01 Jan 2020

# Semi-Annual Progress Report #6

Missouri University of Science and Technology. INSPIRE - University Transportation Center

# UTC Semi-Annual Progress Report #6

**GRANT NO:** 69A3551747126
**GRANT PERIOD:** 11/30/16 – 09/30/22
**REPORTING PERIOD:** 10/1/2019 – 3/31/2020

# Inspecting and Preserving Infrastructure through Robotic Exploration (INSPIRE)

Tier 1 University Transportation Center Sponsored by the Office of the Assistant Secretary for Research and Technology (OST-R)



| | |
|---|---|
| **Submitted to:** | U.S. Department of Transportation (USDOT) Office of the Assistant Secretary for Research and Technology (OST-R) |
| **Submitted by:** | The Curators of the University of Missouri on behalf of Missouri University of Science and Technology, 202 Centennial Hall, Rolla, MO 65409 |
| **Center Director Name and Contact Information:** | Dr. Genda Chen, P.E.<br>Email: inspire-utc@mst.edu; Tel: 573-341-6114 |
| **DUNS:** | 8048837670000 |
| **EIN Number:** | 436003859 |
| **Recipient Identifying Number:** | 00055082 |
| **Report Term or Frequency:** | Semi-annual |
| **Submission Date:** | April 30, 2020 |

**Signature of Submitting Official:** Costas Tsatsoulis

Digitally signed by Costas Tsatsoulis
Date: 2020.04.29 08:53:42 -05'00'

**Dr. Costas Tsatsoulis,** Vice Chancellor of Research and Dean of Graduate Studies, research@mst.edu; 573-341-4134

## TABLE OF CONTENTS

# 1. ACCOMPLISHMENTS

## 1.A - What Are the Major Goals of the Project?

***Center's Mission and Goals***

The mission of the INSPIRE center is to make an impactful contribution to the overall University Transportation Center Program authorized under the Fixing America's Surface Transportation (FAST) Act by providing leadership in research, education, workforce development, and technology transfer aimed at infrastructure inspection and preservation solutions with advanced sensing and robotic technologies for a sustainable and resilient transportation system. This mission becomes increasingly important in addressing greater needs for condition assessment and maintenance of bridges as natural disaster risks increase and approximately 50% of bridges in the National Bridge Inventory approach their design life.

The overarching goals of the center in five years are to transform in at least two demonstration cases from manual to automated inspection and preservation of bridges with sensors, nondestructive evaluation (NDE) devices, multi-modal unmanned vehicles, and data logistics, thus providing cost-effective, consistent, and reliable solutions in bridge condition assessment and maintenance, and to develop diverse transportation workforces mastering the advanced technologies.

***Research Objectives***

To achieve the center's goals, three research objectives of the center are set:

1. To explore, develop, validate, and demonstrate standardized-integrated measurement technologies, decision-making tools, data logistics, and autonomous systems to facilitate the field inspection and maintenance of bridges;
2. To develop, validate, and demonstrate methods of robot-enabled resilience analysis and intervention technologies (retrofit and repair) of bridges; and
3. To develop innovative tools and methods for the next-generation transportation workforce training and the general public education.

***Education Objectives***

Three education objectives are set and achieved through degree-granting programs with transportation components and transportation non-degree programs:

1. To develop new education materials related to advanced sensing and robotic technologies, such as real-world examples and cases that can reinforce the learning objectives of current curriculums, and interdisciplinary topics for senior design/capstone projects that can promote cooperative learning among students from various disciplines;
2. To create new opportunities for knowledge expansion and skill training on non-traditional civil engineering subjects, such as sensing, NDE, and bridge inspection and maintenance with robotics, which can enrich existing civil engineering programs or non-degree certificate programs; and
3. To connect students with transportation industries and professionals through center meetings, annual transportation research board (TRB) meetings, an international conference, and the external advisory committee.

***Workforce Development Objectives***

Two workforce development objectives are set and achieved through various outreach activities and close collaborations with professional organizations such as the Missouri Local Technical Assistance Program (LTAP) and the Center for Worker Education (CWE), New York:

1. To raise the public awareness of changes from adopting advanced technologies and attract new entrants from varying pipelines into transportation-related majors; and
2. To apply the robot simulator and video games developed as part of the research portfolio for a rapid and innovative workforce training of both current and prospective transportation workforces.

***Technology Transfer Objectives***

Three technology transfer objectives are set and achieved through various technology showcases to end users and perspective workforce:

1. To work in partnership with end users to facilitate technology transfer, including state and local governments, non-profit entities, and private enterprises, and assist them in mastering and implementing the developed technologies such as sensors, robots, and image analysis tools;
2. To protect intellectual properties with patent applications through the technology transfer and economic development offices and actively seek their licensing with small businesses such as InnovBot LLC; and
3. To disseminate research results through high quality peer-reviewed journals, conference proceedings, seminars/workshops/short courses, and exhibitions at TRB annual meetings and other national/international conferences.

***Diversity Objectives***

Two diversity objectives are set:

1. To broaden underrepresented minority participation through direct involvement of two minority institutions; and
2. To recruit and retain female and traditionally underrepresented minority students in close collaboration with special programs such as the activities of the Student Diversity, Outreach and Women's Programs office at Missouri S&T.

**1.B - What Was Accomplished under These Goals?**

In Year 4, the INSPIRE UTC received twelve (12) project proposals, including two (2) continuation from Year 3, and ten (10) new projects. The submitted proposals were evaluated by at least one DOT/consulting engineer and one external researcher in the proposed subject area. The evaluation results were reviewed and funding recommendations were made during the executive meeting with the INSPIRE UTC directors and External Advisory Committee on January 29, 2020. All 12 projects were awarded in April 2020.

The accompanying seven-state pooled-fund study No. TPF-5(395): Traffic Disruption-free Bridge Inspection Initiative with Robotic Systems was progressed in two tasks for bridge selection and fabrication of a combined flying and traversing robot, named BIRDS. Specifically, steel-girder bridges in the state of New York, Virginia and Wisconsin, and prestressed concrete girder bridges in Georgia, Texas, and California would be tested. In Missouri, both groups of girder bridges would be tested. The finite element model of the hybrid unmanned vehicle was established to optimize the structural design of the vehicle and understand the aerodynamic stability as the vehicle approaches a bridge girder. This understanding can help develop an effective and practical navigation strategy of the BIRDS in application, providing foundation for workforce training in vehicle operation.

Bi-monthly meetings were held with Principal Investigators (PIs) and students to provide open lines of communication within the Center, and to share important news and announcements with the research team. PIs provide research progress updates, and submit written quarterly reports to the Center.

Table 1 summarizes the major progress made in each of the research topics: sensing and nondestructive evaluation (SN), autonomous systems (AS), inspection and maintenance (IM), retrofit and resilience (RR), and workforce development (WD). Progress evaluation is done in terms of major activities, specific objectives, significant results and key outcomes/achievements.

