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Semi-Annual Progress Report #8

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

UTC Semi-Annual Progress Report #8

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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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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 Air Corp; 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?

To support the technology transfer goal, an accompanying seven-state pooled-fund study No. TPF-5(395): Traffic Disruption-free Bridge Inspection Initiative with Robotic Systems was initiated on August 1, 2019. During the last reporting period, the pooled-fund study progressed in two tasks for bridge selection and fabrication of a combined flying and traversing robot, named BIRDS. Specifically, selection of steel-girder bridges in the state of New York, Virginia and Wisconsin, and prestressed concrete girder bridges in Georgia, Texas, and California was being finalized for field tests starting this summer. In Missouri, both groups of girder bridges would be tested. The girder detection algorithm was developed and tested to guide BIRDS operation. Additionally, the BIRDS' movement in both horizontal and vertical directions can be controlled as designed.

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. N/A. 2. N/A. 3. N/A. 4. N/A. 5. Prepare and review a final report. 6. Fabricate and evaluate printed circuits of the ultrasonic daughter board and pulser board. 7. Prepare laboratory specimens to test and evaluate NDT methods. 8. Prepare and test a significant number of Fe-C coated long period fiber gratings sensors.	1. N/A. 2. N/A. 3. N/A. 4. N/A. 5. Develop and publish a high-quality report on research findings and results. 6. Develop an ultrasonic system for accurate measurement of thickness in steel plates. 7. Identify effective NDT methods for freeze-thaw damage assessment. 8. Develop a probability of detection (POD) for steel corrosion monitoring.	1. N/A. 2. N/A. 3. N/A. 4. N/A. 5. More droplet and immersion tests on steel samples are needed to draw conclusive results. 6. A measurement accuracy of 0.1% in thickness of steel plate in laboratory. 7. Different degrees of saturation (50%-90%) achieved in selected cement pasters. 8. Consistent sensing trend but with a significant variation.	1. Complete. 2. Complete. 3. Complete. 4. Complete. 5. Hyperspectral imaging for steel corrosion detection. 6. Implementable ultrasonic system tested at a bridge with 0.3% accuracy. 7. Strength comparison before and after freeze-thaw degradation. 8. A framework to determine POD developed.
AS	1. N/A. 2. Prepare and review a final report. 3. Prepare and review a final report. 4. Develop autonomous flight control algorithms for the 2nd BIRDS prototype. 5. Control the climbing robot for automatic switch between two operation modes: mobile and inchworm. 6. Build a new climbing robot named Impact-Rover for collection of impact sounding data on ground and walls. 7. Demonstrate the tele-presence of an operator on a collaborative task (e.g., package handling). 8. Complete a four-vacuum-cup TreeFrog robot design to enable its climbing on	1. N/A. 2. Develop and publish a high-quality report on research findings and results. 3. Develop robust robots for vertical mobility on concrete surface and collect data. 4. Develop a solar-powered mobile test facility for field tests at bridge sites. 5. Provide the built climbing robot with an autonomous inspection capability. 6. Develop a field deployable robot for data collection on concrete bridges. 7. Test the tele-presence of operator using an Avatar-Drone. 8. Develop a real-time scour monitoring technique	1. N/A. 2. Successful demonstration of robot prototypes in laboratory and field. 3. Successful demonstration for robot mobility and data recording. 4. Laboratory tests for girder detection and flight control. 5. Implementation of motion planning algorithms on robot's controllers. 6. Functional control system for solenoid-based impact sounding during move-stop-sample operations. 7. Aerial drilling task completed using human-drone interaction. 8. Suction mechanism tested to ensure sufficient force.	1. Complete. 2. Climbing robots tested on steel members and bridges. 3. Final project report completed. 4. ROS software for girder detection and flight control completed. 5. A multi-directional bicycle robot tested for steel inspection. 6. An integrated 3D test position and data analysis in frequency domain for underground object detection. 7. Avatar-Drone for aerial drilling and debris cleaning via a hose. 8. A complete design of climbing robot.

