Implementation of a Fully Autonomous Platform for Assessment of Concrete Bridge Decks RABIT

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Abstract

RABIT (Robotics Assisted Bridge Inspection Tool) provides rapid and automated condition assessment of concrete bridge decks using multiple nondestructive evaluation (NDE) technologies integrated into a robotic platform. In particular, the system is designed to characterize three most common deterioration types in concrete bridge decks: rebar corrosion, delamination, and concrete degradation. For that purpose, the system uses four technologies: electrical resistivity (ER), impact echo (IE), ground-penetrating radar (GPR), and ultrasonic surface waves (USW). In addition, the RABIT has two cameras for high resolution bridge deck imaging to provide a permanent record of the visible deterioration and surface features. The autonomous data collection is complemented by an advanced data analysis, interpretation and visualization. The most of the data analysis is conducted in real or near real time. The results are presented in terms of condition maps and condition indices. The data visualization platform facilitates an intuitive 3-dimensional presentation of the main three deterioration types and deck surface features. The data collection, analysis, and results presentation by the RABIT system are described and illustrated.

INTRODUCTION

Effective bridge management highly depends on accurate and objective information about the condition of bridge components and the bridge as the whole. Among all bridge components, concrete bridge decks in most cases deteriorate faster than others components, primarily due to their direct exposure to traffic and environmental loads. Consequently, the expenditures related to their maintenance, rehabilitation and replacement can exceed by far the expenditures for the same on other components. Therefore, to optimize resources on both the project and network levels, it is imperative to have accurate assessment of their condition, not just at a particular moment, but over a longer time period. Such information will enable more reliable understanding about the deterioration progression, as well as prediction of the remaining period before the deck will require rehabilitation or replacement. Therefore, the performance of concrete bridge decks was identified as the most important bridge performance issue by the Federal Highway Administration's (FHWA's) Long Term Bridge Performance (LTBP) Program.

To create knowledge about the performance of bridge decks, the LTBP Program envisions periodical inspections, and to a minor extent continuous condition monitoring, oft hundreds of bridges throughout the United States in the years ahead. Periodical inspections will have their traditional visual inspection component. However, they will also have an inspection program based on the use of a suite NDE technologies. The initial periodical surveys using multiple NDE technologies (Gucunski *et al*. 2012 and 2013) have demonstrated 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. To make the surveys of hundreds of bridges feasible, the FHWA initiated in 2011 development of a robotic system named RABIT (Robotics Assisted Bridge Inspection Tool) for bridge decks. The main goal of the development was to improve both the speed and automation of data collection and data analysis components, and through those to reduce the costs associated with the application of NDE technologies.

The following sections describe RABIT's components, its field operation, and typical results and tools developed to enhance data presentation and management. The first part of the paper concentrates on the description of typical deterioration in concrete bridge decks and NDE technologies appropriate for their detection and characterization. Only the NDE technologies implemented in RABIT are discussed.

CONCRETE DECK DETERIORATION AND NDE METHODS

The goal of a comprehensive condition monitoring of concrete bridge decks should be the ability to assess and describe the condition at every stage of their lives. While there are many causes of deterioration, the most commonly encountered one is driven by rebar corrosion. As illustrated in Figure 1, the corrosion process can be described as the one initiated by the development of a corrosive environment. The

corrosive environment can further lead to corrosion of rebars, cracking and delamination of concrete, and ultimately to spalling of the deck.

