ROBOTIC PLATFORM RABIT for CONDITION ASSESSMENT of CONCRETE BRIDGE DECKS USING MULTIPLE NDE TECHNOLOGIES

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ABSTRACT - Current assessment of concrete bridge decks relies on visual inspection and use of simple nondestructive and destructive evaluations. More advanced, but still manual nondestructive evaluation (NDE) technologies provide more comprehensive assessment. Still, due to a lower speed of data collection and still not automated data analysis and interpretation, they are not used on a regular basis. The development and implementation of a fully autonomous robotic system for condition assessment of concrete bridge decks using multiple nondestructive evaluation (NDE) technologies is described. The system named RABIT (Robotics Assisted Bridge Inspection Tool) resolves issues related to the speed of data collection and analysis. The system concentrates on the characterization of internal deterioration and damage, in particular three most common deterioration types in concrete bridge decks: rebar corrosion, delamination, and concrete degradation. For those purposes, RABIT implements four NDE technologies: electrical resistivity (ER), impact echo (IE), ultrasonic surface waves (USW) and ground-penetrating radar (GPR). Because the system utilizes multiple probes or large sensor arrays for the four NDE technologies, the spatial resolution of the results is significantly improved. The technologies are used in a complementary way to enhance the overall condition assessment and certainty regarding the detected deterioration. In addition, the system utilizes three high resolution cameras to image the surface of the deck for crack mapping and documentation of previous repairs, and to image larger areas of the bridge for inventory purposes. Finally, the robot's data visualization platform facilitates an intuitive 3-dimensional presentation of the main three deterioration types and deck surface features.

Keywords*:* Concrete, bridge decks, corrosion, delamination NDE, automation, GPR, electrical resistivity, acoustics.

INTRODUCTION

Upkeep of concrete bridge decks is one of the biggest challenges for transportation agencies. The Federal Highway Administration's (FHWA's) Long Term Bridge Performance (LTBP) Program team interviewed a number of state Departments of Transportation (DOTs) regarding the expenditure levels for maintenance, rehabilitation, and replacement of bridges. The conclusion of the interviews was that bridge decks constitute between 50 and 80 percent of the overall expenditures for bridges. This high expense stems from three primary reasons. The first reason is that bridge decks, due to their direct exposure to traffic and environmental loads, deteriorate faster than other bridge components. The second reason is the inspection practices that detect problems only once those have reached their last stage of progression. For example, the predominant practice of condition assessment of concrete bridge decks in the United States is by visual inspection and use of simple NDE tools like chain drag and hammer sounding. While such approaches have its merits, they also have limitations in terms of the early problem detection and characterization of deterioration or defects with respect to their state of progression. The third reason is that rehabilitation practices rarely address early problem mitigation. For all these reasons, the performance of concrete bridge decks was identified as the most important bridge performance issue that needs to be addressed.

The LTBP Program initiated periodical data collection on concrete bridge decks using multiple NDE technologies (Gucunski et al. 2012 and 2013). It was demonstrated during the initial phase of the program that: 1) NDE technologies can provide accurate condition assessment, 2) condition indices obtained from NDE survey results provide more objective condition assessment, and 3) NDE enables monitoring of deterioration progression through periodical surveys. However, it was also recognized that such surveys require significant effort and time, and ultimately represent a significant expenditure. For example, a typical comprehensive survey within the LTBP Program would require a team of five to six specialists and technicians. To address the need for evaluation of hundreds of bridges in the next phase of the Program, the FHWA initiated in 2011 the development of a robotic system for the NDE of concrete bridge decks. The main goal of the development was to improve both the data collection and data analysis components. On the data collection side the concentration was on an increase of speed of data collection and its automation. On the data analysis side, the concentration was on its automation and the enhancement of the current data interpretation and presentation. During the first two years of the development, many of the stated objectives were achieved and RABIT is being deployed on a regular basis.

The paper provides an overview of current NDE of concrete bridge decks and their evaluation using RABIT system. The first part of the paper concentrates on the description of typical deterioration in concrete bridge decks. In the second part, a description of the current practice of NDE of bridge decks, with the concentration on the NDE methods implemented in RABIT. Finally, the third part provides a description of the physical components of the robotic system and their operation. The data collection process, and data analysis and presentation/visualization are presented by sample results.

