University Transportation Research Center - Region 2

Final Report

Robotic Inspection of Bridges Using Impact-echo Technology

Performing Organization: The City College of New York/CUNY

February 2015

Sponsor:
University Transportation Research Center - Region 2

University Transportation Research Center - Region 2

The Region 2 University Transportation Research Center (UTRC) is one of ten original University Transportation Centers established in 1987 by the U.S. Congress. These Centers were established with the recognition that transportation plays a key role in the nation's economy and the quality of life of its citizens. University faculty members provide a critical link in resolving our national and regional transportation problems while training the professionals who address our transportation systems and their customers on a daily basis.

The UTRC was established in order to support research, education and the transfer of technology in the field of transportation. The theme of the Center is "Planning and Managing Regional Transportation Systems in a Changing World." Presently, under the direction of Dr. Camille Kamga, the UTRC represents USDOT Region II, including New York, New Jersey, Puerto Rico and the U.S. Virgin Islands. Functioning as a consortium of twelve major Universities throughout the region, UTRC is located at the CUNY Institute for Transportation Systems at The City College of New York, the lead institution of the consortium. The Center, through its consortium, an Agency-Industry Council and its Director and Staff, supports research, education, and technology transfer under its theme. UTRC's three main goals are:

Research

The research program objectives are (1) to develop a theme based transportation research program that is responsive to the needs of regional transportation organizations and stakeholders, and (2) to conduct that program in cooperation with the partners. The program includes both studies that are identified with research partners of projects targeted to the theme, and targeted, short-term projects. The program develops competitive proposals, which are evaluated to insure the mostresponsive UTRC team conducts the work. The research program is responsive to the UTRC theme: "Planning and Managing Regional Transportation Systems in a Changing World." The complex transportation system of transit and infrastructure, and the rapidly changing environment impacts the nation's largest city and metropolitan area. The New York/New Jersey Metropolitan has over 19 million people, 600,000 businesses and 9 million workers. The Region's intermodal and multimodal systems must serve all customers and stakeholders within the region and globally.Under the current grant, the new research projects and the ongoing research projects concentrate the program efforts on the categories of Transportation Systems Performance and Information Infrastructure to provide needed services to the New Jersey Department of Transportation, New York City Department of Transportation, New York Metropolitan Transportation Council , New York State Department of Transportation, and the New York State Energy and Research Development Authorityand others, all while enhancing the center's theme.

Education and Workforce Development

The modern professional must combine the technical skills of engineering and planning with knowledge of economics, environmental science, management, finance, and law as well as negotiation skills, psychology and sociology. And, she/he must be computer literate, wired to the web, and knowledgeable about advances in information technology. UTRC's education and training efforts provide a multidisciplinary program of course work and experiential learning to train students and provide advanced training or retraining of practitioners to plan and manage regional transportation systems. UTRC must meet the need to educate the undergraduate and graduate student with a foundation of transportation fundamentals that allows for solving complex problems in a world much more dynamic than even a decade ago. Simultaneously, the demand for continuing education is growing – either because of professional license requirements or because the workplace demands it – and provides the opportunity to combine State of Practice education with tailored ways of delivering content.

Technology Transfer

UTRC's Technology Transfer Program goes beyond what might be considered "traditional" technology transfer activities. Its main objectives are (1) to increase the awareness and level of information concerning transportation issues facing Region 2; (2) to improve the knowledge base and approach to problem solving of the region's transportation workforce, from those operating the systems to those at the most senior level of managing the system; and by doing so, to improve the overall professional capability of the transportation workforce; (3) to stimulate discussion and debate concerning the integration of new technologies into our culture, our work and our transportation systems; (4) to provide the more traditional but extremely important job of disseminating research and project reports, studies, analysis and use of tools to the education, research and practicing community both nationally and internationally; and (5) to provide unbiased information and testimony to decision-makers concerning regional transportation issues consistent with the UTRC theme.

Project No(s): 49997-41-24

Project Date: February 12, 2015

Project Title: Robotic Inspection of Bridges Using Impact-echo Technology

Project's Website:
http://www.utrc2.org/research/projects/robotic-inspection-echo-technology

Principal Investigator(s):

Dr. John (Jizhong) Xiao
Associate Professor, Department of Electrical Engineering,
The City College, City University of New York (CUNY) and
Doctoral Faculty of CUNY Graduate Center
Email: jxiao@ccny.cuny.edu

Co-PI(s):

Dr. Anil Agrawal
Professor of Civil Engineering
The City College of New York
160 Convent Avenue
New York, NY 10031
Email: agrawal@ccny.cuny.edu

Performing Organization(s): The City College of New York, CUNY

Sponsor(s):
University Transportation Research Center (UTRC)

To request a hard copy of our final reports, please send us an email at utrc@utrc2.org

Mailing Address:

University Transportation Reserch Center
The City College of New York
Marshak Hall, Suite 910
160 Convent Avenue
New York, NY 10031
Tel: 212-650-8051
Fax: 212-650-8374
Web: www.utrc2.org

Board of Directors

The UTRC Board of Directors consists of one or two members from each Consortium school (each school receives two votes regardless of the number of representatives on the board). The Center Director is an ex-officio member of the Board and The Center management team serves as staff to the Board.

City University of New York
Dr. Hongmian Gong - Geography
Dr. Claire McKnight - Civil Engineering
Dr. Neville A. Parker - Civil Engineering

Clarkson University
Dr. Kerop D. Janoyan - Civil Engineering

Columbia University
Dr. Raimondo Betti - Civil Engineering
Dr. Elliott Sclar - Urban and Regional Planning

Cornell University
Dr. Huaizhu (Oliver) Gao - Civil Engineering
Dr. Mark A. Turnquist - Civil Engineering

Hofstra University
Dr. Dilruba Ozmen-Ertekin - Civil Engineering
Dr. Jean-Paul Rodrigue - Global Studies and Geography

New Jersey Institute of Technology
Dr. Priscilla P. Nelson - Geotechnical Engineering
Dr. Lazar Spasovic - Civil Engineering

New York University
Dr. Mitchell L. Moss - Urban Policy and Planning
Dr. Rae Zimmerman - Planning and Public Administration

Polytechnic Institute of NYU
Dr. John C. Falcocchio - Civil Engineering
Dr. Elena Prassas - Civil Engineering

Rensselaer Polytechnic Institute
Dr. José Holguín-Veras - Civil Engineering
Dr. William "Al" Wallace - Systems Engineering

Rochester Institute of Technology
Dr. James Winebrake

Rowan University
Dr. Yusuf Mehta - Civil Engineering
Dr. Beena Sukumaran - Civil Engineering

Rutgers University
Dr. Robert Noland - Planning and Public Policy
Dr. Kaan Ozbay - Civil Engineering

State University of New York
Michael M. Fancher - Nanoscience
Dr. Catherine T. Lawson - City & Regional Planning
Dr. Adel W. Sadek - Transportation Systems Engineering
Dr. Shmuel Yahalom - Economics

Stevens Institute of Technology
Dr. Sophia Hassiotis - Civil Engineering
Dr. Thomas H. Wakeman III - Civil Engineering

Syracuse University
Dr. Riyad S. Aboutaha - Civil Engineering
Dr. O. Sam Salem - Construction Engineering and Management

The College of New Jersey
Dr. Michael Shenoda - Civil Engineering

University of Puerto Rico - Mayagüez
Dr. Ismael Pagán-Trinidad - Civil Engineering
Dr. Didier M. Valdés-Díaz - Civil Engineering

UTRC Consortium Universities

The following universities/colleges are members of the UTRC consortium.