**Table 1- A summary of research progress**

| Project | Major Activities | Specific Objectives | Significant Results | Key Outcomes |
|---|---|---|---|---|
| SN-1 | Understand the influence of steel reinforcing bars in bridge piers on the ambient magnetic field at a bridge site. | Develop a computational model for the ambient magnetic field around a bridge and validate it with experimental tests. | A good agreement between the numerical and experimental ambient magnetic fields with less than 4% error. | Completion of the final technical report and the final data report of the smart rock project. |
| SN-2 | Compare the performance of two antennas with RT/duroid®6202 and 5880 substrates. | Develop and validate an antenna sensor that can be interrogated over 30 m distance. | Fatigue behavior of dual-mode antenna sensors tested under various power sources. | Completion of the final technical and the final data report of the antenna sensor project. |
| SN-3 | Develop a parameter discrimination method using combined grating and scattering optical fiber sensors for life-cycle monitoring of structures. | Develop a LPFG sensor system for life-cycle monitoring of steel corrosion, and a method for simultaneous strain and mass loss measurement. | Success discrimination of strain and temperature by a combined in-line measurement of grating and distributing fiber optic sensors. | Completion of the final technical and final data report of the fiber optic sensor project. |
| SN-4 | Develop various types of antennas to improve sensitivity for internal defect detection. | Optimize curved horn, pyramidal horn and Vivaldi antennas, and investigate the sensitivity of the range resolution and directional antenna gain pattern. | Successful detection of the simulated delamination with foams than the simulated voids with plastic sheets by the SAR images. | Most sensitive measurement of a curved horn to the effect of plastic sheets due to its antenna gain pattern. |
| SN-5 | Develop a machine learning approach to classify mortar types and determine compressive strengths, and a test protocol to characterize the features of steel structures. | Train a support vector machine for rapid mortar classification, relate hyperspectral imagery features to mortar strength, and characterize corrosion features in steel plates. | Correct classification of mortar types by 90% with support vector machine and about 95% correlation between average reflectance and mortar strength. | Hyperspectral imaging is a promising technique for rapid assessment of early-age strength of concrete pavement and bridge decks. |
| SN-6 | Integrate advanced wireless sensing technologies into a robot platform for autonomous ultrasonic metal thickness measurement. | Develop the functionality of ultrasonic thickness measurement on a mobile platform and use vibration data for tension estimation in steel strands. | Effective thickness estimation from a 2.25 MHz dual-element transducer due to its signal strength and non-overlapping wave groups. | Guidelines for the selection of transducers, pulse generation devices and couplant materials recommended. |
| AS-1 | Verify and validate the air compressor, sound hammer and inspection, preparation and repair of holes and cracks. | Develop technical design requirements for haptic controlled drilling and assess structural condition using machine learning based vision. | Improved performance of inspection and maintenance through visual and haptic sensing. | Paper submission to American Control Conference on using haptics for hole detection with aerial manipulation. |
| AS-2 | Design and test the 3rd prototype of climbing robots that overcome the difficulty in climbing around a concave surface. | Develop a roller-chain-based or inch-worm-based design of robots to hold a NDE device during inspection. | A six degrees-of-freedom body of an inch-worm robot prototyped and tested. | Development of a switching control mechanism of robots including estimation of navigation surface. |
| AS-3 | Develop a multi-chamber rover for rough surface climbing and impact | Design and prototype a new impact solenoid and integrate it into a wall- | Design and test of a new impact solenoid for improved performance as | Success and challenges identified from field types of operation on |

| Project | Major Activities | Specific Objectives | Significant Results | Key Outcomes |
|---|---|---|---|---|
| | sounding mechanism for subsurface detection using a concrete slab with embedded delamination. | climbing robot for NDE tests on reinforced concrete structural surfaces (vertical and underside). | demonstrated from the analyzed sounding data. | curve surfaces and data collection with impact sounding. |
| AS-4 | Develop and build a solar-powered mobile test facility based on a ground vehicle to support field tests at bridge sites and provide wireless communication. | Design and build the second prototype of hybrid flying and traversing unmanned vehicle for inspection of girder bridges and for deployment of climbing robots. | The second generation of a hybrid flying and traversing vehicle designed and under evaluation. | Conceptual design of hybrid flying and traversing vehicle with potential capabilities for bridge inspection |
| IM-2 | Develop impact sounding systems and algorithms for subsurface defect detection, and evaluate their accuracy with a concrete slab specimen with embedded defects. | Develop and compare analysis algorithms of data for improved detectability of delamination in concrete slabs and further understanding of damage detection mechanisms. | Successful detection of shallow delamination and discrimination of frequency features of no delamination by the Hilbert Marginal Spectrum. | Completion of a final technical report that summarizes data analysis algorithms for the detection of delamination. |
| RR-1 | Assess the fragility of bridges, including deck, bearings, shear keys, columns, abutments, and foundation, with and without taking into account foundation scour effects. | Assess how potential measurements of scour surrounding bridge foundations affect predicted risk of the bridges to reach vulnerable damage states, particularly in layered soil deposits. | A significant increase in bridge vertical displacement under scour due to lateral soil layers with non-uniformity | Development of a new fragility analysis approach and framework to account for the local effect of layered soils on the vulnerability of bridges subject to scour. |
| WD-1 | Develop algorithms for data processing and pattern recognition, and create tools for assisting and training users on visual image data analysis. | Develop a bridge element segmentation method that can recover missing data from a single static image detector using spatial correlation of various elements. | Reduction in training time by at least 95% with significant improvement of the neural network performance. | A rapid and accurate segmentation tool for spatially correlated objects using refined transfer learning in the context of semi-supervised learning. |
| WD-2 | Refine user interface designs, finalize two-way communication between the simulator and robots, and search for genetic algorithms for near optimal inspection route. | Optimize inspection paths of multiple robots that are operated by one bridge inspector, and integrate the optimization algorithm into the Simulation Training And Control System (STACS). | Near-optimal workload paths of multiple robots produced on a truss bridge problem within a few minutes using a genetic algorithm. | A training and control interface, STACS, for human operators to oversee a team of autonomous bridge inspection robots. |

Note: to address the 1st research objective; the 2nd objective; and the 3rd objective.

**1.C – What Opportunities for Training and Professional Development Have the Program Provided?**

In this reporting period, the INSPIRE UTC directly involved 12 faculty, 3 post docs, 14 graduate students, and 7 undergraduate students in civil engineering, electrical engineering, mechanical engineering, computer science, and engineering management and system engineering through its research program with 14 projects.

The INSPIRE UTC continued to offer courses that are relevant to the research activities among consortium partners. For example, Dr. Chen offered the undergraduate/graduate course Structural Dynamics in Fall 2019 at Missouri S&T, which attracted 5 graduate and 2 undergraduate students.

**1.D - How Have the Results Been Disseminated?**

The research results from various projects were disseminated through multiple venues, including Invited Presentations, Biannual Newsletters, Quarterly Webinars, and Education and Outreach Activities.