Topic	Major Activities	Specific Objectives	Significant Results	Key Outcomes
	column surface for scour monitoring.	with a robot-mounted soner and altimeter.		
IM	1. N/A 2. Prepare and review a final report. 3. Integrate various components into an impact sounding data collection and recording system for defect detection in hollow structures.	1. N/A 2. Develop and publish a high-quality report on research findings and results. 3. Develop an approach to rate the condition of concrete members based on measurements from robot-mounted sensors (speaker and camera).	1. N/A 2. Empirical mode decomposition effective to cleanse noise from data. 3. Individual components of the sounding tool tested for their compatibility and efficiency.	1. Withdrawn. 2. Final project report completed. 3. An integration framework developed with individual components tested.
RR	1. Analyze both vertical and lateral responses of piles subject to scour in both sand and clay. 2. None to report.	1. Enable both vertical and lateral responses of scoured piles to be monitored. 2. None to report.	1. Computational and experimental verification on the effect of scour in various soil types. 2. None to report.	1. A set of fragility curves and risk updates based on scour data at foundation. 2. Not yet started.
WD	1. Prepare and review a final report. 2. Improve a genetic algorithm with a parallelized implementation for robot inspection routing. 3. Create a training scenario with one UAV for global inspection and three climbing robots for local inspection. 4. Select a web software platform to implement the developed deep learning tool for image segmentation and object detection.	1. Develop and publish a high-quality report on research findings and results. 2. Develop a Simulation Training And Control System (STACS 2) with robot routing plans. 3. Develop an advanced STACS 2 for bridge inspection training. 4. Prototype an interactive web system that guides and assists users in robot-based inspection video analytics.	1. Deep learning effective in segmenting and detecting critical components. 2. Near-optimal inspection routes achieved for less than 10 robots. 3. Tools for generation and positioning of scenario bridges in different trainings. 4. Django language in Python for the development of web interactive system.	1. A framework of training on the use of big data based on deep learning. 2. New control algorithms and models for climbing robots. 3. Training scenarios for comprehensive training. 4. Functions and features of the developed deep learning tool reviewed.

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

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

In this reporting period, the INSPIRE UTC directly involved 12 faculty, 1 post doc, 13 graduate students, and 4 undergraduate students in civil engineering, electrical engineering, mechanical engineering, computer science, and engineering management and system engineering through its research program with 13 on-going projects.

The INSPIRE UTC continued to offer courses that are relevant to the research activities among consortium partners. For example, Dr. Chen offered the graduate course Structural Dynamics and Earthquake Engineering in Winter 2021 at Missouri S&T, which attracted 9 graduate students.

1.D - How Have the Results Been Disseminated?

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

Invited Presentations:

1. Genda Chen. "Robot-assisted Bridge Inspection and Maintenance," Case Western Reserve University, Cleveland, Ohio, March 11, 2021.
2. Pengfei Ma, Liujun Li, and Genda Chen. "Gas Leakage Detection with Hyperspectral Imagery-Based Vegetation Stress Indices," Pipeline Research Council International 2021 Virtual Research Exchange, March 2-5, 2021.
3. Genda Chen. "Future Infrastructure Management using the 4.0 Industry Revolution Technology," Stony Brook University, Long Island, New York, March 1, 2021.
4. Genda Chen. "Robotic Platform for Autonomous Bridge Inspection and Maintenance," First International Conference on Unmanned Aerial Vehicles, Remote Control Vehicles and Remotely Operated Vehicles for Onshore, Offshore and Subsea Asset and System Integrity: DRONES & ROVS, London, UK, February 25-26, 2021.
5. Jinglun Feng, Liang Yang, Haiyan Wang, Yingli Tian, and Jizhong Xiao, "Subsurface Pipes Detection Using DNN-based Back Projection on GPR Data", Proceedings of the IEEE/CVF Winter Conference on Applications of Computer Vision (WCACV2021), January 5-9, 2021, pp. 266-275.

Biannual Newsletters

The INSPIRE UTC publishes biannual newsletters to disseminate research information and enhance public understanding of Center activities. INSPIRE newsletters are distributed to nearly 10,000 people through the Center's listserv, and are made available online at https://inspire-utc.mst.edu/news/. An INSPIRE UTC Newsletter (Vol. 4, No. 2) was published in Fall 2020 and included three technical articles related to INSPIRE research:

- *The Collapse of The Silver Bridge, Dr. Mohamed ElGawady, Missouri S&T*
- *Failure Investigation of Bridge Collapse Due to Scour, Dr. Haibin Zhang, Missouri S&T*
- *An Overview of Fire-Induced Bridge Damage, Yanping Zhu, Missouri S&T*

Quarterly Webinars

The INSPIRE UTC hosts quarterly webinars. Overall, 15 INSPIRE webinars have engaged more than 750 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. Note that the updated statistics during this report period is unavailable due to unexpected changes in Zoom meeting setup to enhance security.