City University of New York (CUNY)
Clarkson University (Clarkson)
Columbia University (Columbia)
Cornell University (Cornell)
Hofstra University (Hofstra)
Manhattan College (MC)
New Jersey Institute of Technology (NJIT)
New York Institute of Technology (NYIT)
New York University (NYU)
Rensselaer Polytechnic Institute (RPI)
Rochester Institute of Technology (RIT)
Rowan University (Rowan)
Rutgers University (Rutgers)*
State University of New York (SUNY)
Stevens Institute of Technology (Stevens)
Syracuse University (SU)
The College of New Jersey (TCNJ)
University of Puerto Rico - Mayagüez (UPRM)

** Member under SAFETEA-LU*

UTRC Key Staff

Dr. Camille Kamga: *Director, Assistant Professor of Civil Engineering*

Dr. Robert E. Paaswell: *Director Emeritus of UTRC and Distin*guished Professor of Civil Engineering, The City College of New York

Herbert Levinson: *UTRC Icon Mentor, Transportation Consultant and Professor Emeritus of Transportation*

Dr. Ellen Thorson: *Senior Research Fellow, University Transportation Research Center*

Penny Eickemeyer: *Associate Director for Research, UTRC*

Dr. Alison Conway: *Associate Director for Education*

Nadia Aslam: *Assistant Director for Technology Transfer*

Nathalie Martinez: *Research Associate/Budget Analyst*

Andriy Blagay: *Graphic Intern*

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2.Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Robotic Inspection of Bridges Using Impact-echo Technology		5. Report Date Feb 12, 2015 6. Performing Organization Code
7. Author(s) Prof. Jizhong Xiao (PI) and Prof. Anil Agrawal (Co-PI)		8. Performing Organization Report No.
9. Performing Organization Name and Address The City College of New York Convent Ave & 140 street New York, NY 10031		10. Work Unit No. 11. Contract or Grant No. 49997-41-24
12. Sponsoring Agency Name and Address University Transportation Research Center The City College of New York 910 Marshak Hall 137th Street and Convent Avenue New York, NY 10031		13. Type of Report and Period Covered Final Report, 10/1/12 -3/31/2014 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

During the first year of the project, we integrate an impact-echo device with a mobile robot for automatic NDT inspection of bridge decks to generate a 2D/3D map showing flaws. We found from field test that most of the bridge decks have groove surfaces to enhance the friction of the vehicles on the bridge. The current Impact-echo device we used doesn't work well in groove surfaces even if it is used in manual operation. After consulting with world renowned scientists and NDT firms, we got to know that the ultrasonic flaw detector with spring loaded sensor may provide a solution to this challenge. Our investigation also show that ground penetration radar (GPR) is very promising in locating subsurface flaws in concrete structure and some GPR models are light-weight with small form factor, which is suitable as NDT payload sensors carried by wall-climbing robots. During the extended project period, we have successfully developed two wall-climbing robot prototypes (Rise-Rover and GPR-Rover) to carry these NDT devices. The field test videos demonstrate the good performance of the robots in scanning vertical walls. The robots provide vertical mobility and are able to operate on both smooth and rough surfaces (brick wall and tile wall) and cross over small gaps between bricks/tiles.

17. Key Words	18. Distribution Statement
Wall-climbing robot, nondestructive testing (NDT), impact echo, ground penetration radar	

19. Security Class if (of this report)	20. Security Class if. (of this page)	21. No of Pages	22. Price
Unclassified	Unclassified	18	

Form DOT F 1700.7 (8-69)

Disclaimer

Table of Contents

List of Figures

List of Tables

Robotic Inspection of Bridges Using Impact-echo Technology

UTRC-RITA Project Final Report

1. Executive Summary

The bridges that were built in the mid 20th century or earlier are reaching their life expectancy, and thus have strong needs for routine inspection and maintenance to ensure sustainability. Millions of dollars have been invested each year to inspect bridges using various non-destructive testing/evaluation NDT/NDE technologies. However, for some difficult to access bridge areas (e.g., bridge foundations and pillars underneath decks), it lacks effective tools and delivery systems for NDT inspection. The objective of this project is to develop wall-climbing robot prototypes carrying NDT devices to automate the inspection process, and thereby decreasing costs, increasing the inspection speed and improving safety. Compared with manual inspection, the wall-climbing robots could scan vertical surfaces of bridge foundations and horizontal surfaces at the bottom of bridge decks, reach hard-to-access places, take close-up pictures, collect NDT data and transmit to host PC for further analysis.

During the first year of the project, we integrate an impact-echo device with a mobile robot for automatic inspection of bridge decks to generate a 2D/3D map showing flaws. We found from field test that most of the bridge decks have groove surfaces to enhance the friction of the vehicles on the bridge. The current Impact-echo device we used doesn't work well in groove surfaces even if it is used in manual operation. After consulting with world renowned scientists and NDT firms, we got to know that the ultrasonic flaw detector with spring loaded sensor may provide a solution to this challenge. Our investigation also show that ground penetration radar (GPR) is very promising in locating subsurface flaws and some GPR models are light-weight with small form factor and can be carried by wall-climbing robot as NDT payload. During the extended project period, we have successfully developed two wall-climbing robot prototypes (Rise-Rover and GPR-Rover) to carry these NDT devices. The field test videos demonstrate the good performance of the robots in scanning vertical walls. The robots are able to operate on both smooth and rough surfaces (brick wall and tile wall) and cross over small gaps between bricks/tiles, and thus provide vertical mobility for NDT inspection of bridges. We call for actions from DoT agencies, NDT equipment firms and NDT industry to support the development and field demonstration of robotic NDT inspection technology for bridges including the bridge decks and vertical surfaces.

2. Background

The civil infrastructure (e.g., buildings, bridges, tunnels, dams, concrete towers) that was built in the mid 20th century or earlier in the United States and across the world is reaching its life expectancy, leaving questions about their structural integrity and deterioration levels. The tragic I-35W bridge collapse [1] in Minnesota in 2007 highlights the needs of infrastructure inspection. The Federal Highway Administration (FHWA) reported that approximately more than 72,000 bridges (12% of all bridges on American roads) are structurally deficient. The average age of bridges in USA is forty-three years old, and most bridges were built to last for fifty-years, so eventually all bridges will become structurally deficient unless they are repaired or replaced [2]. FHWA recommend inspections of normal bridges every 2 years and annually for bridges deemed deficient. To inspect the structural integrity of civil structures, the inspectors need to detect subsurface defects (i.e., cracks, delamination, voids) using NDT instruments such as ground penetration radar (GPR) [3], seismic pavement analyzer (PSA) [4, 5], Ultrasonic instrument [6], impact echo devices [7], etc., in addition to visual inspection of surface flaw.

It is a very challenging job to inspect vertical surfaces and difficult to access places such as bridge foundations (Fig. 1a) and sidewalls (Fig. 1b), bottom surfaces of bridge decks (Fig. 1c, d). Currently, there are no effective ways for vertical surface inspection except to use hand-held NDT instrument by "spider-man" with safety rope, or use scaffolding or special equipment (e.g., snooper truck) (Fig. 1c). It is a dangerous and tedious job for a spider-man to scan a large area of vertical walls with a NDT instrument. It is very time consuming to install scaffold if not impossible, and the use of snooper truck may require blocking traffics. There is a strong need to automate the inspections process for decreasing costs, increasing the inspection speed, and improving safety. Our wall-climbing robots will provide vertical mobility and allow inspections to be performed significantly faster, safer and more thorough, at a lower cost, by eliminating the use of scaffolds.

