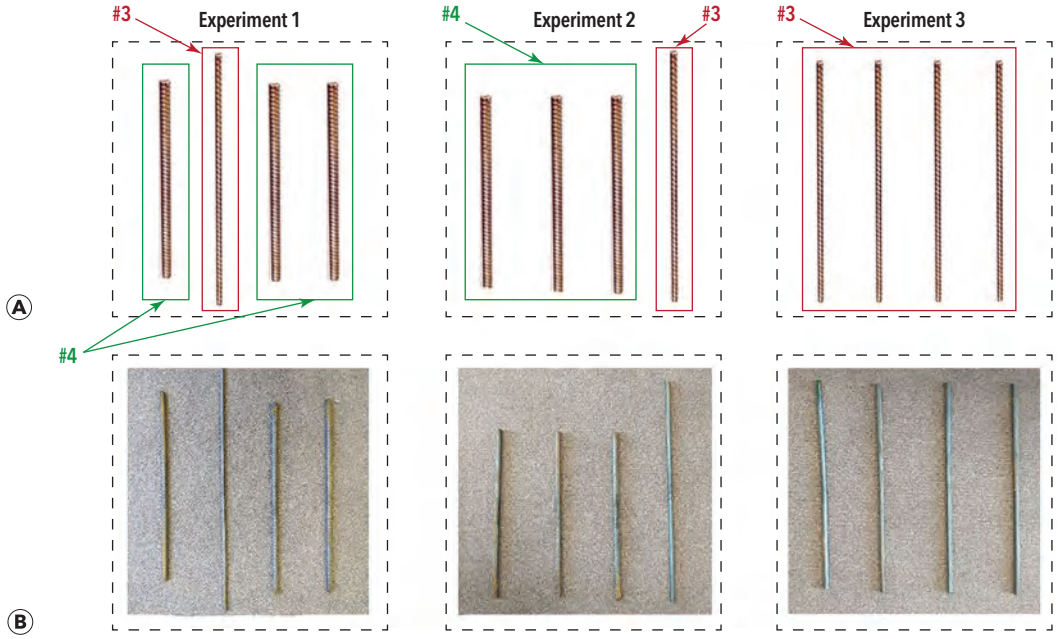


Figure 6. Rebar sample specification: (a) sketch of setup; (b) photo of setup.

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would be carried in the construction field, and at a 45° angle to maximize the FOV and minimize the data collection time. In the first setup, rebar #3 was in the middle; in the second setup, rebar #3 was located on one side; and in the third and final, all the rebars were #3. Figure 6 illustrates the rebar sample specification in this study.

Rebar Layout Scanning Using RGBD Camera

Figure 7 shows the imported data from the camera to CloudCompare and MATLAB. The camera scans the rebar sample and creates a 3D point cloud data. The camera mode that is selected for these experiments is NFOV unbinned, 30 FPS, 720p resolution. Rebar data processing needs to classify the rebar and background. Therefore, the point cloud model in Azure Kinect viewer in the .mkv format needs to be converted out to get a .ply format for further processing. Then, the .ply format point cloud model in CloudCompare software is used for preprocessing and denoising.

Experiment Results and Discussion

In this section, a simplified analysis by clustering that successfully classifies the two different diameters used for this test is proposed. The results show that the proposed automated geometric quality inspection algorithm can help the inspector to identify the #3 rebar that could otherwise be missed by the human eye. The future work of this research is summarized, including accelerated automation of the proposed data collection and analysis.

RGBD Camera Data Analysis and Results

Figure 8 illustrates the clusters. (The blue and yellow colors show rebar #4 and #3, respectively.) The first step for rebar diameter calculation is clustering the data, so a separate cluster corresponds to every single rebar. The second step is to project all the points in a cluster to the plane perpendicular to the rebar orientation. In the third step, the Pratt algorithm is implemented on the projected data.

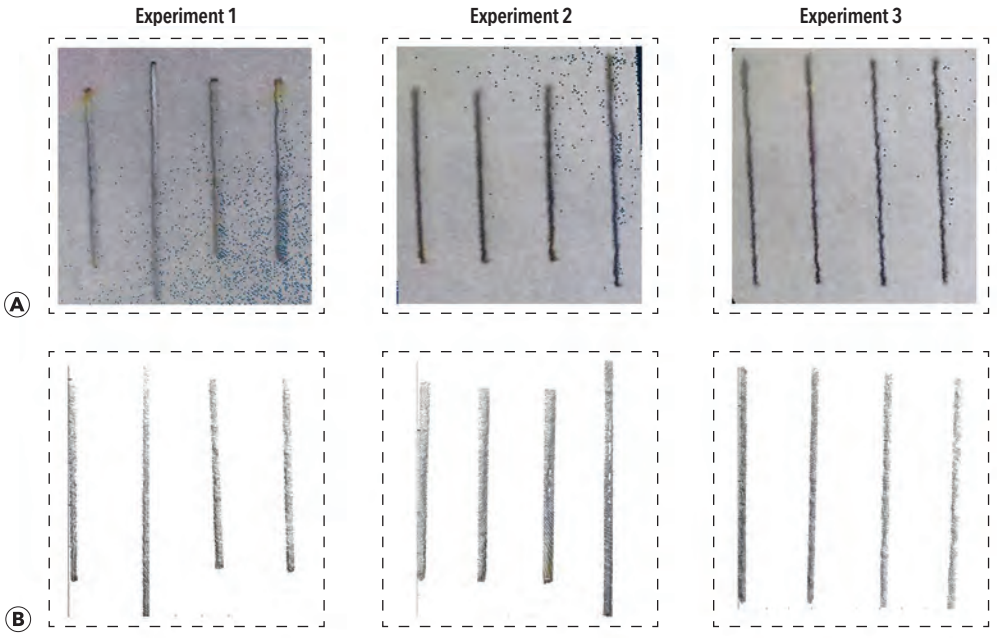


Figure 7. Imported data from camera: (a) model 3D point cloud data; (b) MATLAB plot.

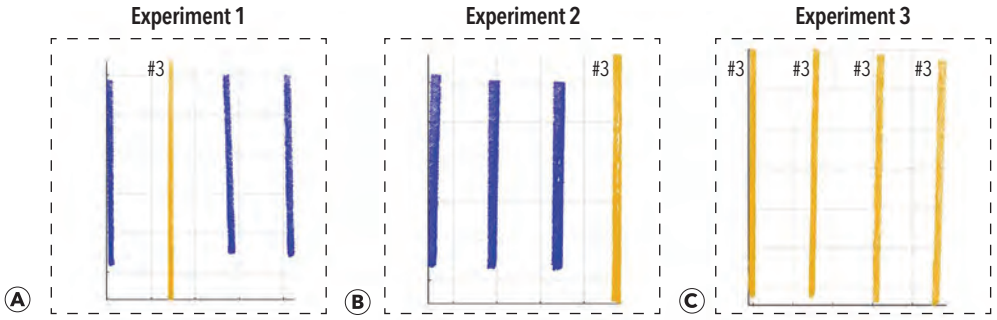


Figure 8. Clustering the model.

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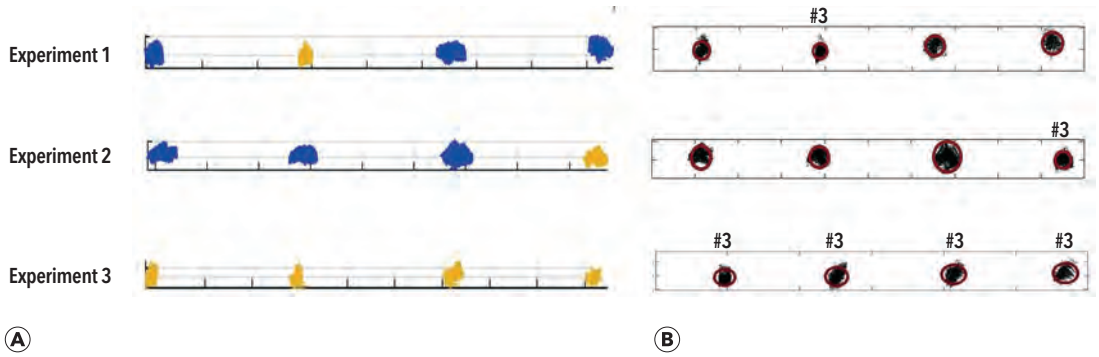


Figure 9. Results of experiment: (a) rebar projection on XZ plane; (b) estimated fitted circle.

TABLE 2
Rebar diameter and acceptable range for algorithm

Bar size	Nominal diameter (in.)	Nominal diameter (mm)	Algorithm acceptable range for each size (mm)	
			Minimum	Max
#3	0.375	9.525	7.938	11.113
#4	0.500	12.700	11.113	14.288
#5	0.625	15.875	14.288	17.463
#6	0.750	19.050	17.463	20.638
#7	0.875	22.225	20.638	23.813
#8	1.000	25.400	23.813	27.025

TABLE 3
Diameter estimation for three experiments

	Estimated diameter (mm)			
	Position 1	Position 2	Position 3	Position 4
Experiment 1	11.9	8.8	12.4	11.6
Estimated size	#4	#3	#4	#4
Experiment 2	13.5	13.2	14.2	9.3
Estimated size	#4	#4	#4	#3
Experiment 3	9.9	9.8	10.2	10.6
Estimated size	#3	#3	#3	#3

TABLE 4
Diameter estimation error for three experiments

	Error (%)			
	Position 1	Position 2	Position 3	Position 4
Experiment 1	-5.96	-7.43	-1.96	-8.55
Experiment 2	6.50	4.55	12.35	-2.17
Experiment 3	4.83	3.56	7.79	12.03

Figure 9a shows the projection of rebars to the XZ plane. The estimated circle based on the Pratt algorithm is shown in Figure 9b.

Table 2 shows the diameter of different sizes of the rebar in inch and mm units. The parameters such as light, camera angle of data collection, distance, selected resolution, and FOV will affect the final result of RGBD camera 3D point cloud data. Those parameters show their effect on how the actual object and the generated 3D point cloud data differ. So, there is an error that can be representative of these effects. To consider all the sources of errors in the proposed algorithm and simplify it for the first step of using an efficient low-cost camera in automated inspection, 50% less or more than any rebar size is considered as the acceptable range for algorithm to estimate the diameter of that size.

Table 3 demonstrates the output of the algorithm for each rebar in three experiments. The results show that for the three experiments, all rebar diameters are correctly estimated by using the 50% methodology explained earlier. Experiment 1 and Experiment 2 have one #3 bar located automatically in positions 2 and 4, respectively. Experiment 3 has all #3 bars located correctly.

Although this algorithm was able to identify the rebar #3 location correctly, there is an error in estimating the exact diameter of the rebar in different positions of each experiment. Equation 1 represents how the error is calculated.

$$\text{Error}(\%) = \frac{(d_{est} - d_{real})}{d_{real}} * 100 \quad (1)$$

where

d_{est} is the algorithm diameter estimation, and
d_{real} is the diameter of the rebar based on its real size.

Table 4 shows the error of the diameter estimation algorithm for each experiment. The average error of the algorithm is 6.47%. So, if the inspector wants to use the RGBD camera to detect the specific size of rebar and estimate the diameter, that can be a helpful way with an estimation of almost 7% error.

This experiment was an example of how the RGBD camera can be used to create the 3D point cloud data of the structure and acquire geometric information of the rebar, which is necessary for inspecting the structure. The density of the rebar, the background, and the environmental condition will impact

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the result of the recorded data from the camera. It makes the process more complicated in terms of computational time and effort. However, the preprocessing step in CloudCompare will help to remove the background and divide the top and bottom layer based on the Z elevation. Eventually, implementing the algorithm on the refined data can be done.

