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Program Progress Performance Report #4

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

UTC Semi-Annual Progress Report #4

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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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Missouri S&T · The City College of New York · Georgia Tech · CU · UNLV · N · East Central College · Lincoln · Ozarks Technical Community College · St. Louis Community College

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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, transportation non-degree programs, and seminars/workshops/short courses:

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:

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, 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?

Twelve (12) projects were awarded in Year 3, including 10 continuing projects from Year 2, and two (2) new projects, led by Missouri S&T and Georgia Institute of Technology. Prior to Year 3 awards, each project proposal was 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 submitted their evaluation results to the Center Director, and funding recommendations were made during an executive meeting with the INSPIRE UTC directors and External Advisory Committee members in December 2018. The INSPIRE UTC Director issued final approval of Year 3 research projects in January 2019. Year 3 project descriptions were posted to the Center's website and to the RiP Database.

Bi-monthly meetings are 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 during the bi-monthly meetings, 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. Continue with field validation tests at one bridge site. 2. Design, build and test a dual-mode antenna sensor with solar panel and button cell battery on RT/duroid® 6202 substrates. 3. Develop a package method to integrate several LPFG sensors into three coaxial steel tubes. 4. Design a double-ridged wideband horn for optimal penetration depth and resolution, and prepare a large 6'×4' steel reinforced concrete slab with various simulated delamination defects and voids. 5. Prepare mortar cubes for various water/cement ratios and test them over time to take hyperspectral images. 6. Develop embedded software to regulate sleep and wake-up modes of the Martlet wireless device.	1. Characterize field performance of smart rocks for bridge scour monitoring. 2. Develop and validate a dual-mode antenna sensor for strain measurement. 3. Develop a Fe-C coated LPFG sensor for simultaneous strain, temperature, and mass loss measurement. 4. Determine optimal measurement technique and system parameters for SAR imaging of concrete structures for rebar corrosion and concrete delamination detection. 5. Understand water/ cement ratio and hydration effects on the hyperspectral features. 6. Integrate advanced wireless sensing technologies to the UNR robot platform.	1. Repeatability within allowable localization error. 2. Increase in interrogation distance with the solar energy charged battery. 3. Both corrosion threshold and corrosion rate monitored. 4. A curve horn with curved aperture having higher gain at low frequency and lower gain at high frequency than its corresponding plain horn. 5. Gradual decrease in difference absorbance with mortar curing time. 6. Automatic return to sleep mode from wake-up mode for power saving when not collecting data.	1. Localization algorithm for one or two rocks. 2. Two antenna sensor prototypes prepared for optimal passive and active (1.8 V) operation. 3. Wall thickness to control the degree of corrosion over time while Fe-C coating determines its corresponding corrosion rate. 4. Prototyping of a curve horn with curved aperture. 5. Difference absorbance as a promising index for mortar hydration monitoring. 6. Single-transducer mode selected to both transmit and receive ultrasonic signals in order to reduce hardware weight.
AS	1. Tune manipulator and gripper for physical interaction with environment and capture multispectral and infrared sensor data for crack and hole identification. 2. Design and integrate a 5 degree-of-freedom robotic arm into a robot for Eddy current tests. 3. Integrate a solenoid-based impact sounding device into a wall-climbing robot for nondestructive tests. 4. Conceptualize Bridge Inspection Robot Deployment Systems (BIRDS).	1. Design and use hyper-redundant serpentine-like limbs for dexterous manipulation, such as air spraying for bearing cleansing and epoxy injection for crack sealing. 2. Develop and prototype a robotic arm on a climbing robot for steel bridge inspection with NDE devices. 3. Design an impacting mechanism as an arm outside the wall-climbing robot. 4. Develop and build a solar-powered mobile test facility based on a ground vehicle.	1. Successful demonstration of hose-handling task using a UAV. 2. A control mechanism developed for user-controlled arm. 3. Demonstrated function of impact sounding device on flat wall surfaces. 4. First design and finite element analysis of a hybrid flying and traversing vehicle as a platform for bridge inspection of girder bridges.	1. Satisfactory drone thrust test with strain gages mounted on a cantilever beam. 2. Demonstrated Eddy Current sensor work and data collection. 3. Impacting mechanism conformable to curved surfaces. 4. Satisfactory stress distribution of a conceived hybrid flying and traversing vehicle under various operation conditions.
IM	1. Compare hammer sounding with electronic chirp sounding on four concrete	1. Develop new fusion strategies of data collected from multiple	1. Unnecessary noise found due to friction or wave reflection at irregular	1. Successful detection of debonding, void, and shallow delamination