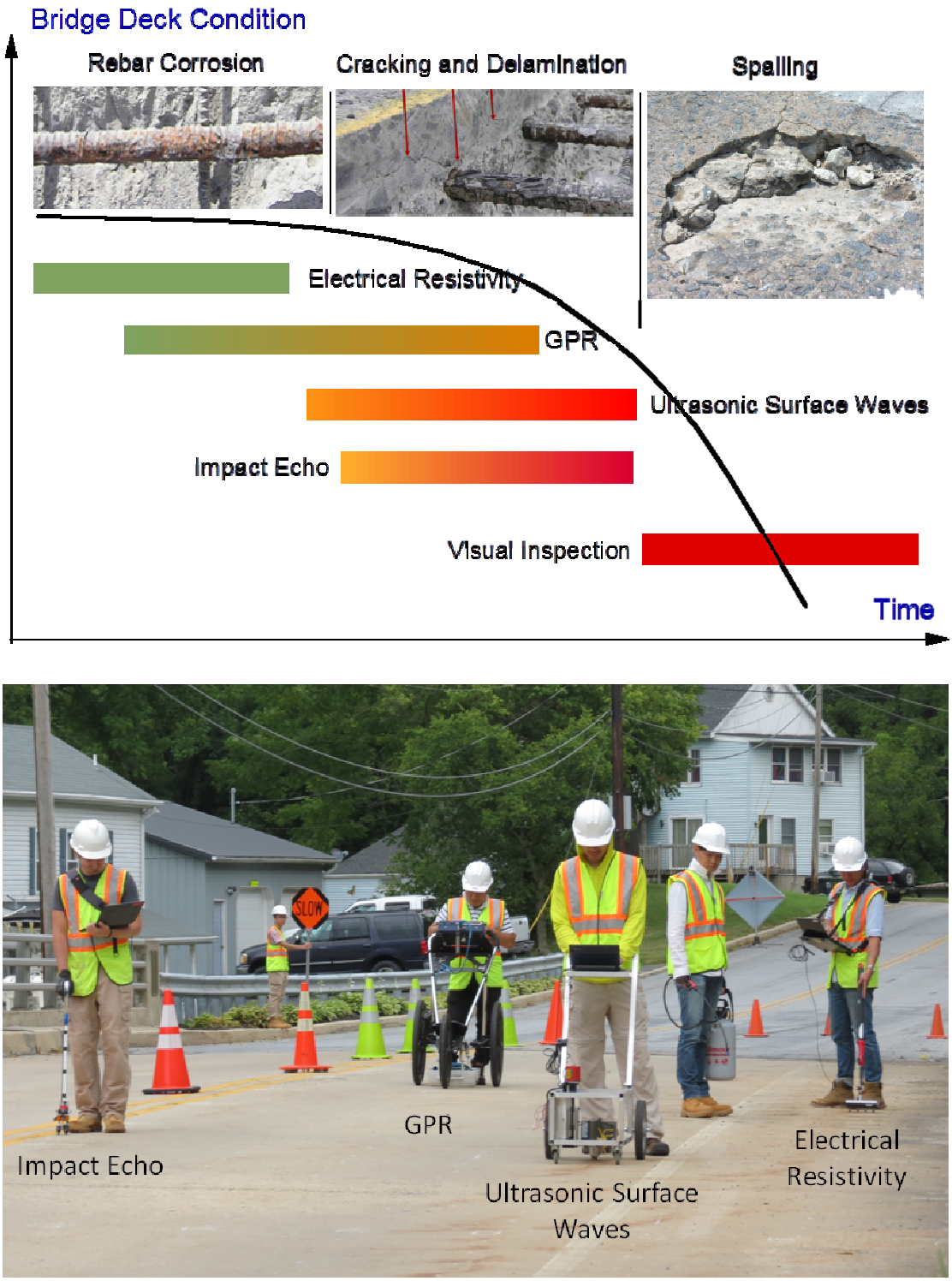

Figure 1. Bridge deck deterioration versus NDE method (top), and NDE data collection (bottom).

Each of the stages of deterioration described in Figure 1 can be detected and characterized by NDE technologies. For example, two ways to characterize corrosive environment are by electrical resistivity (ER), and to some extent by ground penetrating radar (GPR) measurements. Increased electrical conductivity due to presence of moisture, chlorides and salts will lead to a lower measured electrical resistivity by ER, or an increased attenuation of electromagnetic waves measured by the GPR. The electrical resistivity of concrete is typically measured by a four electrode Wenner probe (Brown, 1980). Some researchers have linked the concrete resistivity to the rebar corrosion rate (Gowers and Millard, 1999). As the corrosive environment becomes more severe, it will initiate corrosion of rebars and, micro and macro cracking of concrete. This will be manifested in even more pronounced attenuation of the GPR signal, due to higher moisture and chloride concentrations in cracks. Similarly, presence of cracks will lead to a reduced concrete modulus, which can be effectively measured using ultrasonic surface waves (USW) method (Nazarian et al., 1993).