Further Research

The results show that the RGBD camera can be a low-cost alternative to enhance construction inspectors' capabilities in the global assessment of RC concrete construction, specifically rebar size distinction. The future focus of research is to incorporate RGBD cameras with AI techniques to develop tools to assist the construction inspectors in (a) checking size, number, location, and spacing against shop drawings and plans; (b) checking rebar for proper clearance between bars, joints, and side forms; (c) checking the adequacy of ties and tie downs; (d) checking splice locations and lengths against shop drawings and plans; (e) assuring bars with suitable coating are being used as noted in the plan; (f) detecting coating deficiencies; and (g) recording the placement of rebar in daily reports submitted by the inspector. If successful, the same principles can be extended to assist the construction inspector with post-placement of rebar activities, including assuring the rebar is not displaced during concrete placement and the proper cover is maintained. The final product will be to generate a report of deficiencies on-site so that they can be addressed in a timely fashion to promote durability while avoiding construction delays. Additionally, the digital as-built model showing the rebar location and size can be used to report and record the progress of rebar construction in real time. Requirements on rebar spacing can also be incorporated into the process as an additional measure to assure design drawings meet the applicable specifications (such as AASHTO and ACI). This research also has potential for other applications, such as changes in safety equipment and obstructions/depressions in the construction area to increase worker safety, as well as verification of pipeline/bridge layouts.

Another application that can be considered for the RGBD camera is to combine it with other technologies such as UAVs. The RGBD camera can be mounted on the UAV, which can help the inspector to collect data from a large area in a short time. It should be noted that the camera needs to be mounted on the drone, so a 3D printed setup or gimbal can be used to reduce the vibration and subsequent noises in the data. Then, the inspector would be able to have a digital as-built model of the construction site. Additionally, the inspector can use AR technology and wear a headset on-site to see the real-time 3D data created by the RGBD camera in front of their eyes as it shows which rebar should be replaced in holograms. Also, in the future, the authors would like to compare the results from RGBD and LiDAR, as each has its own advantages. The RGBD camera's application is not limited to the structural construction site; it can also be utilized in quality control of underground utilities as the inspector crew can create a 3D point cloud data model of the underground facilities to detect the defects.

Conclusion

The RGBD camera used in this study has the capability of generating 3D point cloud data of the structure with different features and modes based on the user-specific application. The authors presented a method of using this camera to recognize rebar #3 between rebar of different sizes using the Pratt circle fitting algorithm to estimate the diameter. The results demonstrated that the developed algorithm can automatically and quickly acquire measurements comparable to a tape measure utilizing the inexpensive handheld RGBD camera. This is useful for the inspector to distinguish between rebar of similar sizes, as it is hard to differentiate between them from a distance with human eyes.

This paper also explained the importance of using technologies for automation in the quantification of inspection. It decreases the amount of time required for manually recording data and has the capability of creating permanent construction records. It also lets the inspectors monitor the whole structure's state precisely and comprehensively and creates a large amount of data that could be a source of information and comparison for the next inspection. The results showed that the RGBD camera holds promise as a low-cost alternative to enhance construction inspectors' capabilities in the global assessment of RC concrete construction, specifically rebar size distinction.

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ADVANCING CONDITION ASSESSMENT OF REINFORCED CONCRETE BRIDGE ELEMENTS THROUGH AUTOMATION, VISUALIZATION, AND IMPROVED INTERPRETATION OF MULTI-NDE TECHNOLOGY DATA

NENAD GUCUNSKI*, HUNG MANH LA†, KIEN DINH‡, AND MUSTAFA KHUDHAIR§

ABSTRACT

Economic bridge management requires accurate information about the condition of bridges in the network. Nondestructive evaluation (NDE) has shown high potential in providing accurate condition assessment and, through periodic surveys, development of accurate deterioration, predictive, and life-cycle cost models. To achieve wide adoption by transportation agencies, further advances should be made that would lead to the accuracy of NDE-based condition assessment, reduced costs and traffic interruptions, and minimized risk to transportation workers. The paper discusses the following areas of improvement: increased speed and safety of data collection through the use of robotic systems, and improved data interpretation through visualization and joint analysis of data collected by multiple NDE technologies.

KEYWORDS: reinforced concrete, bridges, GPR, impact echo, ultrasonic surface waves, ultrasonic tomography, electrical resistivity, half-cell potential, visualization

Introduction

Deterioration in reinforced concrete (RC) bridge components is a result of a multitude of actions. Some of the physical factors include repeated application of heavy traffic loading, thermal effects, shrinkage, and freeze-thaw cycles. However, and more often, chemical factors like reinforcement corrosion, alkali-silica reaction, or carbonation have a dominant influence on the deterioration processes. As a result of all these described actions, multiple deterioration and defects will be generated in bridge elements. According to the ASCE 2021 Infrastructure Report (ASCE 2021), nearly 231 000 bridges in the United States need repair and preservation work, and about 5.5% of the bridge deck area is designated as structurally deficient or poor. To improve bridge conditions in the next decade, it is estimated that an increase in annual spending on bridge rehabilitation from US$14.4B to US$22.7B will be needed. Improving the accuracy in the detection and characterization of deterioration and defects of reinforced concrete bridge elements using nondestructive evaluation (NDE) methods is essential for an accurate assessment of best rehabilitation and repair procedures. The condition assessment, paired with an improved speed of NDE data collection and interpretation, will allow economical periodical evaluation of bridges. Such periodical assessments will enable the capture of deterioration processes and defect formation, leading to the development of more accurate deterioration, predictive, and life-cycle cost models (Gucunski et al. 2016; Kim et al. 2019). Ultimately, these will lead to better bridge management.

This paper provides an overview of the current practice of bridge evaluation by NDE methods, recent efforts to improve the speed of NDE data collection through automation and robotics, and improved condition interpretation through advanced visualization and combined analysis of results of multiple NDE technologies. Automation of NDE data collection for bridges in the past 10 years concentrated on the assessment of bridge decks, because they deteriorate faster than other bridge components and the deployment of NDE technologies is simpler. Several automated and robotic systems deploying single or multiple NDE technologies have been developed.

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Most of the systems enable data collection with high spatial resolution through the use of large sensor arrays or multiple probes. On the other hand, the development of robotic systems for other bridge elements with vertical surfaces is far more challenging. Climbing robots for vertical elements have been designed and developed with different locomotion and adhesion methods.

The characteristics, challenges, and applications of these systems are presented. On the condition interpretation side, the results of NDE surveys of bridge elements are most commonly presented in terms of condition maps based on the data collected by particular NDE technologies. While those are essential to describe the surface projection of the location and the severity of deterioration and defects, both elements can be improved through 3D data visualization and joint analysis of data from multiple NDE technologies. The paper specifically discusses recent developments in 3D visualization of ground penetrating radar (GPR) and ultrasonic shear wave data for concrete structures. The combination of these two technologies enables the mapping of reinforcement and clear visualization of the most common defects in concrete such as delamination, rebar debonding, corrosion, honeycombing, and such. Finally, while the use of multiple NDE technologies enables comprehensive evaluation, each NDE technology has limitations due to different parameters affecting the measured values and, thus, the interpretation of their results. To improve the interpretation, a joint analysis of data collected by multiple NDE techniques using machine-learning algorithms that incorporate various influencing parameters or other approaches can be implemented. These are discussed and examples are presented.

Current Practice of Condition Assessment of RC Bridges by Manual NDE Technologies

Deterioration processes in bridge components are often complex and are, thus, manifested through multiple deterioration indicators which can be detected and characterized by different NDE technologies. Some of the technologies can detect and evaluate only a single deterioration indicator, while some can evaluate multiple ones. In addition to defect and deterioration detectability, the methods significantly differ in the speed of data collection and interpretation, ease of use, cost, and level of expertise needed in both data collection and analysis. The following sections describe condition assessment by manual NDE technologies on concrete bridge decks and other superstructure and substructure RC components.

Condition assessment of concrete bridge decks by NDE most commonly concentrates on the evaluation of the state of corrosion, delamination, and concrete quality. It is commonly done on a test grid, for example, 60 × 60 cm (2 × 2 ft), as shown in Figure 1. A comprehensive condition assessment requires the use of multiple technologies. As shown in the figure, five NDE technologies are simultaneously deployed to evaluate the three states. The corrosion evaluation primarily relies on the electrical resistivity (ER) and half-cell potential (HCP) methods, and GPR as a secondary method. The delamination assessment primarily relies on the impact echo (IE) method, with ultrasonic surface waves (USW) and GPR as secondary methods. Finally, USW is a method that provides a quantitative assessment of concrete quality, while GPR is considered a qualitative tool. The results of evaluations are typically presented in terms of condition maps, as shown in the following section in Figure 4.



Figure 1. Manual NDE data collection on a bridge deck (a) using the following NDE technologies: (b) impact echo; (IE); (c) ground penetrating radar (GPR); (d) ultrasonic surface waves (USW) and electrical resistivity (ER); (e) half-cell potential (HCP).

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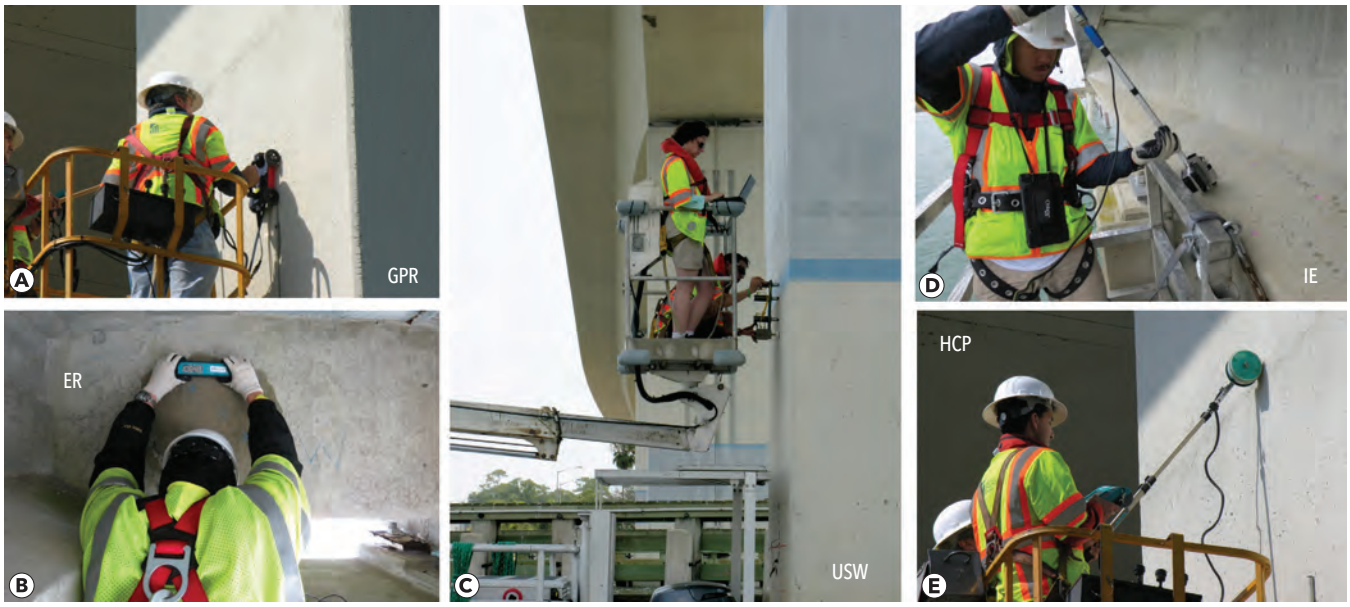


Figure 2. Manual NDE data collection on bridge piers and girders: (a) GPR; (b) ER; (c) USW; (d) IE; (e) HCP.

ER evaluates the corrosive environment of concrete by measuring the resistivity of concrete, which is significantly influenced by the moisture content (Nguyen et al. 2017), chloride concentration (Rupnow and Icenogle 2012), and the presence of cracks. The resistance can be related to the normally observed corrosion rates (Gowers and Millard 1999; Hornbostel et al. 2013). The most commonly used probe for field evaluation is a four-point Wenner probe, shown in Figure 1, which conforms with AASHTO TP 95-11 specifications. On the other hand, HCP provides information about the probability of active corrosion of reinforcement (ASTM C876-15). The method can be used at any time during the life of a concrete structure provided the temperature is above 2 °C (Elsener et al. 2003). HCP has a maximum penetration depth of around 200 mm (Bien et al. 2007). There are different types of HCP probes, also called reference electrodes. A rolling HCP probe is shown in Figures 1 and 2. Because the probe needs to be connected to the steel reinforcement, and the reinforcement needs to be connected to provide continuity throughout the survey area, the method is not appropriate for inclusion in automated or robotic systems.