***Invited Presentations at Professional Meetings, Workshops and Conferences***

1. Agrawal, Anil. "Investigation on Collapse of the Miami Pedestrian Bridge," Resilience, Safety, and Security of Bridges and Tunnels: U.S. and International Topics Workshop at the 99th Transportation Research Board Annual Meeting, Washington, DC, January 16, 2020.
2. Chen, Chen. "Empowering and Rejuvenating Civil Engineering with Informatics, Automation and Actuation," The 10th International Association of Chinese Infrastructure Professionals Annual Workshop on Advancing Intelligent Transportation Infrastructure at the 99th Transportation Research Board Annual Meeting, Washington D.C., January 12, 2020 (keynote presentation).
3. Tien, Iris. "The Role of Infrastructure Systems in Community Resilience," National Academies Arab-American Frontiers of Science, Engineering, and Medicine Symposium in partnership with the Library of Alexandria and the Academy of Scientific Research and Technology, Cairo Egypt, November 17-19, 2019.
4. Chen, Genda. "Robot-assisted Bridge Inspection and Maintenance", the 5th International Conference on Robotics and Artificial Intelligence, Singapore, November 22-24, 2019 (keynote presentation and conference chair).

***Biannual Newsletters***

The INSPIRE UTC publishes biannual newsletters to disseminate research information and enhance public understanding of Center activities. INSPIRE newsletters are distributed to more than 6,600 people through the Center's listserv, and are made available online at https://inspire-utc.mst.edu/news/. An INSPIRE UTC Newsletter (Vol. 3, No. 2) was published in Fall 2019 and included two technical articles related to INSPIRE research:

- *Bridge Inspection Robot Deployment Systems (BIRDS), Dr. Genda Chen, Missouri S&T*
- *A Simulation Training and Control System for Robotic Inspection of Steel Bridges, Dr. Sushil Louis, University of Nevada, Reno*

***Quarterly Webinars***

The INSPIRE UTC hosts quarterly webinars. Overall, 13 INSPIRE webinars have engaged a total of 615 people from 44 US States and 16 different countries and regions, including, Australia, Brazil, Canada, China, Germany, India, Italy, Mexico, Portugal, Serbia, Sweden, Switzerland, Taiwan, United Kingdom, and the US. On average, 53% of the participants are from academia, 20% are from industry, 18% are from Government, and 9% are unknown.

Two webinars were presented in this reporting period, and engaged a total of 106 participants:

1. Simulation Training and Route Optimization for Bridge Inspection was presented on December 4, 2019 by Dr. Sushil Louis, Computer Science and Engineering, University of Nevada, Reno.
2. Non-Contact Air-Coupled Sensing for Rapid Evaluation of Bridge Decks was presented on March 12, 2020 by Dr. Jinying Zhu, Civil Engineering, University of Nebraska Lincoln.

***Education and Outreach Activities***

Dr. Genda Chen's team hosted a one-day transportation camp on November 15, 2019, in collaboration with Mid-America Transportation Center as part of Expanding Your Horizons, Missouri S&T, MO. On February 23rd, 2020, INSPIRE UTC members attended the First Lego League Junior

Competition at the Kaleidoscope Discovery Center in Rolla, MO. Students participated in the National Society of Black Engineers Pre-College Initiative on February 29, 2020 on the S&T campus.

Dr. Hung La's team at the University of Nevada-Reno (UNR) organized several lab open-day events with assistance from undergraduate and graduate students to generate interests to both local elementary and high school students as well as DOT and industry for robotic research.

Dr. Paul Oh's team at the University of Nevada-Las Vegas (UNLV) continued to work with the neighboring Clark County Las Vegas Public Library in the Saturday K-12 programs. Lesson plans include computer-aided design (CAD), 3D printing, and embedded controllers (Arduino). Additionally, the team served institutional outreach programs, namely Upward Bound. This program is UNLV's outreach to middle school students each Saturday led by hands-on STEM labs including drone (programming), augmented reality (projection mapping), and embedded control (Arduino). The team also hosted a student internship which showcased LiDAR mapping and Augmented/Virtual Reality interfaces (such as the Microsoft HoloLens) at the Tesla Reno Gigabyte Factory by providing demos to those in the building construction community.

### 1.E - What Do You Plan to Do during the Next Reporting Period to Accomplish the Goals?

Research projects will continue in the five research categories as described in Table 1. No change will be made to the approved plan. Planned research activities are summarized in Table 2 for each of the active research projects awarded by the INSPIRE UTC.

**Table 2- A summary of planned research activities**

| Project | Project Title | Planned Activities |
|---|---|---|
| SN-4 | 3D Microwave Camera for Concrete Delamination and Steel Corrosion Detection | • Investigate antenna gain pattern effects on SAR image quality, including range resolution and directional gain pattern.<br>• Finish the final report and disseminate the research results through archived journals and conference proceedings. |
| SN-5 | Hyperspectral Image Analysis for Mechanical and Chemical Properties of Concrete and Steel Surfaces | • Continue to test steel samples to understand the transition features from non-corrosion to corrosion areas.<br>• Collect and establish a library of hyperspectral images of steel samples. |
| SN-6 | Autonomous Ultrasonic Thickness Measurement by a Magnet-Wheeled Robot | • Test a steel pedestrian bridge using the new 2.25 MHz transducer.<br>• Investigate the performance of an external ADC chip (up to 125 MHz) using a demo circuit to increase the sampling frequency of Martlet. |
| SN-7 | Health Inspection of Concrete Pavement and Bridge Members Exposed to Freeze-Thaw Service Environments | • Establishment of a spectra library.<br>• Correlation of degree of saturation and spectral signatures. |
| SN-8 | Probability of Detection in Corrosion Monitoring with Fe-C Coated LPFG Sensors | • Develop test protocols for corrosion sensor/mass loss combination. |
| AS-2 | Climbing Robots with Automated Deployment of Sensors and NDE Devices for Steel Bridge Inspection | • Investigate the deployment of climbing robots in multi-cross and curved steel bridges in Y-, K-, and I-shapes to provide autonomous robotic control in real bridges. |
| AS-3 | Autonomous Wall-climbing Robots for Inspection and Maintenance of Concrete Bridges | • Integrate the new solenoid-based impactor into a wall-climbing robot.<br>• Collect and analyze more sounding data from testing slabs in order to demonstrate the performance of the sounding device. |
| AS-4 | Bridge Inspection Robot Deployment Systems (BIRDS) | • Develop a navigation and positioning system for the multimodal vehicle. |