Two webinars were presented in this reporting period, and engaged more than 200 participants:

1. Artificial Intelligence-Empowered Civil Engineer was presented on December 8, 2020 by Dr. Hui Li from Harbin Institute of Technology, Harbin, China.
2. Human-Robot Collaboration for Effective Bridge Inspection in the Artificial Intelligence Era was presented on March 23, 2021 by Dr. Ruwen Qin from Stony Brook University, New York.

Education and Outreach Activities

Dr. Paul Oh's team at the 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-aid-design (CAD), 3D printing, and embedded controllers (Arduino). Due to COVID-19, these programs are being held online. Additionally, the team continues to serve institutional outreach programs, namely Upward Bound. This program is UNLV's outreach to middle schoolers. Each Saturday (09:00-15:00), the team conducts hands-on STEM labs. These labs include drone (programming), augmented reality (projection mapping), and embedded control (Arduino). Due to COVID-19, these programs are also being held online.

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	Autonomous Ultrasonic Thickness Measurement by a Magnet-Wheeled Robot	• Develop a plan to mount and retrieve a ultrasonic transducer on a structural surface with an automatic dispense of attachment adhesive. • Implement wireless transmission of ultrasonic data from the Martlet's onboard SD card to a base station. • Integrate the printed circuit board into a UNR robot and evaluate its performance in laboratory.
	Health Inspection of Concrete Pavement and Bridge Members Exposed to Freeze-Thaw Service Environments	• Prepare concrete, mortar, and cement paste specimens with various degrees of saturation. • Conduct a comparative study on different nondestructive tests to identify the most effective technologies for freeze-thaw degradation characterization. • Correlate the nondestructive tests with hyperspectral imaging.
	Probability of Detection in Corrosion Monitoring with Fe-C Coated LPFG Sensors	• Continue to analyze the test data collected from Fe-C coated long period fiber gratings (LPFG) sensors to understand their variation in measurement of corrosion-induced mass loss. • Develop a framework of determining the probability of detection for Fe-C coated LPFG sensors.
AS	Bridge Inspection Robot Deployment Systems (BIRDS)	• Improve the performance of the second hybrid flying and traversing unmanned vehicle prototype for inspection of girder bridges. • Develop an autonomous transition scheme from flying to traversing mode of operation. • Develop technical specifications of the vehicle for flying, traversing, and their transition performance.
	Nondestructive Data Driven Motion Planning for Inspection Robots	• Build a complete navigation framework that utilizes the previously developed boundary detection algorithm, deep learning method, and hidden Markov model to classify different steel structure shapes. • Continue to investigate the deployment of the robot in actual steel bridges to achieve its autonomy and classification of various structural shapes.
	A Field Deployable Wall-Climbing Robot for Bridge Inspection using Vision and Impact Sounding Techniques	• Select different materials and use 3D printing to construct new treads of the robot to increase its friction and reliability of moving up a vertical wall. • Develop a solution (e.g., an insulation box) to minimize the effect of robot operation noise on the current impact sounding mechanism. • Integrate vision-based positioning into the automatic collection of data to make the robotic sampling much faster than manual data collection.
	Augmenting Bridge Inspection with Augmented Reality and	• Model host reaction forces and experimentally verify the force prediction model.