Topic	Major Activities	Specific Objectives	Significant Results	Key Outcomes
	slabs with known engineered defects and different overlays: debonding, shallow and deep delamination, honeycomb, and void.	NDE devices for improved POD based on further understanding and modeling of damage detection mechanisms.	concrete surface, empirical mode decomposition used to filter out the noise in defect detection.	from the power spectral density of hammer sounding signals.
RR	1. Investigate the impact of varying levels of corrosion on the performance of bridges across potential failure modes and develop a computationally efficient approach for fragility assessment.	1. Develop and validate a framework of bridge condition assessment and prioritizing structures for repair after an extreme event.	1. Complete analysis of failure modes (flexure-critical and shear-critical columns, and short lap splices) under different corrosion effects on rebar.	1. Reduced computational cost with Bayesian updating of bridge parameters using newly collected data.
WD	1. Perform quantitative assessment of transfer learning and implement deep-learning semantic image segmentation algorithms. 2. Use the simulation training and control system (STACS) to investigate the tradeoff between operator control and robot autonomy and optimize an inspection path of multiple robots.	1. Determine the quality of transfer learning and segment multiple classes of bridge elements. 2. Develop the STACS and engineer a near-optimal solution to the intractable multi-robot bridge-path generation problem.	1. Semantic image segmentation for reduced false detection with a compromise on computational speed. 2. Virtual reality augmented simulation, enabling monitoring and control of ROSS-based robots and a simple robot model for STACS and ROSS integration.	1. Transfer learning algorithm for a single bridge element and image segmentation algorithm for recognition of multiple bridge elements. 2. A genetic algorithm for solving the NP-Hard MinMax k-Chinese Postman Problem submitted for publication.

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 5 undergraduate and 16 graduate students through its research program. Its two webinars received a total of 129 participants, 2 of whom requested professional development hours.

1.D - How Have the Results Been Disseminated?

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 5,000 people through the Center's listserv, and are made available online at https://inspire-utc.mst.edu/news/. An INSPIRE UTC Newsletter (Vol. 2, No. 2) was published in Fall 2018 and included three technical articles related to INSPIRE research:

- *Defect Detection of Concrete Structures through Sounding Data Analytics*, Dr. Anil Agrawal, The City College of New York
- *Image Data Analytics to Support Engineers' Decisions-Making*, Dr. Zhaozheng Yin, Missouri S&T
- *Turning Data into Decisions through Bridge Model Updating*, Dr. Iris Tien, Georgia Institute of Technology

Technology Transfer Activities

The INSPIRE UTC hosts quarterly webinars. Overall, 8 INSPIRE webinars have engaged a total of 421 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, 55% of the participants are from academia, 22% are from industry, 18% are from Government, and 5% are unknown.

Two webinars were presented in this reporting period, and engaged a total of 129 participants:

1. *Assistive Intelligence (AI): Intelligent Data Analytics Algorithms to Assist Human* Experts was presented on January 30, 2019 by Dr. Zhaozheng Yin, Computer Science Department, Missouri S&T.
2. *Battery-Free Wireless Strain Measurement Using and Antenna Sensor* was presented on March 6, 2019 by Dr. Yang Wang, School of Civil and Environmental Engineering, Georgia Institute of Technology.

In March 2019, the INSPIRE UTC co-sponsored a technical writing seminar series that engaged a total of 164 participants. The following two seminars were presented by guest speakers and moderated by Dr. Jenny Liu, Civil, Architectural, and Environmental Engineering Department, Missouri S&T:

1. *Six Key Elements of High Quality Technical Writing,* presented on March 8, 2019 by Dr. Xianming Shi, Associate Professor of Civil Engineering, Washington State University.
2. *General Guides to Publish Well-Written Technical Papers,* presented March 22, 2019 by Dr. Jie Han, Glenn L. Parker Professor of Geotechnical Engineering, The University of Kansas.

Dr. Jizhong Xiao of The City College of New York (CCNY) received an NSF I-Corps grant entitled "SenseTech: Non-Destructive Evaluation (NDE) of Aging Infrastructures by Integration of Visual Inspection with 3-D Imaging of Ground Penetrating Radar (GPR)". CCNY will organize I-Corps lectures and workshops, and devote at least 15 additional hours per week for customer discovery to commercialize the technology.

