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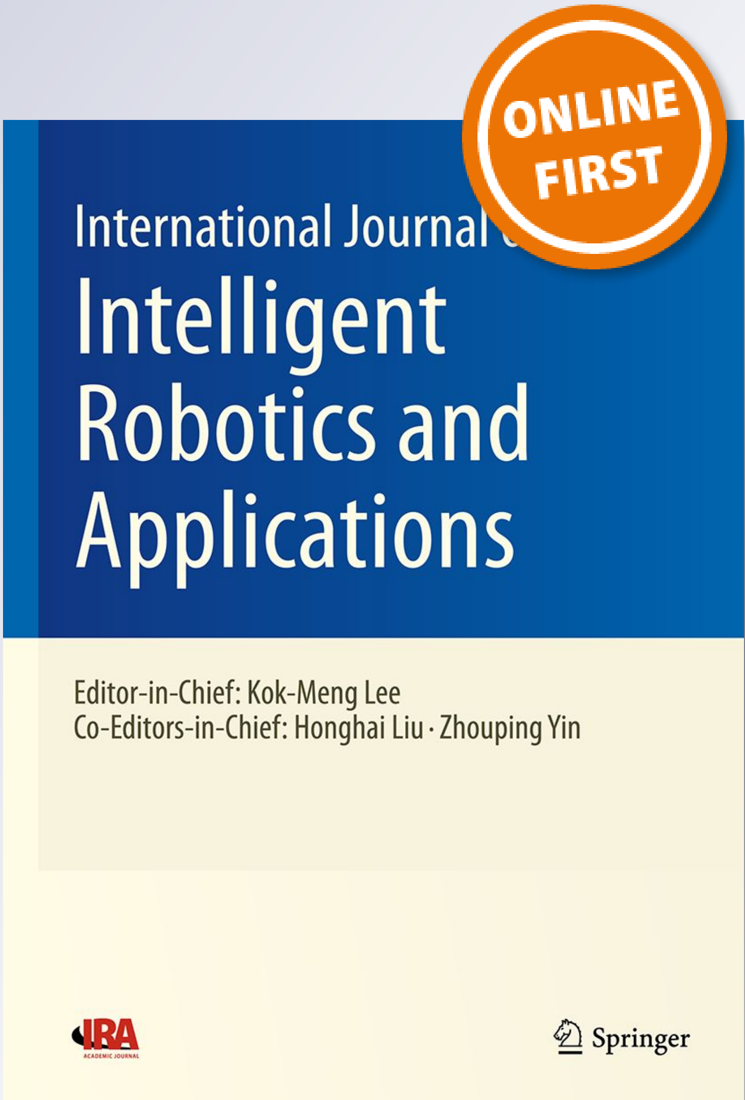

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REGULAR PAPER

RABIT: implementation, performance validation and integration with other robotic platforms for improved management of bridge decks

Nenad Gucunski[1] · Basily Basily[1] · Jinyoung Kim[2] · Jingang Yi[3] · Trung Duong[3] · Kien Dinh[3] · Seong-Hoon Kee[4] · Ali Maher[3]

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Abstract Accurate condition assessment and monitoring of concrete bridge deck deterioration progression requires both use of multiple nondestructive evaluation (NDE) technologies and automation in data collection and analysis. RABIT (robotics assisted bridge inspection tool) for bridge decks enables fully autonomous data collection at rates three or more times higher than it is typically done by a team of five inspectors using manual NDE technologies. The system concentrates on the detection and characterization of three most common internal deterioration and damage types: rebar corrosion, delamination, and concrete degradation. For that purpose, RABIT implements four NDE technologies: electrical resistivity (ER), ground-penetrating radar (GPR), impact echo (IE) and ultrasonic surface waves (USW) method. High productivity and higher spatial data resolution are achieved through the use of large sensor arrays or multiple probes for the four NDE methods. RABIT surveys also complement visual inspection by collecting high resolution images of the deck surface, which can be used for crack mapping and documentation of deck spalling, previous repairs, etc. The NDE technologies are used in a complementary way to enhance the overall condition assessment, certainty regarding the detected deterioration and better identification of the primary cause of deterioration. RABIT's components, operation, field implementation and validation, as well as future integration with a robotic platform for minimally invasive rehabilitation, are described.

Keywords Concrete · Bridge decks · Deterioration · Corrosion · Nondestructive evaluation · Robotics · Rehabilitation · GPR · Impact echo · Electrical resistivity · Surface waves

1 Introduction

Federal highway administration's (FHWA's) long term bridge performance (LTBP) Program has as an overarching objective to collect and manage high-quality quantitative

✉ Nenad Gucunski
gucunski@rci.rutgers.edu

Basily Basily
basily@rci.rutgers.edu

Jinyoung Kim
jinyoungkim@ajou.ac.kr

Jingang Yi
jgyi@soe.rutgers.edu

Trung Duong
trung.duong@rutgers.edu

Kien Dinh
kien.dinh@rutgers.edu

Seong-Hoon Kee
shkee0505@gmail.com

Ali Maher
mmaher@rci.rutgers.edu

1 Rutgers, The State University of New Jersey, 96 Frelinghuysen Rd, Piscataway, NJ 08854, USA

2 Ajou University, Sanhakwon 712, 206 Worldcup-ro, Yeongtong-gu, Suwon-Si, Gyeonggi-do 16499, Republic of Korea

3 Rutgers, The State University of New Jersey, 100 Brett Rd, Piscataway, NJ 08854, USA

4 Department of Architectural Engineering, Dong-A University, 37 Nakdong-Daero, Busan 604-714, Korea

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bridge performance data. The data will from one side help the bridge community better understand bridge performance and deterioration, and from the other facilitate development of more realistic bridge performance models: deterioration, predictive and life-cycle cost models. To enable collection of quantitative and objective data on representative samples of different bridge populations, the Program relies on the use of nondestructive evaluation and sensing technologies. From a number of identified performance issues, the performance of concrete bridge decks was identified as the performance issue of highest importance and urgency. Considering the ambitious LTBP Program's plan of monitoring of a number of clusters of bridges, the need for a rapid and cost effective collection of bridge deck condition data became an imperative. The solution was sought through the development of a fully autonomous robotic system that deploys all the NDE technologies of interest.

In the first 5 years of the LTBP Program, it was demonstrated that NDE technologies can detect and characterize deterioration progression in bridge decks through periodical evaluations, and that the condition can be objectively described (Gucunski et al. 2013). Bridge deck deterioration is often a set of complex processes caused by numerous physical, chemical and other factors. These processes are in many cases connected and accelerate one another, ultimately leading to creation of defects in decks, like cracking and delamination. Therefore, this plurality of deterioration processes and generated defects cannot be captured by a single NDE technology, but requires a complementary multi-technology approach. Four NDE technologies used on a regular basis within the LTBP Program provide the needed ability to describe the most important processes and defects: corrosion, delamination, and concrete quality degradation. The technologies include: electrical resistivity (ER), ground penetrating radar (GPR), impact echo (IE) and ultrasonic surface waves (USW) method.

Attempts to bring automation and robotics into inspection of bridge decks are relatively new. One of the early attempts to automate the data collection was done at German Federal Institute for Material Research and Testing (BAM) through the development of NDT-Stepper (Wiggenhauser 2008). The NDT-Stepper is an automated cart that moves in prescribed constant increments and pneumatically deploys single impact echo and ultrasonic probes. The speed of the Stepper was on the order of 2–3 m/min. BAM has later developed a robotic system BETOSCAN for inspection of reinforced concrete slabs (Raupach et al. 2008; Wiggenhauser 2012). The robotic platform enables deployment of multiple NDE methods and measurements: ultrasonic, potential mapping, microwaves, cover meter, thermometers. As such, BETOSCAN can assess slabs for presence of delamination and voids, corrosion activity, moisture, and others. Lim et al. (2011) used a similar robotic platform to develop a system using vision that can automatically detect and map cracks in concrete slabs.