Topic	Project Title	Planned Activities
	Haptics-based Aerial Manipulation	• Demonstrate the mobile manipulated UAV for high-pressure washing of concrete surfaces.
	Robot-assisted Underwater Acoustic Imaging for Bridge Scour Evaluation	• Design and prototype a four vaccum cups supported TreeFrog robot that can move on the curve/flat surface of RC piers to facilitate scour monitoring. • Integrate the side-scan sonar and the altimeter with the climbing robot, and test system's maneuverability and stability as well as sensors' performance.
IM	"Smart Sounding System" for Autonomous Evaluation of Concrete and Metallic Structures	• Fine tune the components of an electronic sounding device and assemble them into a desired "smart sounding tool." • Manufacture the device for efficient field operation with portability • Create classes of bridges based on collected inspection data. • Define measures of similarity across bridges.
RR	Data-Driven Risk-Informed Bridge Asset Management and Prioritization across Transportation Networks	• Finalize the previously prepared three journal manuscripts and submit them for potential publication. • Investigate the impact of scour on the dynamic buckling of bridges, an unstudied area of bridge performance under scour conditions.
WD	Simulation Training to Work with Bridge Inspection Robots	• Integrate generated trusses into five training scenarios with n flying and k climbing inspection robots and evaluate their utility for workforce training. • Build a c# version of genetic algorithm router for better integration into scenario generation and execution. • Create a template ROS bridge to a robot to make the developed technique generalizable to other robots for monitoring and control in STACS.
	An Interactive System for Training and Assisting Bridge Inspectors in Inspection Video Data Analytics	• Create web-based learning modules for trainees to master cross-disciplinary knowledge and fundamental skills of analytics. • Develop an inspection data analytics tool to assist inspectors in processing and analyzing inspection video data for the condition assessment of bridges.

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

Other Planned Initiatives

1. Abbett Distinguished Seminar Series by Dr. Anand Puppala to be held June 3rd, 2021.
2. INSPIRE UTC Webinar "*Fiber Optic Sensor Based Corrosion Assessment In Reinforced Concrete Bridge Elements And Metal Pipelines"* to be presented by Dr. Genda Chen, Missouri S&T, on June 16th, 2021.
3. INSPIRE UTC Annual Meeting (tentative) August 2021.

2. PARTICIPANTS & COLLABORATING ORGANIZATIONS

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

Consortium Collaborators

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

- Missouri University of Science and Technology - Rolla, MO (lead institution)
- City College of New York - New York, NY
- Georgia Institute of Technology - Atlanta, GA
- 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

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

Internal Partners at Missouri S&T

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

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

Dr. Genda Chen's team has been working actively with seven state Departments of Transportation (listed above) on the pooled-fund study on the field implementation of the advanced technologies developed at INSPIRE UTC.

Dr. Jizhong Xiao's team of the City College of New York accessed Geophysical Survey System Inc. (GSSI)'s test pit to collect ground penetrating radar (GPR)/impact sounding data.

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 subcontracted some research and development work to the City College of New York Robotics Lab.

The University of Nevada, Las Vegas officially began a Phase 2 task order contract with Tesla's Reno-based Gigafactory in March 2020 with researchers on using robots for building inspection. This task order is independent of this INSPIRE UTC project. However, there is some overlap technologically e.g. AR and using robots to monitor sites and manipulate objects. Hence, this UNLV-Tesla collaboration will likely give INSPIRE UTC added visibility.

Dr. Sushil Louis' team has worked with Dr. Hung La and Dr. Genda Chen in obtaining models and simulation data for STACS robots.

Dr. Yang Wang's team is partnered with Dr. Hung La's team from UNR. Dr. Hung La's team has provided the small mobile robot for later integration.