Education and Outreach Activities

During the reporting period, the INSPIRE UTC spent more than 40 contact hours to host and/or support seven outreach events that engaged a total of 262 participants, ages K-12, including more than 64 minority students:

1. Expanding Your Horizons (EYH) Conference on October 5, 2018 at Missouri S&T.
2. Missouri State Future City Competition on January 26, 2019, hosted by the Kaleidoscope Discovery Center on the Missouri S&T campus.
3. National Society of Black Engineers (NSBE) Pre-College Initiative (PCI) Weekend on February 23, 2019 at Missouri S&T.
4. FLL Team Regional Competitions in Columbia, MO, 2019.
5. FLL Junior Expo on February 24, 2019, hosted by the Kaleidoscope Discovery Center on the Missouri S&T campus.
6. Kaleidoscope Discovery Center Robotics Outreach Program activities in Missouri.
7. Lincoln University Summer Research Program presentation on March 19, 2019.

In addition to the above outreach efforts, the University of Nevada, Las Vegas (UNLV) team has a Research Education for Teachers (RET) grant sponsored by NSF. For six (6) weeks each summer, regional high school teachers learn about research in big data and robotics. The goal is to integrate such learning into K-12 curricula. INSPIRE UTC results have been disseminated to 4 K-12 teachers, learning about LIDAR and data acquisition. Such results have also been introduced to middle school students with the team's partnership with the local public library's after-school/weekend STEM programs.

The UNLV team continues to work with the neighboring Clark County Las Vegas Public Library in the Saturday K-12 programs. Lesson plans include computer-aid-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, the team conducts hands-on STEM labs. These labs include drone (programming), augmented reality (projection mapping), and embedded control (Arduino).

Other Accomplishments

In March 2019, the INSPIRE UTC implemented a new Freshman Undergraduate Research Program. Under this program, INSPIRE provides up to (3) $500 research stipends each year to support under-represented freshman who enroll at Missouri S&T. Selected students will participate in a research project under the direction of an INSPIRE faculty advisor. Projects start at the beginning of the fall semester and end at the conclusion of the following spring semester.

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.

Research projects will continue in the five research categories described above. 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 influencing factors. • Prepare a draft final report of this project.
	Battery-free Antenna Sensors for Strain and Crack Monitoring of Bridge Structures	• Perform strain sensing tests on a dual-mode prototype. • Prepare a draft final report of this project.
	In-line Long Period Grating and Brillouin Scattering Fiber Optic Sensors for Strain, Steel Mass Loss, and Temperature Measurement in Bridge Applications	• Monitor the life-cycle performance of metallic structures and steel reinforcement with Fe-C coated LPFG sensors when enclosed in multiple coaxial thin-walled steel tubes so that the times when corrosion rate is measured can be controlled by the wall thicknesses of the tubes. • Perform steel beam tests to quantify the threshold corrosion level and its corresponding corrosion rate.
	3D Microwave Camera for Concrete Delamination and Steel Corrosion Detection	• Determine computationally the efficacy of detecting corrosion on embedded rebar and concrete delamination using SAR imaging techniques. • Compare resonance with harmonic detection techniques for their sensitivity to corrosion-induced and other parameter changes.
	Hyperspectral Image Analysis for Mechanical and Chemical Properties of Concrete and Steel Surfaces	• Cast and test additional concrete specimens for carbonization or corrosion tests to understand their surface characteristics from hyperspectral images. • Collect and establish a library of hyperspectral images of the specimens in different categories.
	Autonomous Ultrasonic Thickness Measurement by a Magnet-Wheeled Robot	• Test hardware components that are incorporated into a low power Martlet wireless sensing device for ultrasonic thickness measurement. • Conduct a preliminary integration of the Martlet wireless sensing device with a magnet-wheeled robot for steel structural inspection.
AS	Mobile-manipulating UAVs for Sensor Installation, Bridge Inspection and Maintenance	• Continue trade-off studies and risk assessment for air compressor and sounding hammer under design. • Test and evaluate these designs for optimal solution.

Topic	Project Title	Planned Activities
	Climbing Robots with Automated Deployment of Sensors and NDE Devices for Steel Bridge Inspection	• Design, build, and test the third generation climbing robot. • Refine 3D SolidWork design to test the robot in various climbing scenarios. • Test robotic prototypes with the STACS for learning, monitoring, and control.
	Autonomous Wall-climbing Robots for Inspection and Maintenance of Concrete Bridges	• Test the wall-climbing robot on a concrete specimen in the Turner Fairbanks of Highway Research Laboratory at Federal Highway Administration. • Collect and analyze visual and sounding data for defect detection.
	Bridge Inspection Robot Deployment Systems (BIRDS)	• Build and test the first prototype of a hybrid flying and traversing vehicle for controllability, stability, and operation time.
IM	Re-Inventing the Bridge Inspection Program	• Secure off-campus non-federal matching funds to meet the center requirements and get this project started.
	Quantitative Bridge Inspection Ratings using Autonomous Robotic Systems	• Develop a directional speaker to excite concrete using electronic sounding. • Collect vibration data from a beam under sounding excitations using LDVs and analyze patterns of the vibration data from sound and defected areas.
RR	Bridge Resilience Assessment with INSPIRE Data	• Conduct sensitivity studies to understand the parameters that significantly influence the impact of scour on expected bridge performance.
WD	A Training Framework of Robotic Operation and Image Analysis for Decision-Making in Bridge Inspection and Preservation	• Develop a semi-supervised iterative learning approach to further reduce man-hours in annotating training data in every iteration. • Develop a region of interest retrieval approach to find out the frames containing specific region of interest from a large pool of video frames.
	Developing a Robotic Simulator and Video Games for Professional and Public Training	• Incorporate changes in robot designs into the third version of STACS. • Seek feedback on STAC's use as a training tool from end users.