| Project | Project Title | Planned Activities |
|---|---|---|
| AS-5 | Nondestructive Data Driven Motion Planning for Inspection Robots | • Develop a robot localization algorithm. |
| AS-6 | A Field Deployable Wall-Climbing Robot for Bridge Inspection using Vision and Impact Sounding Techniques | • Investigate solutions to overcome limitations of current impacting mechanism.<br>• Investigate the impact sounding and impact echo instruments on robot. |
| AS-7 | Augmenting Bridge Inspection with Augmented Reality and Haptics-based Aerial Manipulation | • Prepare and test spring mount, strain gage design, and haptics device fixture.<br>• Conduct a mo-cap evaluation. |
| AS-8 | Robot-assisted Underwater Acoustic Imaging for Bridge Scour Evaluation | • Design and fabricate a dual-chamber robot that can climb on the curve surface of concrete walls and columns. |
| IM-3 | Smart Sounding System for Autonomous Evaluation of Concrete and Metallic Structures | • Develop an electronic sounding tool: further refinement for field testing.<br>• Integrated mapping and sounding data collection. |
| RR-1 | Bridge Resilience Assessment with INSPIRE Data | • Assess the performance of bridges subjected to non-uniform scour.<br>• Investigate the difference in performance across varying degrees of non-uniformity. |
| RR-2 | Data-Driven Risk-Informed Bridge Asset Management and Prioritization across Transportation Networks | • Create classes of bridges based on asset characteristics and collected inspection data. |
| WD-1 | A Training Framework of Robotic Operation and Image Analysis for Decision-Making in Bridge Inspection and Preservation | • Analyze the inference speed of the developed tool with a spatial-temporal coherence method between bridge elements in images.<br>• Test different backbone architectures to determine opportunities of accelerating the inference to have a near real time object detection. |
| WD-2 | Developing a Robotic Simulator and Video Games for Professional and Public Training | • Prepare the final technical report, final data report and other required documents of this project. |
| WD-3 | Simulation Training to Work with Bridge Inspection Robots | • Develop a real-time robot command system interface for monitoring and commanding multiple heterogeneous robots. |
| WD-4 | An Interactive System for Training and Assisting Bridge Inspectors in Inspection Video Data Analytics | • Create learning modules.<br>• Develop the inspection video analytic tool.<br>• Build the central controller. |

Note: to address the 1st research objective; the 2nd objective; and the 3rd objective.

***Other Planned Initiatives***

1. MoDOT Summer Transportation Camp: Missouri S&T will attempt to engage Lincoln University for undergraduate research and serve as host. However, due to the impact of COVID-19, the event will be evaluated at a later date.
2. Educational Module Series for undergraduate students in minor partner institutions
3. OURE with Lincoln University: If students apply without visit to the S&T campus, an attempt will be made to engage the students with undergraduate research collaborations.

## 2. PARTICIPANTS & COLLABORATING ORGANIZATIONS

### 2.A - What Organizations Have Been Involved as Partners?

***Consortium Collaborators***

The consortium members of this University Transportation Center remain the same as proposed originally. The complete list of members includes:

- Missouri University of Science and Technology - Rolla, MO (lead institution)
- City College of New York - New York, NY
- Georgia Institute of Technology - Atlanta, GA
- Iowa State University - Ames, IA
- University of Colorado at Boulder - Boulder, CO
- University of Nevada-Las Vegas - Las Vegas, NV
- University of Nevada at Reno - Reno, NV
- East Central College - Union, MO
- Lincoln University - Jefferson City, MO
- Ozarks Technical College - Springfield, MO
- St. Louis Community College - St. Louis, MO

***External Collaborators***

- Clark County Las Vegas Library https://lvccld.org
- California Department of Transportation https://dot.ca.gov
- Colorado Department of Transportation www.codot.gov
- Georgia Department of Transportation www.dot.ga.gove
- Geophysical Survey System, Inc. (GSSI) https://www.geophysical.com
- InnovBot LLC – a Spinoff Company out of the CCNY Robotics Lab
- Mid-America Transportation Center https://matc.unl.edu
- Missouri Department of Transportation http://www.modot.org
- Nevada Department of Transportation https://www.nevadadot.com/
- New York Department of Transportation https://www.dot.ny.gov
- Paul D. Thompson Consulting Services www.pdth.com
- Rice University, Department of Civil and Environmental Engineering https://ceee.rice.edu
- Stony Brook University https://www.stonybrook.edu/
- Tesla Gigafactory, Reno, NV https://www.tesla.com/gigafactory
- Texas Department of Transportation https://www.txdot.gov
- TranSystems Corporation www.transystems.com
- Turner Fairbanks Highway Research Center of FHWA, McLean, VA https://highways.dot.gov/research
- Virginia Department of Transportation https:// www.virginiadot.org/
- Wisconsin Department of Transportation https://wisconsindot.gov/Pages/home.aspx

***Internal Partners at Missouri S&T***

- Curtis Law Wilson Library/Scholars' Mine http://scholarsmine.mst.edu/
- Department of Civil, Architectural and Environmental Engineering https://care.mst.edu/
- Department of Computer Science https://cs.mst.edu
- Department of Engineering Management and Systems Engineering https://emse.mst.edu/
- Educational Technology http://edtech.mst.edu/
- Research Support Services/MinerFly Team https://itrss.mst.edu/minerfly/
- Student Diversity Initiatives http://sdi.mst.edu/
- System and Process Assessment Research (SPAR) Laboratory https://spar.mst.edu

### 2.B - Have Other Collaborators or Contacts Been Involved?

Geophysical Survey System Inc. (GSSI) granted support to the CCNY team to access their test pit to collect GPR/impact sounding data.

Dr. Agrawal of the City College of New York worked with the Federal Highway Administration (FHWA) Turner Fairbanks Highway Research Center to collect extensive amounts of sounding data.

Georgia Institute of Technology collaborated with the Department of Civil and Environmental Engineering at Rice University.

The University of Nevada, Las Vegas discussed with Tesla Gigafactory researchers on using robots for building inspection.

InnovBot LLC has received a National Science Foundation grant "SBIR Phase I: Robotic Inspection and Data Analytics to Localize and Visualize the Structural Defects of Civil Infrastructure" and will subcontract some research and development work to the City College of New York Robotics Lab.