3. OUTPUTS

3.A - Publications, Conference Papers, and Presentations

Journal Publications

1. H. Ahmed, H.M. La, and K. Tran. "Rebar Detection and Localization for Bridge Deck Inspection and Evaluation Using Deep Residual Network," *Journal of Automation in Construction* 120: 103393, December 2020. https://doi.org/10.1016/j.autcon.2020.103393.
2. R. Al Yamani, and S. Long. "The Application of Fuzzy Analytic Hierarchy Process in Sustainable Project Selection," *Sustainability* 12: 8314, October 9, 2020; https://doi:10.3390/su12208314. Invited Special Issue on Driving Sustainability through Engineering Management and Systems Engineering, Special Issue Editor, Dr. Simon Philbin.
3. Y. Alghamdi, A. Munir, H.M. La. "Architecture, Classification, and Applications of Contemporary Unmanned Aerial Vehicles," *IEEE Consumer Electronics Magazine*, March 2021, DOI: 10.1109/MCE.2021.3063945.
4. R. Cai, T. Han, W. Liao, J. Huang, D. Li, A. Kumar, and H. Ma. "Prediction of Surface Chloride Concentration of Marine Concrete using Ensemble Machine Learning," *Cement and Concrete Research* 163: 106164, October 2020. DOI: 10.1016/j.cemconres.2020.106164.
5. R. Cai, Y. Hu, M. Yu, W. Liao, L. Yang, A. Kumar, and H. Ma. "Skin Effect of Chloride Ingress in Marine Concrete: A Review on the Convection Zone," *Construction and Building Materials* 262: 120566, November 30, 2020. DOI: 10.1016/j.conbuildmat.2020.120566.
6. R. Cai, M. Yu, L. Yang, and H. Ma. "Influence of Data Acquisition and Processing on Surface Chloride Concentration of Marine Concrete," *Construction and Building Materials* 273: 121705, March 1, 2021. DOI: 10.1016/j.conbuildmat.2020.121705.
7. X. Chen, H. Wang, H., A.H.C. Chan, A.K. Agrawal, and Y. Cheng. "Collapse Simulation of Masonry Arches Induced by Spreading Supports with the Combined Finite–discrete Element Method," *Computational Particle Mechanics*, 1-15, October 9, 2020.
8. C.R. Guo, Y.C. Zhang, M.A. Klegseth, J. Gao, and G.D. Chen. "Micrometer-accuracy 2D Displacement Interferometer with Plasmonic Metasurface Resonators," *Optics Letters* 45(23):

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10. D. Hou, D. Chen, X. Wang, D. Wu, H. Ma, X. Hu, Y. Zhang, P. Wang, and R. Yu. “RSM-based Modelling and Optimization of Magnesium Phosphate Cement-based Rapid-repair Materials,” *Construction and Building Materials* 263: 120190, December 10, 2020. DOI: 10.1016/j.conbuildmat.2020.120190.
11. Z. Huang, Y. Huang, W. Liao, N. Han, Y. Zhou, F. Xing, T. Sui, B. Wang, and H. Ma. “Development of Limestone Calcined Clay Cement (LC3) Concrete in South China and its Bond Behavior with Reinforcing Bar,” *Journal of Zhejiang University* – Science A (Applied Physics and Engineering) 21(11): 892-907, November 2020. DOI: 10.1631/jzus.A2000163.
12. J. Hale, and S. Long. “A Time Series Sustainability Assessment of a Partial Energy Portfolio Transition,” *Energies* 14: 141, December 29, 2020; https://doi.org/10.3390/en14010141. Invited Special Issue on Integrated Approaches for Enterprise Sustainability. Special Issue Editor: Dr. Patrycja Habek.
13. M.M. Karim, R. Qin, G. Chen, and Z. Yin. “A Semi-supervised Self-training Method to Develop Assistive Intelligence for Segmenting Multiclass Bridge Elements from Inspection Videos,” *Structural Health Monitoring*. Accepted.
14. R. Konda, H.M. La, and J. Zhang. “Decentralized Function Approximated Q-Learning in Multi-Robot Systems for Predator Avoidance,” *IEEE Robotics and Automation Letter* 5(4): 2377-3766, October 2020, DOI: 10.1109/LRA.2020.3013920.
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17. D. Li, and Y. Wang. "Parameter Identification of a Differentiable Bouc-Wen Model Using Constrained Extended Kalman Filter," *Structural Health Monitoring* 20(1): 360-378, January 1, 2021.
18. X. Liu, Y. Wang, and E. Verriest. "Simultaneous Input-state Estimation with Direct Feedthrough based on a Unifying MMSE Framework with Experimental Validation," *Mechanical Systems and Signal Processing* 147: 107083, January 15, 2021.
19. W. Liao, Y. Zhuang, C. Zeng, W. Deng, J. Huang, and H. Ma. “Fiber Optic Sensors Enabled Monitoring of Thermal Curling of Concrete Pavement Slab: Temperature, Strain and Inclination,” *Measurement* 165: 108203, December 1, 2020. DOI: 10.1016/j.measurement.2020.108203.
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Books or Other Non-periodical One-time Publications – Conference Papers