The RABIT platform brings elements of the previous efforts and implements them in a much bigger robotic platform, where single sensor NDE units are substituted by multiple units or sensor arrays. The paper provides a detailed description of the RABIT system and its operation. The first half of the paper concentrates on the description of the RABIT robotic platform, and NDE sensor and navigational components. The second half of the paper provides samples of RABIT results. Results from two bridges that have been extensively investigated in the past using manual NDE technologies were used for demonstration and validation of the RABIT performance. The comparison of manual and RABIT obtained results is made through condition maps, and calculated condition indices. Finally, an ongoing effort in integration of RABIT with robotic platform ANDERS for joint bridge deck evaluation and rehabilitation is presented.

2 Description of RABIT

The RABIT development started in early 2011. Since the time of the first deployments in 2013, RABIT was continuously improved upon and now is deployed on almost hundred bridges throughout the United States. The following sections describe the robotic platform and installed NDE sensor components, followed by the description of the RABIT's navigation components and data collection processes.

2.1 Robotic platform and NDE components

The RABIT with its main NDE and navigation components marked is shown in Fig. 1. The mobile platform is a Seekur robot manufactured by Adept Mobile Robot, Inc. The platform itself, without sensors, is approximately 1.4 m (4 ft–8 in.) long, 1.2 m (4 ft) wide and 1.1 m (3 ft–8 in.) tall. With all the sensor components fully extended, the RABIT platform is close to 2.7 m (9 ft) long, 1.8 m (6 ft) wide, and with the panoramic camera mounted about 1.5 m (5 ft) high. The high agility of the robotic platform is achieved through electrical all-wheel driving and steering. Four omni-directional wheels allow fast movement from one test location to the next one in any direction. They also enable the platform to move laterally and to turn at a zero radius, which is of major interest during maneuvering on narrow bridges or work zones.

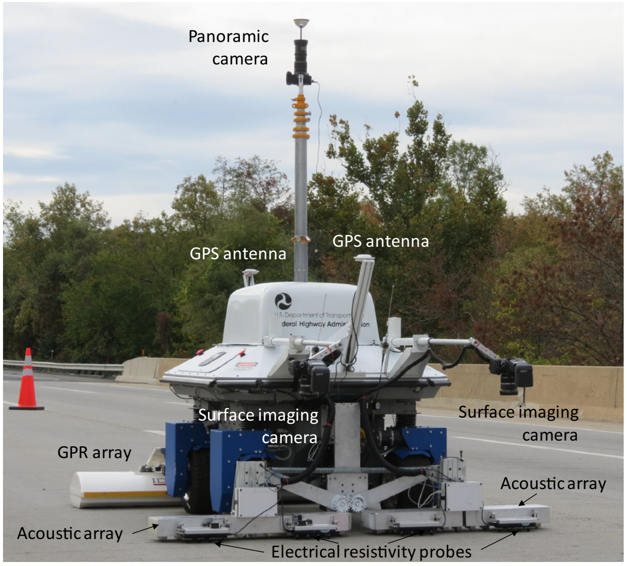

Fig. 1 RABIT during data collection and its components

Two major challenges in the RABIT development were building an accurate and reliable system for robot localization and navigation, and seamless integration of sensor components for fully autonomous data collection. The navigation accuracy on the order of several centimeters (about 2 in.) was achieved by a fusion of three systems. The first system is the differential global positioning system (DGPS) with real-time kinematic (RTK) correction. The DGPS consists of a base-station GPS receiver (visible later in Fig. 7), fixed during the data collection process, and two moving GPS receivers located at the front and back of the robot (Fig. 1). All the GPS units are manufactured by Novatel, Inc. The GPS receivers on the robot receive both the location signal from satellites and a correction signal from the base-station GPS in real time through a separated radio channel. A GPS post-processing program compensates the GPS signal errors and produces a more precise positioning. The second navigation component is an inertial measurement unit (IMU) manufactured by Microstrain, Inc., which is measuring the rotational position. The third system is wheel odometry that enables accurate distance measurement. The information coming from the three navigation components is fused using an extended Kalman filter (EKF) (La et al. 2013). The presence of the IMU and wheel odometry is essential in the areas where there is denial of GPS signal. The seamless robot operation and integration of sensor components was achieved through integrated work of three computers. One computer runs the Linux based path planning and provides robot navigation. The other two computers are running on Windows operating system and are primarily responsible for NDE sensor integration and data collection. There is an RS-232 communication between the two systems to coordinate the navigation and the acquisition programs. All three computers can be reached from outside computers through wireless communication.

The main NDE components installed in RABIT are marked in Fig. 1. There are two main sensor deployment systems on the front and rear ends of the robotic platform. The front deployment system carries two acoustic arrays and four electrical resistivity (ER) probes, while the rear deployment system carries two GPR arrays. Both deployment systems and attached arrays are designed to cover a 1.8 m (6 ft) wide surveying strip, which corresponds to a half-width of a typical travel lane. In addition, there are three cameras, two cameras on the front end for high resolution imaging of the deck surface, and the third camera above the platform for panoramic imaging of wide bridge deck areas. The acoustic arrays are about 0.9 m × 0.2 m boxes, each containing seven accelerometers and four impact sources. The arrangement of the sources and receivers is shown in Fig. 2. The sources are linear solenoid type impactors, while the receivers are accelerometers. The acoustic arrays were designed and manufactured by Geomedia Research and Development, Inc. The arrays were slightly modified by the research team. As illustrated in Fig. 2, each acoustic array enables the conduct of eight impact echo (IE) and up to six ultrasonic surface waves (USW) tests. The IE test is used to detect and characterize delamination (Lin and Sansalone 1997; Sansalone 1997; Carino 2001; Gibson and Popovics 2005; Gucunski et al. 2006). The spacing between a source and near receiver is 7.5 cm (3 in.). The spacing between the sensors allows delamination assessment with a resolution of 15 cm (0.5 ft) in the deck's transverse direction, which is four times higher than the one according to the LTBP Program protocols for data collection (0.6 m) using manual IE devices. The USW test utilizes various combinations of a source and two receivers to conduct the test. The spacing between two receivers is equal to the double source to near receiver spacing, 15 cm (6 in.). The USW test is utilized to assess concrete quality and, thus, possible concrete degradation, by measuring concrete modulus (Nazarian et al. 1993). Instances of significant drops in the measured modulus will often be an indication of presence of delamination or other major defects (Yuan et al. 1999). The acoustic arrays are pneumatically pressed against the deck surface to achieve uniform coupling between the sensors and deck surface.