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

Other Planned Initiatives

1. On May 23-24, 2019, Dr. Iris Tien, Assistant Professor of Civil Engineering at Georgia Institute of Technology and INSPIRE UTC Principal Investigator, will give an invited presentation titled "*Data to Risk-Informed Decisions through Bridge Model Updating*" at the 2nd International Conference on Health Monitoring of Civil and Maritime Structures (HeaMES 2019) in Glasgow, UK.
2. On June 24-26, 2019, Dr. Genda Chen, INSPIRE UTC Director, will attend the 2019 Council of University Transportation Centers (CUTC) Summer Meeting, the University of Oklahoma, Norman, OK.
3. On July 17, 2019, the INSPIRE UTC will host a one-day transportation camp as part of MoDOT's annual Youth Transportation Conference, Missouri S&T, MO.
   On August 4-7, 2019, INSPIRE UTC principal investigators will present research results at the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9) in St. Louis, 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, including:

- 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
- 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

- CCNY Computer Science Department
- Jacobs Engineering Group http://www.jacobs.com/
- Kaleidoscope Discovery Center https://thekaleidoscope.org
- Koch Industries http://www.kochind.com
- McClure Engineering Co. http://www.mcclureeng.com/
- Missouri Department of Transportation http://www.modot.org/
- Rich Robotics Corp http://richrobotics.com
- Rice University
- Northeastern University
- Honeywell, Nevada
- Turner Fairbanks Highway Research Center of FHWA, McLean, VA

Internal Partners at Missouri S&T

- Department of Civil, Architectural and Environmental Engineering http://care.mst.edu/
- 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?

Members of the INSPIRE External Advisory Committee attended a semi-annual meeting in December 2018 to review the overall performance of the center, review the results of the external proposal reviews and make funding recommendations for Year 3.

The University of Nevada, Las Vegas (UNLV) team has been connecting with civil engineering professors at their institution to learn the characterization of concrete. This resulted in dialogs with UNLV alumni working in the region's bridges and facilitated access to the region's bridges and overpasses to acquire sensor data. The Las Vegas office of the Desert Research Institute (DRI) lent the team one of their multi-spectral sensors for data acquisition.

Drs. Frank Jalinoos and Hoda Azari of FHWA provided Dr. Agrawal of CCNY with access to the concrete decks located at the Turner Fairbanks Highway Research Center for impact sounding experiment.

Dr. Wei Jie, a professor of computer science at CCNY, provided a military grade Laser Doppler vibrometer (LDV) that was used to measure the micro-vibration of structure surfaces with high accuracy. Dr. Jie's Ph.D. student at CCNY helped the project staff set up and test the LDV device for measuring the vibration of a metal panel under sweep sounding.