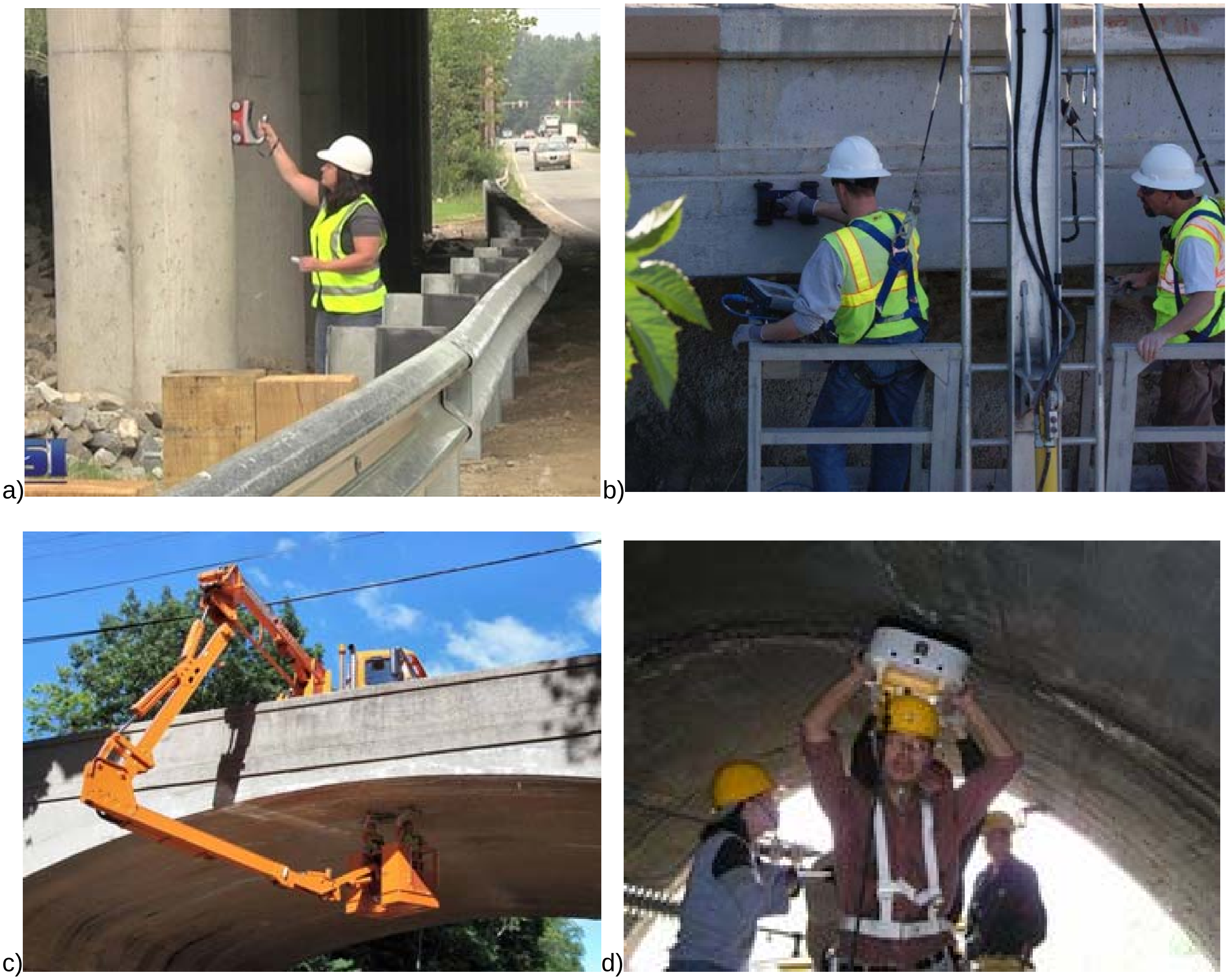


Fig. 1. Manual Inspection using NDT instruments

3. Objective

The objective of this project is to develop a wall-climbing robot prototype carrying NDT devices to conduct automated NDT inspection of bridges. The robot could not only inspect the horizontal surface of bridge decks but also provide vertical mobility to inspect some difficult to access areas, such as the bridge foundations and bottom surface underneath decks.

4. Summary of the Literature Review

Robots with wall climbing capability have been developed by using magnetic devices [8-9], vacuum suction techniques [11-14], attraction force generated by propeller [15, 16], or bio-mimetic approaches inspired by climbing animals [17-19]. For example, robots using permanent magnets or electromagnets are presented in [20-23] for climbing large steel structures and in [24, 25] for internal inspection of iron pipes. Robotics Technologies of Tennessee developed some inspection crawlers [26] for ultrasonic testing of metallic storage tanks, but they all use magnetic adhesion, which does not apply for concrete structures. Other crawlers are used for pipeline inspections [27] which do not have wall-climbing capability. International Climbing Machines (ICM) [28] produces a large robot platform using an AC vacuum motor to generate strong suction and using rolling tread with thick foam to create perfect seal perimeter. The ICM crawler can be used to inspect concrete structures of dams and nuclear power stations [29]. The book chapter [30] by Dr. Jizhong Xiao provides a comprehensive review on the climbing robot technologies.

Different kinds of NDT technologies were developed to inspect the structural integrity and deterioration levels of the concrete structure [5-7]-[31-32], such as the technologies of ultrasound, GPR, laser, infrared thermography, X-rays, gamma rays, impact-echo, etc. Among the available NDE devices, handheld impact-echo, GPR and ultrasound devices are the most commonly used for evaluating concrete and masonry structures.

The impact echo technology was invented by Sansalone [7, 34, 35] and was first commercialized by Impact-echo Instruments LLC. It is the patterns in the waveforms and Power Spectral Density (PSD) of the impact-echo signals that indicate the existence and locations of the flaws. Sansalone [35] pointed out that when the transducer is placed close to the impact point, the response is dominated by P-wave echoes, which can be analyzed by the Fourier transform technique. The PSD of the acoustic signal frequency is used as the source of the signal features, such as in the form of the power accumulation ratio [36], the sound intensity ratio [37], the area of interval PSD [38], etc. The threshold limitation method is a traditional approach [39, 40] to evaluate the impact echo signal. Although it is a simple approach, its sensitivity to the noise makes it unreliable in practical applications. Artificial Neural Network (ANN) is another method that has been used as the classifier for impact-acoustic signal analysis [41]. The drawbacks of ANN are that it needs a large amount of training samples, depends largely on the empirical principles, and also the characteristics of the impact acoustic features suppress the generalization ability of ANN [39]. Support Vector Machine (SVM) is a powerful machine learning approach which was initially designed for binary classification. It has the capabilities of learning procedures with a small sample size [42, 43]. SVM is applied in this research to derive a robust flaw classification from the PSD features of the impact-echo signals.

The current practice of manual inspection of concrete structure using hand-held impact-echo device requires a skilled personnel to select a number of points for testing, and select an appropriate diameter impactor and manually strike the surface. With multiple tests of large structures this becomes a very tedious process. With this point measurement method of local, punctual readings, important information can be missed when the points are badly selected or not enough. Recent research and testing results [44~46] underlined the necessity to do impact-echo measurements in scan mode to avoid incorrect data interpretations caused by badly chosen points for the measurement. The robotic inspection provides a way for scan mode measurements.

5. Summary of the Work Performed

5.1 Development of Impact-echo Inspection Robot

In the first year of the project, we focused on developing NDT-Rover --- a mobile robot equipped with an impact-echo NDT device, including its X-Z control and taping mechanism. Its hardware components are shown in Fig. 2. NDT-Rover uses Pioneer-3T mobile robot as the mobility carrier and uses two motors to control horizontal (X direction) and vertical (Z direction) motion of the Impact-echo device installed on two guided tracks to achieve 2D scanning measurement at multiple points in a line. In addition, an automatic tapping mechanism is designed to strike the steal ball on surface for reliable impact generation. The motion system consists of an Arduino board and four motors, which control the movement and action of the impact-echo device by pulse-width modulation

(PWM) and I/O of the controller as shown in Fig. 3. A laptop PC running the Impact echo data analysis software serves as the user interface, which receives the desired settings for inspection area and desired sampling resolution. The NDT-Rover could perform autonomous navigation and collect/store the impact echo data for off-line data analysis and flaw evaluation through software.

