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

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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)

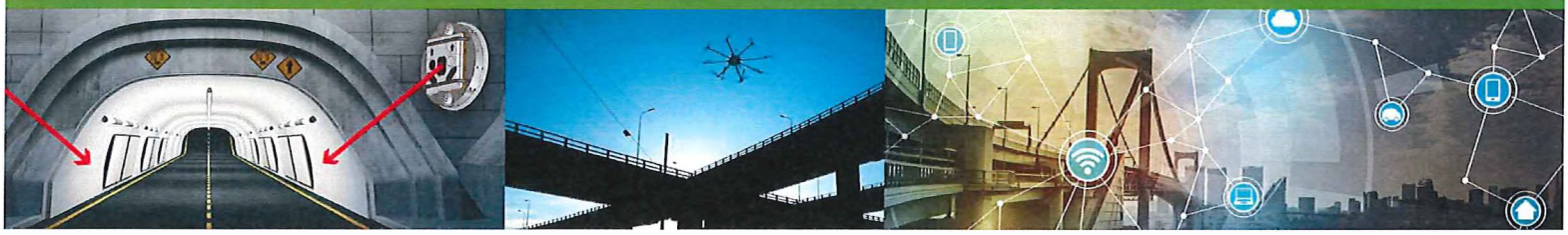

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TABLE OF CONTENTS

1. ACCOMPLISHMENTS 3
1.A - What Are the Major Goals of the Project? 3
1.B - What Was Accomplished under These Goals? 4
1.C – What Opportunities for Training and Professional Development Have the Program Provided? . 7
1.D - How Have the Results Been Disseminated? 7
1.E - What Do You Plan to Do during the Next Reporting Period to Accomplish the Goals? Describe briefly what you plan to do during the next reporting period to accomplish the goals and objectives 8
2. PARTICIPANTS & COLLABORATING ORGANIZATIONS 10
2.A - What Organizations Have Been Involved as Partners? 10
2.B - Have Other Collaborators or Contacts Been Involved? 11
3. OUTPUTS 11
3.A - Publications, Conference Papers, and Presentations 11
3.B - Website(s) or Other Internet Site(s) 15
3.C - New Technologies or Techniques 16
3.D - Inventions, Patent Applications, and/or Licenses 16
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 16
3.F - INSPIRE Research Outputs Performance Metrics 17
4. OUTCOMES 17
4.A - Improved Processes, Technologies, Techniques and Skills 17
4.B - INSPIRE Research Outcomes Performance Metrics 18
5. IMPACTS 18
5.B - Initiation/Strengthening of a Start-up Company 18
5.C - The Body of Scientific Knowledge 19
5.D - Transportation Workforce Development 19
5.E - INSPIRE Impacts Performance Metrics 20
6. CHANGES/PROBLEMS 20
6.A - Changes in Approach and Reasons for Change 20
6.B - Actual or Anticipated Problems or Delays and Actions or Plans to Resolve Them 20
6.C - Changes that Have a Significant Impact on Expenditures 20
6.D - Significant Changes in Use or Care of Human Subjects, Vertebrate Animals, and/or Biohazards 20
6.E - Change of Primary Performance Site Location from That Originally Proposed 20

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?

The INSPIRE UTC received twelve (12) project proposals for possible funding in Year 4, including two (2) continuations from Year 3, and ten (10) new projects. The submitted proposals will be evaluated by at least one DOT/consulting engineer and one external researcher in the proposed subject area. Every effort was made to avoid the conflict of interest during the review process. Reviewers will submit their evaluation results to the Center Director, and funding recommendations will be made during an executive meeting with the INSPIRE UTC directors and External Advisory Committee in December 2019. Once awarded, Year 4 projects will be posted to the Center's website and to the RiP Database.

The INSPIRE UTC held its annual meeting on August 4-7, 2019 in conjunction with the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), St. Louis, MO. Technical presentations were made as part of the SHMII-9 Conference, allowing the INSPIRE PIs to share their research results and seek feedbacks from international participants. The business meeting within the INSPIRE UTC was held at the end of the SHMII-9 Conference, including the kickoff of the TPF (5)-345 Pooled-Fund Study with representatives from seven (7) state departments of transportation.

Bi-monthly meetings were held with Principal Investigators (PIs) 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