## 3. OUTPUTS

### 3.A - Publications, Conference Papers, and Technical Reports

***Journal Publications***

1. Amjadian, M. and **Agrawal, A.** "Planar Arrangement of Permanent Magnets in Design of a Magneto-solid Damper by Finite Element Method," Journal of Intelligent Material Systems and structures, Vol. 31, No. 7, pp. 998-1014, published online February 7, 2020.
2. Cao, R., El-Tawil, S. and **Agrawal, A.** "Miami Pedestrian Bridge Collapse: A Computational Forensic Analysis," ASCE Journal of Bridge Engineering, Vol. 25, No. 1, January 1, 2020.
3. Chen, X., Wang, H., Chan, A. and **Agrawal, A.** "Dynamic Failure of Dry-joint Masonry Arch Structures Modelled with the Combined Finite-discrete Element Method," Computational Particle Mechanics, Published online November 13, 2019.
4. Chen, X., **Agrawal, A.**, El-Tawil, S., Xu, X., Cao, R. and Wong, W. "Inelastic Behavior of a Bridge Bent Subjected to Truck Impact: Experimental and Computational Study," Engineering Structures, Vol. 195, pp. 109543, Published online November 15, 2019.
5. Cook, R., Lapeyre, J., **Ma, H.** and Kumar, A. "Prediction of Compressive Strength of Concrete: A Critical Comparison of Performance of a Hybrid Machine Learning Model with Standalone Models," ASCE Journal of Materials in Civil Engineering, Vol. 31, No. 11, 04019255, doi: 10.1061/(ASCE)MT.1943-5533.0002902, November 2019.
6. Davis, N., Hoomaan, E., **Agrawal, A.**, Sanayei, M. and Jalinoos, F. "Foundation Reuse in Accelerated Bridge Construction," ASCE Journal of Bridge Engineering, Vol. 24, No. 10, 05019010, October 2019.
7. Dvorsky, M., Al Qaseer, M. and **Zoughi, R.** "Detection and Orientation Estimation of Short Cracks Using Circularly-Polarized Microwave SAR Imaging", IEEE Transactions on Instrumentation and Measurement, DOI 10.1109/TIM.2020.2978317, March 4, 2020.
8. Fan, L., Bao, Y., Tan, X., Zhang, Q., Meng, W. and **Chen, G**. "Monitoring Corrosion of Steel Bars in Reinforced Concrete Based on Helix Strains Measured from a Distributed Fiber Optic Sensor," Engineering Structures, 204: 110039, February 1 2020.
9. Farhangi, H., Konur, D., **Long, S.** and **Qin, R.** (2019) "Track Inspection Schedule Planning with Time and Safety Considerations," International Journal of Critical Infrastructures, Vol. 16, No. 3, DOI: 10.1504/IJCIS.2020.10025995, January 1, 2020.

10. Gao, Y., Ghasr, M. and **Zoughi, R.** "Complex Permittivity Extraction from Synthetic Aperture Radar (SAR) Images", IEEE Transactions on Instrumentation and Measurement, DOI 10.1109/TIM.2019.2952479, November 11, 2019.
11. Gude, V., Corns, S. and **Long, S.** "Flood Prediction and Uncertainty Estimation Using Deep Learning," Water, 12,884, doi:10.3390/w12030884, March 21, 2020.
12. Guo, C., Fan, L. and **Chen, G**. "Corrosion-Induced Mass Loss Measurement under Strain Conditions through Gr/AgNW-Based, Fe-C Coated LPFG Sensors," Sensors, March 13, 2020.
13. Hou, D., Zhang, W., Wang, P. and **Ma, H.** (2019). "Microscale Peridynamic Simulation of Damage Process of Hydrated Cement Paste Subjected to Tension," Construction and Building Materials, Vol. 228, 117053, doi: 10.1016/j.conbuildmat.2019.117053, December 20, 2020.
14. Jalinoos, F., Amjadian, M., **Agrawal, A.**, Brooks, C. and Banach, D. "Experimental Evaluation of Unmanned Aerial System (UAS) for Measuring Bridge Movement," ASCE Journal of Bridge Engineering, Vol. 25, No. 1, Paper No. 04019132, published online October 29, 2019.
15. Liao, W., Kumar, A., Khayat, K. and **Ma, H.** "Multifunctional Lightweight Aggregate Containing Phase Change Material and Water for Damage Mitigation of Concrete," Materials & Manufacturing, Vol. 6, pp. 49-61, doi: 10.30919/esmm5f606, December 2019.
16. Lapeyre, J., **Ma, H.** and Kumar, A. "Effect of Particle Size Distribution of Metakaolin on Hydration Kinetics of Tricalcium Silicate," Journal of the American Ceramic Society, Vol. 102, No. 10, pp. 5976-5988, doi: 10.1111/jace.16467, October 2019.
17. Qu, H., Li, T., Cain, J. and **Chen, G.** "Early Detection of Wire Fracture in 7-wire Strands through Multiband Wavelet Analysis of Acoustic Emission Signals," Engineering Structures, Vol. 207, 110277, March 15, 2020.
18. Sun, X., Du, Y., Liao, W., **Ma, H.** and Huang, J. "Measuring the Heterogeneity of Cement Paste by Truly Distributed Optical Fiber Sensors," Construction and Building Materials, Vol. 225, pp. 765-771, doi: 10.1016/j.conbuildmat.2019.07.187, November 20, 2019.
19. Tan, B., Okoronkwo, M., Kumar, A., **Ma, H.** "Durability of Calcium Sulfoaluminate Cement Concrete," Journal of Zhejiang University – Science A (Applied Physics and Engineering), Vol. 21, No. 2, pp. 118-128, doi: 10.1631/jzus.A1900588, February 28, 2020.
20. Tran, K., Nguyen, T. and **Agrawal, A.** "Evaluation of Bridge Abutment with Ultra-seismic Waveform Tomography: Field Data Application," Journal of Nondestructive Evaluation, Vol. 38, No. 4, Article 95, December 2019.
21. Yang, F., Yan, D., Tang, F., **Chen, G.**, Liu, Y. and Chen, S. "Effect of Sintering Temperature on the Microstructure, Corrosion Resistance and Crack Susceptibility of Chemically Reactive Enamel (CRE) Coating," Construction and Building Materials, Vol. 238, March 30, 2020.
22. Zhu, Y., Zhang, Y., Hussein, H. and **Chen, G**. "Flexural Strengthening of Reinforced Concrete Beams or Slabs Using Ultra-High Performance Concrete: A State of the Art Review," Engineering Structures, 205: 110035, February 15, 2020.
23. Zhu, Y., Zhang, Y., Hussein, H., and **Chen, G**. "Numerical Modeling for Damaged Reinforced Concrete Slab Strengthened by Ultra-High Performance Concrete Layer," Engineering Structures, December 6, 2019, https://doi.org/10.1016/j.engstruct.2019.110031.

***Books or Other Non-periodical One-time Publications – Conference Papers***

1. Ahmed, H., **La, H.** and Pekcan, G. "Rebar Detection and Localization for Non-Destructive Infrastructure Evaluation using Deep Residual Networks," 14th International Symposium on Visual Computing (ISVC), Lake Tahoe, NV, October 7-9, 2019.

2. Billah, U., Tavakkoli, A. and **La, H**. "Concrete Crack Pixel Classification using an Encoder Decoder Based Deep Learning Architecture," the 14th International Symposium on Visual Computing (ISVC), Lake Tahoe, NV, October 7-9, 2019.
3. Lee, C. and **Tien, I.** "Effect of Network Supply Connectivity on Vulnerability of Critical Infrastructure Systems," Resilience Week, San Antonio, TX, November 4-7, 2019
4. Nguyen, S. and **La, H**. "Development of a Steel Bridge Climbing Robot," Proceedings of the 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Macau, China, November 4–8, 2019. (Best Paper Finalist on Safety, Security, and Rescue Robotics)
5. Pham, A., **La, H.**, La, K. and Nguyen, M. "A Magnetic Wheeled Robot for Steel Bridge Inspection," International Conference on Engineering Research and Applications (ICERA), Thai Nguyen, Vietnam, December 1-2, 2019.
6. Vega, F. and **Oh, P.Y.** "Service Robot Navigation and Computer Vision Application in a Banquet Hall Setting," IEEE Computing and Communication Workshop and Conference (CCWC), Las Vegas, NV, January 6-8, 2020.
7. Yang, L., Li, B., Yang, G., Chang, Y., Liu, Z., Jiang, B. and **Xiao, J.** "Deep Neural Network based Visual Inspection with 3D Metric Measurement of Concrete Defects using Wall-climbing Robot," 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp.2849-2854, Macau, China, November 4-8, 2019**.**