The two Hi-Bright GPR arrays manufactured by IDS (Ingegneria dei Sistemi), Italy, on the rear end of RABIT have in total 32 bow-tie type antennas, each of a 2.0 GHz center frequency. Each GPR array box contains eight pairs of antennas of dual-polarization, as illustrated in Fig. 3. Antennas of dual polarization can improve GPR data analysis in situations when the top rebar is not in the preferred orientation, which is being transverse to the RABIT

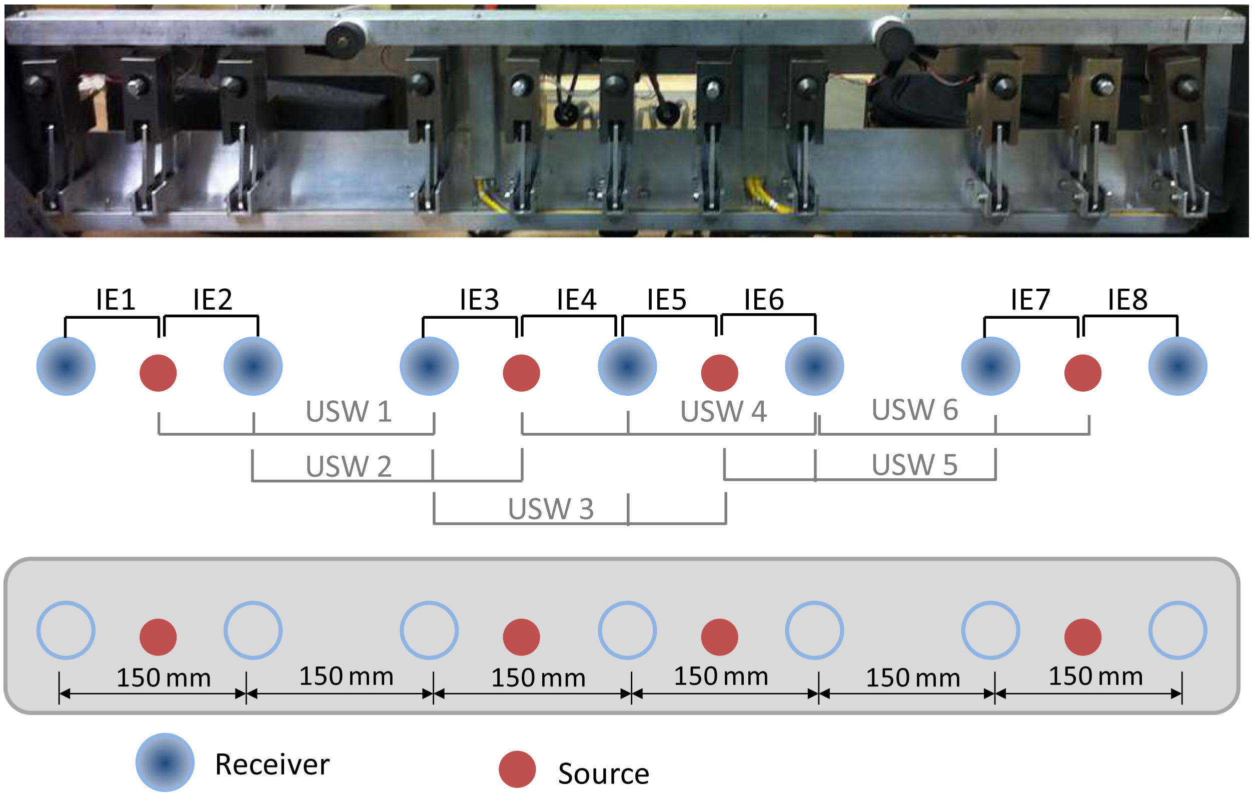

Fig. 2 Photo of the interior of acoustic array (*top*) and schematic of the arrangement of sensors and receivers and corresponding tests (*bottom*)

survey direction. The spacing between antennas is 10 cm (4 in.), providing a six times higher spatial resolution in the transverse deck direction than according to the LTBP Program protocols that call for a 0.6 m (2 ft) spacing between survey lines. A minor loss of spatial resolution with the current antenna arrangement is the spacing between the end antennas of the two arrays, which is about 25 cm (10 in.). The primary objectives of GPR surveys are evaluation of corrosive environment, mapping of rebars and other metallic objects, concrete cover measurements, and summary condition assessment of bridge decks. The GPR based condition assessment of concrete bridge decks has been described in many publications (Maser 1992; Roberts et al. 2001; Barnes and Trottier 2000; Gucunski et al. 2008) and ASTM standard (2008).

There are four ER probes of Wenner type attached to the front end of acoustic arrays. The primary objective of ER measurements is to evaluate the corrosive environment and to it correlate corrosion rates (Brown 1980; Gowers and Millard 1999). The Resipod probes manufactured by Proceq have four electrodes with a 50 mm (2 in.) spacing between them. The spacing between the probes is about 45 cm (22 in.). As illustrated in Fig. 4, electrical current is induced through two outer electrodes and the potential of the generated electrical field measured using two inner electrodes. The two are used to calculate the electrical resistivity. To establish the electrical contact between the deck surface and probes, the probes' electrodes are being continuously moistened using a spraying system. The spraying system sprays water on each of the electrodes using very fine copper tubes at the end of each data collection cycle. Finally, the two high resolution cameras are deployed ahead and above the acoustic arrays (Fig. 1) to take high resolution images of the deck surface. Each of the cameras captures approximately 1.2 m × 0.9 m (4 ft × 3 ft) deck area. While the camera resolution can be varied, it is set to capture sub-millimeter cracks. The third camera is placed on a pneumatic mast at the center of the robotic platform (Fig. 1), which can lift it up to a 4.5 m (15 ft) height. The camera has a 360° mirror (Fig. 4) to capture panoramic images of wider bridge deck areas.

2.2 Data collection operations

The robot navigation is designed to cover the rectangular-shape survey area of a straight line bridge. It consists of straight line scans, each of them covering a 1.8 m (6 ft) wide strip. Omni-motion planning is done to navigate the robot at the end of each line to the next one. The navigation program consists of two sub-programs, namely linear motion planning (LMP) and omni motion planning (OMP). The LMP controls the robot to follow a straight line and the

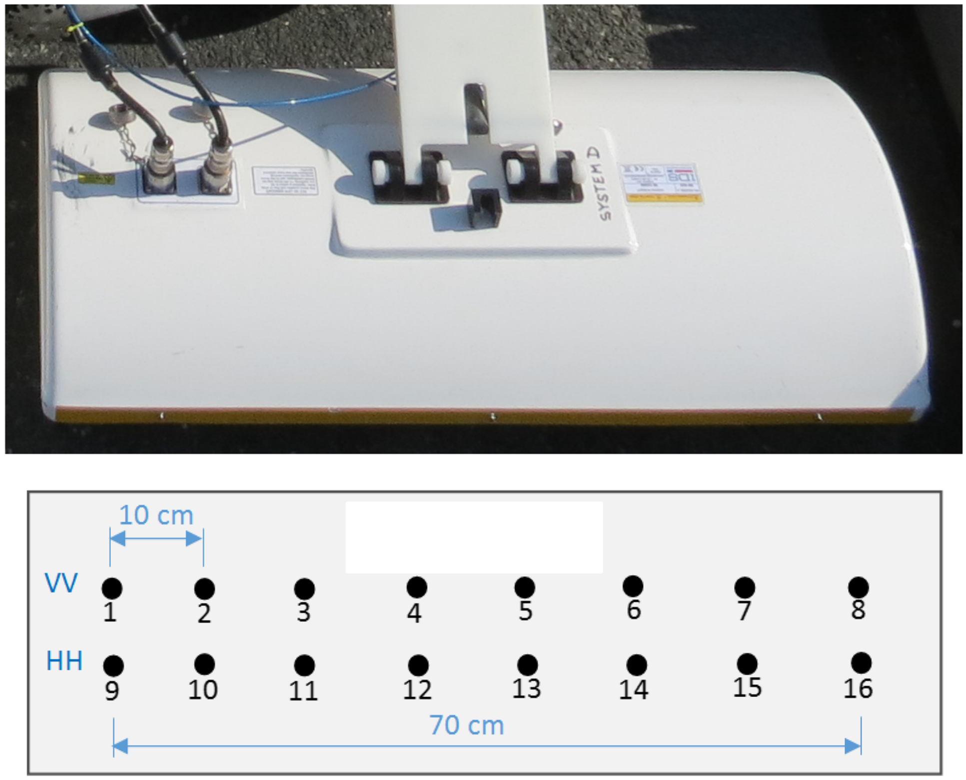

Fig. 3 Photo of an IDS Hi-Bright GPR antenna array (*top*) and schematic of the arrangement of antennas (*bottom*)