Delamination detection and characterization are primarily done using acoustic methods. Among acoustic methods, impact echo is the most commonly used. IE examines the transient response of a plate-like structure subjected to an acoustic pulse. The objective of the IE test is to detect resonant modes (Sansalone and Carino 1989). The peaks in the response spectrum represent either the thickness stretch Lamb wave modes (Gibson and Popovics 2005) or flexural modes (Kee and Gucunski 2016). The delamination depth can be obtained from the resonant frequency. In the case of shallow delamination (shallower than about 50 mm), where the resonant frequency is high, a more reliable approach is using a constant-phase IE approach (Almallah and Gucunski 2019). Air-coupled IE, in which contact sensors are replaced by microphones (Zhu and Popovics 2007) or MEMS (Sun et al. 2018), opens opportunities for rapid data collection. Another acoustic method that will be discussed later, ultrasonic tomography (UST), provides more detailed imaging of delaminated elements. Finally, shallow delamination can be rapidly detected using infrared thermography (IRT) (Maser and Roddis 1990; Maierhofer et al. 2001). However, delamination detection significantly depends on environmental conditions (Washer et al. 2009).

The quantitative assessment of concrete quality is most frequently assessed by the measurement of concrete elastic modulus using the USW method (Nazarian et al. 1994). The USW modulus evaluation relies on the measurement of the velocity of propagation of surface waves of wavelengths shorter than the deck thickness. The presence of shallow delamination often leads to the measurement of an apparent low concrete modulus (Azari et al. 2012). Typical USW devices consist of a source and two receivers. One of the devices, the portable seismic property analyzer (PSPA), is shown in Figures 1 and 2. GPR provides a qualitative assessment of the deck condition. The condition assessment is based on the evaluation of the amplitude of electromagnetic waves reflected from the top rebar layer (Barnes and Trottier 2000; Maser and Bernhardt 2000; Tarussov et al. 2013). Using certain thresholds, most often related to the results from other NDE technologies, areas with high signal attenuation in the obtained map are described as deteriorated concrete (Barnes et al. 2008). Consideration of the variability of concrete cover thickness and concrete conductivity is essential for an accurate assessment of signal attenuation (Dinh et al. 2016). Bridge deck evaluation by GPR can be conducted using ground-coupled (Figure 1) and air-coupled antennas. Typical productivity for ER, HCP, and IE data collection using the shown devices is about 100 m² (1000 ft²) on a 60 × 60 cm (2 × 2 ft) test grid. It is about 25 m² (250 ft²) for

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USW and about 500 m² (5000 ft²) for GPR on survey lines with a 60 cm (2 ft) spacing. More information about the performance of NDE technologies for the condition assessment of bridge decks can be found in an SHRP 2 report (Gucunski et al. 2013).

Condition assessment of other bridge components can be done using the same NDE technologies and devices as for concrete bridge decks. The biggest challenge in the NDE technology deployment is access to the element to be evaluated. The application of the previously described five NDE technologies in the condition assessment of concrete bridge piers and prestressed girders is shown in Figure 2.

Automation of NDE Data Collection

Comprehensive condition assessment of concrete bridges can be done using manual NDE technologies. However, and as illustrated in the previous section, manual multi-NDE technology data collection requires significant time and effort. In addition, in bridge deck evaluation, and in cases when superstructure and substructure evaluation is done using snoopers, work zones for inspection cause traffic interruptions. All are adding to the cost of inspections, slowing or interrupting the traffic flow, and increasing risks for the inspectors and the traveling public. Considering that there are more than 620 000 bridges in the US, manual inspection and condition monitoring of the bridge network using NDE is not feasible. Automation of NDE data collection is, therefore, critical for their wide adoption as a tool for accurate condition assessment and monitoring and, thus, economic bridge management. The following sections describe some efforts in the automation of NDE data collection in the inspection of bridge decks and other bridge components.

Automation of Bridge Deck NDE

One of the earliest attempts for automated multi-NDE of concrete bridge decks was the robotic system BETOSCAN developed at the German Federal Institute for Material Research and Testing (BAM) (Raupach et al. 2009). BETOSCAN enabled the deployment of multiple NDE devices: ultrasonic, potential mapping, microwaves, and cover meters. While the system had significant capabilities, it could be deployed in the evaluation of smaller areas only because of a single NDE sensor installation. The RABIT (Robotics Assisted Bridge Inspection Tool) platform (Gucunski et al. 2017) brings elements of the previous efforts and implements them in a much bigger robotic platform with multiple NDE devices or sensor arrays (Figure 3).

RABIT integrates four NDE technologies: ER, GPR, USW, and IE. There are four ER probes and two acoustic arrays on the front end of the platform. The two acoustic arrays are equivalent to 16 IE devices and 12 USW devices. Two GPR arrays are mounted on the rear end of the platform, each having eight antenna pairs of dual polarization. Finally, two high-resolution cameras for deck surface imaging are mounted on the front end. RABIT is a fully autonomous system, whose navigation was achieved through an integration of the differential global positioning system (DGPS), inertial measurement unit (IMU), and the wheel odometry. The data collection path is preprogrammed in terms of the deck sections to be evaluated and increments in the data collection. All the NDE data are streamed and monitored in real-time in the command van (Figure 3). The data collection production rate depends on the length of the bridge and data collection increment. For bridge decks approximately 100 m (330 ft) long, and data collection increment of 0.6 m (2 ft), RABIT can evaluate about 350 to 400 m² (3500 to 4000 ft²) per hour.

A sample of results from the RABIT includes the condition maps of a bridge shown in Figure 4, the ER map describing the severity of the corrosive environment, the IE delamination map, and GPR and USW maps of qualitative and quantitative concrete quality assessment. The condition maps are complemented by a high-resolution image of the deck surface which is obtained from stitched camera images. A section of the bridge deck with visible cracks is shown in the same figure. Such images become permanent records of the deck surface that can be reviewed at any time.

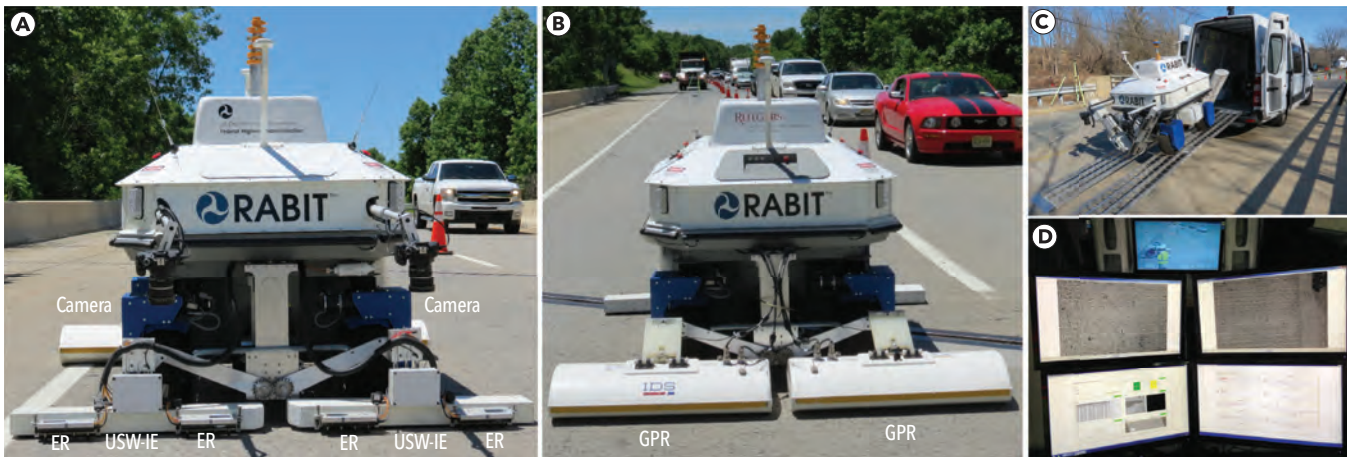


Figure 3. Robotic platform RABIT: (a) front view; (b) back view; (c) unloading from the command van; (d) screens in the command van.

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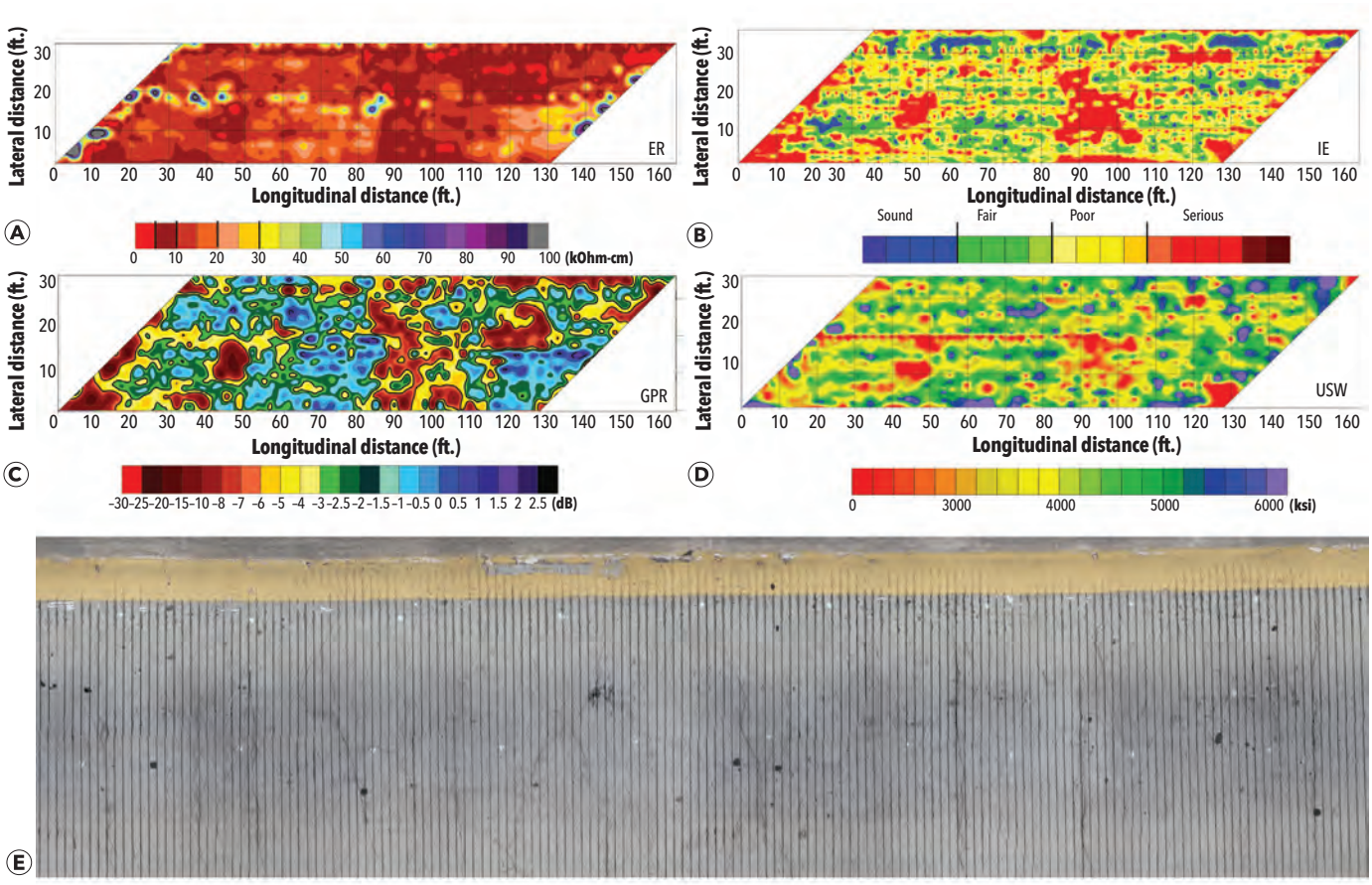


Figure 4. Condition maps from four NDE technology surveys: (a) ER; (b) IE; (c) GPR; (d) USW; and (e) section of the deck surface image.