***Final Technical Reports of Projects***

1. Anil Agrawal. Quantitative Bridge Inspection Ratings Using Autonomous Robotic Systems. Final Report No. INSPIRE-005, March 31, 2020.
2. Genda Chen, Haibin Zhang, and Zhaochao Li. UAV-enabled Measurement for Spatial Magnetic Field of Smart Rocks in Bridge Scour Monitoring. Final Report No. INSPIRE-002, April 31, 2020.
3. Genda Chen, and Chuanrui Guo. In-line Long Period Grating and Brillouin Scattering Fiber Optic Sensors for Strain, Temperature, Chloride Concentration, and Steel Mass Loss Measurement in Bridge Applications. Final Report No. INSPIRE-003, April 31, 2020.
4. Paul Oh, Blake Helmet and D. Kim. Augmenting Bridge Inspection with Augmented Reality and Haptics-based Aerial Manipulation. Final Report No. INSPIRE-004, March 31, 2020.
5. Yang Wang, and Dan Li. Battery-Free Antenna Sensors for Strain and Crack Monitoring. Final Report No. INSPIRE-001, March 31, 2020.

**3.B - Website(s) or Other Internet Site(s)**

- Advanced Robotics and Automation Laboratory: https://ara.cse.unr.edu
- INSPIRE University Transportation Center: https://inspire-utc.mst.edu
- Research in Progress Database: https://rip.trb.org/
- Evolutionary Computing Systems Laboratory: https://ecsl.cse.unr.edu/projects/bridge_inspection/index.html

**3.C - New Technologies or Techniques**

Affiliated research faculty developed the following technologies during the reporting period:

- Dr. Genda Chen's team designed the second prototype of a hybrid flying and traversing vehicle for bridge inspection and maintenance. The computational fluid model identified the turbulent flow as the vehicle approaches the bottom of a bridge girder.
- Dr. Genda Chen's team developed a support vector machine for the classification of mortar types and the estimate of early-age mortar compressive strengths from hyperspectral imaging.

- Dr. Genda Chen's team demonstrated the life-cycle performance of an integrated system of long-period fiber grating sensors for temperature, strain, and mass loss measurements.
- Dr. Ruwen Qin's team developed a new tool for efficiently, effectively detecting and segmenting multiclass bridge elements from big complex inspection video captured by mobile robotic inspection platforms. The tool is developed based on transfer learning, temporal coherence analysis, and semi-supervised self-training methods.
- Dr. Iris Tien's team developed a new technique for numerical modeling of reinforced concrete columns with short lap splices. The newly developed technique for regularization of force-based numerical elements results in accurate, robust, and consistent results across scales and the number of integration points used. The team also developed a new approach to model and assess the performance of bridges subject to scour located in layered soil profiles which account for impacts of both soil stress history and layered soil effects.
- Dr. Yang Wang's team developed a small-size ultrasonic pulser board for generating an excitation pulse at up to 300V while being powered on 9V batteries to significantly improve the signal-to-noise ratio for ultrasonic thickness detection.
- Dr. Jizhong Xiao's team developed an impacting sounding mechanism that is used to generate sounding data for nondestructive evaluation (NDE) of delamination.
- Dr. Reza Zoughi's team studied the fundamental aspects of high-frequency synthetic aperture radar (SAR) imaging as it directly relates to image resolution pertinent to NDE applications such as bridge deck delamination and corrosion in rebar detection. This fundamental study has involved the influence of antenna beamwidth and directional gain pattern on the synthetic aperture radar image resolution in the cross-range and range directions.

**3.D - Inventions, Patent Applications, and/or Licenses**

- Jizhong Xiao received Patent U.S. 10,532,781, "Robotic Device for Providing Vertical Mobility", issued on January 14, 2020, Inventors: Jizhong Xiao, Kenshin Ushiroda, Guoyong Yang, SaiadiVishnu Saniegepalli.
- Jizhong Xiao submitted a continuation-in-part of U.S. Patent Application 16/309,308, to include new inventions and claims on vertical mobility on concave and convex surfaces.

**3.E – Other Products, such as Data or Databases, Physical Collections, Audio or Video Products, Application Software or NetWare, Analytical Models, Educational Aids, Courses or Curricula, Instruments, Equipment, or Research Materials**

***Video Products***

In the reporting period, the 2 quarterly webinars were video recorded and stored at Missouri S&T's data repository site – scholarsmine.mst.edu/inspire_webinars.

***Final Data Reports of Projects***

1. Genda Chen, and Chuanrui Guo. In-line Long Period Grating and Brillouin Scattering Fiber Optic Sensors for Strain, Temperature, Chloride Concentration, and Steel Mass Loss Measurement in Bridge Applications. Data Report No. INSPIRE-003, April 31, 2020.
2. Paul Oh, Blake Helmet and D. Kim. Augmenting Bridge Inspection with Augmented Reality and Haptics-based Aerial Manipulation. Data Report No. INSPIRE-004, March 31, 2020.
3. Yang Wang, and Dan Li. Battery-Free Antenna Sensors for Strain and Crack Monitoring. Data Report No. INSPIRE-001, March 31, 2020.

***Educational Modules***

1. Anil Agrawal. Signal Processing and Sounding Data Analysis for Detecting Concrete Delamination, March 31, 2020.
2. Genda Chen. Magnetic Field, Measurement, and Application in Bridge Scour Monitoring, April 31, 2020.
3. Paul Oh. Introduction to Light Detection and Ranging (LiDAR)
4. Yang Wang. Wireless Patch Antenna Sensors for Strain and Crack Monitoring, March 31, 2020.

### 3.F - INSPIRE Research Outputs Performance Metrics

| Research Outputs - Performance Measures | Cumulative Total |
|---|---|
| 1. At least 5 journal publications and books per investigator | 6.75 |
| 2. At least 15 keynote/invited presentations delivered at national and international conferences in 5 years | 27 |
| 3. 4 webinars/year | 4/Year |
| 4. 2 NDE/sensor prototype in 5 years | 3 |
| 5. 1 robotic training simulator in 5 years | 1 |

## 4. OUTCOMES

### 4.A - Improved Processes, Technologies, Techniques and Skills

Dr. Anil Agrawal's team furthered the understanding of concrete defect detection using electronic sounding data analytics. The newly developed high-directional speaker is more portable than the mechanical impactor. Due to its simple configuration, the amplifier tube can be connected to a crawler or UAV to operate near the surface of a reinforced concrete structure and shoot high-speed sounding signal to the area of interest.

Dr. Genda Chen's team designed the second prototype of a hybrid flying and traversing vehicle that enables rapid, high quality data collections during inspection of an entire bridge system.