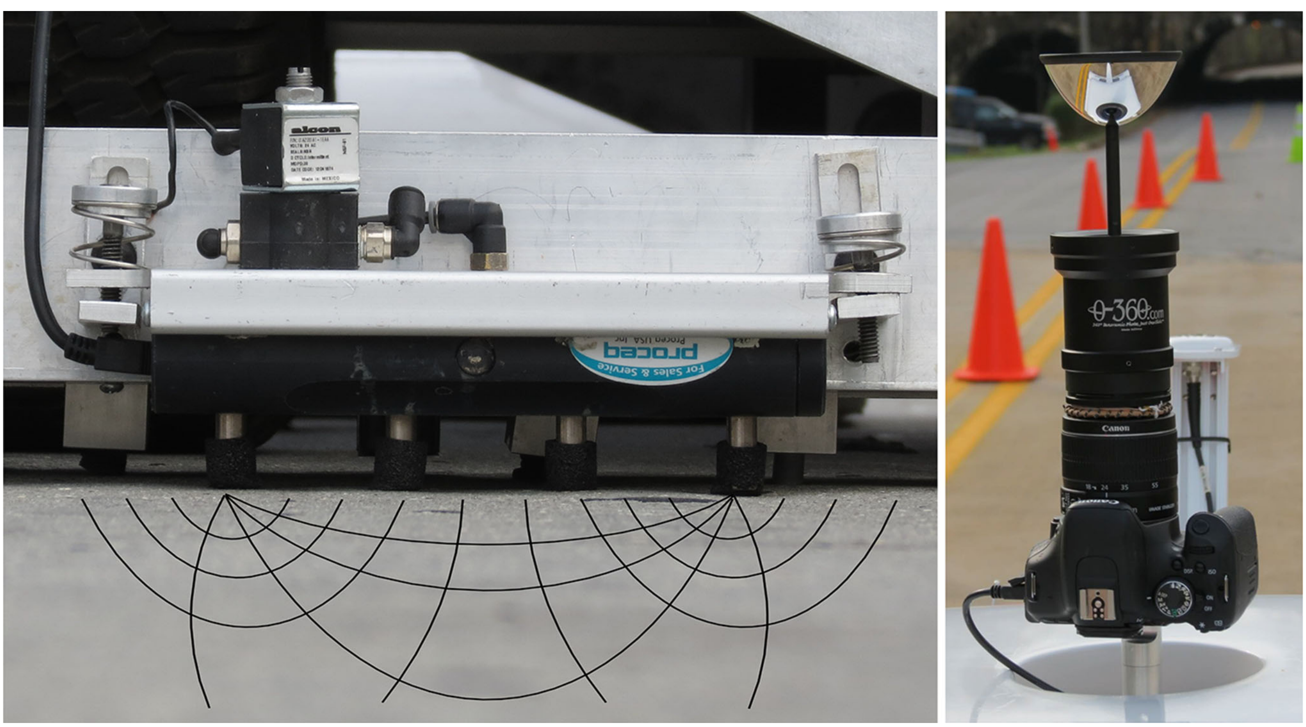

Fig. 4 Electrical resistivity (Wenner) probe (*left*) and panoramic camera with a mirror (*right*)

OMP transits the robot from an end of a scan line to the beginning of the next scan line. The OMP takes the safety issues into account by moving the robot in such a way that it will never cross outside the surveying region and interfere with the ongoing traffic. At the beginning of the data collection process, the GPS base station, visible on the

Fig. 5 Command van: RABIT transportation (*left*) and control screens (*right*)

tripod on the left side of Fig. 7, collects information from as many satellites as available about its location. The process takes, in most cases, about 20 min and needs to be done only once for a particular bridge. It is followed by recording of three GPS points at the rectangle corners using a portable cart with a GPS system. Based on these three points, the navigation program will interpolate the coordinates of the starting and end points of each line to feed into the LMP program. It will also interpolate the coordinates of the safe turning points to feed into the OMP program. As the result, the robot will first move along a straight line to a desired location, controlled by the LMP program. Then, the RABIT will go to the safe location to turn around 180° and move to the starting location of the next scan, controlled by the OMP program. The scanning will continue in a zigzag-shape trajectory (La et al. 2013).

During the data collection, the robot stops at a predefined distance, typically every 0.6 m (2 ft) to allow NDE sensors to be deployed and data collected. It takes 5–6 s for the acoustic array sensors and resistivity probes to accurately acquire and transfer the data to the command center. The speed of the robot is also limited by the GPR arrays to achieve high spatial resolution of GPR data. For the current configuration, the RABIT takes 3–4 s to move between two test points, or 9–10 s between two data collections. NDE data at each point is saved together with its corresponding location to aid the data processing. The location is in a local coordinating system for each bridge, which can be interpolated from the three GPS points collected at the beginning of the data collection process. The RABIT collects data at rates of about 320–360 m^2/h (approximately 3500–4000 ft^2/h). This is about three to four times faster than a team of five NDE technicians using manual technologies. The increased productivity is also reflected in a reduced cost of the NDE surveys by RABIT. Based on the SHRP 2 study on the performance of manual NDE technologies (Gucunski et al. 2013), a combined data collection and analysis cost per square foot of a bridge deck for the four NDE technologies is about $2. The RABIT unit cost is about 50–60% of the manual testing cost for bridges with the deck larger than 10,000 square feet. Considering additional cost reductions because of shorter traffic control deployments, indirect savings stemming from reduced traffic interruptions, reduced exposure of bridge inspectors in the work zone, the benefits are obvious.

A part of the RABIT system is the "command van", which serves two roles. The first role is to transport the RABIT between bridges to be tested. As shown in Fig. 5, the RABIT's sensor arrays are folded to a V-shape position for transportation. The RABIT is unloaded from the van using a pair of foldable aluminium ramps. A joystick or notebook computer is used to manoeuvre the robot during unloading. It is loaded into the van the same way, but this time with an assistance of a winch mounted inside the van. The second and primary role of the van is to serve as a command center for all RABIT operations. All the data collected by RABIT: from the NDE sensor arrays and probes, digital cameras, GPS and other positioning units, is wirelessly transmitted to the van. All the data is being displayed as collected on four large monitors, as shown in Fig. 5. All but GPR data can be analyzed in real or near-real time. The movement of RABIT is monitored in two ways. An image of the RABIT on the bridge deck from the van's rooftop camera (Fig. 5) is displayed on one of two additional smaller monitors, while the RABIT's position based on the GPS coordinates is presented on a schematic of the bridge deck on one of the four large displays.

3 Performance validation surveys

RABIT was deployed and its performance evaluated on a number of bridges in the States of New Jersey, Delaware, Maryland, Virginia and Pennsylvania between 2013 and 2015. Two bridges in New Jersey and Virginia were selected to illustrate the RABIT survey results. The first bridge is Municipal Drive Bridge over Pohatcong Creek in Pohatcong Township (Pohatcong Bridge), New Jersey, while the second one is the State Route 15 over Interstate 66 bridge in Haymarket, Virginia (Haymarket Bridge). These two bridges were selected because those were also surveyed, multiple times, using manual NDE technologies over the last 5 years.