While the data collection speed of RABIT is significantly higher than of the manual data collection (approximately three times higher than a team of five NDE technicians), it could be significantly increased through the use of air-coupled and/or rolling probes that would eliminate RABIT's test point stops. As an example, the use of air-coupled acoustic and vertical electrical impedance (alternative to ER) testing, along with GPR and high-definition imaging, was implemented on an NDE platform that enabled data collection at a walking speed (Pashtouni et al. 2020).

Climbing Robots for Bridge Superstructure and Substructure

The development of climbing robot systems for bridge inspection has received great attention recently (Tirthankar et al. 2018; Nguyen and La 2021). Inspired by the way that animals and insects move, robots have demonstrated the feasibility of climbing over different connectors and surfaces on bridges (Minor et al. 2000; Nguyen and La 2019; Nguyen et al. 2020). However, each bridge has many locations to be checked, and they are usually not close together, so it will take a long time for those climbing robots to complete the inspection of a bridge, not to mention that the calculation to move also takes a lot of time and requires intelligent algorithms. Studies on using drones for inspection have found that drones allow a quick, efficient overview without being limited to the bridge element material. However, a comprehensive inspection of bridges requires multiple positions for in-depth testing, while the current drone capabilities can provide only a visual inspection. Unlike the approaches mentioned above, a new hybrid robotic design is presented, which considers the advantages of a drone's flying flexibility and a mobile robot's steady climbing capability to perform in-depth inspections of bridges. With the new design, the in-depth inspection of the bridge will also be conducted faster because of the drone's maneuverability. The mobile robot part is equipped with permanent magnets that can change the distance from the steel surface. Changing the distance between the magnet and the steel surface allows the robot to switch its operating modes between landing, taking off, and moving.

The design concept of this robot is illustrated in Figure 5. The robot is integrated with multiple sensors: Intel camera T265 and GPS for robot location tracking, infrared sensors for a safe landing, and a GMR sensor for crack detection. The onboard computer for processing is a Raspberry Pi 4. The PX4 flight controller is for controlling the robot. The robot is surrounded by a sphere cage to protect it from a collision with the bridge. Overall, the robot is designed to work in two modes:

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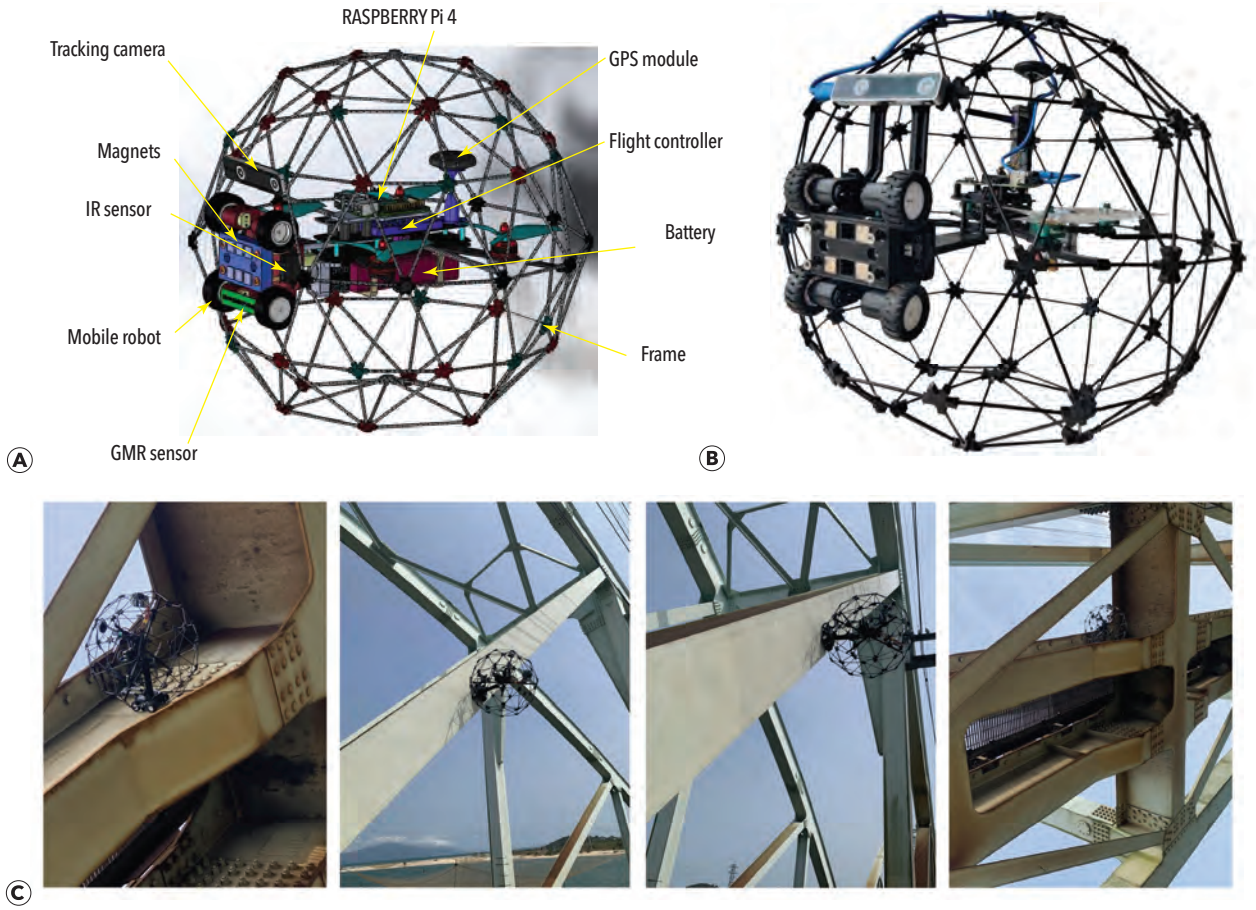


Figure 5. Flying robot with sensor integration: (a) overall design; (b) as built; and (c) images of the robot climbing on vertical surfaces of steel bridge elements.

mobile and drone. The mobile part allows the robot to cling to steel surfaces and move like other conventional mobile robots. A new robot version will be able to cling to any material type surface, including concrete. On the robot, the body is attached to magnets to create an attractive force when the robot clings to a steel surface. The distance between the magnet array and the steel face is controlled by two pull motors. This distance is adjusted depending on the working condition of the robot. If the robot needs to cling strongly to the structure, then the distance is 0. Several images of the robot climbing on vertical structures of the bridge are shown in Figure 5. The robot was in mobile mode, using its wheels to climb on the elements. As shown, the robot can climb on tall elements and access difficult-to-reach areas to perform inspections. If the robot needs to climb on the bridge, then the distance is larger than 0 (e.g., 0.3 cm) to allow easy crawling of the robot. The drone mode allows the robot to fly between inspection areas. In this mode, the robot uses a high-resolution camera to capture images or record video of the surface of the bridge elements and joints. At the same time, the robot sends images to the inspector for live viewing. To navigate the robot in the drone mode, the inspector wears a VR headset (5.8 GHz) to receive video data from the robot's camera for observation of the environment at a distance of up to around 2 km. The robot uses its camera to detect available surfaces to land on the element (switching from the flying to the mobile mode). The robot relies on the values of two infrared sensors along with an intelligent landing algorithm to determine if the point in front is a safe position to land.

The robot was deployed to collect data on several bridges. Both mobile and drone modes were tested to validate the design. The left side of Figure 6 shows a snapshot of a video recording of a highway bridge taken by the robot in the flying mode. There are two high-resolution images on the right of the figure showing cracked pier surface areas from the robot's flight close to the pier.

Advanced Data Visualization

Like the automation discussed above, 3D visualization of NDE data is another area where improvements can be made for a more comprehensive and effective assessment of concrete bridges. Visualization allows NDE data to be presented in an intuitive manner, which will, in turn, facilitate the understanding and further analysis of NDE test results. Unlike the conventional data processing methods, which are used to detect the presence of anomalies through measurement of

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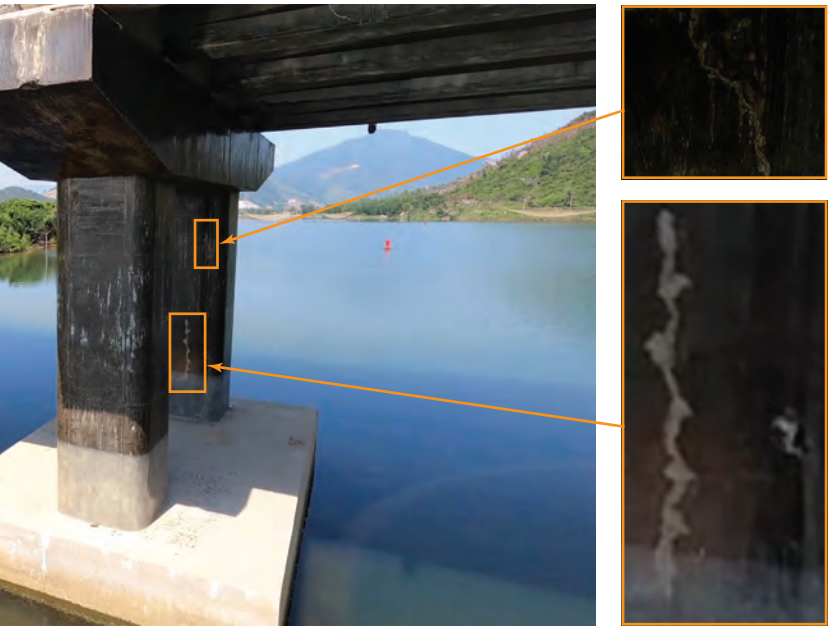


Figure 6. A snapshot from a recorded video taken by the robot. Two zoomed-in areas on the right side show the crack location.

different physical properties of concrete, data visualization may help identify the exact location and shape of structural defects. As an example, it is known that the data collected by GPR contain significant information about the bridge deck condition (Tarussov et al. 2013). However, a major drawback of it is that its data in raw form are complex in nature, large in volume, and difficult to understand, and therefore can only be analyzed by GPR experts (Gucunski et al. 2013; Tarussov et al. 2013; Dinh et al. 2019). Even when GPR data are interpreted by GPR experts, the process is usually time-consuming and labor-intensive. In addition, the results can vary significantly between analysts. As illustrated in the subsequent paragraphs, these issues can be minimized, if not eliminated, through developing a standard procedure for visualizing and analyzing 3D images. It is noted that, while 3D visualization can be implemented for various technologies (Kim et al. 2017), herein it is demonstrated in the data collected by GPR and ultrasonic shear wave imaging devices.

GPR was developed originally as a geophysical imaging technique (Daniels 2004). GPR experts would review the collected GPR data, usually in the form of B-scans, to identify different subsurface layers and/or anomalies. For concrete applications, the evaluation results are conventionally presented in the form of contour maps of rebar reflection amplitude, on which the areas of low signal amplitude indicate the likelihood of rebar corrosion and/or concrete delamination, as was shown in Figure 4. Although this method has been validated for many bridge decks, it also has some significant limitations, as pointed out in the existing literature. First, the method can lead to deceptive results due to factors affecting the amplitudes such as depth, surface anomalies, reinforcing bar spacing, reinforcing bar configuration, and polarization effects (Tarussov et al. 2013). Second, it is not suitable for analyzing time-series data with the possibility of suggesting false improvement of the concrete condition over time (Dinh et al. 2015). The ability to map the locations of rebars, tendons, voids, concrete delaminations, and so on, is of great interest to fully understand the condition of concrete bridge elements. The benefit of 3D visualization for the condition assessment of concrete bridges is illustrated in Figure 7. In this figure, the conventional method for presenting the condition map (Figure 7a) is compared with the one based on the 3D visualization technique (Figure 7b) for a concrete deck where a significant amount of salt was added to concrete mixes during construction in one section of the deck. The resulting areas of a highly corrosive environment are marked on the maps. With such ground-truth information, one can easily observe in Figure 7a, the areas of false-positive diagnosis of a highly corrosive environment associated with the conventional method. As a comparison, that is not the case with the map in Figure 7b, which clearly shows the locations of all rebars as well as the sections of rebars affected by corrosion.