Topic	Major Activities	Specific Objectives	Significant Results	Key Outcomes
SN	1. Develop a localization algorithm for more than one smart rocks deployed in close distance and continue with field validation tests. 2. Compare the performance of two antenna sensors with RT/duroid®6202 and 5880 substrates and conduct the multi-physics simulation of antenna sensors. 3. Develop a parameter discrimination method using one LPFG sensor with different cladding modes and evaluate the performance of distributed fiber optic sensors in large-scale composite beams. 4. Develop various types of antennas to improve sensitivity for internal defect detection. 5. Develop a test protocol to characterize the features of concrete structures. 6. Integrate advanced wireless sensing technologies into a robot platform for autonomous ultrasonic metal thickness measurement.	1. Develop a UAV platform for magnetic field measurement and characterize field performance of smart rocks for bridge scour monitoring. 2. Develop and validate an antenna sensor that can be interrogated over 30 m distance. 3. Develop a LPFG sensor system for life-cycle monitoring of steel corrosion, and a simultaneous strain and mass loss measurement method. 4. Develop and optimize a Vivaldi antenna and a double-ridged horn antenna through simulations and experiment, and investigate the nonlinear effect of distributed rebar on corrosion detectability. 5. Understand the characteristics of mortar samples with various water-cement ratios using hyperspectral imaging and machine learning. 6. Develop the functionality of ultrasonic thickness measurement on a mobile platform and use vibration data for tension estimation in steel strands.	1. Consistent smart rock positioning obtained through additional field tests. 2. Fatigue behavior of dual-mode antenna sensors tested under various power sources. 3. Three Fe-C coated LPFG sensors and one dual-mode (6th and 7th) LPFG sensor inside three coaxial steel tubes for strain, temperature, and mass loss measurements in life-cycle evaluation. 4. Vivaldi and ridged horn antennas designed, simulated and fabricated for testing, and electromagnetic simulations done to determine the influence of corrosion on rebar resonant properties. 5. Support vector machine used to classify the types of mortar and determine the mortar strength. 6. A 2.25 MHz dual-element transducer is required, taking into account the natural frequency, bandwidth, damping ratio and internal electric circuit.	1. Implementation of one smart rock in bridge scour application. 2. Strain sensing performances of a dual-mode antenna sensor under various power sources. 3. Coaxial steel tubes protecting inside LPFG sensors and providing critical corrosion stages in the life cycle of steel with corresponding corrosion rate. 4. An equivalent circuit model for the nonlinear effect of rebar—rebar contact evaluated with the 3rd-order harmonics from a microwave. 5. Hyperspectral imaging for early-age strength estimation of concrete pavement. 6. Transmitting and receiving of an ultrasonic sensing board on the Martlet wireless unit successfully tested on a Georgia Tech mobile robot.

Topic	Major Activities	Specific Objectives	Significant Results	Key Outcomes
AS	1. Design and deploy UAVs equipped with robotic limbs to augment bridge maintenance. 2. Design, simulate and test the 3rd prototype of climbing robots that overcome the difficulty in climbing around a concave surface. 3. Develop a multi-chamber rover for rough surface climbing and impact sounding mechanism for subsurface detection using a concrete slab with embedded delamination. 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.	1. Integrate operator expertise in performing bridge-related maintenance through visual and haptic sensing needed during bridge inspection, maintenance and repair. 2. Develop a roller-chain-based or inch-worm-based design of robots with a 5-DOF arm to hold a NDE device during inspection. 3. Design a wall-climbing robot suction mechanism effective for both convex and concave surfaces, and an impact sound system that can slide along a guided track for continuous sampling. 4. Design and prototype a Hybrid flying and traversing unmanned vehicle for inspection of girder bridges and for deployment of climbing robots.	1. Augmented and virtual reality giving operators an immersive presence while inspecting and repairing bridges. 2. A more efficient design of robot to ensure it can climb on complex steel structures or transition from one surface to another whole supporting a NDE device. 3. Demonstrated field performance of the robot suction mechanism on a wind turbine blade, and impact sounding data collection from a concrete slab. 4. The first generation of a hybrid flying and traversing vehicle tested successfully for manual switch between flying and traversing modes.	1. Testing and evaluation of air compressor, sound hammer, and repair of holes and cracks. 2. Eddy Current sensor integration into the climbing robot to collect data with real-time observation on operation and inspection. 3. Success and challenges identified from field types of operation on curve surfaces and data collection with impact sounding. 4. A feasible new concept of hybrid flying and traversing vehicle for bridge inspection and maintenance.
IM	1. Develop impact sounding systems for subsurface defect detection and algorithms for delamination detection, and evaluate their accuracy with a concrete slab specimen with defect holes.	1. Develop new fusion strategies of data collected from multiple NDE devices for improved POD based on further understanding and modeling of damage detection mechanisms.	1. Mixed modes of signals found in both solid and delamination areas using the EMD method mainly because the sounding source used generated compression waves in all directions.	1. Directional speaker needed and prototyped based on the analysis of electronic chirp sounding signals between solid and shallow-delaminated areas of a concrete slab.
RR	1. Assess the fragility of bridge systems, including deck, bearings, shear keys, columns, abutments, and foundation, with and without taking into account foundation scour effects.	1. Advance the modeling for risk assessment of bridges vulnerable to scour in layered soils, particularly taking into account varying levels of scour in layered soil profiles.	1. Soil stress history and scour hole dimension effects identified from soil removal during scour, and effect of a layered soil profile observed.	1. Local effect of foundation scour on the risk assessment of bridges considered through the change of surrounding soil profile and stress history.