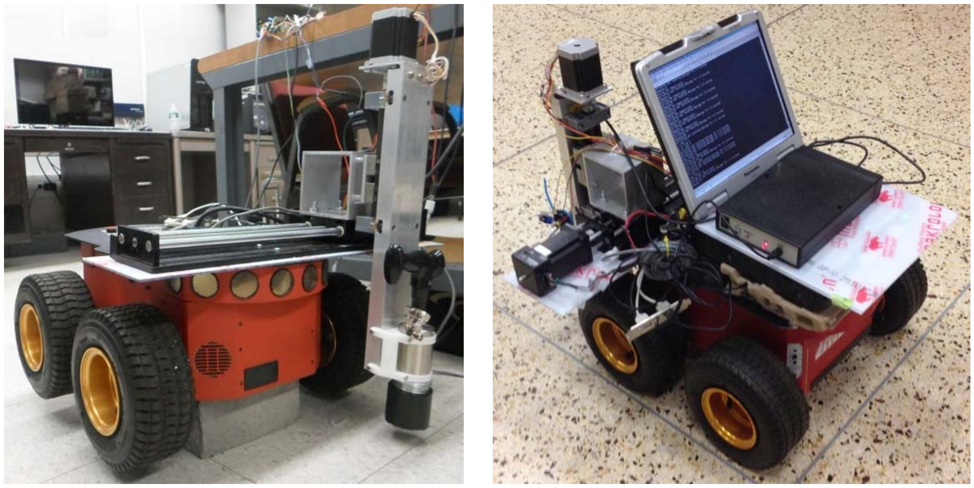


Fig. 2 NDT-Rover equipped with Impact-echo device and motion control system in X-Z directions and an automatic tapping mechanism

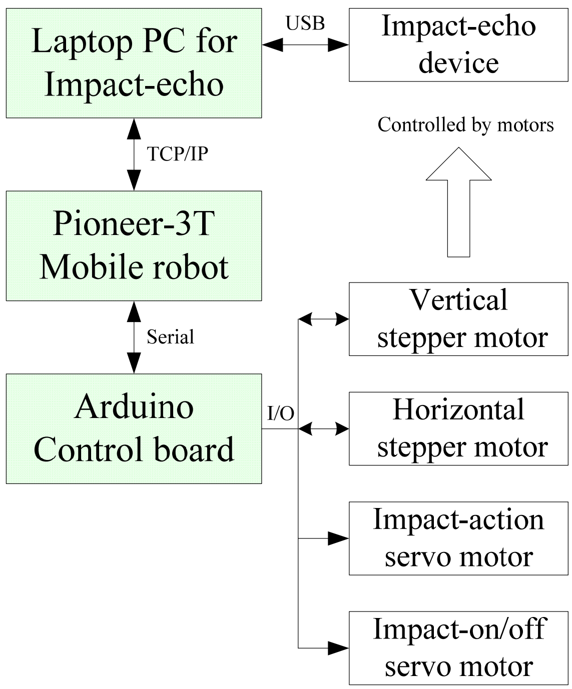


Fig. 3 Hardware system of the NDT-Rover inspection robot

The navigation software of the NDT-Rover is based on Robot Operating System (ROS) to control the mobile robot and to localize itself using the wheel odometer feedback. For measurement in scan mode, commands are sent to the motion system to control the movement of the impact-echo device, and trigger the impact-echo tapping mechanism. The NDT data at each inspection position is acquired by the impact-echo device and sent to the PC for data analysis by the software provided by the vendor. We also implemented a least square SVM machine learning approach to perform the flaw classification based on the features extracted from the impact-echo signal PSD [47]. Given the desired inspection settings and the area to be investigated, the NDT-Rover can perform the automatic inspection on bridge decks by moving to the desired position, striking the impactor at multiple positions along a line, collecting the NDT data, and moving to next positions until it collected enough data to cover the area for off-line analysis. The NDT data collected from the 2D scan is processed and visualized to show the existence of the inner concrete flaws.

5.2 Data Collection in New York Flushing 149th St. Bridge

We collected NDT data at the bridge deck (Fig.4) of Flushing 149th street between Barton Ave and 41st Ave, New York City on Nov. 16, 2012. This bridge was found to have visible cracks and possible invisible flaws in the deck (As we can see in the left figure). The 100 samples data were acquired which represents 10x10 testing points on the bridge deck.

Fig. 4 Collect data manually using impact-echo on a bridge in Flushing, NYC

Impact-echo technology is a novel NDE approach based on mechanical stress wave propagation in a solid medium, which is used for detecting the internal defects of a medium, especially concrete. When the concrete surface is subject to a mechanical shock (tapping on a concrete surface with a small steel ball), a mechanical stress propagates in the form of spherical waves within it. When the stress wave encounters the interface of the medium, reflection will be produced due to the different wave impedance on both sides of the interface medium. The device from Impact-echo Instruments LLC used in this research is shown in Fig. 5.

Fig. 5 a) Impact echo device from Impact Echo Instruments, LLC at Ithaca, New York, which is founded by Mary J. Sansalone in 1997. Item 1 is a set of 10 impactor, item 2 includes two hand-held transducers, item 3 is a dual-head transducer to measure the wave speed.

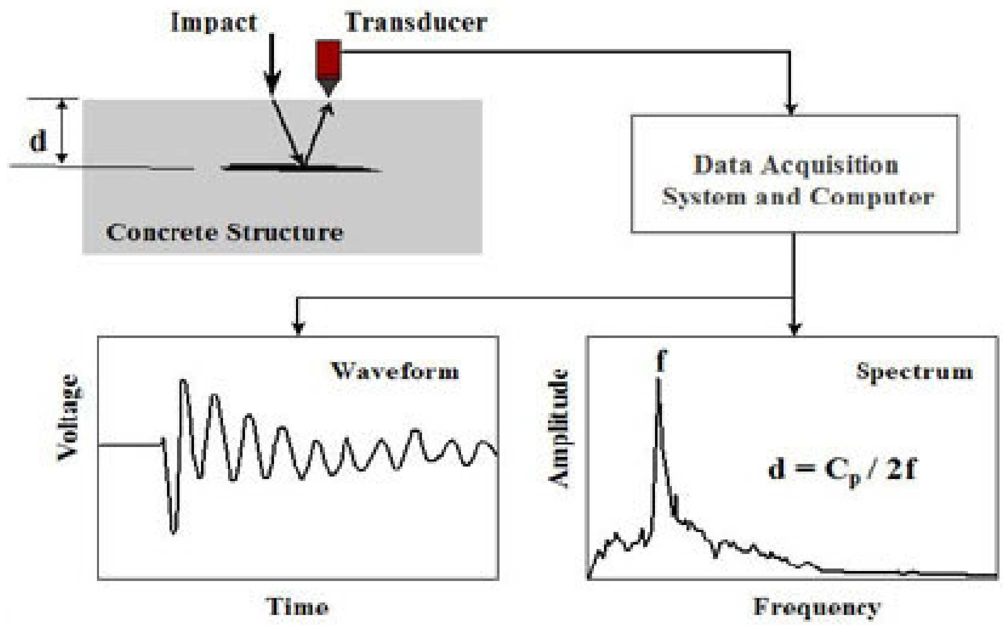
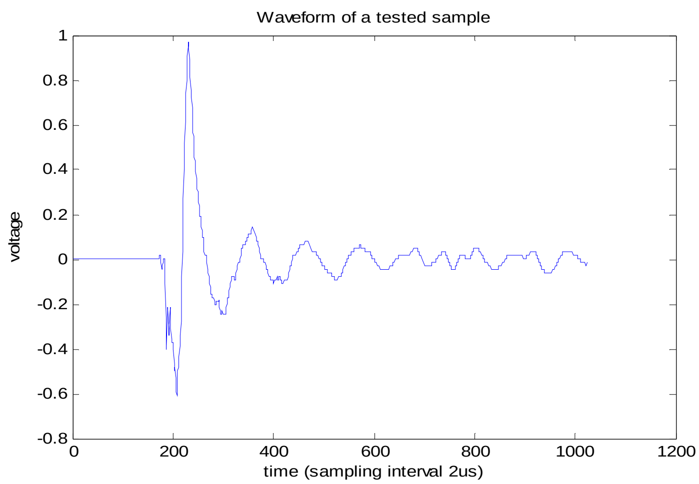


Fig.5 b) Schematic diagram and sample signal illustrating how Impact-echo works

The PSD distributions of the impact-echo signals have been analyzed empirically for comparison with the SVM classification, based on the methodology as descripted in reference [47]. The patterns in the PSD of the waveforms provide information about the locations and existence of the visible and invisible flaws in the bridge deck, and the thickness of the deck. The temporal signals and PSDs of a no-flaw signal and a flaw signal are shown below.