Ultrasonic shear wave tomography has recently become a commonly used technology for imaging concrete structures. It works by using multiple dry-point-contract (DPC) transducers to transmit and receive shear wave signals (De La Haza et al. 2013). The data obtained from a large number of transducer couples/pairs are then used to reconstruct the interior/volumetric image of concrete. A 3D image created from such

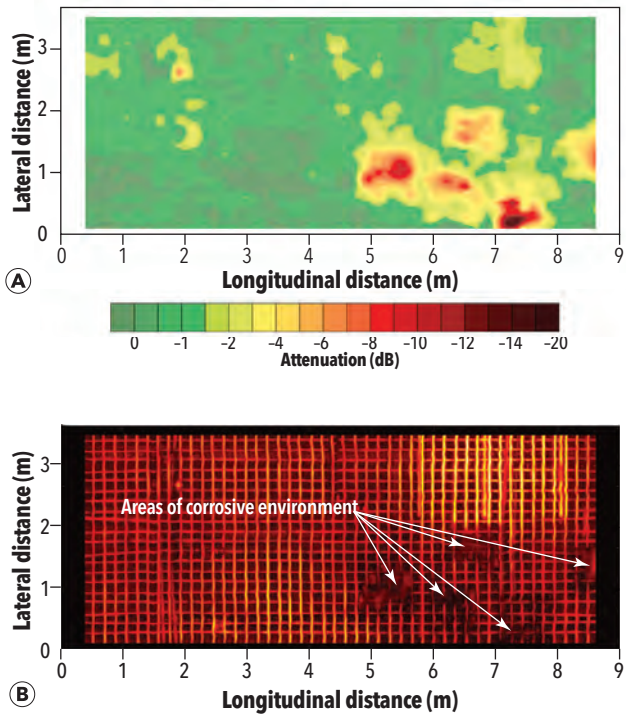


Figure 7. Presenting concrete bridge deck condition: (a) conventional method; (b) 3D visualization method (Dinh et al. 2019).

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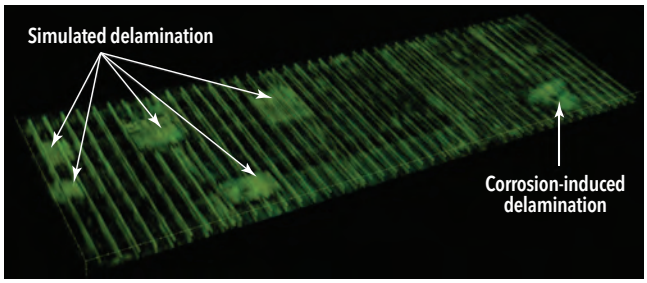


Figure 8. 3D visualization of bridge deck specimen from ultrasonic shear wave data.

data for a section of the above concrete bridge deck specimen is shown in Figure 8. The image clearly shows the locations and shapes of simulated delamination, which was embedded into the deck during construction. It is worth noting that a delaminated area caused by corrosion is displayed in the image. This area coincides with an area of the corrosive environment depicted in Figure 7. The delamination is visible in the 3D image created from the ultrasonic shear wave data. The same is not the case with the one reconstructed from the GPR data. According to Dinh and Gucunski (2021), some factors might affect the visibility of delamination in GPR images such as the thickness of delamination, antenna frequency, signal attenuation, the proximity of steel bars, and so on. On one side, this indicates the need for using multiple NDE technologies for a comprehensive evaluation of concrete bridge elements. On the other side, which is of more interest to this section, it showcases the benefits of 3D visualization of NDE data for concrete bridges.

Improved Interpretation of Multi-NDE Technology Data

It has been recognized that NDE results may be affected by many parameters such as the degree of saturation, concrete cover, delamination depth, and similar. For example, Robles et al. (2022) summarized the effects of multiple parameters, including temperature, the presence of steel reinforcement, cracks and delamination defects, specimen geometry, and concrete composition on ER results. Because of that, corrections including the effects of those parameters should be incorporated to improve the data interpretation, which can be achieved through a joint analysis of results from multiple NDE technologies.

The joint analysis approach is illustrated for the HCP data collected on a bridge specimen at the BEAST (Bridge Evaluation and Accelerated Structural Testing) facility at Rutgers University. The measured potential of corrosion activity is, among others, affected by the moisture content of concrete, concrete cover thickness, presence and moisture condition of delamination, and electrical resistivity of concrete. The four parameters can be evaluated using different NDE technologies, as illustrated in Figure 9. For example, the MoistSCAN device (Goeller and Jungstadt 2018) was used to estimate the degree of saturation of the concrete slab, as shown in Figure 9a. On the other hand, the concrete cover thickness was obtained from the GPR survey, as shown in Figure 9b. The IE results provide information about the delamination location and depth, as shown in Figure 9c. In addition, the results of ER measurements, as shown in Figure 9d, have been taken into consideration to correct the HCP measurement results.

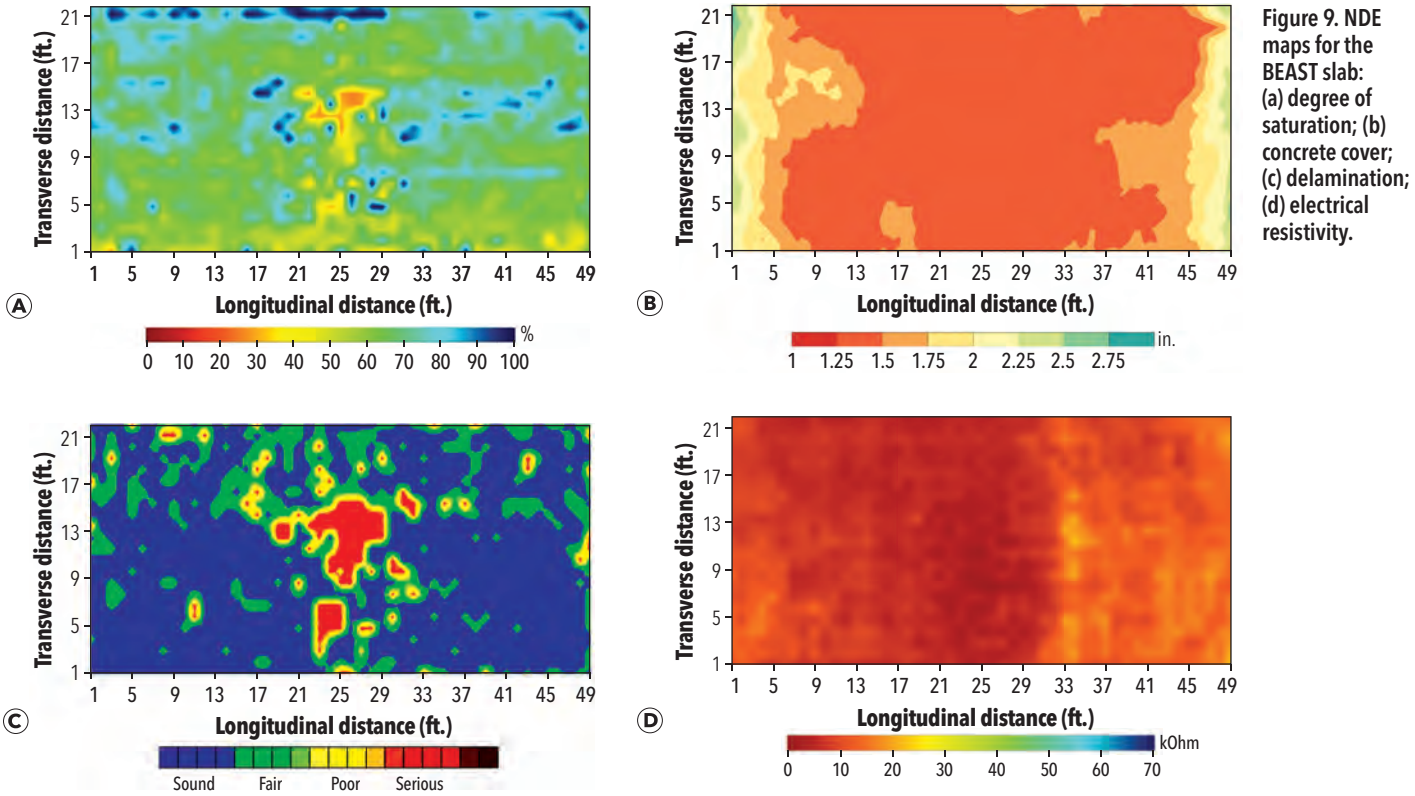


Figure 9. NDE maps for the BEAST slab: (a) degree of saturation; (b) concrete cover; (c) delamination; (d) electrical resistivity.

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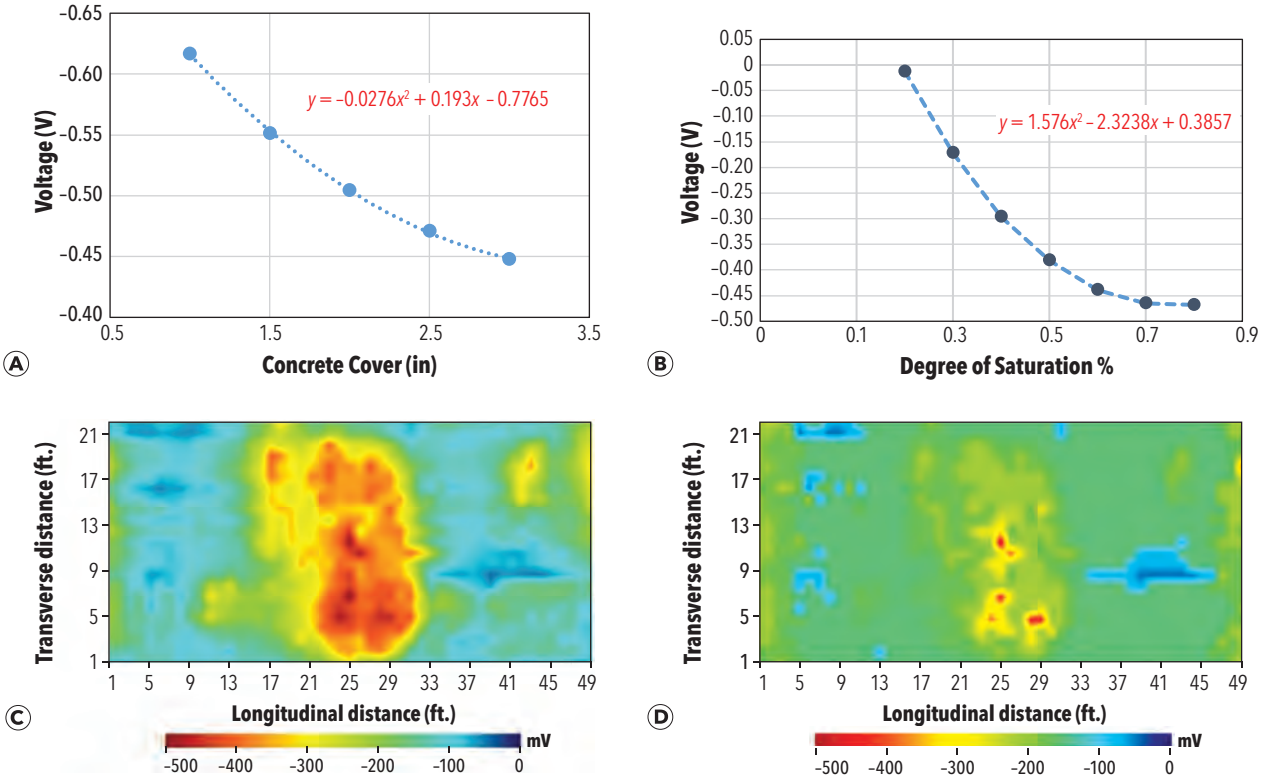


Figure 10. Improved HCP results interpretation: (a) calibration curves for concrete cover and (b) degree of saturation; and condition maps: (c) before and (d) after implementation of the algorithm.