Delamination of the deck can be detected and characterized using impact echo (IE) test. The goal of the IE test is to measure bridge deck resonant frequencies by applying a small impact and measuring the deck response by a nearby receiver. The resonances in the signal represent "reflections" from the bottom of the deck or delamination, or flexural oscillations of the delaminated part of the deck (Sansalone, 1993). Presence of delamination also affects the measurement of concrete modulus. Therefore, significant reductions in the modulus measured by the USW test are most often an indication of delamination. Likely delamination is also detected in the zones of high attenuation of GPR signal (Barnes and Trottier, 2000). In the condition assessment process, the GPR can provide also information about the rebar placement and concrete cover thickness. Implementation of the four described NDE technologies using manual devices is illustrated in Figure 2. The data collection is typically conducted on a 0.6 m by 0.6 m test grid.

RABIT'S PHYSICAL COMPONENTS AND DATA COLLECTION

The RABIT system and its schematic are shown in Figures 2 and 3, respectively. The robotic system with fully deployed sensors is approximately 2.7 m long and 1.8 m wide. On the front end of the robot there are two acoustic arrays of the total width of 1.8 m, and four ER probes spaced approximately 50 cm apart. Each of the acoustic arrays contains four impact sources and seven receivers that enable seven IE and up to six USW measurements. Therefore, RABIT's acoustic arrays can be considered to be equivalent to fourteen IE and eight or more USW devices shown in Figure 1. In addition to improving the speed of data collection, the large number of sensors also enables assessment of delamination and concrete quality at a much higher spatial resolution than it is being done using manual technologies on a previously described 60 cm grid. Four Wenner ER probes are attached to the front side of the acoustic arrays. To establish electrical contacts between the deck surface and probes, the probes' electrodes are being continuously moistened using a spraying system that sprays on each of the electrodes water using very fine copper tubes at the

end of each data collection cycle. Finally, two cameras electrically extended in front of the acoustic arrays capture high resolution images of the deck surface for mapping of cracks, spalls, previous repairs and other surface anomalies. The images that are being taken every 60 cm are later stitched into one or more large high resolution images of the bridge deck surface.

Figure 2. The RABIT's front end with acoustic arrays, ER probes and cameras.

Two GPR arrays are attached on the rear side of RABIT, shown as white boxes in Figure 2. Each of the arrays has sixteen GPR antennas, or eight pairs antennas of dual polarization. Antennas of dual polarization enhance data analysis when the top rebar is not in the preferred orientation, which is being transverse to the bridge longitudinal direction. Also, a pneumatic mast can be observed at the center of the robotic platform which carries a camera.. The mast can lift a camera with a 360 degree mirror up to 4.5 m for panoramic imaging of wider bridge deck areas.

The robot's movement can be controlled in multiple ways: using a keyboard, joystick, Android type device, or even an Iphone. However, for a fully autonomous movement, the robot relies on the fusion of data from three positioning systems or devices. The primary navigation system is a differential global positioning system (GPS), for which the robot uses two GPS antennas mounted on the robot's front and rear ends. The antennas are visible in Figure 2 as arms slightly above the robotic platform. The third GPS antenna, the base station, is placed on a tripod, typically at

the beginning or the end of the bridge.. The survey starts with taking of the GPS coordinates of the GPS base station, which needs to be done only once for a particular bridge. The two other positioning devices include an on board inertial measurement unit (IMU) and a wheel encoder, or distance measurement instrument.