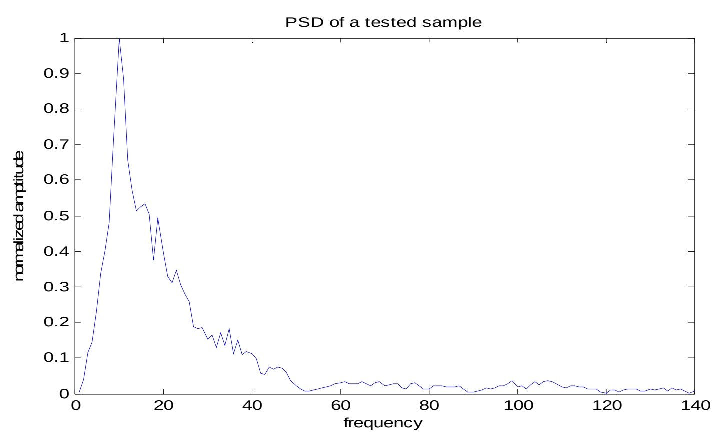


Fig.6 a) Waveform/PSD of a tested sample without flaw

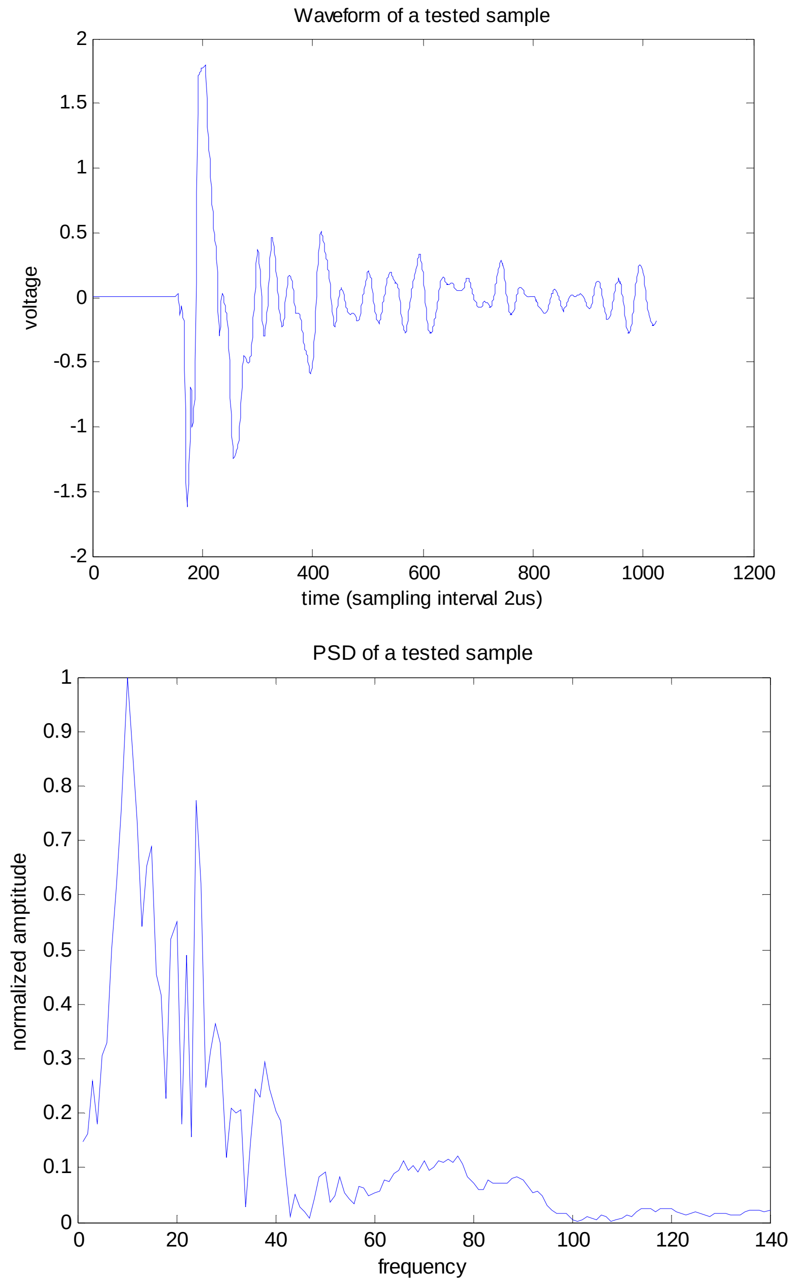


Fig.6 b) Waveform/PSD of a tested sample with flaw

The empirical analysis for the whole data set and the partial test data set are shown in Table 1.

TABLE I

EMPIRICAL ANALYSIS FOR DATA SET

	Samples	Rate
Non-flaw samples among 100 whole data points	86	86%
Flaw samples among 100 whole data points	14	14%
Non-flaw samples in test set of 40 data points	34	85%
Flaw samples in test set of 40 data points	6	15%

After the PSD analysis, classification is conducted to automatically classify the flaw/non-flaw point. First, the SVM is used as the learning model. The impact-echo acoustic sound in the experiment is first divided into a training data set and a test data set. The training data set is used to train the SVM model and then the model is evaluated by the test data set. The training set contains 60 samples, among which 5 samples are labeled as flaws. Certain features are critical factors for the SVM classification. In this impact-echo NDE testing case, we cut the

PSD into several intervals, so that cumulative PSD area (CPA) and cumulative PSD ratio (CPR) can be calculated based on the maximum, minimum, and average values in each interval. CPA and CPR are chosen as the features for the SVM training, since they represent the main characteristics of the flaws based on the empirical analysis. The training stage is implemented using the LS-SVMlab (LS-SVM: least square SVM) library, and Radial Basis Function (RBF) kernel is selected as the kernel transform for the SVM training. Fig. 7 shows the SVM classifier which is the curve between two classes.

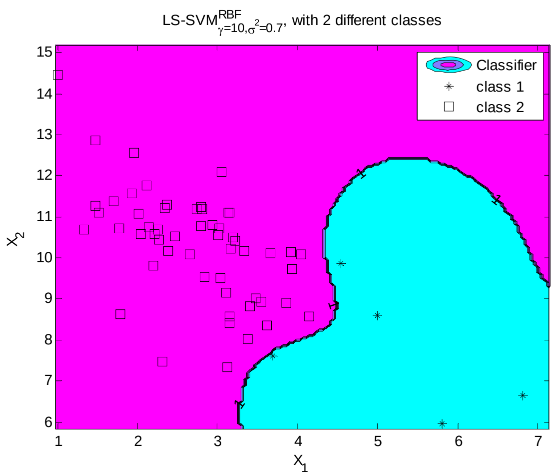


Fig. 7 SVM model from training

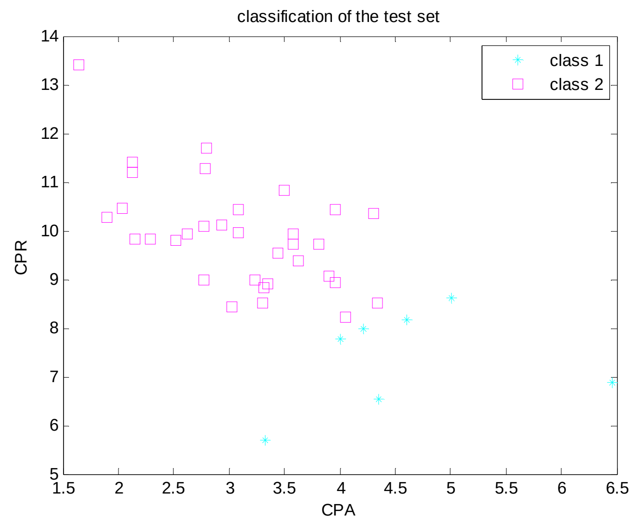


Fig.8 SVM model verification

After the training procedure, the SVM Model is tested. The SVM classifier was verified with the test data set. To illustrate the performance of the SVM methodology, the result was compared with the outcome from empirical analysis of the impact-echo NDE signals. As shown in Fig. 8, the test data set was classified by the SVM model. Table 2 shows the testing result.

TABLE II

COMPARISON OF EMPIRICAL ANALYSIS AND SVM ANALYSIS

	Empirical analysis	SVM analysis
Flaw detected / total number of points	15%	17.5%
Misdetection rate	N/A	5%
False alarm rate	N/A	2.5%

We conducted data analysis and finally visualize the detected flaws in 3D spaces. After we evaluated all the data sets, the detected flaws are displayed in the 3D visualization model, shown in Fig. 9. The group position of some detected points in the space can also indicate a high possibility of flaws existing in the corresponding positions of the inner bridge deck.