Topic	Major Activities	Specific Objectives	Significant Results	Key Outcomes
WD	1. Develop algorithms for data processing and pattern recognition, and create tools for assisting and training users on visual image data analysis. 2. Refine user interaction and user interface designs, finalize two-way communication between the simulator and robots, and search for genetic algorithms for optimal or near optimal inspection route.	1. Develop a bridge element segmentation method that can recover missing data from a single static image detector using temporal information of successive frames. 2. 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).	1. Significant reduction in false negative detection of features from segmented images using the new bridge element segmentation method. 2. Promising results from an evolutionary computing approach for near-optimal, balanced workload paths in a reasonable amount of time.	1. An assistive model that uses collaborative human and artificial intelligences for segmenting important bridge elements and improving the offline trained model iteratively to refine image segmentation quality. 2. The genetic algorithms for inspection route optimization of multiple robots integrated into STACS.

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 7 undergraduate and 22 graduate students through its research program. Its two (June and September) webinars received a total of 88 participants.

1.D - How Have the Results Been Disseminated?

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 5,800 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. 1) was published in Spring 2019 and included two technical articles related to INSPIRE research:

- *Wireless Strain Measurement Using An Antenna Sensor, Dr. Yang Wang, Georgia Institute of Technology*
- *UAV-Enabled Smart Rock Positioning for Bridge Scour Monitoring, Dr. Genda Chen, Missouri S&T*

Quarterly Webinars

The INSPIRE UTC hosts quarterly webinars. Overall, 9 INSPIRE webinars have engaged a total of 509 people from 44 US States and 15 different countries, including Australia, Brazil, Canada, China, Germany, India, Italy, Mexico, Portugal, Serbia, Sweden, Switzerland, Taiwan, United Kingdom, and the US. On average, 56% of the participants are from academia, 21% are from industry, 18% are from Government, and 5% are unknown.

Two webinars were presented in this reporting period, and engaged a total of 88 participants:

1. A Performance-Based Approach for Loading Definition of Heavy Vehicle Impact Events was presented on June 5, 2019 by Dr. Anil Agrawal, Structural and Bridge Engineering, City College of New York.
2. Data to Risk-Informed Decisions through Bridge Model Updating was presented on September 25, 2019 by Dr. Iris Tien, School of Civil and Environmental Engineering, Georgia Institute of Technology.

International Conference

On August 4, 2019, the INSPIRE UTC co-sponsored a workshop and a short course with the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), St. Louis, MO, which engaged a total of 31 participants.

1. A six-hour short course, *Strain-Based Structural Health Monitoring Using Fiber Optic Sensors,* was presented by Dr. Branko Glisic of Princeton University.
2. A three-hour workshop, *Structural Health Monitoring Education,* was offered by Dr. Vijay Gopu of Louisiana State University.

During the SHMII-9 Conference, 21 papers were presented by the INSPIRE UTC investigators. They are listed in Section 3A.

Education and Outreach Activities

Dr. Paul Oh's team at University of Nevada-Las Vegas (UNLV) continues 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 serves 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 participated in the Nevada-wide Robotics STEM program sponsored by Tesla, which is an event brought to over 50 K-12 science teachers for intensive training.

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

Topic	Project Title	Planned Activities
SN	UAV-enabled Measurement for Spatial Magnetic Field of Smart Rocks in Bridge Scour Monitoring	• Continue to validate the field performance of smart rocks in bridge scour monitoring and characterize the effects of various influence factors. • Process the field test data with two smart rocks for repeatability of test results.
	In-line Long Period Grating and Brillouin Scattering Fiber Optic Sensors for Strain, Steel Mass Loss, and Temperature Measurement in Bridge Applications	• Package Fe-C coated and regular LPFG sensors in three coaxial thin-walled steel tubes for critical corrosion threshold measurements and their corresponding corrosion rate measurement, taking into account strain and temperature effect. • Document the technical specifications of the packaged sensors for potential field installation and demonstration.
	3D Microwave Camera for Concrete Delamination and Steel Corrosion Detection	• Use the fabricated Vivaldi and ridged horn antennas for delamination detection in a reinforced concrete slab. • Investigate and use a circuit model to simulate the metal-metal contact