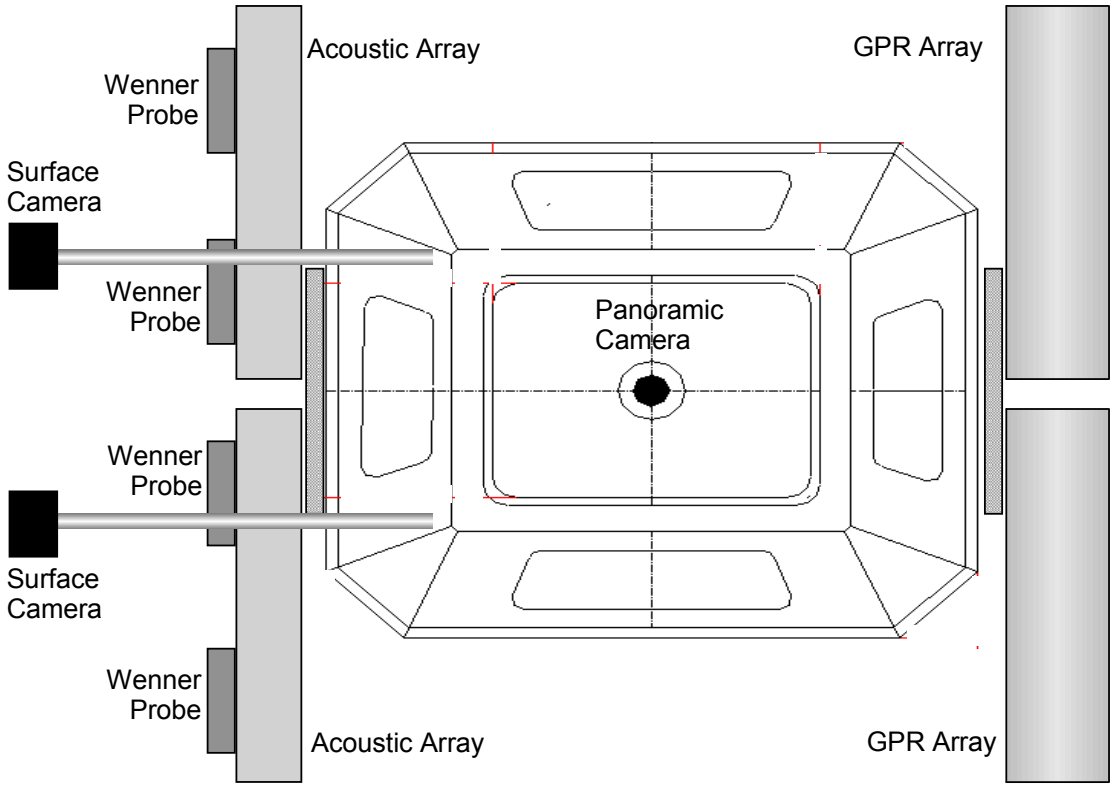

Figure 3. Plan view of RABIT and its components.

The path planning algorithms embedded in RABIT allow fully autonomous surveys using several options. However, the data collection is mostly conducted by multiple parallel sweeps in the longitudinal bridge direction. GPS coordinates at three arbitrarily selected points on the bridge deck are sufficient to fully define the data collection path. Each RABIT sweep covers a 1.8 m wide strip, equivalent to the width of the acoustic and GPR arrays. The array width also enables coverage of a typical traffic lane 3.6 m wide in two sweeps. A typical path planning diagram is illustrated in Figure 4. High agility of the robotic platform is enabled by four omni-directional wheels, which allow RABIT to move laterally and to turn at a zero radius, or to move fast between two test points. The robot moves and stops to deploy the sensor arrays to collect data at prescribed increments, typically every 30 or 60 cm.

The RABIT is transported between bridges in a van, from which it can unload and load itself by driving on a pair of foldable ramps. However, a more important function of the van is to serve as a command centre. The data from the sensor arrays, probes and cameras are wirelessly transmitted to the van, where it is displayed and monitored in real time. The van has six displays: four main displays to monitor data

collection, show generated condition maps and calculated condition indices, and two smaller displays to monitor robot movement and survey progression.