3.1 Pohatcong bridge survey

The Pohatcong Bridge is a single span, steel girder bridge built in 1978. The bridge deck is a bare concrete deck 38.2 m (125 ft) long. It is 11.3 m (37 ft) wide, between a sidewalk on one side and a curb on the other. The bridge has a skew of 45°. The bridge deck received National Bridge Inventory (NBI) rating 6 (satisfactory condition) during the 2000–2014 period. As the results will show, the rating does not reflect the actual level of deterioration

Fig. 6 Manual NDE data collection on the Pohatcong Creek Bridge (*top*) and NDE sensors (*bottom*)

obtained from the NDE results. The average daily traffic (ADT) and average daily truck traffic (ADTT) is around 1100 and 10, respectively. The deck surface has visible signs of deterioration, primarily fine cracks. The bridge was surveyed by RABIT in May of 2015, while the most recent complete manual survey was done in August of 2014. The manual survey was conducted on a 0.6 m × 0.6 m (2 ft × 2 ft) grid using four NDE technologies implemented in RABIT: ER, IE, USW and GPR (Fig. 6). The first and last lines of the grid for manual testing were offset 0.3 m (1 ft) from the curb and sidewalk, respectively. The GPR scanning was conducted in the longitudinal direction of the bridge, since the top rebars were in the deck's transverse direction, at sampling rates of about 200 samples/m (60 samples/ft). A GSSI 1.6 GHz ground-coupled antenna was used in the survey. Other manual NDE equipment included Proceq's Resipod for ER, GRD's portable seismic property analyzer (PSPA) for USW, and IE Cane developed at Rutgers for IE testing. The RABIT's scanning path was planned similarly, with a 0.3 m (1 ft) offset from the curbs (Fig. 7). It took six RABIT passes to cover the entire bridge deck width. Also, all the manual point measurements close to the joints were taken around 0.3 m (1 ft) away from the joints.

The results of ER and GPR surveys are shown in Fig 8. For both ER and GPR similarity of the manual and RABIT obtained results can be observed. The similarity is especially pronounced for the GPR condition maps. The RABIT's ER map describes an overall more severe corrosive environment than the manual ER map, which can be attributed to the seasonal effects. Also, also there is a noticeable similarity between the ER and GPR maps. The zones of lowest resistivity in the ER maps match the zones of highest attenuation levels in the GPR maps, which confirms that both measurements are in a great part controlled by the electrical conductivity of concrete. To quantify the overall deck condition with respect to the corrosive environment and anticipated corrosion rates, an ER condition index is used. The condition index represents, on the scale 0 (worst) to 100 (best), a weighted average of percentages of deck area in different condition states. In particular:

$$ER \quad Condition \quad Index = \frac{A_{Very \quad Low} \times 100 + A_{Moderate} \times 50 + A_{High} \times 0}{A_{Total}}. \tag{1}$$

where $A_{Very\ Low}$, $A_{Moderate}$, and A_{High} are the areas with ER in their ranges of <40, 40–70, and >70 kΩ cm, respectively, and A_{Total} is the total surveyed area. The three condition states were identified based on the results of a correlation study of results from ER and half-cell potential (HCP) surveys (Gucunski et al. 2017; Pailes 2014). The ASTM C876-09 standard (2009) provides three distinct zones with respect to the probability of active corrosion from a HCP survey. The three weight factors: 100, 50 and 0, were adopted by the FHWA's LTBP Program as estimates of significance of deterioration process severity. Similarly, the overall condition based on the GPR results is

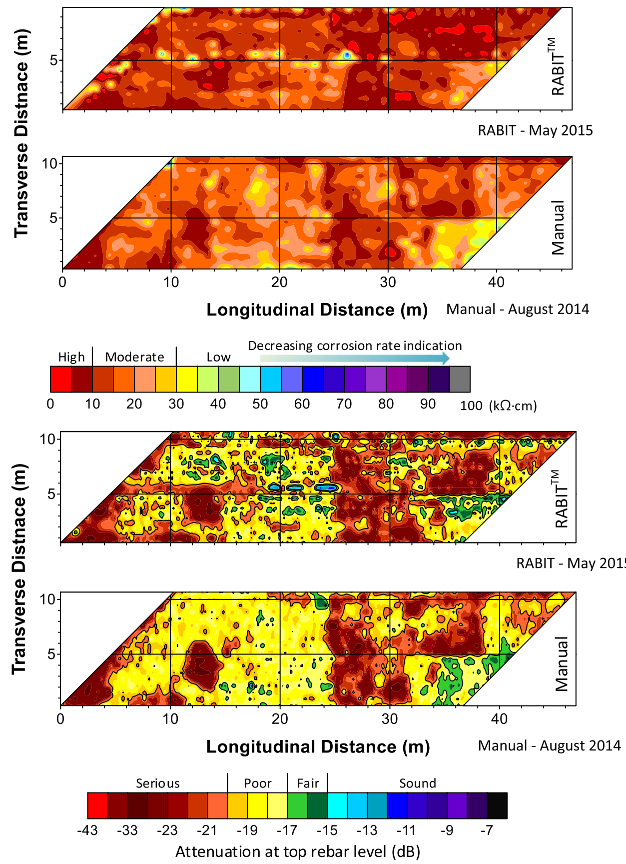

Fig. 8 ER (*top*) and GPR (*bottom*) condition maps for the Pohatcong Bridge

Fig. 7 RABIT data collection on the Pohatcong Creek Bridge (photo: N. Romanenko, Rutgers University)

Table 1 Condition indices and average concrete modulus for Pohatcong Bridge from RABIT and Manual NDE Surveys

NDE	Condition index	Percentage of deck area			
ER		High	Moderate		Very low
RABIT™	1.4	98	2		0
Manual	0.4	99	1		0
GPR		Serious	Poor	Fair	Good
RABIT™	28.6	41	44	12	3
Manual	24.2	34	56	10	5
IE		Serious	Poor	Fair	Good
RABIT™	32.3	50	11	25	14
Manual	36.0	38	10	43	10
USW	Average *E* (GPa)	STDEV (GPa)	<20 GPa	20–30 GPa	>30 GPa
RABIT™	25.50	6.55	38	36	27
Manual	24.48	4.07	51	43	7

described by the GPR condition index calculated according to

$$GPR \quad Based \quad Condition \quad Index = \frac{A_G \times 100 + A_F \times 70 + A_P \times 40 + A_S \times 0}{A_{Total}}. \tag{2}$$

where A_G, A_F, A_P, and A_S are the areas with the GPR signal attenuation (normalized dB) ranges of >-15, -15 to -17, -17 to -20, and <-20, respectively. It should be mentioned that the given GPR ranges were formed for the manual 1.6 GHz ground-coupled antenna. Similar to the ER, since the GPR provides a qualitative assessment of the condition of the deck with respect to corrosion and possible delamination, the given ranges were identified based on the previous correlations with other NDE technologies that characterize corrosion and delamination. Based on the number of survey results, an attenuation equivalency of the Hi-Bright antennas was found so that the condition index formula can be applied. The condition indices and percentages of the deck area receiving different grades for ER and GPR are shown in Table 1. The condition indices for both ER and GPR are very low, and there are only minor differences between the condition indices and deck area percentages from the RABIT and manual testing.

The results of delamination surveys using IE and concrete quality surveys using USW for both manual and RABIT testing are depicted in Fig. 9. While the manual and RABIT results, respectively, identify similar problematic areas, a much higher data resolution can be observed in the RABIT condition maps. Also, a number of low modulus areas in the USW maps match the delaminated areas in the IE maps, as described earlier in the discussion on the USW test. To compare the overall assessment by the two approaches, the condition index with respect to delamination and the concrete average modulus were calculated. The condition index with respect to delamination was calculated according to

$$Delamination \quad Index \quad (IE) = \frac{A_{Good} \times 100 + A_{Fair} \times 50 + A_{Poor} \times 50 + A_{Serious} \times 0}{A_{Total}}. \tag{3}$$

where A_{Good}, A_{Fair}, A_{Poor}, and $A_{Serious}$ are the areas in "Good", "Fair", "Poor", and "Serious" conditions. The good grade is assigned to the areas where there are no signs of delamination, fair and poor to the areas with signs of incipient delamination, and serious to the areas with a fully developed delamination characterized by a low frequency response (Sansalone 1997; Gucunski et al. 2006). Similar to the ER condition index, the three weight factors: 100, 50 and 0, were adopted by the FHWA's LTBP Program as estimates of delamination severity. The condition index with respect to delamination and percentages of the deck area receiving different grades are shown in Table 1. The average concrete modulus and its standard deviation are also provided in the table. The delamination index from RABIT is slightly lower than from the manual testing. On the other hand, the average modulus and the standard deviation, from the RABIT's USW testing are higher than from the manual testing.