To enable improved data interpretation, a series of finite element models have been prepared to simulate the effect of mentioned parameters on the results of various NDE technologies using COMSOL Multiphysics software. The results of the finite element models were used to produce an algorithm that mitigates the effects of different parameters on the results of the HCP. The effect of two of the parameters—the moisture content and concrete cover thickness—is illustrated in Figure 10. The HCP results before and after applying the algorithm are shown in the same figure. The raw HCP data in Figure 10c shows that the middle area of the slab has high potential values (more negative values) indicating an anticipated high corrosion activity, while the edges tend to have fewer negative values. On the other hand, the HCP measurement is modified based on four different parameters: the degree of saturation, concrete cover, delamination depth, and electrical resistivity, which are shown in Figure 10d. It can be seen clearly that the algorithm has reduced the high potential voltages in the middle of the slab because this area has a thin concrete cover (25 to 38 mm, or 1 to 1.5 in.), as shown in Figure 9b, and also has a higher degree of saturation, as shown in Figure 9a. The reference model that was used to produce the algorithm is the model that has a 40% degree of saturation, a 50 mm concrete cover, and has no delamination as well as no corrosion in the reinforcement steel bar. In general, the algorithm has modified the HCP measurements by shifting the collected values to the right of the scale (fewer negative values), while the right and left edges had almost no changes in the potential values. The changes were primarily controlled by the effect of concrete cover thickness.

Conclusion

NDE will be essential for both the safety of bridges and their economic management. On the safety side, NDE technologies enable the detection and characterization of defects and deterioration on fracture-critical bridge members. On the bridge management side, periodical NDE surveys enable the development of more reliable deterioration, predictive and life-cycle cost models and, thus, timely implementation of preventive maintenance, rehabilitation, and repair. To achieve wide acceptance of NDE in the condition assessment and monitoring of bridges, improvements are needed in the speed of data collection, the ability to deploy NDE technologies on hard-to-reach bridge components, and the NDE data interpretation. The first two will lead to a significant reduction in NDE survey costs, traffic interruptions, and risks for the bridge inspectors and drivers, while the third will lead to an accurate interpretation of the condition.

The presented robotic systems are illustrations of the potential for improvements in the speed of data collection, simultaneous deployment of multiple NDE technologies, reduction in the number of bridge inspectors needed to

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conduct NDE surveys, and accessibility of all bridge components. At the same time, the presented examples of enhanced visualization of NDE data and improved interpretation of NDE results through a joint analysis of results of multiple NDE technologies illustrate the potential for both more reliable and intuitive detection of defects and a more objective description of the condition.

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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

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

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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

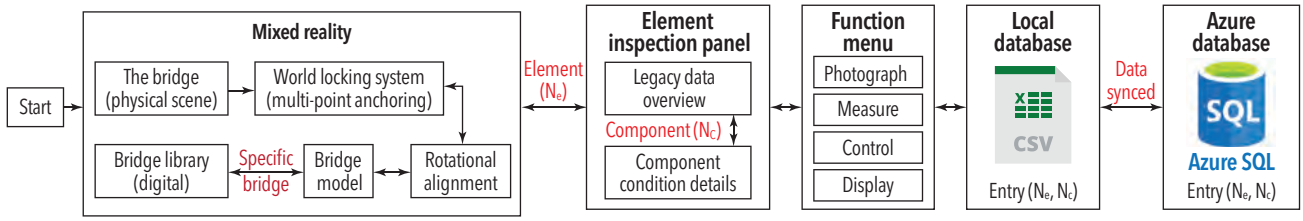


Figure 1. Bridge inspection app workflow: a mixed reality interface.

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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

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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.

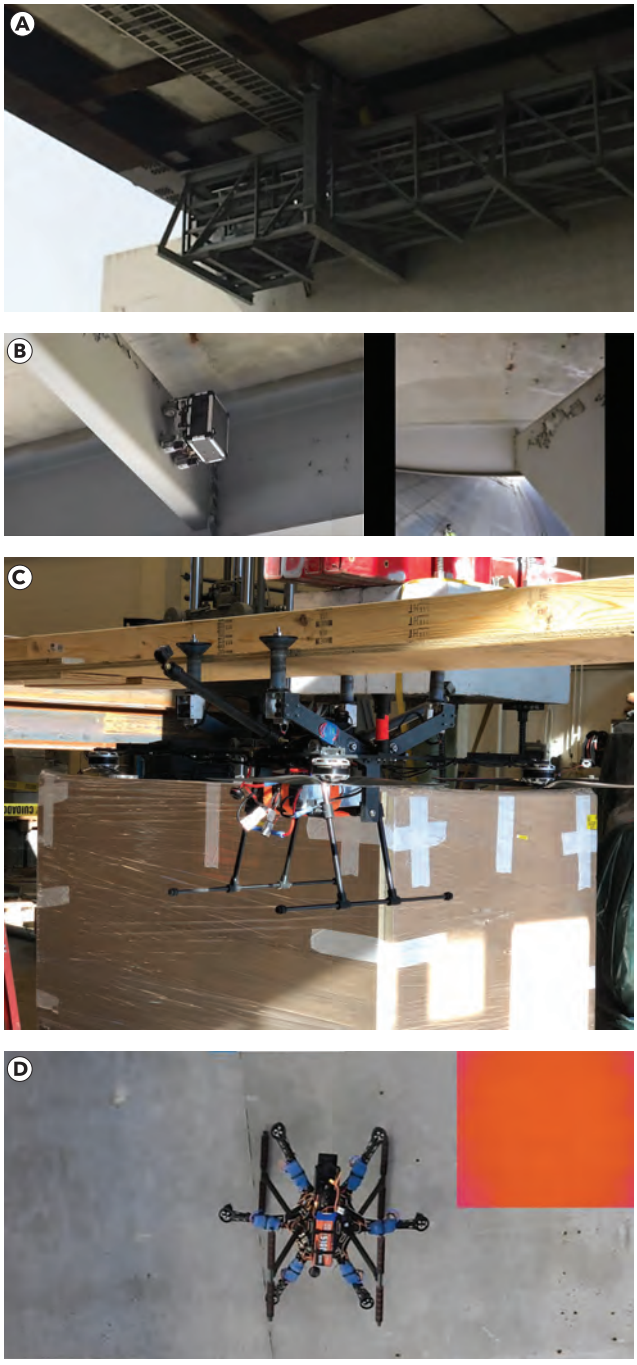


Figure 3. Bridge-attached platforms for close-in bridge inspection: (a) the moving platform in current practice; (b) the proposed structural crawler with four magnet wheels, which carries a RGB camera for visual inspection; (c) the proposed hybrid flying and traversing uncrewed vehicle (BridgeBot) attached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

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- 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.

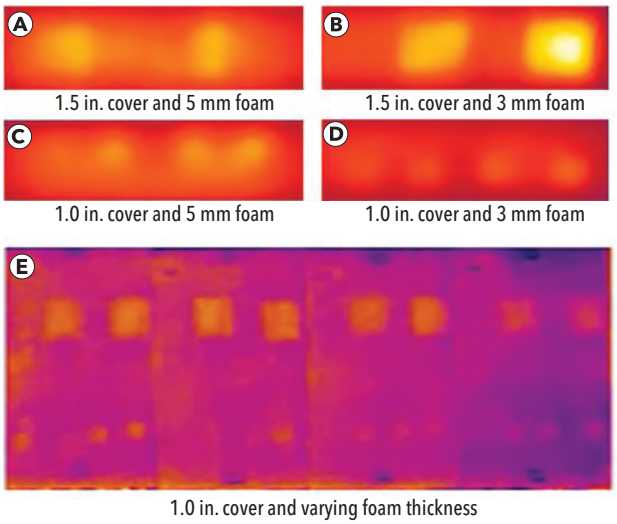


Figure 4. Thermal images of delamination with varying concrete covers and foam depths: (a) 1.5 in. (3.8 cm) cover and 5 mm foam; (b) 1.5 in. (3.8 cm) cover and 3 mm foam; (c) 1 in. (2.5 cm) cover and 5 mm foam; (d) 1 in. (2.5 cm) cover and 3 mm foam; (e) 1 in. (2.5 cm) cover and varying foam thickness.

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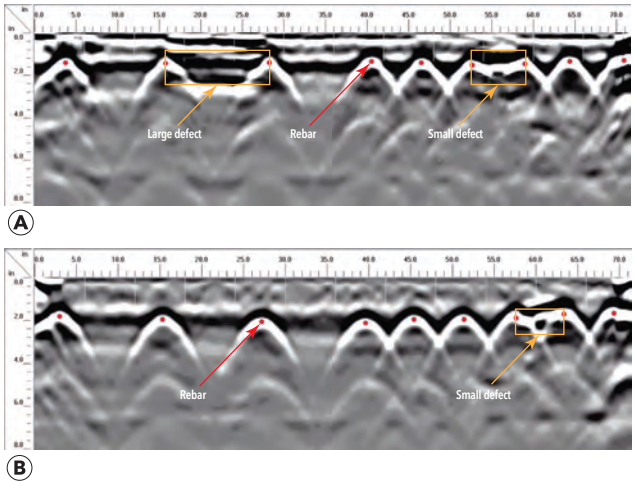


Figure 5. Line scans of GPR on the top and bottom surfaces of the concrete deck: (a) top surface with 1 in. (2.5 cm) concrete cover; (b) bottom surface with 1.5 in. (3.8 cm) concrete cover.

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.

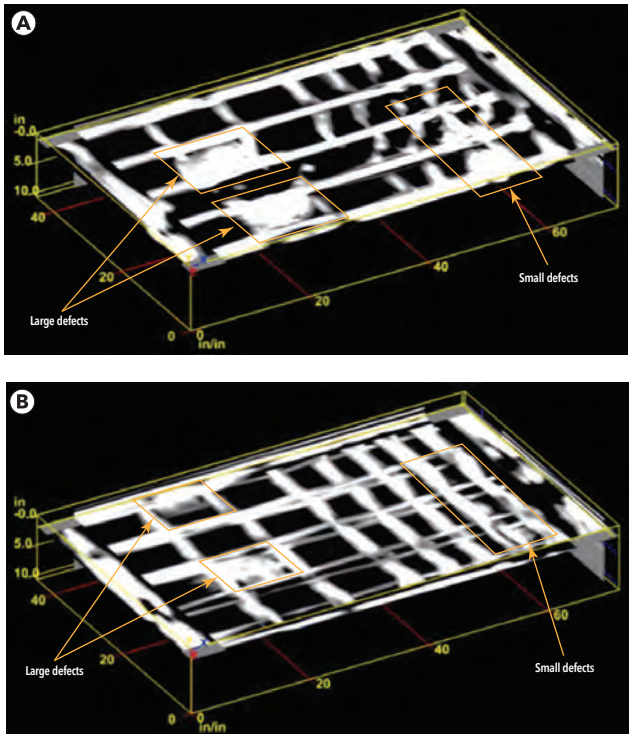


Figure 6. Isotropic view of GPR results from the concrete deck: (a) top surface with 1 in. (2.5 cm) concrete cover; (b) bottom surface with 1.5 in. (3.8 cm) concrete cover.

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 grid-lines. 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 quantitively, 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.

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

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ASNT Treasurer Brad Pence presented the Society's financial report at ASNT 2022: The Annual Conference in Nashville, Tennessee.

The following is a transcript of the financial report provided by ASNT Treasurer Brad Pence at the Annual Meeting of the Members, which took place at ASNT 2022: The Annual Conference in Nashville, Tennessee, on Monday, 31 October 2022.

The information I am presenting is from the audited financial statements for fiscal year 2022, which ended 30 June 2022. I am pleased to report the auditors presented an unqualified opinion, which represents the highest standard for audit of financial systems, and no significant findings were reported.

Fiscal year 2022 will be remembered as the year the volatile markets took back some of the value of our investments. ASNT enjoyed the extended bull market since 2009 like everyone else: our investments grew from $24,315,443 in 2018 to $33,008,765 in 2021. If you recall, the S&P 500 total returns for those years was between 18% to 31% annually. In 2022, the markets dropped and remain depressed. The ASNT investment balance declined around $5.6 million in value during fiscal year 2022.

Despite the reduced value of the investments, ASNT's balance sheet remains strong. ASNT assets are more than $32 million. This includes investments of $27.4 million, long-term assets that include the Columbus property of $2.0 million, and current assets of $2.5 million.

A key indicator of fiscal health is the level of an organization's financial reserves. Benchmark for nonprofit associations is 12 months of operating capital in reserve. Given ASNT's annual operating activity of $9.4 million, ASNT has almost three years of operating capital in reserve, or three times the recommended level.