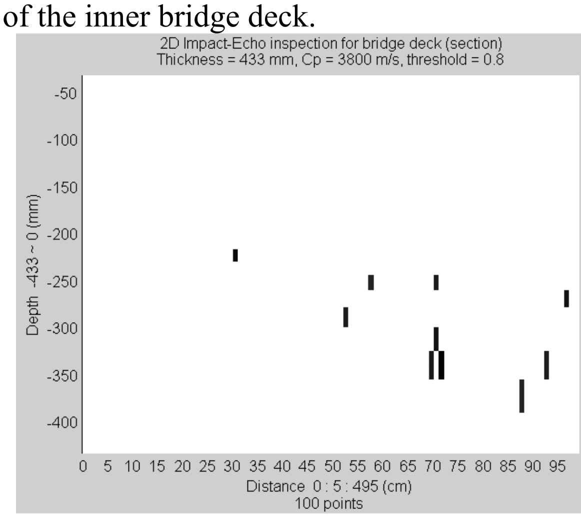
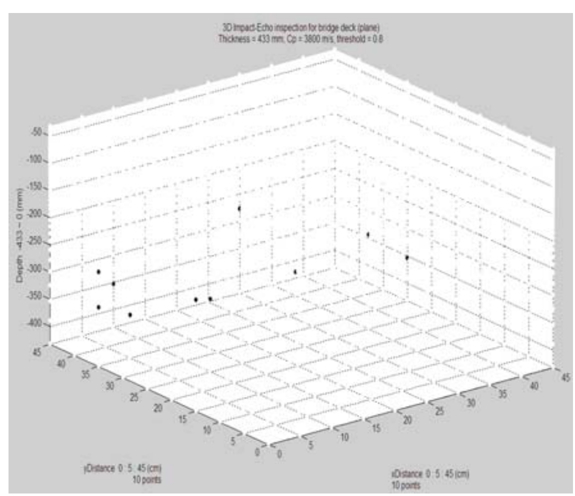


Fig. 9 a) 2D Impact-echo field flaw data



b) 3D Impact-echo field flaw data

5.3 Development of Rise-Rover wall-climbing robot

In the second year of the project, we focused on developing a new wall-climbing robot prototype named as Rise-Rover as shown in Fig. 10. Rise-Rover is a heavy-duty vertical mobility cart that uses two drivetrain modules to carry NDE instrument in the middle payload compartment for detecting subsurface defects. The innovations are the fault tolerant design using two drivetrain modules with custom designed treads to carry a heavy payload of NDT instrument. The custom designed tread uses light-weight foam encapsulated by silicon rubber. It is soft, durable and conformable to surface irregularities. Each module has multiple suction chambers on tread that allow the robot to cross over gaps/grooves/cracks without loss of adhesion. The introduction of ducted fans allows for re-attachment to the wall surface for increased reliability. Each drivetrain module has a dimension of 8 x 21 x 5.5 inch, weights 10 lb, and can generate normal suction force of 30lb. Pull-up force of Rise-Rover (i.e., payload carrying on vertical wall) is 16 lb, and the locomotion speed of Rise-Rover is 30 meters/minute. The Rise-Rover videos can be seen at http://tinyurl.com/Rise-Rover-1, and http://tinyurl.com/Rise-Rover-2.

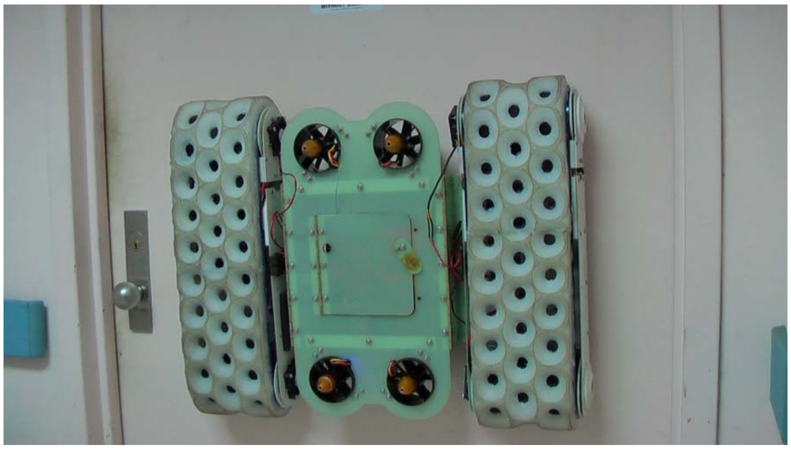


Fig. 10, The Rise-Rover consists of two drivetrain modules that can carry heavy NDT instrument in the middle payload compartment. Four ducted fans are used to push the robot against wall enhancing the reliability and enabling reattachment to wall-surface if the robot accidentally lose suction. The custom designed tread using light-weight foam encapsulated by silicon rubber is soft and conformable to surface irregularities.

5.4 Development of GPR-Rover Wall-climbing Robot

In the project extension period, we collaborate with Geophysical Survey Systems, Inc (GSSI) to custom design a wall-climbing robot (named as GPR-Rover) to carry GSSI 300/800 MHz dual-frequency antenna which is able to locate targets at depths of up to 5 m (16 ft), ideal for NDT inspection of concrete structures (such as dams, tunnels) and utility surveys as shown in Figure 11. GSSI is the world leader in GPR and Electromagnetic Induction Instruments. It sells over 50% of the world's GPR equipment throughout the United States and in 40 countries around the world. As shown in Fig. 11, GPR-Rover uses the whole round body as the vacuum chamber and two high speed suction motors to generate much stronger normal suction force (>100 lb) than that of Rise-Rover, thanks to the innovative design of the flexible skirt seal. The videos demonstrating the performance of GPR-Rover on cinder block wall with gaps and on walls covered with tiles can be found**:** http://preview.tinyurl.com/GPR-Rover-1**,** http://preview.tinyurl.com/GPR-Rover-2

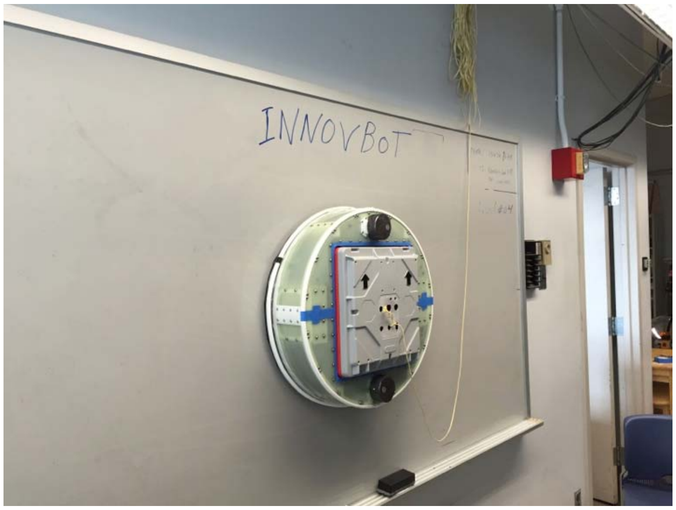


Fig. 11. The GPR-Rover carrying antenna 300/800 on a vertical wall surface. *The GPR-Rover can perform NDT inspection on both rough and smooth inclined/vertical surfaces. The 300/800 MHz dual frequency GPR antenna module in the plastic shell can be fit into the middle payload compartment of the GPR-Rover.*

6. Conclusions and Recommendations

Our investigation showed that the current Impact-echo device we used in the project doesn't work well in groove surface. The vendor's suggestion of grinding groove surface before use is not a viable solution. We found that **Acoustic Control Systems, Ltd** has low-frequency ultrasonic flaw detector A1220 MONOLITH which is suitable for solving thickness measuring and flaw detection tasks for difficult materials, such as concrete, stone, asphalt, etc. The device uses the spring loaded sensor that can adjust for a surface roughness up to 10mm as shown in Figure 12. This provides a possible solution to deal with NDT inspection of groove surface on bridge decks. Furthermore, the GSSI's GPR antenna 300/800 is designed for applications requiring penetration down to 1 m ~6 m, including void detection, concrete thickness assessment and shallow pipe location. GSSI's other GPR models such as the popular handheld StructureScan devices using high frequency antenna (2600 MHz) are able to locate rebar, conduits, cables, and voids in depths of up to **40 cm** (16 inches), ideal for concrete inspection. We recommend the use of these NDT devices in building inspection.