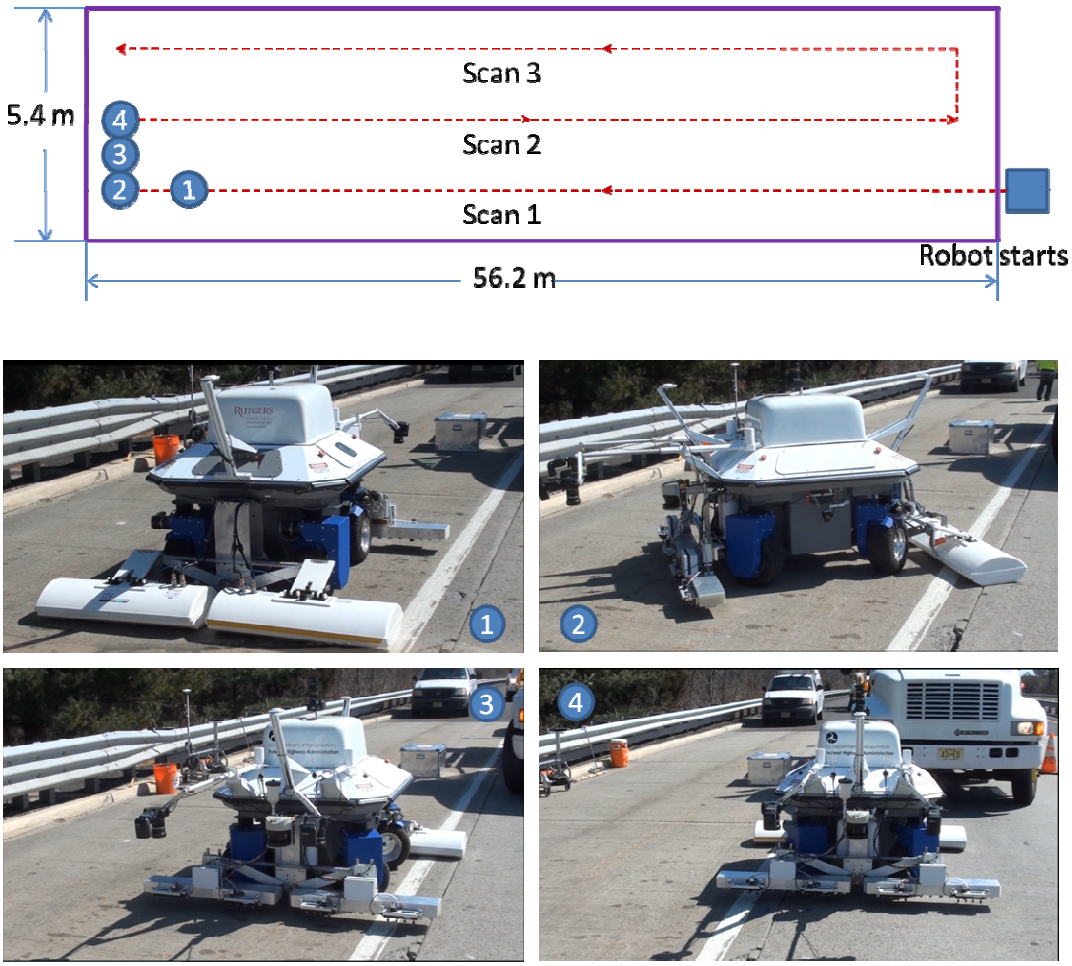

Figure 4. Typical RABIT surveying path (top) and images of corresponding RABIT movements (bottom).

RABIT can collect data at production rates of about 300 to 350 m^2 of a bridge deck area per hour. This is about three-fold production rate of a team of five NDT technicians conducting the same set of surveys using manual NDE technologies..

DATA ANALYSIS AND PRESENTATION

The most important results of RABIT surveys are condition maps and calculated condition indices with respect to different deterioration types. The RABIT allows for near real time analysis and display of IE, USW and ER condition maps. An example is a delamination map shown in Figure 5, which is being generated and displayed during an actual data collection. The data can be reanalyzed in the office and the results plotted in the same way as the results from manual NDE surveys. An example of a set of condition maps: a delamination map from IE, a concrete quality

(modulus) map from USW, and a corrosion resistivity (rate) map from ER, is shown in Figure 6. In all the maps, zones of the deck described in hot colors (reds and yellows) are indications of areas with more severe deterioration or defects.