CONCRETE DECK DETERIORATION

Deterioration in concrete bridge decks can be caused by a number of causes of chemical, physical and even biological nature. Because of it, different NDE technologies will be more effective in their detection and characterization. The most common cause of deterioration is corrosion that will typically lead to concrete delamination and spalling, as shown in Figure 1.

Figure 1 *Typical concrete bridge deck deterioration and damage: rebar corrosion (left), delamination (middle), and deck spalling (right).*

It should be also mentioned that delamination can be induced by repeated overloading and fatigue of concrete (Gucunski et al. 2013). Corrosion and delamination are also the deterioration types of the highest interest to bridge owners, since the most of the repairs are related to those. However, some other deteriorations (e.g. alkali-silica reaction, delayed ettringite formation, carbonation), will primarily cause material alterations, in terms of a reduced elastic modulus or strength, or changed electrical and chemical properties. Deterioration of bridge decks is often accelerated by the lack of maintenance, or use of improper procedures during their construction, especially during concrete curing. Therefore, information obtained from the data collected using multiple NDE technologies will be necessary to identify the primary causes of deterioration.

CURRENT PRACTICE OF NDE OF BRIDGE DECKS

Today, NDE technologies are most commonly used to assess whether a deck requires and what type rehabilitation, or to identify areas that should be rehabilitated/repaired. However, for effective bridge management, bridge owners should develop strategies regarding the selection of NDE technologies. Such strategies should enable capturing deterioration in concrete bridge decks at all stages of their development. For example, in a case where deterioration is primarily caused by corrosion, the process can be described as the one initiated by the development of a corrosive environment. One of the ways to detect and characterize corrosive environment is by using a electrical resistivity (ER) measurement. As the corrosive environment becomes more severe, it will initiate corrosion activity in rebars. Furthermore, rebar corrosion will induce micro and macro cracking of concrete. This will be manifested in delamination of the deck, which can be detected and characterized using impact echo (IE). It will also be reflected in the reduction of concrete elastic properties, which can be measured using the ultrasonic surface waves (USW) method. Implementation of the mentioned and additional NDE technologies is illustrated in Figure 2, where measurements by all are being taken on a 0.6 m by 0.6 m test grid.

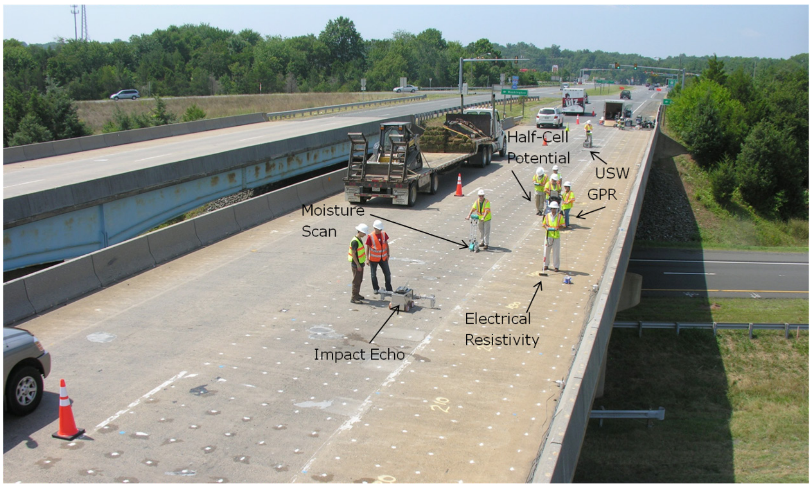

Figure 2 *Most commonly used NDE technologies in detection of corrosion induced deterioration.*

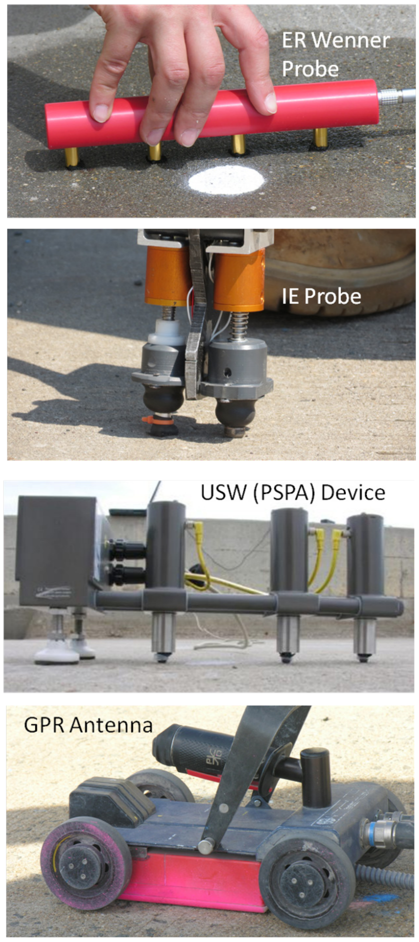

Figure 3 *Samples of probes and devices of NDE technologies implemented in RABIT.*