3. OUTPUTS

3.A - Publications, Conference Papers, and Presentations

Journal Publications

1. Chuanrui Guo, Liang Fan, Chenglin Wu, **Genda Chen**, and Wei Li. "Ultrasensitive LPFG Corrosion Sensor with Fe-C Coating Electroplated on a Gr/AgNW Film," Sensors and Actuators B: Chemical,283: 334-342, December 11, 2018, published, federal support acknowledged.
2. Fujian Tang, Yizheng Chen, Chuanrui Guo, Liang Fan, **Genda Chen**, and Yan Tang. "Field Application of Magnet-based Smart Rock for Bridge Scour Monitoring," ASCE Journal of Bridge Engineering, 24(4), April, 2019, published.
3. Fujian Tang, Yizheng Chen, Zhaochao Li, Xiuyan Hu, **Genda Chen**, and Yan Tang. "Characterization and Field Validation of Smart Rocks for Bridge Scour Monitoring," Structural Health Monitoring, January 22, 2019, published.
4. Hongya Qu, Tiantian Li, and **Genda Chen.** "Multiple Analytical Mode Decompositions (M-AMD) for High Accuracy Parameter Identification of Nonlinear Oscillators from Free Vibration," Mechanical Systems and Signal Processing, 117: 483-497, February 15, 2019, published.
5. Hongya Qu, Tiantian Li, and **Genda Chen**. "Multiple Analytical Mode Decompositions for Nonlinear System Identification from Forced Vibration," Engineering Structures, 173: 979-986, October 2018, published.
6. F. Jalinoos, M. Amjadian, **A.K. Agrawal,** C.N. Brooks, and D. Banach. "Experimental Evaluation of Unmanned Aerial System (UAS) for Measuring Bridge Movement," Journal of Bridge Engineering, 2019, under review.
7. Liang Fan, Yi Bao and **Genda Chen.** "Feasibility of Distributed Fiber Optic Sensor for Corrosion Monitoring of Steel Bars in Reinforced Concrete," Sensors, 18(11): 3722, November 1, 2018, doi:10.3390/s18113722, published.
8. Liang Fan, Yi Bao, Weina Meng and **Genda 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, published.
9. Yi Bao, Ying Huang, Matthew S. Hoehler and **Genda Chen.** "Review of Fiber Optic Sensors for Structural Fire Engineering," Sensors 2019, 19,877, doi:10.3390/s19040877, February, 2019, published.
10. Ying Huang, Yi Bao, **Genda Chen** and Zhi Zhou. "A Constrained Cylinder Model of Strain Transfer for Packaged Fiber Bragg Grating Sensors Embedded in Inelastic Medium," Structural Control and Health Monitoring, January 11, 2019, DOI: 10.1002/stc.2335, published.
11. Y. Zhang, and **I. Tien.** "Bayesian Updating of Fragility Curves with Application to Corroded Bridges," Structural Safety, under review, federal support acknowledged.
12. Y. Zhang, R. DesRoches, and **I. Tien**. "Impact of Corrosion on Risk Assessment of Shear-Critical and Short Lap-Spliced Bridges," Engineering Structures, 189: 260-271, June 2019, published, federal support acknowledged.

Books or Other Non-periodical One-time Publications

1. **Agrawal, A.K.** "Detection of Defects in Concrete Structures through Sounding Data Analytics," 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure, (SHMII-9), August 4-7, 2019, St. Louis, MO, submitted, federal support acknowledged.
2. Cao, R. and **Agrawal, A. K.** "Defect Detection of Concrete Structures through Sounding Data Analytics", 9th International Conference on Structural Health Monitoring of Intelligent

Infrastructure (SHMII-9), August 4-7, 2019, St. Louis, M), 2019, under review, federal support acknowledged.

3. Deniz, S., Altamirano, L., **Hament, B.,** et al. "Computer Vision for Attendance and Emotion Analysis in School Settings"; IEEE 9th Annual Computing and Communication Workshop and Conference (CCWC), Las Vegas, NV; January 2019.
4. Dreher, A., Chung, K., **Hament, B**., et al. "Towards Tattoo Previewing and Other Augmented/Mixed Reality Applications with Microsoft Kinect"; IEEE 9th Annual Computing and Communication Workshop and Conference (CCWC), Las Vegas, NV; January 2019.
5. Ghasr, M.T., S. Barker, **R. Zoughi**, and G. Chen. "Microwave High-Resolution 3D SAR Imaging of Corroded Reinforcing Steel Bars in Concrete Subjected to Accelerated Electrochemical Corrosion," 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), St. Louis, MO, August 4-7, 2019, submitted, federal support acknowledged.
6. Gibb, Spencer, Hung Manh La, and **Sushil Louis**. "A genetic algorithm for convolutional network structure optimization for concrete crack detection," 2018 IEEE Congress on Evolutionary Computation (CEC). IEEE, 2018, published.
7. Gibb, Spencer, **Hung Manh La**, and Sushil Louis. "A genetic algorithm for convolutional network structure optimization for concrete crack detection," 2018 IEEE Congress on Evolutionary Computation (CEC). IEEE, 2018, published.
8. H. Ahmed, **H. M. La**, and N. Gucunski. "Rebar Detection using Ground Penetrating Radar with State-of-the-art Convolutional Neural Networks," 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), August 4-7, 2019, St. Louis, MO, accepted, federal support acknowledged.
9. **Hament, B., Oh, P.Y**.; "Considerations for Hose-Wielding UAV for Civil Infrastructure Cleaning"; International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), St. Louis, MO; August 2019; under review, federal support acknowledged.
10. Liang Yang, Bing Li, Guoyong Yang, Yong Chang, Zhaoming Liu, Biao Jiang, **Jizhong 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), under review.
11. Liang Yang, Hao Jiang, Zhouyuan Huo, **Jizhong Xiao**. "Visual-GPS: Ego-Downward and Ambient Video based Person Location Association," 2019 Conference on Computer Vision and Pattern Recognition Workshop, under review.
12. Liang Yang, Yong Chang, Biao Jiang, **Jizhong Xiao**. "Visual SHM for Concrete Infrastructure Using a Wall-climbing Robot," 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), 2019, accepted, federal support acknowledged.
13. Liang Yang, Yong Chang, Stanislav Sotnikov, Jinglun Feng, Bingbing Li, and **Jizhong 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), under review.
14. Liu, C., L. Fan, S. Barker, M.T. Ghasr, G. Chen, and **R. Zoughi**, "Microwave High-Resolution 3D SAR Imaging of Corroded Reinforcing Steel Bars in Concrete Subjected to Accelerated Electrochemical Corrosion," 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), St. Louis, MO, August 4-7, 2019, accepted, federal support acknowledged.