Most of the differences between the manual NDE and RABIT results are attributed to the use of different sensors and probes. The only identical probes in the manual and

RABIT testing were ER Proceq Resipod probes. Still, the surveys were taken 9 months apart, during different seasonal conditions that, in addition to continued deterioration, could have affected the electrical conductivity of concrete. The manual GPR survey was conducted using a 1.6 GHz antenna, while the RABIT's GPR arrays have antennas with a 2.0 GHz center frequency. Similarly, there are differences between sensors used in the IE and USW devices. In the case of IE, where the delamination grades are assigned based on both the dominant frequency peak and the measured energy in the rest of the spectrum, the grades may differ slightly. Similar differences between the results were observed during a SHRP 2 study (Gucunski et al. 2013), where a number of participants using the same NDE technology, but different sensors or devices, provided close, yet not identical results. Finally, some of the differences in the condition maps are a result of interpolation during plotting. The data from manual NDE surveys is collected with equal spatial resolution in the longitudinal and transverse deck directions. On the other hand, the RABIT's data have a significantly higher resolution in the transverse direction, affecting the data interpolation process.

The combined condition index from RABIT and manual NDE surveys, calculated as a simple average of condition indices from IE, ER and GPR, is 20.8 and 20.2, respectively. Bridge owners should calculate the combined index as a weighted average. The weights for different NDE technologies results should be defined based on the significance of a particular type of deterioration in the bridge management decision making. For example, some bridge owners guide their decisions regarding rehabilitation or repair of bridge decks primarily, or solely, based on the state of delamination. On the other hand, some agencies are primarily concerned about the state of corrosion. To reflect such practices, the weight factors for condition indices describing the state of delamination or corrosion should receive higher values, respectively. Finally, while it took 4 h to grid and collect data using the manual NDE technologies, the RABIT data collection took only slightly more than an hour.

3.2 Haymarket bridge survey

The Haymarket Bridge is a two-span continuous steel girder structure with a bare concrete deck. The bridge was constructed in 1979. The bridge deck is 84.1 m (276 ft) long, 13.8 m (42 ft) wide and on an average 21.5 cm (8.5 in.) thick. The bridge has a skew angle of 17 degrees. The top rebar mat has epoxy coated rebars, while the bottom mat has bare rebars. The deck was extensively evaluated by NDE technologies. It was surveyed four times as a part of the LTBP Program using manual NDE technologies, in 2009, 2011, 2014 and 2015, and a section of the deck was surveyed in 2010 by multiple NDE teams as a part of the SHRP 2 study on the performance of NDE technologies (Gucunski et al. 2013). The performance of four manual NDE technologies: IE, GPR, USW and ER, was validated through coring of the Haymarket Bridge deck and through ground truth information for a fabricated

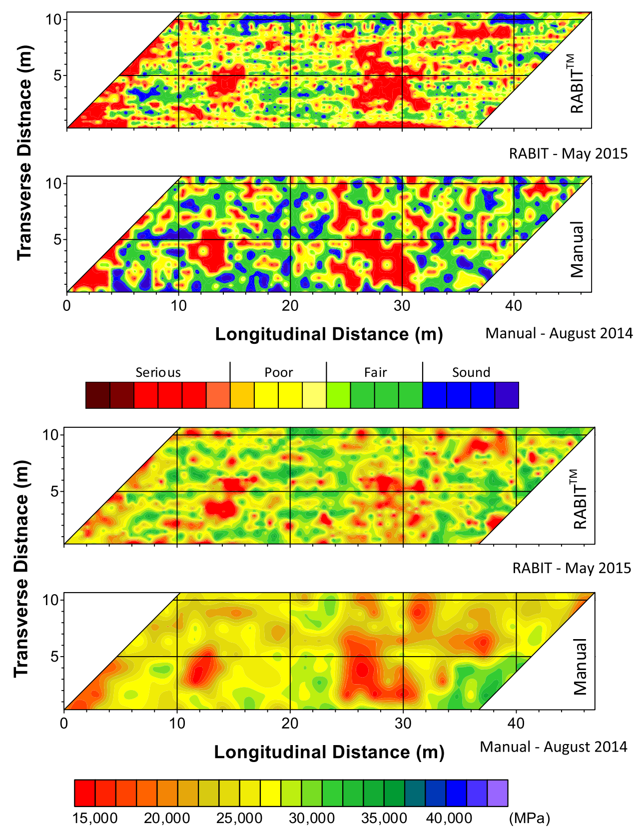

Fig. 9 IE (*top*) and USW (*bottom*) condition maps for the Pohatcong Bridge

Fig. 10 View of the deck and RABIT data collection on the Haymarket Bridge

slab with defects during the SHRP 2 study (Gucunski et al. 2013). Therefore, the same information on the Haymarket Bridge, and comparisons with the manual NDE results, were of special importance for the RABIT performance validation. The bridge deck received NBI rating 6 during the 1992–2014 period. Similar to the Pohatcong Bridge, it does not reflect the actual deterioration level obtained from the NDE evaluations. The average daily traffic (ADT) and average daily truck traffic (ADTT) for the past 5 years were around 13,000 and 600, respectively. The deck surface had numerous signs of deterioration, such as cracks and patches from previous repairs, as can be observed in Fig. 10.

The results from the ER and GPR surveys are shown in Fig. 11. For both surveys, there is a high similarity between the condition maps obtained from the manual and RABIT data collections. The similarity is especially pronounced for the ER condition maps, which, unlike the Pohatcong Bridge, can be attributed to the survey at the same time. In general, a study of a number of NDE bridge deck surveys have shown that the highest correlation between the commonly used NDE methods is achieved between ER and GPR (Pailes 2014). In addition, and similar to the Pohatcong Bridge, there is a noticeable similarity between the ER and GPR maps in the zones of lowest resistivity matching the zones of highest attenuation levels. The ER and GPR based condition indices and percentages of the deck area receiving different grades are shown in Table 2. Again, the indices from both RABIT and manual surveys are very low and take close values.

The results of IE and USW surveys for both manual and RABIT testing are presented in Fig. 12. Again, there are many similarities in identification of the most of delaminated sections of the deck between the manual and RABIT results. However, there are also some differences in the appearance of the delaminated zones, which are in the great part a result of much higher spatial resolution of the RABIT data. The calculated delamination indices provide a very similar result (Table 2), which can be attributed to the fact that those are calculated from the actual test point results, not from the areas resulting from the data interpolation. The combined condition index, calculated as a simple average of condition indices from IE, ER and GPR is 26.0 and 26.1 for the RABIT and manual NDE, respectively. The USW modulus map obtained from the manual testing appears to be much smoother than the one