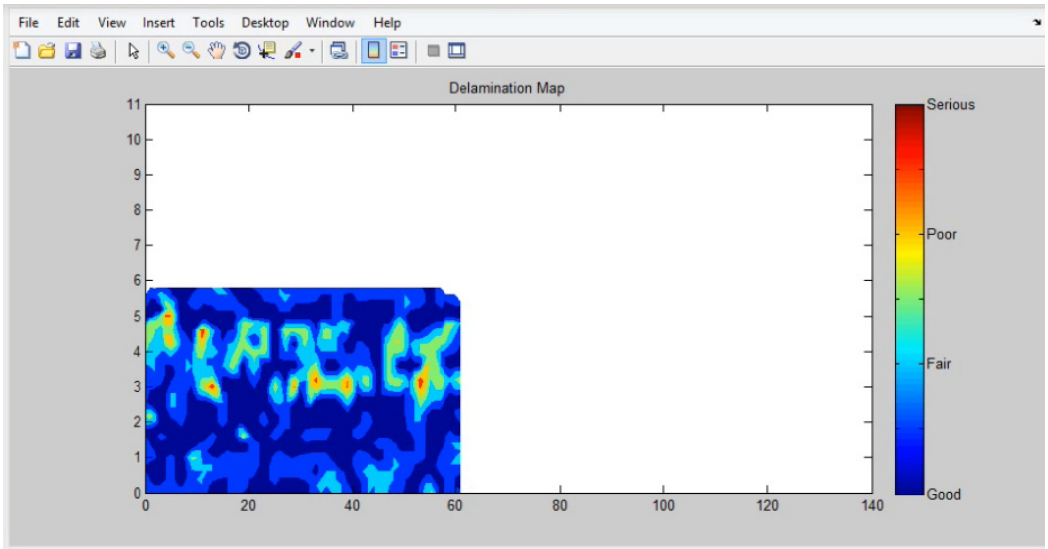

Figure 5. Near real time generation adn display of the delamination map during the RABIT data collection.

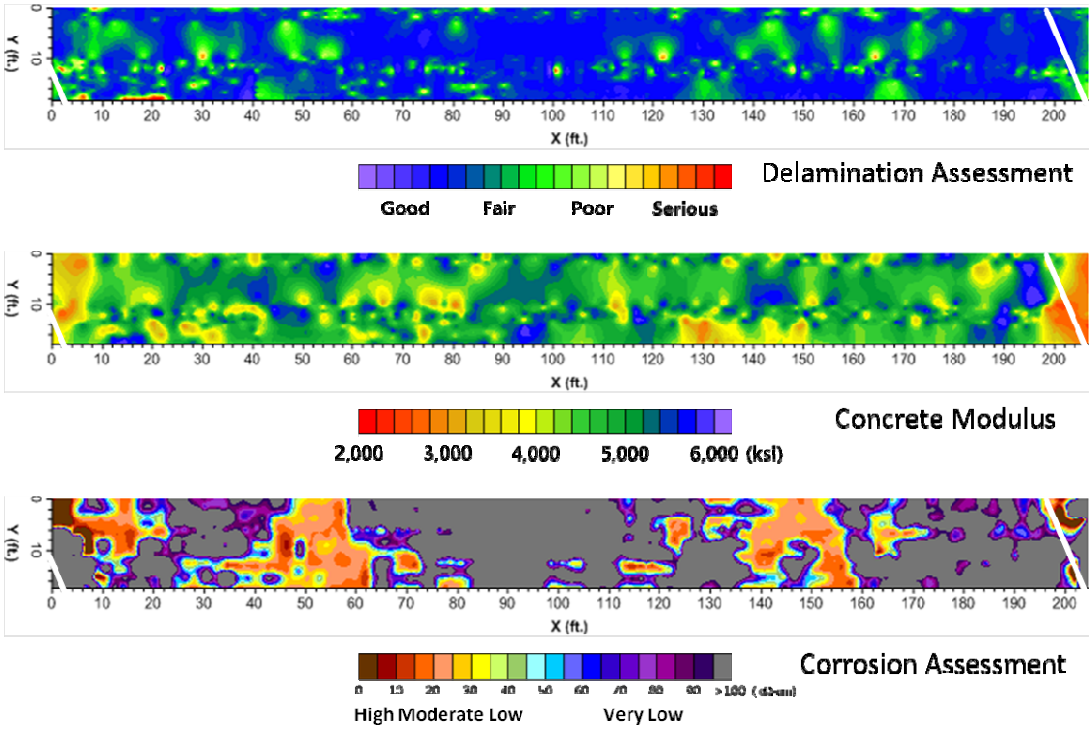

Figure 6. Delamination, concrete quality and corrosion assessment maps from a bridge deck survey by RABIT.

In addition to the NDE condition maps, deck surface images are stitched into a single or multiple large high resolution images of the bridge deck. A special image review tool was developed that enables review of the deck surface at different levels of detail. The tool also allows identification of different features, like cracks, spalls and patches, in terms of their position, dimensions or spacing. A high resolution image of a section of the bridge and a zoomed in image of a detail around the joint is shown in Figure 7.