ASNT has Board-designated net assets of $20 million, which includes our operating reserves and opportunity reserves. The remaining $6.3 million in reserves is available for operations. All net assets are without donor restrictions. The opportunity reserves are to be used to fund new business opportunities, such as



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ANCIAL REPORT FOR FY2022

new programs and new products. ASNT has never had to tap our opportunity reserves. This is most likely due to the large balance of undesignated reserves available. This will continue to be the case for the foreseeable future.

With the adoption of the ASNT Strategic Plan for 2022-2026, ASNT anticipates a period of significant financial investments to fund strategic initiatives designed to grow and enhance the association. The plan contemplates a total investment of as much as $14 million over five years. Rest assured that each and every initiative is closely considered, analyzed, and justified before the Board of Directors approves its funding. The Board of Directors then closely oversees progress against the initiatives to ensure the funds are spent appropriately. The investments in these initiatives show up as expenses on the Statement of Activities. For the fiscal year 2022, we recorded more than $560,647 in expenditures to support strategic initiatives.

ASNT's revenues for the year were $7.35 million, which was an improvement of 11% over the prior year. While revenues in conferences rebounded somewhat due to the running of the Annual Conference, revenues in all areas remained somewhat depressed following the pandemic. This is consistent with what we are seeing across the association community; the discussion has turned toward recognizing this may be our new normal.

With the return of in-person meetings, costs to support our governance and volunteer activities returned to pre-pandemic levels. The main difference from prior years is due to a change in our accounting practices: we now record staff labor costs in the program area they support. In this case, the governance and volunteer expenses are about $130,000 higher than 2019 due to the allocation of labor costs to these accounts. Other costs in this area include volunteer travel and board and committee meeting costs that were lower than pre-pandemic levels.

Administrative expenses are those expenses related to operating the company, but not directly related to programs in support of volunteer and governance activities. They are overhead-type costs. Our total costs returned to pre-pandemic levels, although what we spent money on shifted in some areas. For example, whereas depreciation expenses for software acquisition and software development investments averaged $625,000 annually between 2018 and 2021, those costs have been cut in half as we change out obsolete IT systems. This is offset by increased expenses in contracted services as we develop, configure, and implement the new association management system and certification management system.

When the strategic initiative expenditures are included, ASNT's net deficit for the year was $2 million.

Lastly, members should be aware that the Business and Finance Committee, which is well represented here today, is deeply engaged in the financial oversight of the association. The committee meets monthly to review financial reports and to question management on the details. Business cases providing financial analysis and justification for any new projects are required; the committee closely evaluates these business cases before providing its assessment and recommendations to the Board of Directors. We realize that we cannot rely on gains from our investments to cover operating losses indefinitely, and we continue to work to identify ways to mitigate the financial impact from the pandemic while at the same time providing the resources needed to operate and grow the association. ME

STATEMENT OF FINANCIAL POSITION

Assets	**2022**	**2021**
Cash	208,741	1,062,706
Accounts receivable*	300,996	249,669
Inventories, net	1,219,628	1,170,512
Prepaid expenses	476,287	230,741
Employee Retention Credit receivable	263,466	--
Total current assets	2,469,118	2,713,628
Property and equipment, net	2,042,624	1,410,162
Investments	27,446,632	33,008,765
Other assets	86,406	49,937
TOTAL	32,044,780	37,182,492

Net Assets without Donor Restrictions	**2022**	**2021**
Available for operations	6,260,131	12,838,683
Board designated	20,020,872	18,925,216
Total net assets	26,281,003	31,763,899

Revenue	**2022**	**2021**
Membership	883,253	846,513
Subscriptions and advertising	689,398	710,570
Book sales	1,351,770	1,444,466
Conferences	1,322,365	263,605
Learning programs	261,629	323,688
Technical services and certification	2,839,542	3,038,360
TOTAL	7,347,957	6,627,202

Expenses	**2022**	**2021**
Program expenses	5,219,532	4,869,244
General, admin, and fundraising	4,172,339	3,531,026
TOTAL	9,391,871	8,400,270

CHANGE IN NET ASSETS FROM OPERATIONS	(2,043,914)	(1,773,068)
Other Income		
Miscellaneous	54,658	35,050
Net investment return	(4,562,133)	6,886,049
Paycheck Protection loan forgiveness	805,027	770,952
Bureau of Worker's Compensation refund	-	11,473
Employee Retention Credit income	263,466	-
TOTAL	(3,438,982)	7,703,524
CHANGE IN NET ASSETS WITHOUT DONOR RESTRICTIONS	(5,482,896)	5,930,456

*net of allowance for doubtful accounts

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CHARLOTTE

CHARLOTTE, NC
23 SEPTEMBER 2022
41 ATTENDING

▶ The Charlotte Section kicked off the 2022–2023 program year with the 28th Annual Shrimp Boil. The agenda included the Section's monthly meeting and the introduction of honored special guest ASNT President Danny Keck, who gave a presentation of ASNT's five-year plan for growth and improvement. Outgoing Section Chair Rod Stephens was also recognized. After the Section meeting, members and guests enjoyed a shrimp boil dinner prepared by longtime Charlotte Section member Bob Smilie. The event was hosted and sponsored by FlawTech.

GREATER HOUSTON

HOUSTON, TX
15 SEPTEMBER 2022
35 ATTENDING

▶ The Greater Houston Section hosted a "student hour" to introduce local NDE students to the NDE industry outside of the classroom. The following members donated their time to speak to the group: Section Chair Stacy Cotie, Samuel (Roger) Jordan, and Xavier Quintanilla. Students attended from the following schools: San Jacinto College, Ocean Corp., Lone Star College, and North Harris Community College. Cotie covered the benefits of being part of a professional society such as ASNT, both at the local and national level. Jordan discussed his personal career in the NDT industry and the awards and scholarships that the Section offers to students and technicians. Quintanilla discussed and presented his career path on becoming an expert in the robotics field within the inspection industry.

GREATER LOS ANGELES

LOS ANGELES, CA
13 SEPTEMBER 2022
20 ATTENDING

▶ The Greater Los Angeles Section held a meeting at Bruce's Prime Rib and Spirits in Santa Fe Springs, California. The speakers were Board members, who introduced themselves and described their background, title, and tasks for the 2022–2023 program year.

OLD DOMINION

RICHMOND, VA
26 SEPTEMBER 2022
11 ATTENDING

▶ The Old Dominion Section held a meeting at the Atlee Branch of the Hanover County Public Library. John C. Duke, Jr., visited to deliver a presentation on areas of emphasis for the Society and to hear feedback from the Section. Section Chair Nicholas Wennberg reviewed the events of the summer with interest to the Section and thanked some individuals for their help in attaining the Gold ranking in ASNT's President's Award program, particularly Treasurer Lisa Barony and Dr. Deonna Woolard for producing the annual yearbook.

ROCKFORD STATELINE

ROCKFORD, IL
11 OCTOBER 2022
8 ATTENDING

▶ The Rockford Stateline Section held a virtual meeting featuring a presentation given by Stuart A. Kleven of Alloyweld Inspection titled "Qualification of Digital Computed (CR) X-ray Systems." ME

SPOTLIGHTCHARLOTTE



The Charlotte Section kicked off the 2022–2023 program year with the 28th Annual Shrimp Boil, which featured a presentation from ASNT President Danny Keck. Charlotte Section Chair Roy Duce (left) presented a Speaker's Award to Keck.

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TIMOTHY ARMITT

2022 ASNT Fellow Timothy Armitt is the managing director of Lavender International Non-Destructive Testing Consultancy Services Ltd., UK, and founder/president of Lavender International Non-Destructive Testing USA LLC. He has over 42 years' experience in NDT, including 40 years with UT, 27 years with time of flight diffraction (TOFD), and 20 years with phased array ultrasonic testing (PAUT) ranging across petrochemical, chemical, nuclear, fossil fuel and renewable power generation, naval ships and submarines, aerospace, automotive, and rail industries.

Armitt has initiated and led the development of new technologies and training programs. He has also led the development of the Lavender Sample Library in Houston, a collection of genuine service-damaged samples collected from donors when a plant is retired from service, secured for practical experience for students. Armitt has also been involved in research and development initiatives, including managing the Joint Industry Project (JIP) study, which investigated the effectiveness of NDT in detecting high-temperature hydrogen attack (HTHA). He has also been involved in the creation and development of novel inspection applications, such as the TULA probe and LIMBO TOFD solution.

Armitt is a fellow of BINDT and the Institute of Condition Monitoring. He has been a keynote speaker, author, and presenter of more than 70 papers/presentations at international conferences.



STEVEN BRADY

2022 ASNT Fellow Steven Brady, PhD, is a physicist at the Boeing Company. He has been researching and developing NDT devices and methods since 2004 and holds more than 25 patents in the field. Brady thrives on developing inspection technologies from the lab all the way through to production implementation in the transportation sector, where they can help to create a safer world. Brady has been active in ASNT for many years and serves on the Board of the Pacific Northwest Section. He has presented at regional, national, and international NDT conferences, and published and refereed articles in the field.

ABOUT THE FELLOW OF ASNT AWARD

A Fellow of ASNT is an individual member of the Society who is of outstanding professional distinction and who has made continued significant contributions to the advancement of NDE/NDT.

NOMINATIONS OPEN

ASNT is currently accepting nominations for the following awards: Advancement of Active Military and Veterans in NDT Recognition, Advancement of Women in NDT Recognition, and Mentoring Award. Nominations for the Advancement of Active Military and Veterans in NDT Recognition, Advancement of Women in NDT Recognition, and Mentoring Award must be received on or before 5 March 2023. Visit asnt.org/awards for more information. Questions? Contact Heather Cowles at 1-800-222-2768 ext. 216 or by email at awards@asnt.org.



JOCELYN LANGLOIS

2022 ASNT Fellow Jocelyn A. Langlois's involvement in ASNT started in 1994 and continues to this day. She is an ASNT Past President and a Lifetime Member of ASNT.

After attending the International Ultrasound Institute in Dallas, Texas, and working for a time in the medical ultrasonics field, Langlois enrolled in the NDT school in Pasco, Washington. She began working at Sigma Transducers in 1988 doing testing, which morphed into testing and design. In 2000, she became president of the company. Although currently semi-retired, Langlois still produces the occasional transducer while working with young people with special needs at the local school district and participating in STEM outreach days. In 2019, she was awarded the ASNT Recognition for the Advancement of Women in NDT.



ROMAN GR. MAEV

2022 ASNT Fellow Roman Gr. Maev PhD, is the founding Director-General of the Institute for Diagnostic Imaging Research, University of Windsor–a multidisciplinary, collaborative research

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and innovation consortium–and a Distinguished University Professor.

The diverse range of disciplines encompassed by Maev includes theoretical fundamentals of physical acoustics, research in ultrasonic and nonlinear acoustical imaging, and nanostructural properties of advanced materials and its analysis. One of his research directions is focused on the development of advanced nondestructive methods and NDE equipment. He has published nearly 600 peer-reviewed items, including 25 books and chapters in books, and has 42 issued patents and 20 patents pending (filed).

Maev is a recipient of many international awards. He is a Fellow of IEEE, as well as a Distinguished IEEE Lecturer; a Fellow of the British Institute of NDT (BINDT); a Fellow of CINDE; and a Fellow of RSNTTD. In 2012 he was awarded the Research Award for Sustained Excellence by ASNT. In 2018, Maev was the recipient of The Roy Sharpe Award in recognition for his outstanding contribution to NDT by BINDT. Following, in 2021, he received the ASNT Mentoring Award. He is also a member of both the ASNT Research and Engineering Councils.



PIERVINCENZO RIZZO

2022 ASNT Fellow Piervincenzo Rizzo, PhD, earned a Laurea (five-year degree equivalent to a MS) in Aeronautical Engineering from the University of Palermo, Italy. He earned a MS and a PhD in Structural Engineering in 2002 and 2004, respectively, from the University of California, San Diego. He is a Full Professor at the University of Pittsburgh's Department of Civil and Environmental Engineering, where he founded the Laboratory for Nondestructive Evaluation and Structural Health Monitoring studies.

Rizzo's research interests are in NDE and structural health monitoring (SHM), using stress waves and thermography. His research has been funded by the National Science Foundation, the Pennsylvania Department of Transportation, the Federal Railroad Administration, the National Academies of Science, TTCI, and ASNT, as well as internal grants from the University of Pittsburgh. Rizzo was the recipient of the 2002 ASNT Fellowship Award, the 2007 ASNT Faculty Grant Award, the 2009, 2015, and 2019 ASNT Fellowship Research Award, and two ASNT Outstanding Paper Awards (in 2013 and 2017).