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2. H.D. Bui, S. Nguyen, U.H. Billah, C. Le, A. Tavakkoli, and H.M. La. "Control Framework for a Hybrid-steel Bridge Inspection Robot," The 2020 *IEEE/RSJ International Conference on Intelligent Robots and Systems,* pp. 2585-2591, October 25-29, 2020, Las Vegas, NV, USA.
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4. J. Hale, S. Long, S. Corns, and C. Dagli. "A Computational Intelligence Approach to Transitioning an Electricity Portfolio," *Proceedings of the IISE Annual Conference and Expo 2020*, New Orleans, LA, June 2020. Invited Session.
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6. D. Kim, and P.Y. Oh. "Human-Drone Interaction for Aerially Manipulated Drilling Using Haptic Feedback," *IEEE International Conference on Intelligent Robots and Systems* (IROS), Las Vegas, NV, Oct 25-30, 2020.
7. S. Louis. "Open source public project repository, Github. https://github.com/sushillouis/Stacs.

Final Technical Reports of Projects

1. A.K.Agrawal, M. Ettouney, X. Chen, H. Li, and H. Wang. Steel Truss Retrofits to Provide Alternate Load Paths for Cut, Damaged, or Destroyed Members. PUBLICATION NO. FHWA-HRT-20-055 U.S., Federal Highway Administration, October 2020.
2. A. Alhaj, L. Fan, G.D. Chen, and H.M. Ma. Hyperspectral Imaging Analysis for Mechanical and Chemical Properties of Concrete and Steel Surfaces. Final Report No. INSPIRE-009, March 31, 2021.
3. J.Z. Xiao, L. Yang, J.L. Feng, and E. Hoxha. Autonomous Wall-climbing Robots for Inspection and Maintenance of Concrete Bridges. Final Report No. INSPIRE-008, February 30, 2021.

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

- Advanced Robotics and Automation Laboratory: https://ara.cse.unr.edu
- Center for Intelligent Infrastructure: https://cii.mst.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
- Open Source STACS Software: https://github.com/sushillouis/Stacs (main and Pronto2 branches)

3.C - New Technologies or Techniques

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

- Dr. Anil Agrawal's team, inspired by the sounding data analysis, has extended the concept of data filtering to high-frequency noise in theoretical and experimental data from high speed impact of trucks on bridge piers and barriers. This will be a significant publication impacting engineering disciplines requiring complex explicit finite element simulations using software such as LS-DYNA.
- Dr. Genda Chen's team began to investigate data fusion of multimodal imagers for element classification and damage/deterioration detection in the framework of deep learning. Once available, the data fusion technique will enable the identification of multiple defects from both physical and chemical changes on structural surface and subsurface.
- Dr. Hung La's team has built a control framework for the climbing robot to automatically switch between two modes: mobile and inch-worm in order to execute the inspection of a complete bridge including joints.
- Dr. Sushil Louis' team has created a template training scenario with one flying inspection robot and three climbing robots. The team also developed a tool to quickly generate bridge truss structures and made it possible to write out the joint coordinates of a bridge truss to a file in order for a C++ genetic algorithm to generate near-optimal routing for *k* inspection robots.
- Dr. Hongyan Ma's team has selected cement pastes, prepared concrete, mortar and cement paste specimens, selected NDTs to characterize the strength development associated with freeze-thaw degradation.
- Dr. Paul Oh's team has created a VR headset and Unity software environment for maintenance of bridges using a dual-arm manipulator.
- Dr. Iris Tien's team has combined numerical and experimental approaches to verify the ability to assess both vertical and lateral responses of bridge piles subject to scour in sandy and clay soils.
- Dr. Yang Wang's team has printed circuits of the designed ultrasonic daughter and pulser boards to obtain accurate thickness. An onboard SD card data saving method was implemented using a Martlet device for stable data collection using an 80MHz frequency with a new oscillator that implements a higher sampling frequency and improves resolution in thickness measurement.
- Dr. Jizhong Xiao's team has produced an Impact-Rover that hosts both impact sounding and impact echo devices using a MEMS microphone which provides a robotic solution to generate and analyze the impact sounding data for NDE of underground defects. The team collected impact sounding data on CCNY/InnovBot concrete slabs using a robot for faster sampling and automatic record of locations.