Topic	Project Title	Planned Activities
		nonlinear effect to verify the harmonic measurement method theoretically. • Develop with an array of the Vivaldi antennas an adaptive SAR imaging algorithm that allows for "higher synthetic aperture gain" at lower frequencies while generating higher resolution images at higher frequencies.
	Hyperspectral Image Analysis for Mechanical and Chemical Properties of Concrete and Steel Surfaces	• Continue to test concrete specimens based on the developed metric to understand their surface characteristics, e.g., early-age strength measurement. • Collect and establish a library of hyperspectral images of the specimens. • Test steel specimens to investigate the feasibility of hyperspectral imaging for corrosion monitoring.
	Autonomous Ultrasonic Thickness Measurement by a Magnet-Wheeled Robot	• Advance the previously designed wireless sensing device for ultrasonic thickness measurement. • Design and test a push-pull mechanism for a transducer to attach firmly on the surface of a steel member. • Validate the performance of the wireless device on a robot platform for ultrasonic thickness measurement extracted from received ultrasonic signals.
AS	Mobile-manipulating UAVs for Sensor Installation, Bridge Inspection and Maintenance	• Continue to trade studies and risk assessment for the human-in-the-loop tele-operation of drones for bridge inspection and repair. • Improve a force transducer for accurate haptic force measurements and the 3D systems touch sensor's support for constrained motion.
	Climbing Robots with Automated Deployment of Sensors and NDE Devices for Steel Bridge Inspection	• Improve the 3rd climbing robot design and then manufacture its prototype. • Refine the 3D simulation design in SolidWork to test the robot in various climbing scenarios (e.g., rusted and curve surfaces, and bolt and joint passing). • Test the robotic prototype with the STACS for learning, monitoring, and control for various actions.
	Autonomous Wall-climbing Robots for Inspection and Maintenance of Concrete Bridges	• Design a 5-DOF arm to be installed on the robot to facilitate camera positioning and manipulation tasks • Investigate the causes for weak sound generated by the solenoid-based impactor and propose a solution to fix the problem.
	Bridge Inspection Robot Deployment Systems (BIRDS)	• Develop technical specifications of the hybrid flying and traversing unmanned vehicle for flying, traversing, and their transition performance. • Improve the autonomous operation of the hybrid vehicle for inspection of girder bridges.
	Quantitative Bridge Inspection Ratings using Autonomous Robotic Systems	• Continue to process impact sounding data from the reinforced concrete slab with pre-engineered defects. • Test large steel girders of bridges with various types of defects for effectiveness of defect detection with impact sounding. • Develop a software module in MATLAB for quick analysis of the impact sounding data, which will be implemented in autonomous inspection.
RR	Bridge Resilience Assessment with INSPIRE Data	• Investigate and quantify the effect of varying soil properties on bridge vulnerabilities due to scour. • Conduct the dynamic analysis of bridges in varying soil conditions.
WD	A Training Framework of Robotic Operation and Image Analysis for Decision-Making in Bridge Inspection and Preservation	• Use the spatial correlation between bridge elements in an image to further improve the quality of multiclass object detection and minimize the size of the initial training dataset. • Explore different backbone architectures for accelerated inferences in order to have a near real time object detection.
	Developing a Robotic Simulator and Video Games for Professional and Public Training	• Update the 3rd iteration of STACS development testing with the latest changes in robot designs. • Refine and improve the genetic algorithm for more accurate and faster results on larger problem instances.

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

Other Planned Initiatives

1. On November 15, 2019, the INSPIRE UTC and MATC will host a one-day transportation camp as part of Expanding Your Horizons, Missouri S&T, MO.
2. On November 22nd-24th 2019, Dr. Genda Chen, INSPIRE UTC Director, will deliver a keynote presentation titled, *"Robot-assisted Bridge Inspection and Maintenance"* and serve as Program Co-Chair at the 5th International Conference on Robotics and Artificial Intelligence
3. On February 23rd, 2020, Dr. Genda Chen, INSPIRE UTC Director, will attend the First Lego League Junior Competition at the Kaleidoscope Discovery Center in Rolla, MO.

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. But one subcontract was initiated during this reporting period for Dr. Reza Zoughi due to his move from Missouri University of Science and Technology to Iowa State University. 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
- University of Colorado at Boulder - Boulder, CO
- Iowa State University-Ames, IA
- 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

- InnovBot LLC - CCNY Robotics Lab
- Department of Civil and Environmental Engineering at Rice University https://ceee.rice.edu
- Tesla Gigafactory, Reno, NV https://www.tesla.com/gigafactory
- The Las Vegas office of the Desert Research Institute (DRI)
- 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
- Missouri Department of Transportation http://www.modot.org
- Nevada Department of Transportation https://www.nevadadot.com/
- Texas Department of Transportation https://www.txdot.gov
- New York Department of Transportation https://www.dot.ny.gov
- TranSystems Corporation www.transystems.com
- Geophysical Survey System, Inc.

- Paul D. Thompson Consulting Services www.pdth.com
- Turner Fairbanks Highway Research Center of FHWA, McLean, VA
- Rice University

Internal Partners at Missouri S&T

- Department of Civil, Architectural and Environmental Engineering http://care.mst.edu/
- Department of Engineering Management and System Engineering https://emse.mst.edu/
- Missouri S&T Virtual Reality Laboratory
- Research Support Services/MinerFly Team https://itrss.mst.edu/minerfly/
- Student Diversity Initiatives http://sdi.mst.edu/
- Educational Technology http://edtech.mst.edu/
- Curtis Law Wilson Library/Scholars' Mine http://scholarsmine.mst.edu/
- Mid America Transportation Center

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

The City College of New York sent two undergraduate students from underrepresented group, Marcos Fermin and Carlos Cedeno, for a 10-week summer internship at Georgia Institute of Technology.