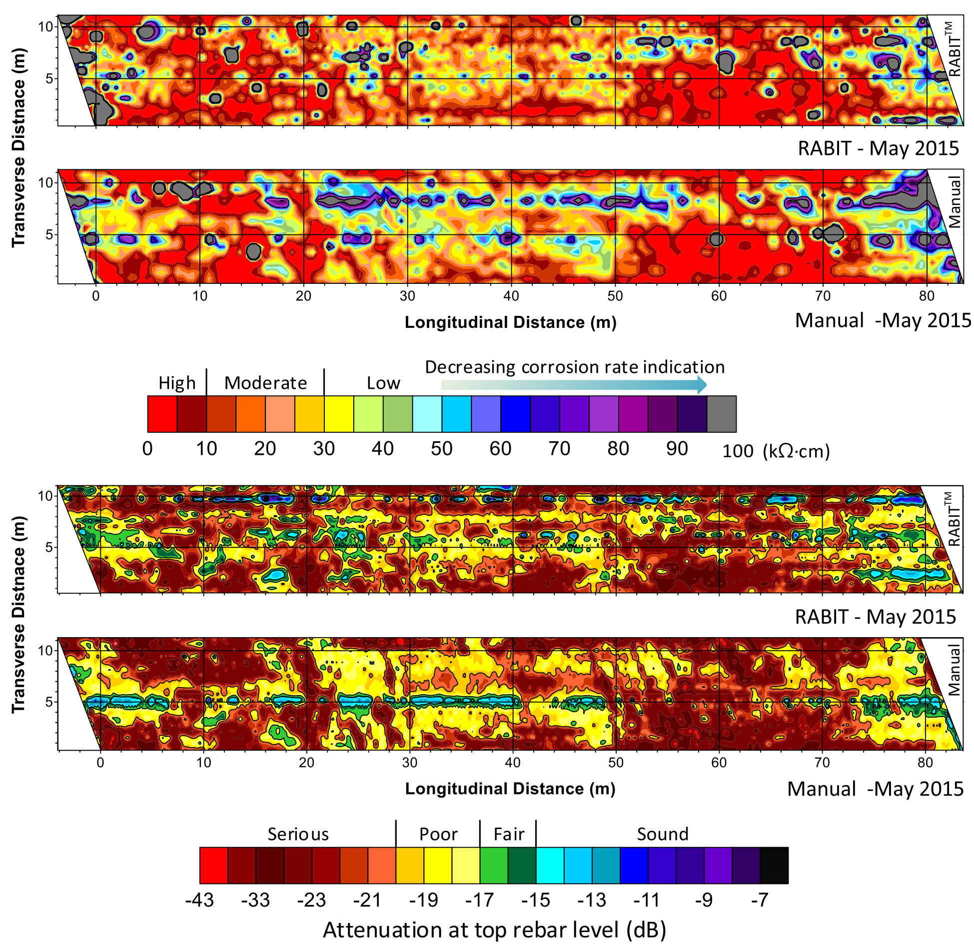

Fig. 11 Comparison of ER (*top*) and GPR condition maps (*bottom*) from the manual and RABIT surveys of the Haymarket Bridge

Table 2 Condition indices and average concrete modulus for Haymarket Bridge from RABIT and Manual NDE surveys

NDE	Condition index		Percentage of deck area		
ER			High	Moderate	Very low
RABIT	9.9		86	8	6
Manual	14.7		78	14	8
GPR		Serious	Poor	Fair	Good
RABIT	26.2	50	35	10	5
Manual	24.2	52	37	6	5
IE		Serious	Poor	Fair	Good
RABIT	41.9	37	14	28	21
Manual	39.3	45	7	31	21
USW	Average *E* (GPa)	STDEV (GPa)	Percentage of deck area		
			<20 GPa	20–30 GPa	>30 GPa
RABIT	23.91	11.72	46	24	30
Manual	20.74	6.81	73	20	7

from the RABIT survey. The reason is the manual USW data collection on a 1.2 m × 1.2 grid, which was the only option to complete the survey of the entire bridge deck during the allocated traffic control window. Similar to the Pohatcong Bridge, low concrete modulus areas in the USW maps match the delaminated areas in the IE maps. The concrete average modulus, standard deviation and percentages of deck area in different concrete modulus ranges are provided in Table 2.

Finally, to illustrate the importance of the imaging capability of the RABIT, a stitched image of the surface of the bridge deck is shown in Fig. 13. The image describes approximately a 2.7 m (9 ft) long and 1.8 m (6 ft) wide section of the deck. Repairs from interventions at different times can be observed in the figure. The high resolution image of the deck becomes a permanent record of the visible condition that can be used in mapping of visible features, such as cracks and repairs, or future comparisons. The surface image can overlay a 3D image of the interior of a bridge deck that enables integration and visualization of the results of multiple NDE technologies (Kim et al. 2017).

4 Future integration of robotic evaluation and problem mitigation

The ability to detect and characterize early deterioration or defect development should be complemented by the ability for their mitigation for the maximum benefit. The current

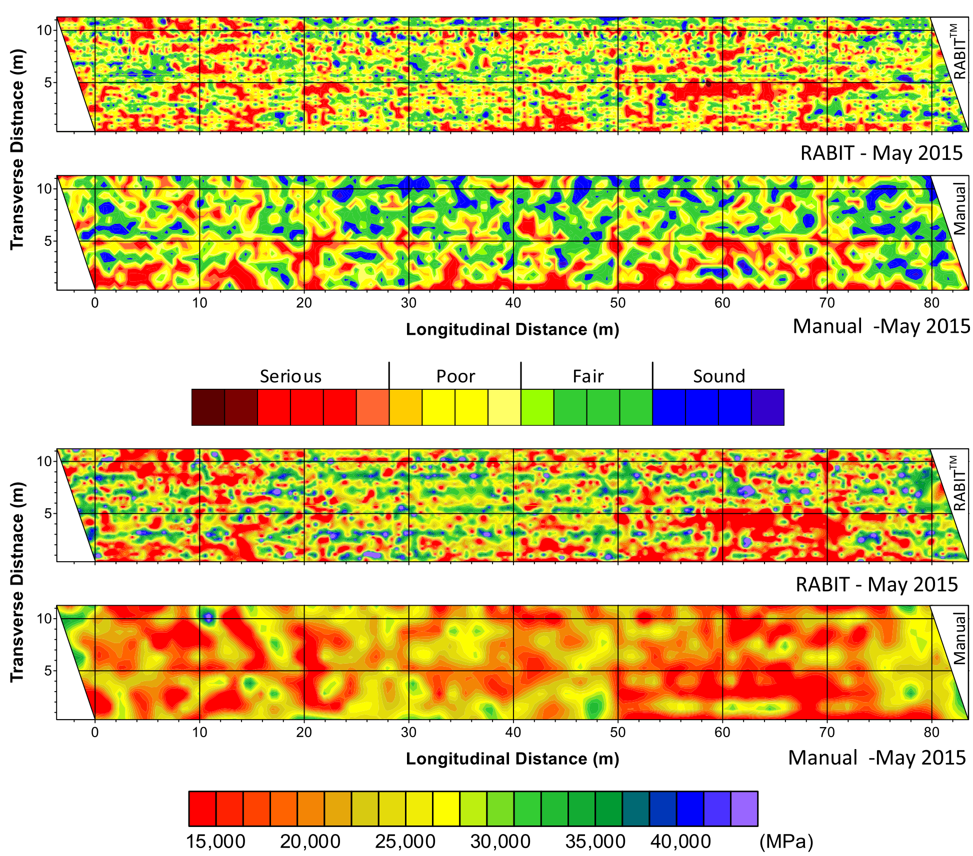

Fig. 12 Comparison of IE (*top*) and USW condition maps (*bottom*) from the manual and RABIT surveys of the Haymarket Bridge

Fig. 13 Stitched image of a section of the Haymarket Bridge deck

practice of partial- and full-depth repairs of concrete bridge decks are being done at advanced stages of delamination. The repairs involve removal of damaged concrete, and rust and other deleterious materials from reinforcing steel, and placement of the repair material. This is a labor intensive and expensive process. In contrast to this approach, concentration of the current research is development and implementation of a minimally invasive rehabilitation (MIR) strategy for early problem intervention. The MIR's approach concentrates on mitigation of early stage delamination and cracking using robotics. To repair a delamination, a group of small diameter holes is drilled and a specially developed cement based material is injected. The injection is done under a combination of low pressure on one, and vacuum on the other side of the end-effector, to fill the delamination and connecting cracks within the deck. While the intervention will not always fully correct the problem, it will extend the life of a bridge deck. The MIR robot, named ANDERS, and the robotic end-effector for material delivery are shown in Fig. 14.