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

- J.Z. Xiao, K.S. Ushiroda, G.Y. Yang, S.V. Saniegepalli, and Y.F., Song. "Robotic Device for Providing Vertical Mobility," Continuation Patent Application No. 16/740,883, filed on January 13, 2020 and noticed for allowance and fees on February 10, 2021.

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 – https://scholarsmine.mst.edu/inspire_webinars.

Dr. Sushil Louis of University of Nevada at Reno placed open source STACS software on Github (https://github.com/sushillouis/Stacs which serves as a public project repository resource for INSPIRE UTC and other projects related to autonomy and bridge inspection.

Dr. Jizhong Xiao of City College of New York (CCNY) collected structure spalling and crack (CSSC) dataset that includes 820 images with pixel-level labeling and augmentation by image flipping, rotation, and sub-cropping for training and validation of CNN-based visual inspection algorithms. The dataset will be stored at Missouri S&T's data repository.

3.F - INSPIRE Research Outputs Performance Metrics

Research Outputs - Performance Measures	Cumulative Total
1. At least 5 journal publications and books per investigator/year	4.3
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 has completed the conceptual design of a sounding tool and continues to add modifications as needed with individual components that has been checked out for compatibility and efficiency when integrated into a smart sounding tool. The team has successfully obtained the tracking record using the Intel realsense T265 tracking camera with Robot operating system (ROS), incorporated a bluetooth speaker with amplifier, and are working on the assembly of MEMS microphones in array and GPS to obtain location accuracy.

Dr. Genda Chen's team developed a comprehensive sensor calibration framework and procedure as well as examples. At INSPIRE UTC, visible, thermal, hyperspectral, and LiDAR images are acquired in large quantity. To ensure their usefulness, these imaging devices (or cameras) will be calibrated on a regular basis before extensive field tests are conducted.

Dr. Hung La's team has built a control framework to control the climbing robot to automatically switch between two modes (mobile and inch-worm; built a steel bar/structure boundary detection algorithm using a depth camera integrated robot; validated and optimized the motion planning algorithm to determine the best path to help the robot transit efficiently on steel structures and implemented the motion planning on the robot low and high level controllers. The team built and tested a multi-directional bicycle robot for steel structure inspection and a 3D map of the inspected area using SLAM for robot navigation. The team also developed a visual-servo localization algorithm and a deep learning based defect (rust) detection algorithm with implementation on the robot to show real time results.

Dr. Sushil Louis' team has begun developing a new version of open source STACS software on Github

at https://github.com/sushillouis/Stacs, which serves as a resource for INSPIRE UTC and other projects related to autonomy and bridge inspection. They also provide significant improvements to the Genetic Algorithm approach which increases the utility to the NP-Hard Min-Max k-Chinese Postman problem, Arc Routing and Discrete Optimization. The team completed the first version of the STACS environment and published results showing the efficacy of the approach to optimal balanced route generation.

Dr. Sushil Louis' team has made progress on the next version of STACS environment and has created a template training scenario with one flying inspection robot and three climbing robots. The team also created new capabilities: 1) better simulation physics to enable going over truss member edges and enabled easier point and click for commanding climbing robot movement; 2) expanded and integrated virtual reality (VR) capabilities of simulation to handle desktop display or VR based hardware; 3) began integrating new version of Dr. Hung La's robot (version 3) into STACS in the development branch of the code.

Dr. Hongyan Ma's team elucidated various methods to generate and control the degree of saturation in concrete, selected relevant NDTs to evaluate the status of concrete and designed mix proportions of concrete, mortar and cement paste for further aging studies.

Dr. Iris Tien's team has been focused on the verification of a new methods to analyze vertical and lateral response of piles subject to scour in both sand and clay, as well as conducting numerical and experimental verification using results from multiple studies in the literature of piles under varying scour conditions and soil types which is necessary to increase confidence in results obtained of impacts of scour on structural responses using the new methodology.

Dr. Jizhong Xiao's team has fabricated, assembled and tested a new climbing robot (Impact-Rover) which is able to perform move-stop-sample operations to collect a series of sounding data at adjustable spacing along perpendicular lines to the moving direction on ground surface and performed experimental testing and collection of impact sounding data and signal analysis on CCNY/InnovBot concrete slabs. The team has developed a method to detect underground objects by Visual Simultaneous Localization and Mapping (V-SLAM) and Fast Fourier Transform (FTT) and Frequency Density and Power Spectral Density (PSD) plots to process impact sounding signal and frequency peaks.