Geophysical Survey System Inc. (GSSI) granted the CCNY team to access their test pit to collect GPR data and hired a summer intern.

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. The Las Vegas Office of the Desert Research Institute (DRI) lent the team one of their multi-spectral sensors for data acquisition

InnovBot LLC has received a NSF 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 Presentations

Journal Publications

1. Brinker, K., M. Vaccaro and **R. Zoughi**. "Application-Adaptable Chipless RFID Tag: Design Methodology, Metrics, and Measurements," IEEE Transactions on Instrumentation and Measurement, [(DOI 10.1109/TIM.2019.2938131)], August 2019.
2. Cao, R., **A. Agrawal**, S. El-Tawil, X. Xu, and W. Wong. "Performance-Based Design Framework for Bridge Piers Subjected to Truck," ASCE Journal of Bridge Engineering, 24(7): 04019064, July 2019.

3. Cao, R., S. El-Tawil, **A. Agrawal**, X. Xu, and W. Wong. "Behavior and Design of Bridge Piers Subjected to Heavy Truck Collision," ASCE Journal of Bridge Engineering, 24(7): 04019057, July 2019.
4. Cao, R., **A. Agrawal**, S. El-Tawil, X. Xu, and W. Wong. "Heavy Truck Collision with Bridge Piers: Computational Simulation Study," ASCE Journal of Bridge Engineering, 24(6): 04019052, June 2019.
5. Cimellaro, G., P. Crupi, H. Kim, and **A. Agrawal**. "Modeling Interdependencies of Critical Infrastructures after Hurricane Sandy," International Journal of Disaster Risk Reduction, 38: 101191. August 2019.
6. Dang, A., **H. La**, T. Nguyen, and J. Horn. "Formation Control for Autonomous Robots with Collision and Obstacle Avoidance Using a Rotational and Repulsive Force Based Approach," International Journal of Advanced Robotic Systems, 16(3): 1729881419847897, May 2019. USDOT/INSPIRE UTC support acknowledged.
7. Fan, L., Y. Bao, W. Meng and **G. Chen**. "In-situ Monitoring of Corrosion-induced Expansion and Mass Loss of Steel Bar in Steel Fiber Reinforced Concrete Using a Distributed Fiber Optic Sensor," Composites B: Engineering, 165: 679-689, May 15, 2019.
8. Gallion, J., A. Minachi, J. Correa, and **R. Zoughi**. "Microwave Detection of Metal Thinning on Steel Surfaces Covered by Sandy Oil Residues," Materials Evaluation, 77(6): 797-809, June 2019.
9. Gao, Y., M. Ghasr and **R. Zoughi**. "Effects of and Compensation for Translational Position Error in Microwave Synthetic Aperture Radar (SAR) Imaging Systems," IEEE Transactions on Instrumentation and Measurement, [(DOI 10.1109/TIM.2019.2910340), 11 April 2019.
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11. Horst, M., M. Ghasr and **R. Zoughi**. "A Compact Microwave Camera Based on Chaotic Excitation Synthetic Aperture Radar (CESAR)," IEEE Transactions on Antennas and Propagation, 67(6): 4148-4161, June 2019.
12. **La, H.**, T. Dinh, N. Pham, Q. Ha, and A. Pham. "Automated Robotic Monitoring and Inspection of Steel Structures and Bridges," Robotica, 37(5): 947-957, May 2019. USDOT/INSPIRE UTC support acknowledged.
13. Laviada, J., B. Wu, M. Ghasr, and **R. Zoughi**. "Nondestructive Evaluation of Microwave-Penetrable Pipes by Synthetic Aperture Imaging Enhanced by Full-Wave Field Propagation Model," IEEE Transactions on Instrumentation and Measurement, 68(4): 1112-1119, April 2019.
14. Li, T., G. Yan, F. Yuan, and **G. Chen**. "Dynamic Structural Responses of Long-span Dome Structures Induced by Tornadoes," Journal of Wind Engineering & Industrial Aerodynamics, 190: 293-308, July 2019.
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Books or Other Non-periodical One-time Publications – Conference Papers

1. Ahmed, H., **H. La** and N. Gucunski. Rebar Detection Using Ground Penetrating Radar with State-of-the-art Convolutional Neural Networks, Proceedings of the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), St. Louis, MO, August 4-7, 2019.
2. Alhaj, A., H. Qu, H. Zhang, G. Chen, N. Anderson, and E. Torgashov. Evaluations of GPR and PSPA Surveying on Top and Bottom Surfaces of a Reinforced Concrete Bridge Deck, Proceedings of the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), St. Louis, MO, August 4-7, 2019.