Dr. Hung La's team developed practical climbing robot platforms for steel bridge inspection and software for climbing robot navigation and control. The team also developed software for climbing robot navigation and control and processing robotic data and non-destructive evaluation (NDE) data. A switching control mechanism for autonomous navigation of bridge-inspection robots was also developed. This feature enhances the flexibility of navigation and inspection. The team can estimate available surface for navigation using area, plan and height availability and determine the mobile control framework and magnetic adherence distance controller that are critical in robot navigation.

Dr. Sushil Louis' team improved the route-planning algorithm and documentation for the end-to-end pipeline to convert a real-world bridge model to a representation amenable to optimization algorithms in order to produce high-quality results within a practical amount of time.

Dr. Ruwen Qin's team used a developed tool in which inspectors are not required to manually search regions of interest from big complex video data. The tool will automatically perform this task and allow inspectors to concentrate on knowledge-intensive tasks of bridge inspection.

Dr. Iris Tien's team finalized work and submitted a journal publication on utilizing scour inspection data to update the assessment and prediction of the performance of bridges in layered soils. The method can be used to quantify the risk associated with varying levels of scour for bridge in layered soils in

which a significant increase in bridge vertical displacement under scour was found compared with an unmodified soil modeling approach. The impact of soil stress history and layered soil effects was quantified through nonlinear time history analyses and seismic fragility assessments.

Dr. Yang Wang's team established a specialized 2.25Mhz dual element transducer that provides a good thickness measurement of thinner plates, using water couplant. The 400 volt pulser assists in offering a significantly higher signal-to-noise ratio that improves the accuracy of thickness measurement. A small-size ultrasonic pulser board was developed which may product up to 300V using 9V batteries which has significantly improved the signal-to-noise ratio for thickness detection.

Dr. Jizhong Xiao's team modified the climbing robot design to integrate the new solenoid-based impact sounding device on the robot base, and produced a prototype with new cover that has groove to be carried by a UAV manipulator.

Dr. Reza Zoughi's team found that antenna gain pattern influences the spatial and range resolution of synthetic aperture radar (SAR) imaging technique for NDE applications. The reason for this influence has been fully analyzed and the related formulas in SAR imaging theory are updated and improved. This process resulted in improved understanding of the SAR imaging technique and its applicability to NDE of concrete structures.

### 4.B - INSPIRE Research Outcomes Performance Metrics

| Research Outcomes – Performance Measures | Cumulative Total |
|---|---|
| 1. 1 recommended federal policy change on bridge inspection frequency | 0 |
| 2. At least 1 manual of practice related to inspection/preservation with mobile robots in 5 years (recommended policy change for inspection protocol) | 0 |

## 5. IMPACTS

Dr. Anil Agrawal's team improved the efficiency of current defect detection for concrete structures by developing automated impact sounding tools. A software module in MATLAB will facilitate the implementation of the approach for practical applications. It was found that the noise generated by the wall-climbing crawler itself can be used for detecting damages in concrete and metallic structures.

Dr. Genda Chen's team developed a support vector machine for the classification of mortar types and the determination of compressive strength from hyperspectral features, which enables early-age strength estimation and type identification of pavements. Dr. Genda Chen's team also developed a life-cycle corrosion monitoring technique using a combination of grating and scattering fiber optic technologies for a rapid, spatial distribution of corrosion along steel members.

Dr. Yang Wang's team developed an innovative robotic sensing technology that can autonomously perform ultrasonic thickness measurement on steel bridge members.

Dr. Sushil Louis' team uses a computational tool, STACS, to help reduce the total cost of a bridge inspection by significantly reducing the number of human operators needed to perform a bridge inspection. A team of several robots can be utilized to reduce the number of operators, which leads to salary savings and efficiency and thus to more frequent inspections and safer bridge infrastructure.

Dr. Hung La's team developed a switching control mechanism for autonomous navigation of bridge-inspection robots which was designed with a unique feature of switching in two modes to enhance the flexibility of navigation and inspection of automated bridge inspection efforts. The team introduced

novel concepts of robotic sensing, localization and navigation in confined space or complex steel structure, which advances existing work and provides an implementable tool to enable automated bridge inspection and evaluation process.

Dr. Paul Oh's team tested, evaluated, verified and validated robotic platforms including the design, development and deployment of unique aerial manipulators in the aerial manipulation area.

Dr. Ruwen Qin's team developed tools that will make data-driven asset management of bridges possible and increase the work efficiency of inspectors by 99%. The tool development process is reduced by 85% compared to existing practices.

Dr. Iris Tien's team developed a regularization approach for accurate, robust, and consistent computational modeling of reinforced concrete columns with short lap splices, which addresses the scaling, convergence, and finite element size issues.

Dr. Reza Zoughi's team work provides a fundamental description of expected image resolution for SAR imaging techniques. This knowledge will significantly impact the system design parameters when implementing SAR imaging techniques in many industries including inspecting of concrete structures.

Dr. Jizhong Xiao's team selected and tested a new impact solenoid on the wall-climbing robot and produced preliminary results that are promising in subsurface pipeline applications.

**5.B - Initiation/Strengthening of a Start-up Company**

Dr. Hung La's team established a start-up company, Automated Inspection Robots (AIR) Corp. in January 2020.

Dr. Jizhong Xiao's team developed a new prototype as a complete, self-contained robotic NDE tool with vertical mobility that carries an RGB-D camera, GPR sensor and impact sounding device to detect surface flaws and subsurface defects. InnovBot LLC is a CUNY spin-off company founded by Prof. Xiao that dedicated to the commercialization of wall-climbing robot technologies.

**5.C - The Body of Scientific Knowledge**

Dr. Genda Chen's team developed a further understanding of the corrosion mechanism of Fe-C coated LPFG sensors that are integrated into coaxial steel tubes for both short- and long-term corrosion assessment. The Fe-C composition is similar to that of the steel member to be monitored and the steel tube has the same materials as the steel member. Each LPFG sensor has two steps. The initial step occurred as chloride ions penetrated through the depth of the Fe-C layer and the last step happened after the chloride ions reached the surface of optical fiber and spread laterally along the length of the fiber, thus accelerating the corrosion process.

Dr. Hung La's team introduced novel concepts of climbing robot design and implementation, robotic sensing, localization and navigation, which advances the existing work and provides the research community with a new and implementable tool to enable automated bridge inspection and evaluation process. The proposed rigorous magnetic force analysis can serve as a framework to calculate and design different types of steel inspection robots.

Dr. Sushil Louis' team mapped multi-robot bridge inspection to the well-known and computationally intractable MinMax K-Chinese postman problem. The solution to the problem will significantly improve the Genetic Algorithm approach that increases utility to the current issue and other related problems in

Arc Routing and Discrete Optimization. The team also developed new functionality in the STACS software to perform a mock inspection task to train human operators in using the system.

Dr. Paul Oh's team used a human-in-the-loop approach that is focused on the convergence of information technologies to improve US economic competitiveness.

Dr. Ruwen Qin's team researched collaborative artificial and human intelligences that can assist each other to become more powerful and capable than individuals.