Fig. 12, The picture of the ultrasonic flaw detector A1220 MONOLITH from **Acoustic Control Systems, Ltd.** The spring loaded sensor is a matrix of sensor head that is conformable to rough surface.

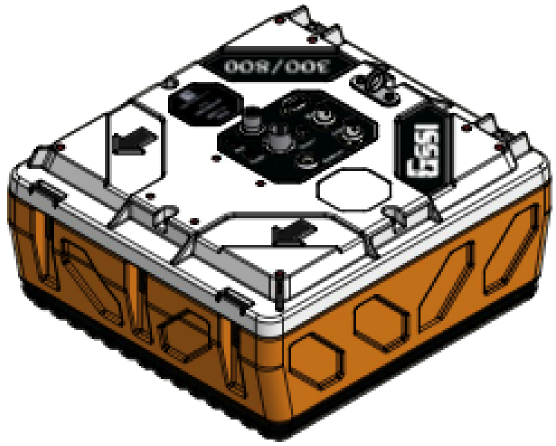


Fig. 13, The GSSI GPR antenna 300/800 is designed for applications requiring shallow penetration down to 1 m ~ 6m, including void detection, concrete thickness assessment and shallow pipe location.

Our Rise-Rover and GPR-Rover robots have enough payload capacity to carry these NDT sensors for monitoring the structural health of bridges, not only on bridge decks but also reach difficult to access places, such as the vertical surfaces of bridge foundations and horizontal surfaces at the bottom of bridge decks. These wall-climbing robots provide vertical mobility for NDT inspection of "big flat things", such as bridges, building facade, dams, etc., both vertically and horizontally, and on both smooth and rough surfaces.

The flaw classification method based on Support Vector Machine (SVM) seems to be promising. More testing data and comparison with ground truth data are required to verify the method.

7. Publication and Patent

a) Bing Li, Jing Cao, Jizhong Xiao, Xiaochen Zhang, Hongfan Wang, "Robotic Impact-echo Non-Destructive Evaluation based on FFT and SVM", Proceedings of the 11th World Congress on Intelligent Control and Automation, Shenyang, China, June 29~July 4, 2014, pp2854~2859.

b) "Robotic Device for Navigating Inclined Surfaces", Jizhong Xiao, Kenshin Ushiroda, PCT International Patent Application Serial No. PCT US2014/026125, International Filing Date: March 18, 2014.

8. Bibliography

[1] S. Hao. “I-35W Bridge collapse”. Journal of Bridge Engineering, 15(5), 608-614. 2009.

[2] “Number of structurally deficient bridges in U.S. Declines", Published June 16, 2014, http://www.homelandsecuritynewswire.com/dr20140616-number-of-structurally-deficient-bridges-in-us-declines

[3] D. Jeffrey. "Ground penetrating radar fundamentals." Prepared as an Appendix to a report to the US EPA, Region V, Department of Geological Sciences, The Ohio State University, 2000.

[4] N. Soheil, M.R. Baker, K. Crain. Development and testing of a seismic pavement analyzer. No. SHRP-H-375. 1993.

[5] G. Nenad, and A. Maher. Evaluation of seismic pavement analyzer for pavement condition monitoring. No. FHWA-NJ-2002-012, 2002.

[6] Tan, K. S., et al. "Ultrasonic evaluation of cement adhesion in wall tiles." Cement and Concrete Composites 18.2 (1996): pp.119-124. Sansalone, Mary J., and William B. Streett. "Impact-echo. Nondestructive evaluation of concrete and masonry." 1997

[7] Sansalone, Mary J., and William B. Streett. "Impact-echo. Nondestructive evaluation of concrete and masonry." 1997

[8] J.C. Grieco, M. Prieto, M. Armada, and P.G. Santos, “A Six-Legged Climbing Robot for High payloads”, IEEE International Conference on Control Applications, Italy, 1998, pp. 446-450.

[9]L. Guo, K. Rogers, and R. Kirkham, “A Climbing Robot with Continuous Motion”, IEEE International Conference on Robotics and Automation, pp. 2495-2500, USA,1997.

[10] S. Hirose and H. Tsutsumitake, “Disk Rover: A Wall-Climbing Robot Using Permanent Magnet Disks”, IEEE/RSJ International Conference on Intelligent Robots and Systems, USA, 1992, pp. 2074-2079.

[11] S. Galt and B.L. Luk, “Smooth and Efficient Walking Motion and Control for an 8-Legged Robot”, UKACC International Conference on Control, vol. 2, pp. 1652-1657, 1997.

[12] A. Nagakubo and S. Hirose, “Walking and Running of the Quadruped Wall-Climbing Robot,” IEEE International conference on Robotics and Automation, pp. 1005-1012, 1994.

[13] P.G. Backes, et al., “The Multifunction Automated Crawling System (MACS),” IEEE International Conference on Robotics and Automation, pp. 335-340, USA, 1997.

[14] J. Savall, A. Avello, and L. Briones, “Two Compact Robots for Remote Inspection of Hazardous Areas in Nuclear Power Plants,” IEEE International Conference on Robotics and Automation, pp.1993-1998, 1999.

[15] A. Nishi and H. Miyagi, “A Wall-Climbing Robot Using Propulsive Force of Propeller”, Fifth International Conference on Advanced Robotics, pp. 320-325, 1991.

[16] A. Nishi, “Development of Wall-Climbing Robots”, Computer and Electrical Engineering, 22(2), pp.123-149, 1996.

[17] M.P. Murphy and M. Sitti, “Waalbot: An Agile Small-Scale Wall-Climbing Robot Utilizing Dry Elastomer Adhesives”, IEEE/ASME Transactions on Mechatronics, 2007, vol. 12(3), pp. 330-338.

[18] S. Kim, A.T. Asbeck, M.R. Cutkosky, and W.R. Provancher, “SpinybotII: Climbing Hard Walls with Compliant Microspines”, Proc. of the 12th International Conference On Advanced Robotics (ICAR ’05), Seattle, WA, USA, 2005, pp. 601-606.

[19] S. Kim, M. Spenko, S. Trujillo, B. Heyneman, D. Santos, and M.R. Cutkosky, “Smooth Vertical Surface Climbing With Directional Adhesion”, IEEE Transactions on Robotics, 2008, vol. 24(1), pp. 65-74.

[20] Y. Wang, S.L. Liu, D.G. Xu, Y. Z. Zhao, H. Shao, and X. S. Gao, “Development and Application of wall-climbing robots”, Proc. of the 1999 IEEE International Conference on Robotics and Automation, Detroit, MI, USA, 1999, pp. 1207-1212.

[21] L.P. Kalra, JGu, and M. Max, “Wall-Climbing Robot for Oil Tank Inspection”, Proc. of the IEEE International Conference on Robotics and Biomimetics (ROBIO 2006), Kunming, China, 2006, pp. 1523-1528.

[22] J.C. Grieco, M. Prieto, M. Armada, and P. Santo, “A Six-Legged Climbing Robot for High Payloads”, Proc. of the 1998 IEEE International Conference on Control Applications, Trieste, Italy, 1998, 1: pp. 446-450.

[23] W.M. Shen, J. Gu, and Y.J. Shen, “Proposed Wall-Climbing Robot with Permanent Magnetic Tracks for Inspecting Oil Tanks”, Proc. of the IEEE International Conference on Mechatronics & Automation, Niagra Falls, Canada, 2005, 4: pp. 2072-2078.

[24] Y. Kawaguchi, I. Yoshida, H. Kurumatani, T. Kicuta, and Y. Yamada, “Internal Pipe Inspection Robot”, Proc. of the 1995 IEEE International Conference Robotics and Automation, Nagoya, Japan, 1995, 1: pp. 857-862.

[25] L.Z. Sun, X.J. Qin, and C.M. Wang, “Micro Robot in Small Pipe with Electromagnetic Actuator”, Proc. of the 1998 International Symposium on Micromechatronics and Human Science (MHS ’98), Nagoya, Japan, 1998, pp. 243-248.