3. Billah, U., **H. La**, N. Gucunski, and A. Tavakkoli. Classification of Concrete Crack Using Deep Residual Network, Proceedings of the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), St. Louis, MO, August 4-7, 2019.
4. Chao, R. and **A. Agrawal**. Defect Detection of Concrete Structures through Sounding Data Analytics, Proceedings of the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), St. Louis, MO, August 4-7, 2019.
5. Fan, L., A. Alhaj, **H. Ma,** and **G. Chen**. Assessing Moisture Content on the Surface of Mortar Samples from Hyperspectral Imaging, Proceedings of the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), St. Louis, MO, August 4-7, 2019.
6. Fan, L., Y. Bao, and **G. Chen**. Corrosion-Induced Deterioration Assessment at Steel-Concrete Interface Based on Hoop Strains Measured with Distributed Fiber Optic Sensors, Proceedings of the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), St. Louis, MO, August 4-7, 2019.
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9. Hament, B., and P. Oh. Considerations for Hose Wielding UAV for Civil Infrastructure Cleaning, Proceedings of the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), St. Louis, MO, August 4-7, 2019.
10. Harris, N., S. Liu, **S. Louis**, **H. La**. Optimizing Routes for Safe Robot-Automated Bridge Inspection. In Proceedings of the 2019 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR), Würzburg, Germany, September 2-4, 2019.
11. Harris, N., S. Liu, **S. Louis**, and **H. M. La**. A Genetic Algorithm for Multi-Robot Routing in Automated Bridge Inspection, The Genetic and Evolutionary Computation Conference (GECCO), Prague, Czech, July 13-17, 2019.
12. Klegseth, M., Y. Bao, L. Fan and G. Chen. Distributed Strain Measurements in a Steel-Concrete Composite Floor Beam under Multi-Point Loading at Ambient Temperature, Proceedings of the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), St. Louis, MO, August 4-7, 2019.
13. Li, D., and **Y. Wang**. Thermally-Stable Passive Wireless Antenna Sensor for Strain Sensing, Proceedings of the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), St. Louis, MO, August 4-7, 2019.
14. Liu, S., N. Harris**, S. Louis**. A Genetic Algorithm for Minmax k-Chinese Postman Problem with Applications to Bridge Inspection, Proceedings of the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), August 4-7, St. Louis, MO, 2019.
15. Liu, C., S. Barker, L. Fan, M. Ghasr, G. Chen, and R. Zoughi. Microwave High-Resolution 3D SAR Imaging of Corroded Reinforcing Steel Bars in Mortar Subjected to Accelerated Electrochemical Corrosion, Proceedings of the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), St. Louis, MO, August 4-7, 2019.

16. Nguyen, S., and **H. La**. Roller Chain-Like Robot For Steel Bridge Inspection, Proceedings of the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), St. Louis, MO, August 4-7, 2019.
17. Reven, A., C. Fritsche, and **G. Chen**. Unmanned Aerial and Traversing Robot as Mobile Platform for Bridge Inspections, Proceedings of the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), St. Louis, MO, August 4-7, 2019.
18. **Wang, Y.**, X. Dong, and D. Li. A Non-Convexity Study in Finite Element Model Updating, Proceedings of the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), St. Louis, MO, August 4-7, 2019.
19. Cedeno, C., M. Fermin, **Y. Wang**. Autonomous Ultrasonic Thickness Measurement by a Magnet-Wheeled Robot, Georgia Institute of Technology Summer Undergraduate Research in Engineering/Science Research Symposium & Poster Session, Atlanta, GA, May 19 – July 26, 2019.
20. Yang, L., Y. Chang, B. Jiang, **J. Xiao**. Visual SHM for Concrete Infrastructure Using a Wall-climbing Robot, Proceedings of the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), St. Louis, MO, August 4-7, 2019.
21. Yang, L., Y. Chang, S. Sotnikov, J. Feng, B. Li and **J. Xiao**, Automated Wind-turbine Blade Inspection Using Acoustic Sensors and Visual SLAM, IEEE International Conference on CYBER Technology in Automation, Control, and Intelligent Systems (IEEE-CYBER 2019), Suzhou, China, July 29 - August 2, 2019.
22. Yang, L., B. Li, G. Yang, Y. Chang, Z. Liu, B. Jiang, **J. Xiao**. Deep Neural Network based Visual Inspection with 3D Metric Measurement of Concrete Defects using Wall-climbing Robot, IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2019), Macau, China, November 4-8, 2019.
23. Zhang, H., S. Hou, J. Ou and **G. Chen.** Smart Aggregate-Based Seismic Stress Monitoring of RC Column for Numerical Model Updating, Proceedings of the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), St. Louis, MO, August 4-7, 2019.
24. Zhang, H., Z. Li, A. Reven, B. Scharfenberg, **G. Chen**, and J. Ou. UAV-Based Smart Rock Positioning for Determination of Bridge Scour Depth, Proceedings of the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), St. Louis, MO, August 4-7, 2019.
25. Zhang, Y., R. DesRoches, and **I. Tien**. Updating Bridge Resilience Assessment Based on Corrosion and Foundation Scour Inspection Data, Proceedings of the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), St. Louis, MO, August 4-7, 2019.
26. Zhao, T., **Z. Yin**, **R. Qin**, and **G. Chen**. Image Data Analytics to Support Engineers' Decision-Making, Proceedings of the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), St. Louis, MO, August 4-7, 2019.