Dr. Iris Tien's team developed a method for accurate, robust, and consistent numerical modeling of reinforced concrete columns with short lap splices. The developed regularization approach can be used in other modeling problems, where there are issues with objectivity of results based on scaling, convergence, and finite element size impacts.

Dr. Yang Wang's team developed new knowledge on autonomous ultrasonic thickness measurement technology for bridge monitoring which has the potential to be adopted in bridge monitoring practices.

Dr. Jizhong Xiao's team developed robotic hardware and NDE data analysis software that are likely to increase the knowledge base and address robotic inspection challenges on a variety of infrastructures, for example, the wall-climbing robot by providing vertical mobility to conduct NDE on difficult-to-access locations. The proposed image processing algorithms will enable the robot to acquire knowledge and increase intelligence for autonomous operation, while the impact sounding technology will provide an alternative way for detection of delamination.

Dr. Reza Zoughi's team improved the theory of SAR imaging technique by updating electromagnetic expressions which now include an antenna gain pattern factor. The new theory was corroborated by performing electromagnetic simulations, which are validated by experimental results from concrete delamination detection.

**5.D - Transportation Workforce Development**

Dr. Genda Chen of Missouri University of Science and Technology taught an undergraduate/graduate course on CE5280 Structural Dynamics, which is relevant to the analysis of bridges under dynamic loads. Dr. Chen trained five graduate students on four INSPIRE UTC projects.

Dr. Hung La of University of Nevada Reno introduced automated infrastructure inspection concepts using robots into the current robotics courses: CPE470/670-Autonomous Mobile Robots, CS791-Special Topics on Robotics, and CS455/655-Mobile Sensor Networks. He is also developing a new course: CPE471/671 Advanced Robotics. The team organized several lab open day events with assistance from undergraduate and graduate students to generate robotic interests. The undergraduate and graduate students fully participated in all phases of the project and received training through hands-on design, fabrication, prototyping and programming of the robots.

Dr. Sushil Louis of the University of Nevada Reno graduate and undergraduate students have developed the STACS software interface, as well as tested and improved the Genetic Algorithm for route planning, the writing of data generating tools, developed a pipeline for real-world bridge inspections and written papers for submission to international conferences. The team began to develop test cases in the STACS training software to teach human operators to use the software, and receive training to oversee a team of robots during a bridge inspection task. The training task is expected to be a good approximation of real-world bridge inspection, utilizing a team of heterogeneous robots to cooperatively inspect a bridge which will assist and refresh in workforce development and skills training. One MS degree student graduated during the reporting period.

Dr. Ruwen Qin of Missouri S&T developed the skill to collaborate closely with artificial intelligence by engaging the development of the tool for detecting and segmenting multiclass bridge elements from inspection video data. This collaboration effectively addresses the limitation of artificial intelligence, highlighting the critical role of transportation workers for future bridge inspection and maintenance.

Dr. Iris Tien of Georgia Institute of Technology provided opportunities to graduate trainings in research activities in transportation, written communication of research results (preparing, editing, and revising manuscripts for publication), and oral communication (oral presentations at professional conferences).

Dr. Yang Wang of Georgia Institute of Technology offered one female graduate student work on transportation-related research with faculty associated with the university transportation center.

Dr. Jizhong Xiao of the City College of New York inspired innovation and supported the training of traditionally underrepresented students (undergraduate and graduate) to meet the critical need for sustainable infrastructure.

### 5.E - INSPIRE Impacts Performance Metrics

| Research Impacts – Performance Measures | Cumulative Total |
|---|---|
| 1. At least 50% reduction of the total cost of a traditional in-depth bridge inspection that requires the use of heavy lifting equipment. | 0 |
| 2. At least 5 patents generated in 5 years and at least 1 associated technology applied in practice. | 6 |

## 6. CHANGES/PROBLEMS

### 6.A - Changes in Approach and Reasons for Change

***COVID-19 Impact on Research Approach***

Except for Iowa State University, all project investigators stretched their time in conducting computational modeling and simulation as well as literature search and paper preparation while holding off experimental works due to no laboratory access.

Drs. Anil Agrawal and Jizhong Xiao's campus at City College of New York is in telework mode from home, focusing on the 3D printing enclosure design of an impact sounding tool, CAD modeling and software programming, and the preparation of a journal manuscript based on prior work.

Dr. Hung La and Dr. Sushil Louis' campus at the University of Nevada, Reno is in telework mode continuing with computational work only.

Dr. Paul Oh's campus at the University of Nevada, Las Vegas is in telework mode, continuing computational work.

Dr. Genda Chen and Ruwen Qin's campus at Missouri S&T is in telework mode continuing computational work on related projects and providing bi-weekly project updates via zoom meeting.

Dr. Iris Tien and Yang Wang's campus at Georgia Institute of Technology is in telework mode, remotely continuing computational work and finishing circuitry design, simulations and simple prototyping.

Dr. Reza Zoughi's campus at Iowa State University allows access to facilities by following provided guidelines though faculty are encouraged to work remotely. Little impact is observed on the project development of analytical/numerical model variations for assessing range resolution in SAR images.

**6.B - Actual or Anticipated Problems or Delays and Actions or Plans to Resolve Them**

***COVID-19 Impact on Research Progress Delay***

In general, computational modeling and simulation work continues with little impact. But most of experimental works are on hold.

Dr. Genda Chen's work on hardware integration and prototyping of robots and unmanned aerial vehicles are on hold.

Dr. Hung La and Dr. Sushil Louis' work related to hardware integration, robot part manufacturing, robot test and validation is on hold. The investigation of workforce training software is also difficult since social distancing makes it impossible to observe users' interaction with data in the laboratories.

Dr. Ruwen Qin's computational work on multiple workstations simultaneously becomes less efficient.

Dr. Yang Wang's project progress is expected with delay due to the COVID-19.

**6.C - Changes that Have a Significant Impact on Expenditures**

Dr. Jizhong Xiao's visiting scholar left the project team. Dr. Xiao is currently in the process of recruiting new students/visiting scholars to continue design tasks.

***COVID-19 Impact on Research Expenditure***

Research students and faculty are paid based on the actual work completed. In general, work efficiency of the research projects is at approximately 50%. For all INSPIRE projects, the completion of the scopes during the COVID-19 period remains uncertain.

Dr. Anil Agrawal's campus projected absence from campus until July-August 2020.

Dr. Hung La's expenditures on robotic, sensor and other related components has been delayed.

Dr. Paul Oh's travel has ceased for all university business, work and research at this time.

Dr. Jizhong Xiao's trip to Turner-Fairbank Highway Research Center was postponed due to travel restrictions.

Dr. Yang Wang's travel restrictions may extend into the summer, impacting expenditures associated with the minority student exchange program with City College of New York and the student visit to the University of Nevada, Reno.

**6.D - Significant Changes in Use or Care of Human Subjects, Vertebrate Animals, and/or Biohazards**

Nothing to report.

**6.E - Change of Primary Performance Site Location from That Originally Proposed**

Nothing to report.