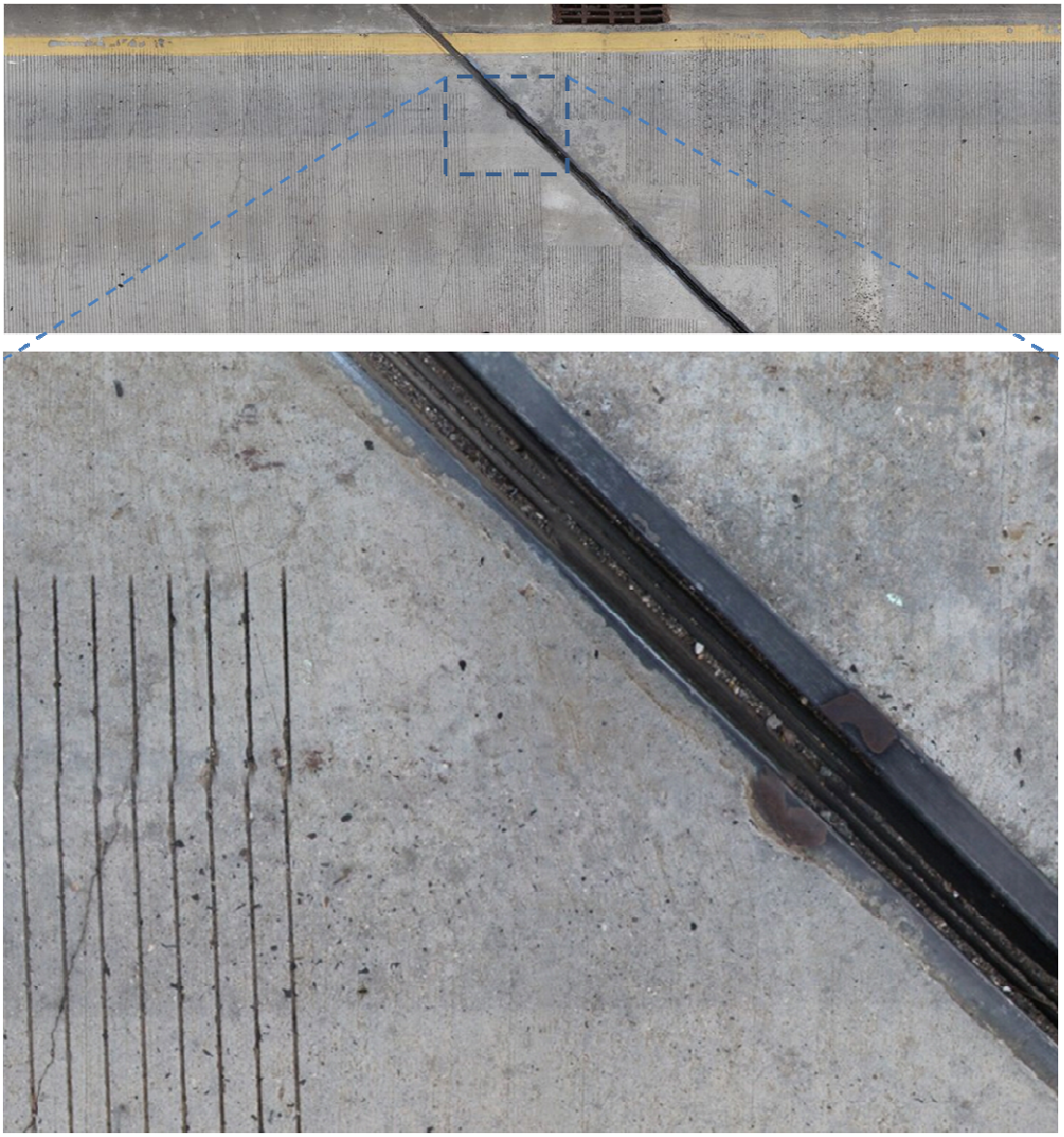

Figure 7. Stitched image of a section of a bridge deck (top) and a zoomed in image of an area around a joint (bottom).