Invited Presentations

1. Genda Chen. "Empowering and Rejuvenating Civil Engineering with Informatics, Automation and Actuation," Georgia Institute of Technology, September 23-24, 2019.

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. Anil Agrawal's team developed a high-directional and low-cost electronic sounding tool for delamination detection in reinforced concrete structures and formulated a specific data analysis process using cross-correlation and empirical mode decomposition for useful feature extraction from the electronic sounding data.
- Jizhong Xiao's team developed an impacting sounding mechanism that is used to generate sounding data for nondestructive evaluation (NDE) of delamination.
- Ruwen Qin's team developed a method for recovering false negative data using temporal information of neighboring frames in videos and an iterative semi-supervised learning approach that effectively integrates human intelligence and artificial intelligence.
- Dr. Reza Zoughi's team designed a full-wave electromagnetic simulations using CST Microwave Studio to determine the influence of corrosion on the resonant properties of a number of rebar without being encased in concrete. The team designed a double-ridged waveguide horn antenna to provide higher gain, and larger bandwidth with a lower operating frequency. It has been investigating a method to detect presence (or degree) of corrosion by measuring the power in the generated 3rd-order harmonics from conducting junctions.
- Dr. Genda Chen's team designed and tested the first prototype of a hybrid flying and traversing vehicle for bridge inspection and maintenance. The laboratory test identified the low stiffness area (four arm connection with the main frame of the Hybridge vehicle) for improvement.
- Dr. Genda Chen's team demonstrated that hyperspectral imaging is promising for the estimate of early-age compressive strengths of concrete and the classification of types of concrete by water-cement ratios.
- Dr. Genda Chen's team also demonstrated the functionality and performance of a packaged long-period fiber grating sensors system for temperature, strain, and mass loss measurements.

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

- Jizhong Xiao received notice of allowance from USPTO on September 5, 2019 that the patent application 16/309,308 "Robotic Device for Providing Vertical Mobility", has been allowed for issuance as a patent.

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

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

Two-volume proceedings from the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9) were prepared for both domestic and international conference participants. The proceedings will be submitted to the International Society for Structural Health Monitoring of Intelligent Infrastructure (ISHMII) for potential posting at its website.

3.F - INSPIRE Research Outputs Performance Metrics

Research Outputs - Performance Measures	Cumulative Total
1. At least 5 publications per investigator in 5 years	6
2. At least 15 keynote/invited presentations delivered at national and international conferences in 5 years	23
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 found to be more portable than the mechanical impactor system and has the potential to generate good inspection results. Due to its simple configuration, the amplifier tube can be connected to a crawler or UAV that can be operated near the surface of a reinforced concrete structure and shoot the high-speed sounding signal to the area of interest.

Dr. Yang Wang's team established promising performance with a single-substrate dual-mode antenna sensor prototype that was designed to best match the active impedance of a RFID chip. While a longer interrogation distance is achieved when operated in active mode with an onboard button cell rechargeable battery, the dual-mode sensor also performs well in passive mode when the battery power is depleted from lack of solar charging.

Dr. Yang Wang's team discovered that the wireless ultrasonic measurement can be more reliable for thicker specimens. Integration with a climbing robot requires the use of elastomer couplant instead of oil couplant, which results in certain loss of accuracy.

Dr. Iris Tien's team quantified the impact of scour on the predicted performance and risk of bridges. These outcomes increased the understanding of the critical levels of scour that lead to substantive increases in risk for bridges. The work from this period has resulted in a new, robust method to assess vulnerability of scoured bridges located in layered soils. The method can be used to quantify the changes in risk to bridges with varying levels of scour. Comparing risk assessment results across bridges with varying soil profiles and scour levels will enable a more efficient and effective management of bridges through prioritization of retrofit and rehabilitation resources to the most vulnerable bridges.

Dr. Sushil Louis' team produced a Prototype STACS simulation training and control software package for bridge inspection and increased the understanding of the optimization problems in path generation for bridge inspection robots and produced a new formulation and new optimization technique for automated bridge inspection with autonomous robots.

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 processing robotic data and non-destructive evaluation (NDE) data and trained students in future technologies, techniques, and skills required for automated bridge inspection with autonomous robots

Dr. Ruwen Qin's team used iterative transfer learning to effectively and efficiently improve the adaptability of machine learning algorithms to new tasks by increasing the understanding of the benefits

of letting artificial intelligence and humans collaborate with each other. Collaboration and partnership between artificial and human intelligences can potentially play an important role in bridge inspection.