Furthermore, there are efforts in developing an efficient cooperative control strategy for the heterogeneous robot team, including the robotic NDE and MIR systems, conebots (traffic cone robots) and aerial robots. Since both RABIT and ANDERS MIR robotic systems navigate using a common differential GPS, the activities are concentrating on their synchronized operation in terms of activity sequencing and collision avoidance. The use of conebots in robotic setting up of a work zone is also explored. The formation control aims a team of conebots to set up the work zone of a desired shape, but in a way that is compliant with the current manual work zone setting up protocols. Overall, the goal of this research effort supported by National Science Foundation's NRI Program is to establish human-robot collaboration that will reduce negative impacts on traffic flow and safety, while maintaining an effective and efficient operation of evaluation and rehabilitation robotic systems.

Fig. 14 Mobile manipulator-based autonomous rehabilitation platform ANDERS (*top*), and 5-DoF manipulator with drilling/filling robotic end-effector (*bottom*)

5 Conclusions

The use of robotics in inspection and problem mitigation of concrete bridge decks will lead to more efficient and cost effective management of bridges. While individual robotic systems have been, or are being developed, their synchronized operation will be an essential part to achieve the ultimate benefit from their development. The robotic platform RABIT builds on the best practices of NDE and visual inspection for concrete bridge decks to improve the speed, accuracy and cost of data collection, and comprehensiveness of the condition interpretation. The three attributes of the data collection are stemming from the use of a large number of sensors and sensor arrays and their simultaneous application, fully autonomous RABIT motion and reduced traffic closures. In addition, the deployment of RABIT significantly reduces risks to bridge inspectors due to a smaller number of personnel needed and their reduced exposure to the passing traffic. The comprehensiveness of the condition assessment is achieved through a significantly higher spatial data resolution, and multi NDE technology data collection, including imaging, for improved correlations between the visible and hidden deterioration and damage. A comparison of the results from comparative surveys of the two bridges using manual NDE technologies and RABIT has demonstrated similarity of the obtained results, but with the RABITs data being of higher resolution and collected three times faster. Implementation of RABIT opens opportunities for the condition assessment and monitoring of large populations of bridges and, thus, collection of large volumes of data. Those data are of critical importance for the development of more realistic concrete deck deterioration models, as well as more realistic predictive and life cycle cost models.

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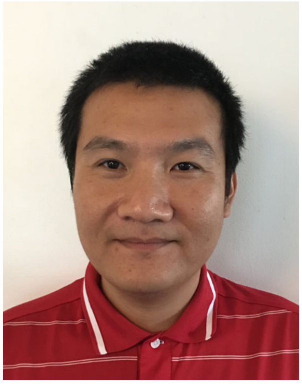
Nenad Gucunski is Professor and Chairman of Civil and Environmental Engineering at Rutgers University. He is also Director of Infrastructure Condition Monitoring Program at Rutgers' Center for Advanced Infrastructure and Transportation (CAIT). His primary expertise is in nondestructive testing/evaluation (NDT/NDE) of transportation infrastructure, soil dynamics, problems of dynamic soil-structure interaction, numerical modeling, and geophysical methods. He published more than 200 publications, primarily on various aspects of the development of NDE/NDT technologies, and their application and automation. Dr. Gucunski and his team are the recipient of the 2014 ASCE Charles Pankow Award for Innovation for the development of RABIT (Robotics Assisted Bridge Inspection Tool) for bridge decks. Dr. Gucunski received his B.S. degree in civil engineering from University of Zagreb, Croatia, and M.S. and Ph.D. degrees in civil engineering from The University of Michigan.

Basily Basily received his B.S and M.S degrees from Cairo University, Egypt, and his Ph.D. from Aston University, Birmingham UK, all in Mechanical Engineering. He was a lecturer at Birmingham University, UK, Professor at Mechanical and Design Department, Cairo University, and is currently Research Professor at Rutgers University, NJ, USA. His research interests include: Machine Design, Mechatronics, and innovative manufacturing processes. Dr. Basily holds sixteen international patents in his field of interest.

Jinyoung Kim is an Assistant Professor at Ajou University, Korea. He received his B.S. and M.S. degrees in Architectural Engineering from SungKyunKwan University, Korea in 2006 and 2008, respectively. He attended the graduate school in civil engineering at the University of Texas at Austin to pursue his doctoral degree. He earned his doctoral degree in May of 2013. His research areas over the last five years include: (1) development of automated NDE utilizing robotic-assisted inspection tool, (2) health monitoring of civil infrastructures using self-sustainable wireless sensor networks, and (3) smart building solutions.

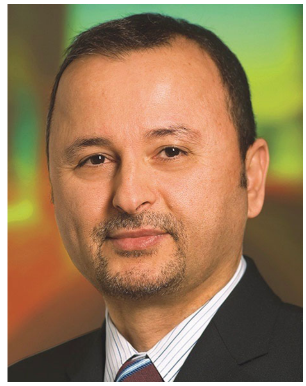
Jingang Yi received the B.S. degree in electrical engineering from Zhejiang University, Hangzhou, China, in 1993, the M.Eng. degree in precision instruments from Tsinghua University, Beijing, China, in 1996, and the M.A. degree in mathematics and the Ph.D. degree in mechanical engineering from the University of California, Berkeley, in 2001 and 2002, respectively. He is currently an Associate Professor of Mechanical Engineering at Rutgers University. His research interests include autonomous robotic systems, dynamic systems and control, mechatronics, automation science and engineering, with applications to biomedical systems, civil infrastructure and transportation systems. Dr. Yi is a Fellow of American Society of Mechanical Engineers (ASME) and Senior Member of the IEEE. He is a recipient of the 2010 US NSF CAREER Award.

Trung Duong completed his M.S and Ph.D. degrees in Mechanical and Aerospace Engineering at the Oklahoma State University, Oklahoma, USA in 2009 and 2013, respectively. He is a Research Associate at Center for Advanced Infrastructure and Transportation (CAIT), Rutgers the State University of New Jersey. He involved in research activities of the Long-Term Bridge Performance (LTBP) program funded by the Federal Highway Administration (FHWA) in U.S. Department of Transportation and the Bridge Resource Program (BRP) funded by the New Jersey Department of Transportation. His research interests are mobile robotics, NDE technologies, image processing, and computer vision.



Kien Dinh received his B.S from National University of Civil Engineering in Vietnam, M.S from National Taiwan University, and Ph.D from Concordia University in Canada, all in civil engineering. He is currently a postdoctoral researcher at Marshall University in West Virginia and was previously a research associate at Rutgers University, New Jersey. His research interests include nondestructive testing techniques for concrete structures, deterioration modeling and infrastructure management.

Seong-Hoon Kee is Assistant Professor in the Department of Architectural Engineering, Dong-A University, Busan, South Korea. He was a Postdoctoral Research Associate at the Center for Advanced Infrastructure and Transportation (CAIT), Rutgers, the State University of New Jersey, New Brunswick, NJ. He received his PhD in Civil Engineering from the University of Texas at Austin, Austin, TX. His research interests include automated nondestructive testing, structural health monitoring, and chloride-induced deterioration of concrete.



Ali Maher is Professor of Civil and Environmental Engineering at Rutgers University. He is also Director of Rutgers' Center for Advanced Infrastructure and Transportation (CAIT), which has been for twenty years selected as USDOT Tier 1 and National University Transportation Center (UTC). His expertise spans the areas of ground improvement, soil dynamics, infrastructure asset management, nondestructive testing, environmental geotechnology, and new technology vehicles.Dr. Maher received his degrees in civil engineering from the University of Michigan: B.S. in 1978, M.S. in 1985, and Ph.D. in 1988.