To date, he has authored 104 refereed papers, 8 book chapters, and 170+ conference proceedings, abstracts, and technical reports. He is the first person who has received both the Achenbach Medal (in 2012) and the SHM Person of the Year Award (in 2015).

JOSEPH A. TURNER

2022 ASNT Fellow Joseph A. Turner, PhD, is currently the Robert W. Brightfelt Professor of Mechanical and Materials Engineering and Director of the Nano-Engineering Research Core Facility (NERCF) at the University of Nebraska-Lincoln (UNL). He received his BS (Eng. Sci.) and MEng (Eng. Sci. Mech.) degrees from Iowa State University and his PhD (Theoretical and Appl. Mech.) from the University of



Illinois at Urbana-Champaign (UIUC). After a postdoctoral experience at UIUC, he served as an Alexander von Humboldt Postdoctoral Fellow at the Fraunhofer Institute for Nondestructive Testing (IZFP) in Saarbrücken, Germany, before joining UNL. He is a Fellow of the Acoustical Society of America and recipient of the Wilhelm Bessel Forschungspreis from the Alexander von Humboldt Foundation. The expertise within his QUISP (Quantitative Ultrasonics for Inspection and Structural Prognosis) group is focused on ultrasonic inspection and microstructure characterization. Their research is important for the safety of manufactured components and has been applied to aerospace materials, railroad track and rolling stock, and additive manufacturing of metals among others. Turner is currently an Associate Technical Editor of *Research in Nondestructive Evaluation* and serves as the chair of the ASNT Publications Committee of the Research Council. ME

NEWCERTIFICATIONS

ACCP Level II

Oghenenyerovwo Omonigho
Felix E. Olivares
Rebecca A. Parott
Michael Ritzer
Tyler Stephens

ACCP Level II CWI

Mitchell Ballard
Nathan Didion
Tracy L. Essary
John R. Graham
Bradley Hayden
Steven D. Jannsen
Ken Sheng Lee
Manuel Martinez Montes
Chris Morr

ACCP Professional Level III

Royce Schuening

ASNT NDT Level II

Erik Jones
Bryan McConnell

ASNT NDT Level III

Graeme Baxter
Caitlyn Brown
Neil Debski
Sumesh Dharmadathan
Keith T. Dockery
Alejandro Govea
Matthew Herndon
Dhanabal Jalachandran
Mohammad Ali Khan
Adam McConaghy
Subhasish Nandi
Rickfy Perdhana
Jason Andrew Rutledge
Votti Shyam Sai
Christian Todd
Nicholas Virbitsky

ISQ - Oil & Gas (UTT)

Mark Bermudez
Devin Casse
Tylor Mueller
Kyle Podoll

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Kaitlyn Grantner has joined ASNT as an Instructional Designer. Grantner has experience working within learning and development for a tier-one automotive manufacturer and most recently an association serving finance professionals. She completed her MS in Organizational Performance and Workplace Learning through Boise State University. Grantner currently lives in Kentucky with her husband and a variety of animals. She enjoys showing her dogs, reading, and a variety of outdoor activities.



AcousticEye Ltd., a provider of noninvasive tube inspection for the global heat exchanger and boiler NDT (nondestructive testing) markets, announced that **Howard Houserman** has joined the company's advisory board. A prominent figure in the NDT industry with extensive experience, particularly in the nuclear power generation field, Houserman was Past President, CEO, and Chairman of Zetec Inc., a worldwide vendor of eddy current and ultrasonic testing equipment. Prior to his long tenure at Zetec, which also included management of field operations, Houserman worked at Westinghouse as a lead engineer for steam generator inspections.

APPOINTMENTS

ASNT member **Andy Shingledecker** has started a new position with Campos EPC as the area manager for a new location coming to Tulsa, OK.

Omar Saad has started a new position as sales engineer at Integrity Scientific & Laboratory Equipment in Dubai, UAE. ME

Do you have news *you'd like to share with the NDT community?* **People Watch** *publishes notices of ASNT members' promotions, retirements, honors, and other milestones. Please send notices to the ASNT press release inbox at press@asnt.org.*



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INTERNATIONAL SYMPOSIUM ON NONDESTRUCTIVE CHARACTERIZATION OF MATERIALS

ASNT invites you to submit a proposal to present at the 17th International Symposium on Nondestructive Characterization of Materials (ISNDCM) in Zurich, Switzerland, on 15–17 August 2023. The main focus of ISNDCM is the use of NDE methods as an investigation tool to determine a material's properties and characterize parts of materials or features detected within them. This symposium encourages presentations addressing current and future issues, covering theoretical and experimental work. Of considerable interest will be state-of-the-art developments and applications where the complex nature of materials is recognized. Furthermore, discussions on the applications and possibilities for multitechnique measurements of interdependent parameters and the evaluation of the data through sophisticated computer analyses are also encouraged.

Abstracts should be submitted to asnt.org by **31 March 2023**.

SPECIAL ISSUE OF *RNDE* ON MACHINE LEARNING IN NDE

Recent advancements in artificial intelligence (AI), including new strategies for capturing, storing, analyzing, and interpreting data, have the potential to revolutionize the nondestructive evaluation (NDE) of materials and structures in many ways. The field of NDE can significantly benefit from new machine learning (ML) and deep learning (DL) algorithms, increased computer processing power, the accessibility of mobile internet, the availability of substantial amounts of high-quality data, and modern data storage technology.

The focus of this special issue is to consolidate recent research activities that utilize existing or new AI/ML methods to advance the state of NDE. These include but are not limited to: (a) the design and development of novel algorithms adapted for NDE data acquisition, analysis, modeling, or prediction; (b) implementation of existing AI/ML algorithms to new NDE application; and (c) data-driven methods for extracting relevant information from NDE data sets compared to conventional approaches.

To be considered for this special issue, manuscripts are required to demonstrate a significant contribution to the field of NDE with carefully documented methodology and results, reporting model performance compared to conventional approaches, and including relevant code in public depositories (such as GitHub) following common practices in the field of ML.

Scope:

- Artificial intelligence
- Machine learning
- Deep learning
- Computer vision
- Signal and image processing
- Big data
- Time series analysis
- Surrogate modeling
- Pattern recognition

Editors

- Elizabeth Gregory, NASA: elizabeth.d.gregory@nasa.gov
- Hossein Taheri, Georgia Southern University: htaheri@georgiasouthern.edu.

Journal homepage and author guidelines are available at asnt.org/rnde. Submit your special issue paper by **1 May 2023** at mc.manuscriptcentral.com/urnd. Please include in your paper submission's cover letter that you are submitting for the ML special issue.

ASNT RESEARCH SYMPOSIUM

The American Society for Nondestructive Testing (ASNT) will hold its 31st Research Symposium 26–30 June 2023. The theme for the Symposium is "Exploring the Future of Nondestructive Evaluation." The symposium will not only spotlight cutting-edge research but also the students who are the future of NDE research.

The ASNT Research Council Program Committee seeks the following proposals:

- Technical presentations
- Student poster presentations
- Panel sessions

Proposals should:

- Address important research questions
- Increase the knowledge and skills of scholars and industry professionals
- Promote the development of the NDE profession
- Showcase methodological rigor

All session topics that are relevant to the NDE community will be considered for inclusion in the program.

Submissions for the technical program must be accompanied by a two- to four-page Proceedings Paper to be considered for presentation. Papers will be peer reviewed, and accepted/presented papers will be included in the conference proceedings. Each submission will be reviewed and scored by at least two peer reviewers. Acceptance notification will be made by 1 April 2023.

For more information, go to asnt.org/events. The deadline for submitting a proposal is **15 February 2023**. ME

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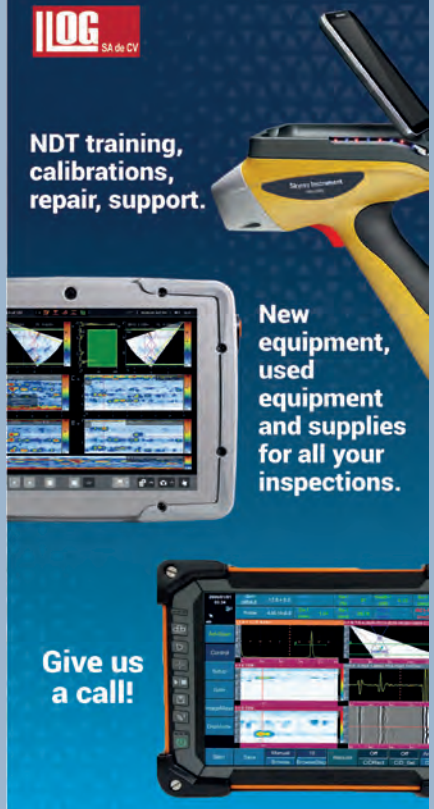
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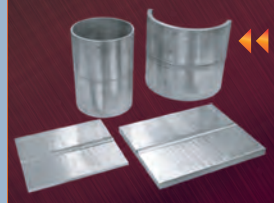
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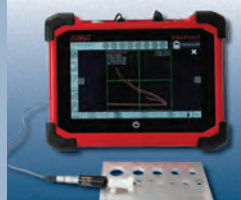
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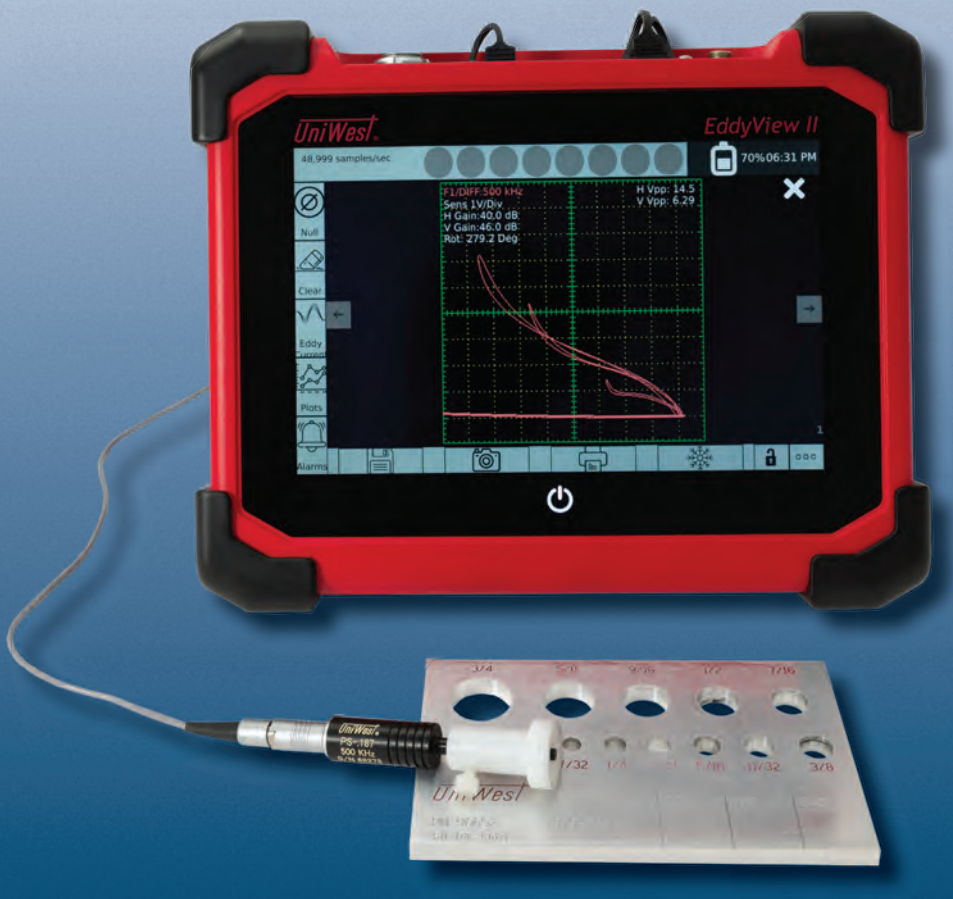
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