Dr. Genda Chen's team developed the first prototype of a hybrid flying and traversing vehicle that enables high quality data collections during inspection of an entire bridge system. Once further developed, such a vehicle is easy to adopt by practical engineers since it is similar to the inspection platform that is currently used in practice.

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 worked to improve 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. The sounding devices are easy to be implemented in robotic systems, like unmanned aerial vehicles (UAVs). Use of noise generated by the wall-climbing crawler will be a significant development in detecting damages in concrete and metallic structures.

Dr. Yang Wang's team developed an innovative robotic technology that can autonomously perform ultrasonic thickness measurement on steel bridge members and is more reliable for wireless ultrasonic measurement in thick specimens.

Dr. Sushil Louis' team discovered that STACS will help reduce the total cost of a bridge inspection by reducing the number of human operators needed to monitor and control multiple inspection robots. This reduction in the number of operators required will lead to significant salary savings and thus to more frequent inspections and safer bridge infrastructure.

Dr. Hung La's team contributed to the automated bridge inspection efforts. Once completed successfully, the proposed research will provide a new automation-assisted inspection system that is non-destructive, comprehensive, rapid, and cost effective for all stages of bridge deterioration.

Dr. Ruwen Qin's team developed algorithms will help improve the efficiency of inspectors, letting them focus on more knowledge-intensive and high value-added tasks.

Dr. Genda Chen's team developed the first hybrid vehicle of its kind that can facilitate on-site inspection of large-scale bridges using multiple climbing robots in a rapid and collaborative manner. This vehicle will potentially play a critical role in automated bridge inspection.

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

Dr. Jizhong Xiao's team results have the potential to be developed into a new product 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. Yang Wang's team developed new knowledge regarding dual-mode antenna sensing technology and autonomous ultrasonic thickness measurement technology for bridge monitoring.

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 give back to the operations research community and other engineering disciplines impacting work in logistics, scheduling, and other routing problems in fields from VLSI design to mathematics. The team will now provide significant improvements to their Genetic Algorithm approach which will increase its utility to this problem and other related problems in Arc Routing and Discrete Optimization.

Dr. Jizhong Xiao's team developed image processing algorithms that will enable a climbing robot to acquire knowledge and increase intelligence for autonomous operation. The impact sounding technology developed in collaboration with Dr. Anil Agrawal's team will provide an alternative way for detection of delamination.

Hung La's team introduced novel concepts of climbing robot design and implementation, 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 in the future.

Dr. Ruwen Qin's team researched artificial and human intelligence collaboration that is more powerful and capable than otherwise.

Dr. Iris Tien's team helped understand the effect of layered soils on vulnerability of bridges subject to scour. Rather than single layer assumptions, the proposed model of layered soils accounted for varying soil layers in risk assessments of scoured bridges.

Dr. Genda Chen's team further understood the corrosion mechanism of Fe-C layer applied on the surface of long period fiber gratings in two distinct 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 along the length of the fiber, thus accelerating the corrosion process.

5.D - Transportation Workforce Development

Dr. Yang Wang of Georgia Institute of Technology offered one undergraduate course related to bridge analysis, CEE3055 Structural Analysis in Spring 2019, and one graduate course, CEE6511 Random Vibration in Spring 2019. Dr. Wang also trained two female graduate students through research.

Dr. Sushil Louis of the University of Nevada Reno supported a faculty member for STACS user interface and user interaction design and trained one undergraduate student on the funded project. The project applied 3D simulation and virtual reality technologies into automated infrastructure inspection research on Nevada Bound tours (for K-12 students) at the University of Nevada Reno. Dr. Louis' team used materials from this project for a class on CS381 Game Engine Design and CS776 Evolutionary Computation. The team has also begun to develop test cases in the STACS training software to teach human operators to use the software, and get trained to oversee a team of robots during a bridge inspection task. The training task should be a good approximation of a real-world bridge inspection, utilizing a team of heterogeneous robots to cooperatively inspect a bridge.

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. He has organized several lab open day events to generate interests to robotic research in both local elementary and high school students as well as DOT and industry. Both undergraduate and graduate students have been trained through hands-on design, fabrication, prototyping and programming of the robots.

Dr. Ruwen Qin of Missouri University of Science and Technology developed a workforce training tool involving machine learning algorithms, and trained a graduate student on this project on how to implement deep learning models in solving transportation related problems.

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.

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.	5

6. CHANGES/PROBLEMS

6.A - Changes in Approach and Reasons for Change

Nothing to change in approach.

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

Co-PI, Dr. Zhaozheng Yin, and his student left Missouri University of Science and Technology. A no-cost extension was requested to deliver all proposed tasks.

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

Since Dr. Zhaozheng Yin's departure, Dr. Ruwen Qin's project has been underspent. Due to this change, part of the committed matching funds from Dr. Zhaozheng Yin was no longer available. New matching funds will be identified to meet the UTC requirements.

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

Dr. Reza Zoughi moved from Missouri University of Science and Technology to Iowa State University. His project is transferred to Iowa State University as a subcontract per USDOT's approval.