Manual equivalents of the probes and devices of NDE technologies implemented in RABIT are shown in Figure 3. Electrical resistivity is a descriptor of corrosive environment. Dry concrete will pose a high resistance to the passage of current, and thus will be enable to support ionic flow. On the other hand, presence of water and chlorides in concrete, and increased porosity due to damage and cracks, will increase ion flow, and thus reduce resistivity. Resistivity is typically measured using a four electrode Wenner probe, shown in the figure. The two outer probes are used to induce the current into concrete, while the inner two to measure the potential of the generated electrical field. From the two the electrical resistivity of concrete is calculated (Brown 1980). An impact echo (IE) probe consists of a mechanical impactor and a receiver. When an impact is applied, bridge deck resonances will be induced. The resonances represent “reflections” from the bottom of the deck or delamination, or flexural oscillations of the delaminated part of the deck (Sansalone, 1993).

Concrete modulus is measured using the USW method by devices similar to the one in the figure, called portable seismic property analyzer (PSPA) (Nazarian et al. 1993). The device has a single impact source and at least two receivers that measure the velocity of surface waves (phase velocity) generated by an impact. The phase velocity profile is used to assess the average concrete modulus or modulus profile. Qualitative assessment of concrete deck can be made using ground penetrating radar (GPR). Electromagnetic waves generated by an emitting antenna are in part being reflected from the objects and interfaces of materials of different dielectric properties and detected by a receiving antenna. The strength of the reflection from the top rebar, which is typically described as the attenuation of the signal, is used to characterize corrosive environment and possible delamination (Barnes and Trottier 2000). The attenuation of the GPR signal is primarily affected by the changes in concrete conductivity and dielectric value. Concrete filled with moisture and chlorides is highly conductive and causes strong wave attenuation. Therefore, the GPR assessment often provides a good description of corrosive environment. In addition, GPR surveys enable rebar mapping and the measurement of concrete cover, which in some cases may point insufficient and variable cover as a contributing factor to accelerated deterioration.

BRIDGE DECK INSPECTION USING RABIT

Description of Physical Components and Data Collection

The robotic system with its main NDE and navigation components marked is shown in Figure 4. On the RABIT’s front end there are two acoustic arrays of the total width of 1.8 m, which matches the scanning width of the system. Each acoustic array contains four impact sources and seven receivers. They are used in different combinations to enable multiple impact echo and USW measurements. In particular, RABIT’s acoustic arrays can be considered to be equivalent to fourteen IE and eight or more USW devices. This large number of sources and receivers facilitates IE data collection at about 15 cm spatial resolution, and USW concrete modulus measurements at a 25 cm resolution in the robot’s transverse direction. This is a much higher spatial resolution than a previously described 60 cm resolution commonly used in deck testing, and identified in the current LTBP Program protocols for data collection. The resolution in the direction of the robot movement can be controlled by the robot movement and sampling. Four Proceq Resipod electrical resistivity (Wenner) probes are attached on the front side of the acoustic arrays. To establish electrical contacts between the deck surface and probes, the probe electrodes are being continuously moistened using a spraying system. There are two high resolution cameras that are being used to capture the deck surface for mapping of cracks, spalls, previous repairs and other surface anomalies. Each of the cameras, once the images are stitched, covers approximately a 60 by 90 cm area.

Figure 4 *Front end of RABIT with NDE and navigation components.*

Two IDS (Italy) Hi-Bright GPR arrays are attached on the rear side of the deployment mechanism (Figure 4). Each of the arrays has sixteen antennas, or two sets of eight antennas with dual polarization. The third camera (not visible in the figure) is placed on a pneumatic mast in the middle of the robot that can lift the camera up to a 4.5 m height. The camera has a 360 degree mirror that enables panoramic images of the surrounding of the tested area.