Finally, one of the products of the RABIT project is a platform for 3D visualization of the data collected by RABIT. The platform enables integration and visualization of

the NDE results and images in a very intuitive way. Delamination, corrosion and degradation in concrete quality are presented as objects of different colors and shapes describing the severity of deterioration or defects in a common 3D space. For example, delamination is presented as thin surfaces at the measured delamination depth. The severity of delamination is described through different levels of color intensity and surface translucency. Similarly, zones of low concrete modulus concrete are described as clouds of different translucencies and color intensity. The program allows that only objects describing different severity levels be displayed, to avoid oversaturation of the image with secondary features. Similarly, the corrosive environment is displayed through coloring of the rebars, where most commonly hot colors are used to indicate highly corrosive environment, while the rest of the rebars are displayed in neutral colors. A screen capture of the program for visualization with a 3D image of a small section of a deck is shown in Figure 8. The surface of a 3D deck volume, not shown in the figure, can be overlaid by a high-resolution image of the deck surface, like the one shown in Figure 7. This feature allows comparisons of the signs of deterioration observed on the surface of the deck and the underlying deterioration and damage detected by the NDE technologies. In addition, the ability to present information from all the technologies in a common space allows identification of highly deteriorated areas with higher confidence, as well as better understanding of likely causes of deterioration.

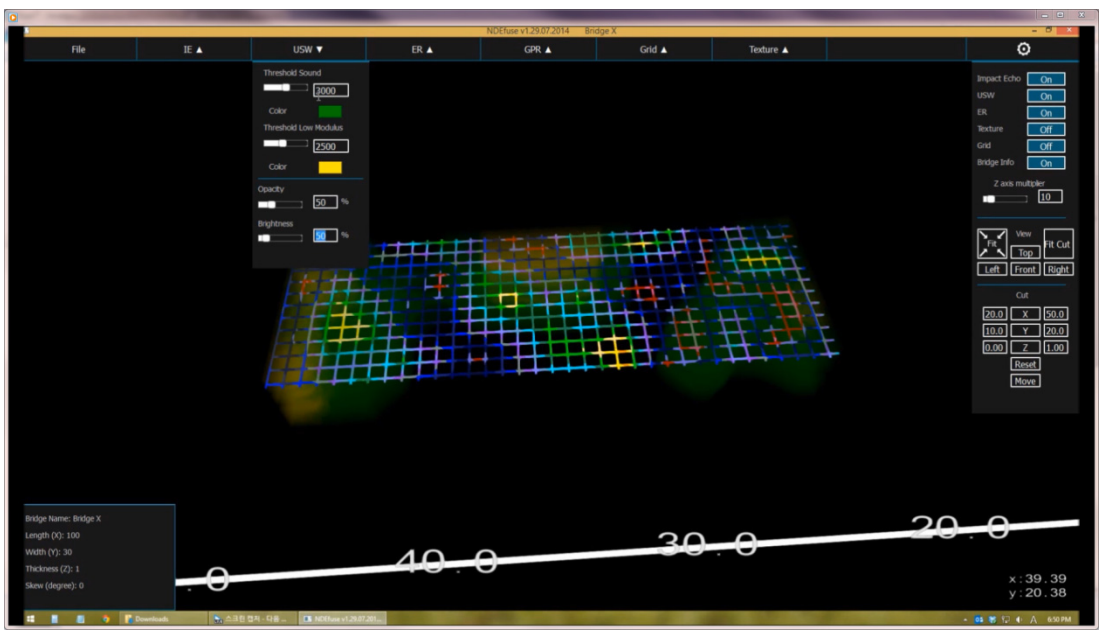

Figure 8. Screen capture of the program for 3D visualization of NDE results and camera images.

CONCLUSIONS

Individual NDE technologies and visual inspection have their strong sides, but also limitations in terms of the information they can provide about the condition of a

concrete bridge deck. In addition, the most of the NDE surveys using manual technologies require longer traffic closures and, thus, longer traffic interruptions. The robotic platform RABIT with integrated NDE technologies overcomes those deficiencies in several ways:

1. Due to a rapid and fully autonomous data collection, the traffic interruptions are significantly reduced and the data collection is conducted with a much smaller workforce. This can significantly reduce the data collection costs.
2. The data collection using RABIT significantly reduces the exposure of bridge inspection crews to the passing traffic and, thus, reduces the safety risks.
3. The ability to simultaneously deploy multiple NDE technologies, with a significantly higher number of sensors, enables detection and characterization of deterioration at a much higher spatial resolution and with a higher confidence level.
4. The associated programs for visualization of NDE results and deck surface images facilitate a more complete and more intuitive presentation of the deterioration and defects in the deck. The 3D visualization platform, in particular, enables a rapid review of possible correlation between the damage observed on the surface and internal deterioration processes.

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