15. Nicholas Harris, **S. Louis**, S. Liu, "A Genetic Algorithm for Multi-Robot Routing in Automated Bridge Inspection," Proceedings of the 2019 Genetic and Evolutionary Computing Conference (GECCO), Prague, Czech Republic, 2019, accepted.
16. **Qin, Ruwen**. "A Framework of Training Robotic Operation, Image Analysis, and Decision-Making for Inspecting and Preserving Transportation Infrastructure," 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), August 4-7, 2019, St. Louis, MO, 2019, accepted, federal support acknowledged.
17. S. T. Nguyen, and **H. M. La.** "Roller Chain-Like Robot For Steel Bridge Inspection," 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), August 4-7, 2019, St. Louis, MO, accepted, federal support acknowledged.
18. Sehgal, H. La, **S. Louis** and H. Nguyen, "Deep Reinforcement Learning Using Genetic Algorithm for Parameter Optimization," 2019 Third IEEE International Conference on Robotic Computing (IRC), Naples, Italy, 2019, pp. 596-601.doi: 10.1109/IRC.2019.00121, published.
19. Sehgal, **H. La**, S. Louis and H. Nguyen. "Deep Reinforcement Learning Using Genetic Algorithm for Parameter Optimization," 3rd IEEE International Conference on Robotic Computing (IRC), Naples, Italy, 2019, pp. 596-601.doi: 10.1109/IRC.2019.00121, published.
20. **Sushil J. Louis**, Tianyi Jiang, and Siming Liu. 2018. "Real-time strategy game micro for tactical training simulations," In Proceedings of the Genetic and Evolutionary Computation Conference Companion (GECCO '18), Hernan Aguirre (Ed.). ACM, New York, NY, 1656-1663. DOI: https://doi.org/10.1145/3205651.3208288, published.
21. U. H. Billah, **H. M. La**, A. Tavakkoli, and N. Gucunski. "Classification of Concrete Crack using Deep Residual Network," 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), August 4-7, 2019, St. Louis, MO, accepted, federal support acknowledged.
22. **Wang, Yang**. "Thermally-Stable Passive Wireless Antenna Sensor for Strain Sensing," 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9), August 4-7, 2019, St. Louis, MO, 2019, accepted, federal support acknowledged .
23. Zhang, Y., DesRoches, R., and **Tien, I**. "Updating Bridge Resilience Assessment Based on Measured Corrosion Data," 6th Annual University Transportation Centers Conference for the Southeastern Region, Clemson University, Clemson, SC, 2018.

Keynote Presentations

1. **Genda Chen**. "*Sensor-enhanced Analysis and Behavior of Steel Beams in Fire,*" 5th World Congress and Exhibition on Construction and Steel Structure, Los Angeles, CA, October 5-6, 2018.
2. **Genda Chen**. "*High Performance Bridges with Sustained Materials, Automated Preservation, and Informed Decision: a Life-cycle Perspective,*" 15th International Symposium on Structural Engineering (ISSE-15), Hangzhou, China, October 25-27, 2018.
3. **Genda Chen** and Hongya Qu. "*Short-time Continuous Wavelet Transform of the Response of Time-varying Systems*," 2018 International Conference on Sensor Networks and Signal Processing (SNSP 2018), Xi'an, China, October 28-31, 2018.
4. **Genda Chen**. *"Emerging Roles of Autonomous Systems, Structural Health Monitoring and Nondestructive Evaluation in Bridge Inspection and Maintenance,"* SPIE Smart Structures + Nondestructive Evaluation conference, Denver, CO, March 3-7, 2019.
5. Chuanrui Guo and **Genda Chen**. "*Exploring Graphene Growth from Soybean Oil and its Application in Fiber Optic Corrosion Sensors*," Global Conference on Carbon Nanotubes and Graphene Technologies, Milan, Italy, March 28-29, 2019.