The robot's movement can be controlled using a keyboard, joystick, Android type device, or even Iphone. For a fully autonomous movement, the robot uses three systems or devices. The primary navigation system is a differential GPS, for which the robot uses two Novatel antennas mounted on the robot, and the third one on a tripod, the base station. In addition, RABIT has on board inertial measurement unit (IMU) and a wheel encoder. The information from the three systems is fused using a Kalman filter to facilitate movement with an accuracy of about 5 cm. High agility of the robotic platform is enabled by four omni-directional wheels, which allow the robot to move laterally and to turn at a zero radius. These wheels also allow fast movement from one test location to the next one in any direction. With all the NDE sensors fully deployed, the robot is about 2.1 m long and 1.8 m wide.

The survey is conducted by multiple sweeps of the robot in the longitudinal bridge direction. Each sweep covers a 1.8 m wide strip, equivalent to one half width of a typical traffic lane 3.6 m wide. At the end of a strip, RABIT translates to the next strip and rotates 180 degrees before proceeding with another sweep. The survey starts with taking of the GPS coordinates of the GPS base station. This needs to be done only once for a particular bridge. Afterwards, the data collection path can be fully defined by taking GPS coordinates at three arbitrarily selected points on the bridge deck.

The data collection is fully autonomous. It can be done in either the full data collection mode, or the scanning mode. In the full data collection mode, the robot moves and stops at prescribed increments, typically 30 to 60 cm, and deploys the sensor arrays to collect the data. In the scanning mode, the system moves continuously and collects data using only the GPR arrays and digital surface imaging.

The data from the sensor arrays and probes, and digital cameras are wirelessly transmitted to the "command van" shown in Figure 5. RABIT can collect data on approximately 300 m2 of a bridge deck area per hour. In the continuous mode, the production rate is more than 1,000 m2 per hour.

Figure 5 *Command van and data collection and robot monitoring displays.*

The data collection process can be monitored in real time in the command van, as illustrated in Figure 5. Four main displays are used for that purpose, as well as for the display of real time, or near real time, construction of condition maps for some NDE technologies and stitched deck surface images. The summary of all the functions that can be displayed, or will be available in the near future, on the four monitors are listed in Table 1. In addition, two smaller displays enable monitoring of the robot movement and survey progression.

Data Analysis, Interpretation and Visualization

The most important results of RABIT surveys are condition maps. An example of those are a delamination map from impact echo and concrete modulus map from USW (Figure 6).

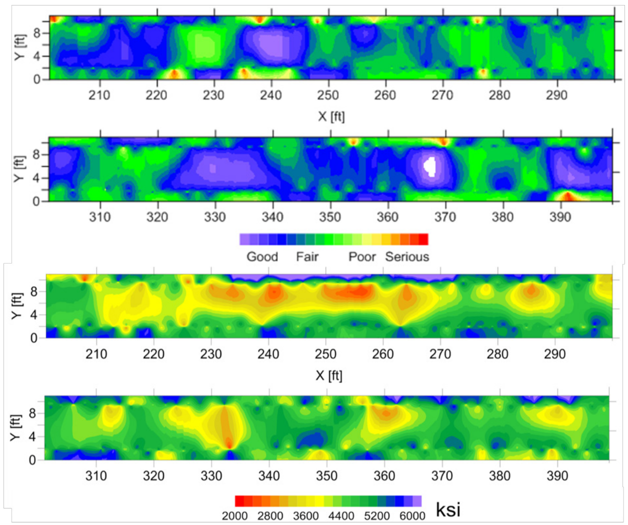

Figure 6 *Delamination map (top) and concrete modulus map (bottom).*

GPR	USW	Impact Echo	Electrical Resistivity	Imaging (Cameras)	Other
Data collect. (B-scan)	Data collection	Data collection	Data collection	Surface image	Condition rating
Condition map	Concrete quality map	Delamination map	Condition map	Crack mapping	Robot position
Concrete cover				Panoramic view	

Table 1 *Display Functions in the Command Van*

Figure 7 *High resolution images of the deck surface.*

In addition, collected deck surface images are stitched into a single or multiple large high resolution images of the bridge deck. The images are imported into an image viewer that allows review at different zoom levels, and identification of position and dimensions of identified features. Two high resolution images of two sections of the bridge are shown in Figure 7, the left one showing a joint, the second transverse cracking of the deck. Finally, a 3D visualization platform enables integration and visualization of the NDE results and images in an intuitive way. The main internal deterioration types: corrosion, delamination, and concrete degradation (low quality concrete), and the deck surface defects are presented in a common 3D space. This data presentation is illustrated in Figure 8. Zones of low concrete modulus concrete are described as clouds of different translucencies and color intensity. On the other hand, delaminations are presented as predominantly horizontal thin clouds at the depth and position as detected by the IE test. The severity of delamination is presented through the variation of translucency and color of the image. Similarly, the corrosive environment is displayed through coloring of the rebars. Hot colors (reds and yellows) are an indication of highly corrosive environment and, thus, expected high corrosion rates, while cold colors (blues and greens) are an indication of low corrosive environment and, thus, low corrosion rates. Finally, the surface of this 3D deck volume, not shown in the figure, is overlaid by a high-resolution image of the deck surface, as those shown in Figure 7.