[26] Robotics Technologies of Tennessee, http://www.robotictechtn.com/products/mobileinspection-systems/

[27] “iPeck Pipeline Inspection”, http://www.ipek.at/

[28] http://www.icm.co/

[29] E. Strickland, “Crawler Bot Could Inspect Nuclear Power Stations”, IEEE Spectrum, September 5, 2013.

[30] J. Xiao and H. Wang, “Advances in Climbing Robots”, in Contemporary Issues in Systems Science and Engineering, IEEE Press/Wiley, Edited by M.C. Zhou, H. X. Li, and M. Weijnen, Chapter 22, in press.

[31] S. Yang, L. Gu, and R. F. Gibson. "Nondestructive detection of weak joints in adhesively bonded composite structures." Composite Structures 51, no. 1 (2001): pp.63-71.

[32] McCann, D. M., and M. C. Forde. "Review of NDT methods in the assessment of concrete and masonry structures." NDT & E International 34, no. 2 (2001): pp.71-84.

[33] Mori, K., et al. "A new non-contacting non-destructive testing method for defect detection in concrete." NDT & E International 35.6 (2002): pp.399-406.

[34] Olson, Larry D. "Innovations in bridge superstructure condition assessment with sonic and radar methods." NDE/NDT for Highways and Bridges. New York City, NY, USA, American Society for Nondestructive Testing, 2010.

[35] Sansalone, Mary. "Impact-echo: the complete story." ACI Structural Journal 94, no. 6, 1997.

[36] Carino, Nicholas J. "The impact-echo method: an overview." In Proceedings of the 2001 Structures Congress & Exposition, pp. 21-23. Washington, DC, American Society of Civil Engineers, (2001): pp.21-23.

[37] Hu. Wu, and M. Siegel. "Correlation of accelerometer and microphone data in the “coin tap test”." Instrumentation and Measurement, IEEE Transactions on 49.3 (2000): pp.493-497.

[38] K.P. Liu, et al. "Wall inspection system for safety maintenance of high-rise buildings." International Journal of Performability Engineering 3.1 (2007): pp.187.

[39] Tong, F., et al. "Evaluation of tile–wall bonding integrity based on impact acoustics and support vector machine." Sensors and Actuators A: Physical 144.1 (2008): pp.97-104.

[40] Ito, Y., and T. Uomoto. "Nondestructive testing method of concrete using impact acoustics." NDT & E International 30, no. 4 (1997): pp.217-222.

[41] Luk, B. L., K. P. Liu, Z. D. Jiang, and F. Tong. "Robotic impact-acoustics system for tile-wall bonding integrity inspection." Mechatronics 19, no. 8 (2009): pp.1251-1260.

[42] C. Cortes, and V. Vladimi. "Support-vector networks." Machine learning 20, no. 3 (1995): pp.273-297.

[43] Burges, Christopher JC. "A tutorial on support vector machines for pattern recognition." Data mining and knowledge discovery 2, no. 2 (1998): pp.121-167.

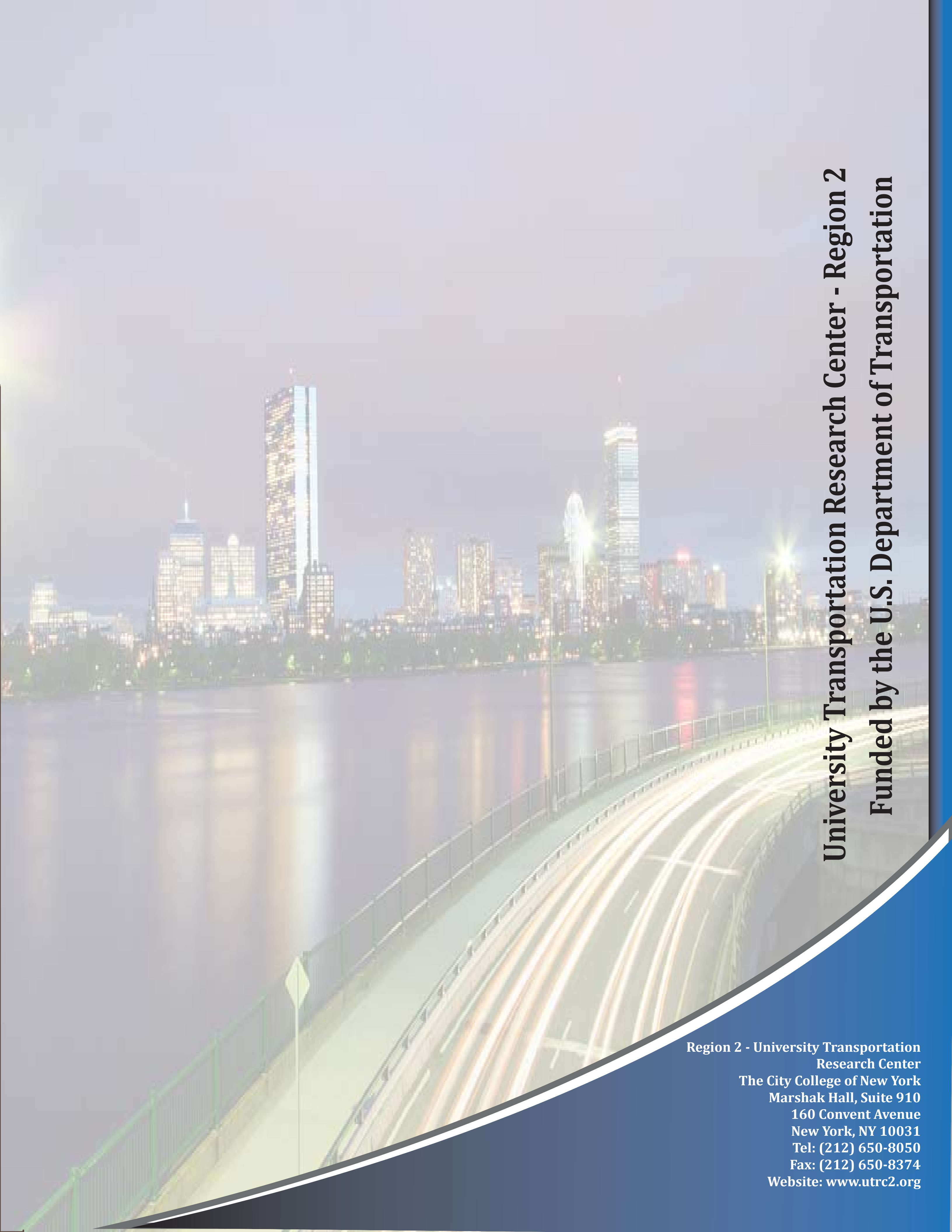
[44] Technical report, “Impact-Echo-techniques for crack depth measurement”, Sustainable Bridges, SB3.7, 2007-11-30.

[45] Markus Kruger, Christian U. Grosse, “Crack Depth Determination using Advanced Impact-Echo Techniques”, ECNDT 2006, Tu.4.2.2.

[46] Colla, C., Schneider, G., Wöstmann, J., Wiggenhauser, H. 1999. Automated Impact-Echo: 2- and 3-D imaging of concrete elements. NDT.net, Vol. 4, No. 5, 1999.

[47] Bing Li, Jing Cao, Jizhong Xiao, Xiaochen Zhang, Hongfan Wang, "Robotic Impact-echo Non-Destructive Evaluation based on FFT and SVM", Proceedings of the 11th World Congress on Intelligent Control and Automation, Shenyang, China, June 29~July 4, 2014, pp2854~2859.

[48] "Robotic Device for Navigating Inclined Surfaces", Jizhong Xiao, Kenshin Ushiroda, PCT International Patent Application Serial No. PCT US2014/026125, International Filing Date: March 18, 2014.



University Transportation Research Center - Region 2
Funded by the U.S. Department of Transportation

Region 2 - University Transportation Research Center
The City College of New York
Marshak Hall, Suite 910
160 Convent Avenue
New York, NY 10031
Tel: (212) 650-8050
Fax: (212) 650-8374
Website: www.utrc2.org