Invited Presentations

1. **Genda Chen**. "*High Performance Bridges with Sustained Materials, Automated Preservation, and Informed Decision: a Life-cycle Perspective*," Zhejiang University, October 25-27, 2018.
2. **Genda Chen**. "*Emerging Roles of Automation and Informatics in Construction and Preservation of Civil Infrastructures*," China Communication Construction Company, Beijing, December 9, 2018.
3. **Genda Chen**. "*Automation and Informatics in Civil Engineering*," Hong Kong Polytechnic University, December 21, 2018.
4. **Genda Chen**. "*Adaptive Wavelet Transform of Time Series: Theory and Application*," Tongji University, March 13, 2019.

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

- INSPIRE University Transportation Center- https://inspire-utc.mst.edu/
- Research in Progress Database- https://rip.trb.org/
- Advanced Robotics and Automation Laboratory- https://ara.cse.unr.edu
- 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 developed a robust procedure for graphene/nano silver wires synthesis and Fe-C coated long period fiber grating (LPFG) sensor fabrication. The results are shared and disseminated through a journal publication in Sensors and Actuators B: Chemical.
- Dr. Reza Zoughi's team designed a wideband antenna that will likely make high-resolution SAR images efficient.
- Dr. Anil Agrawal's team tested a unique electronic sounding source, vibration speaker, to excite concrete for delamination detection.
- Dr. Anil Agrawal's team developed sounding data analysis techniques for defect detection in concrete structures. The results are shared and disseminated through a technical article published in the Fall 2018 INSPIRE Newsletter.
- Dr. Iris Tien's team developed a Bayesian updating technique to efficiently update assessments of bridge fragility based on newly collected data with greatly reduced computation time. The technique is being shared and disseminated through a possible publication in the top journal Structural Safety under review.
- Dr. Ruwen Qin's team developed a transfer learning algorithm that utilizes inspector's knowledge and iteratively updates the offline trained algorithm for refining image segmentation quality.
- Dr. Jizhong Xiao's team developed an impacting mechanism used to generate sounding data for non-destructive evaluation (NDE) of delamination.

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

- On March 7, 2019, Dr. Genda Chen and the Missouri S&T Office of Technology Transfer & Economic Development filed a provisional patent application titled "*BridgeBot – a Hybrid Unmanned Aerial/Traversing Vehicle for Automated Bridge Inspection*", US Provisional Patent

Application No. 62/815,033. iEdison Invention Report No. 0578005-18-0005/Invention Report No. 19MST007 on October 2, 2018.

- In April 2019, Dr. Hung La and the Office of Enterprise and Innovation at UNR elected not to pursue a non-provisional application for the invention previously reported in IR No. 0829903-17-0004, UNR ID# UNR18-005. UNR waived title in iEdison.

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 and 2 additional technical writing webinars were video recorded and stored at Missouri S&T's data repository site – scholarsmine.mst.edu/inspire_webinars.

Dr. Genda Chen's team developed a localization algorithm for two smart rocks deployed at 2 m apart. Dr. Iris Tien's team developed a new bridge fragility curve development model using the Bayesian approach for efficient updating as additional data are made available, which will greatly reduce computational time. Dr. Reza Zoughi's team developed a wideband antenna model that allows the team to study the influence of corroded reinforcing bars on the microwave propagation in concrete.

3.F - INSPIRE Research Outputs Performance Metrics

Research Outputs - Performance Measures	Cumulative Total
1. At least 5 publications per investigator in 5 years	7.1
2. At least 15 keynote/invited presentations delivered at national and international conferences in 5 years	15
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. Yang Wang's team developed a new dual-mode (passive and active) antenna sensor that would improve the bridge monitoring performance over a conventional RFID chip in passive mode only. The antenna and its charging circuit are housed on a single substrate for easy installation in field applications.

Dr. Iris Tien's team developed a computationally efficient Bayesian updating approach that allows the quantification of corrosion impact on the performance of bridges. The new approach will increase our understanding of the critical levels of corrosion that lead to substantive increases in risk for bridges.

Dr. Anil Agrawal's team increased the understanding of concrete defect detection using sounding data analytics, which can potentially improve the current practice with conventional chain dragging.

Dr. Hung La's team developed climbing robot platforms supporting nondestructive evaluation devices, which can improve safety and data quality in bridge inspection.

Dr. Sushil Louis's team developed prototype STACS simulation training and control software package that will improve the efficiency of bridge inspection with multiple robots.