CONCLUSIONS

Implementation of NDE in condition assessment of bridge deck will be essential for effective management of bridges. RABIT with its integrated multiple NDE technologies and vision, fully autonomous and rapid data collection, and near real time data analysis and interpretation, overcomes the past obstacles related to slow data collection and interpretation. In addition, rapid and fully autonomous data collection will significantly reduce the required workforce and exposure of the bridge inspection crews to the passing traffic. It will also in long term reduce costs of comprehensive bridge decks inspections, and make the assessment of a large population of bridges feasible.

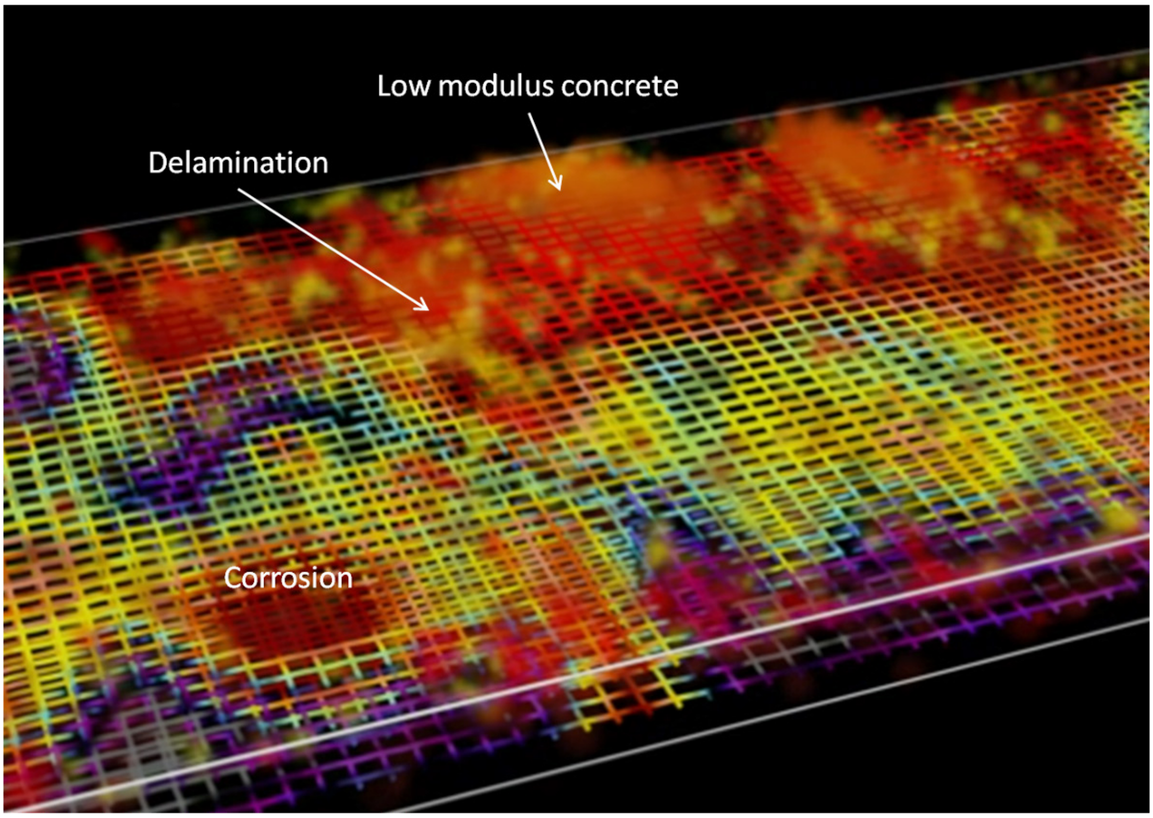

***Figure 8** 3D visualization of the detected deterioration and defects.*

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