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

5.A - The Effectiveness of the Transportation System

The INSPIRE team developed a few automated inspection systems that are nondestructive, efficient, and cost effective for inspection of bridges at all stages of deterioration. In particular, the climbing robots developed by Dr. Hung La's team can be used to reduce the labor hours of inspectors and improve inspectors' safety by sending robots to difficult-to-access areas. The controllable electronic sounding tools developed by Dr. Anil Agrawal's team will improve the efficiency of current defect detection for concrete structures using chain dragging.

Dr. Genda Chen's team developed smart rock technologies that will improve the efficiency of current scour monitoring for scour-critical bridges. Dr. Iris Tien's team developed software based on Bayesian updating technique to rapidly estimate the impacts of scour and thus help decision-making in the case of a major flood event, ensuring the safety and reliability of bridges.

Dr. Ruwen Qin's team developed deep learning algorithms that can process video images at least times faster than manual processing frame-by-frame. The end results of this program will allow inspectors focused on more knowledge-intensive and high value-added tasks.

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

Dr. Hung La's team has developed three versions of magnet wheel based robot prototypes that can climb over flat and curved, top and bottom, and smooth and bumpy surfaces of steel structures. These robots are promising for inspection of steel bridges, laying a foundation for establishment of a start-up company under Dr. La's consideration.

Dr. Jizhong Xiao's team will potentially develop a new product of self-contained robots that are equipped with an RGB-D camera, a GPR sensor and an impact sounding device to detect surface flaws and subsurface defects. The addition of this product will strengthen the capability of InnovBot LLC as a CUNY spin-off company dedicated to the commercialization of wall-climbing robot technologies.

5.C - The Body of Scientific Knowledge

Drs. Anil Agrawal and Jizhong Xiao developed an impact sounding technology that requires the fundamental understanding of a unidirectional sounding speaker and mechanism. The technology has significant impacts in civil engineering application once installed on a climbing robot with vertical mobility. The robot-assisted impact sounding technology will provide an alternative way for detection of delamination in multiple disciplines.

Dr. Genda Chen's team developed a long period fiber grating (LPFG) sensor for monitoring and measurement of multiple parameters such as strain, temperature, and corrosion induced mass loss. These parameters were discriminated by combining distinct characteristics of two cladding modes of light propagation with different installation schemes of two auxiliary optical fibers. Such a compact and

high-precision LPFG sensor can be multiplexed to enable unique applications in civil infrastructure. The sensing technology is transferrable to other disciplines, such as aerospace industry.

Dr. Hung La's team has introduced novel design and implementation concepts of climbing robots on magnet wheels, advancing existing literature and providing 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. Sushil Louis's team has mapped multi-robot bridge inspection to a well-known and computationally intractable MinMax K-Chinese postman problem. The results in engineering solutions 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.

Dr. Iris Tien's team developed a comprehensive, risk-based understanding of the impacts of corrosion and scour on bridge performance. This new development enables a quantification of the effects of corrosion level on the risk of a bridge under various loadings, which impacts the field of civil engineering.

5.D - Transportation Workforce Development

INSPIRE University Transportation Center offered substantial support and research environment/ opportunities to both undergraduate and graduate students. It provided training in technical writing from preparing through editing to revising manuscripts and reports for publication. For example, Dr. Yang Wang of Georgia Institute of Technology offered one transportation-related undergraduate course during the reporting period and supervised two female graduate students who work on transportation-related research.

Dr. Jizhong Xiao of City College of New York (CCNY) inspired innovations and supported the training of the future workforce from traditionally underrepresented students at CCNY (21.3% Black and 32.2% Hispanic) to meet the critical national need for sustainable infrastructure.

Dr. Sushil Louis of the University of Nevada Reno (UNR) applied 3D simulation and virtual reality technologies into automated infrastructure inspection research on Nevada Bound tours (for K-12 students) at UNR. Research results also enriched the preparation of curricula on game engine design (CS 381) and evolutionary computation (CS 776).

Dr. Hung La of UNR 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 has organized several open-lab events to generate interests to robotic research and applications for local elementary and high school students, DOT engineers, and engineers in private sectors. Both undergraduate and graduate students have been trained through hands-on design, fabrication, prototyping and programming of robots.

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.	4

6. CHANGES/PROBLEMS

6.A - Changes in Approach and Reasons for Change

Nothing to report.

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

The University of Colorado at Boulder project was delayed due to lack of appropriate match funds. While the PI will continue to seek external match funds from qualified sources (e.g., state DOTs), the PI agrees for the Center to contract a similar project to another qualified expert in the following years and ensure that the original scope of the Center is covered.

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

Nothing to report.

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

Pending approval by the OST-R Grant Manager, the University of Colorado at Boulder project may be performed by another organization in the INSPIRE Center in the following years.