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

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 program will also seek to replace the traditional mechanical-impact devices, such as the hammer, with much more controllable electronic-sounding devices, which are also easier to be implemented in the robotic systems, like unmanned aerial vehicles (UAVs).

Dr. Genda Chen's work on hybrid vehicles will enable bridge inspection from the underside of bridge decks with minimum or no impact on traffic on roadways. Such inspections would be safer, cheaper, and faster. Currently autonomous engagement with a bridge girder is being developed.

Dr. Hung La's team's work will contribute to the automated bridge inspection efforts. The successful completion of the proposed research will provide a new automation-assisted inspection system that will be non-destructive, comprehensive, rapid, and cost effective for all stages of bridge deterioration.

Dr. Sushil Louis' team began developing a new version of open source STACS software which serves as a resource for INSPIRE UTC and other projects related to autonomy and bridge inspection. The team discovered that STACS will improve safety and drastically cut costs of bridge inspections by significantly reducing the number of human operators needed to perform a bridge inspection. Utilizing a team of several robots allows the task to be completed quickly and reduces salary costs associated with bridge inspection.

Dr. Hongyan Ma's team developed a deeper understanding with the mechanism of freeze-thaw cycling induced damages to concrete and how to evaluate it. The developed technology could be transplanted to solve similar problems in other disciplines such as ceramic/glass engineering and geological engineering. If successful, the developed technology will be easily transferred to DOTs and transportation serving companies.

Dr. Paul Oh's team research impacts the design, development and deployment of aerial manipulators. Aerial manipulation and human-in-the-loop control would augment the performance of bridge workers with new tools.

Dr. Iris Tien's team worked on creating the ability to assess both vertical and lateral responses of bridge piles subject to scour, as well as to assess these responses in both sandy and clayey soils. This creates a comprehensive approach to risk assessment by scoured bridges that has not been previously possible.

Dr. Yang Wang's team developed an innovative robotic sensing technology that can autonomously perform ultrasonic thickness measurement on steel bridge members. The sensing technology has the potential to be adopted in bridge monitoring practices.

Dr. Jizhong Xiao's team's proposed R&D on robotic hardware and NDE data analysis software is likely to increase the knowledge base and tackle the robotic inspection challenges on a wide range of infrastructures. More specifically, the wall-climbing robot will provide vertical mobility to conduct NDE on difficult-to-access locations.

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

Dr. Hung La's team has created a start-up company, Automated Inspection Robots (AIR) Corp., it was established in January 2020. The team is currently working on a SBIR proposal to request for funding to support this start-up company.

Dr. Jizhong Xiao's research may develop 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. Genda Chen's team worked towards the in-depth understanding of remote sensing with dual-sensor

FLIR Duo Pro R640 Infrared camera and Nano-Hyperspec camera as well as different LiDAR scanners. The understanding of imaging mechanisms from various devices helps acquire high-quality inspection data when installed on a UAV.

Dr. Hung La's team developed a good understanding of the magnetic force required in future design and calculation of different types of steel inspection robots.

Dr. Hongyan Ma's team helps understand the effectiveness of nondestructive testing and hyperspectral imaging for the evaluation of freeze-thaw degradation.

Dr. Iris Tien's team helps to understand the effect of soil types on both the horizontal and vertical stability requirements of bridges.

Dr. Jizhong Xiao's team helps understand the source of robot operation noise and develop a filtering approach to remove noise in impact sounding and impact echo data analysis.

5.D - Transportation Workforce Development

Dr. Genda Chen of Missouri University of Science and Technology provided training opportunities of graduate students on interdisciplinary research topics involving civil engineering, computer science, electrical engineering, and mechanical engineering. This school of students will contribute the much-needed workforce related to the remote sensing and data analytics in transportation infrastructure.

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. Dr. Hung is developing a new advanced robotics course: CPE471/671 Advanced Robotics, and its curriculum has been submitted and under review by the UNR Curriculum committee. Besides, Dr. Hung has organized several lab open day events to generate robotic interests to both local elementary and high school students as well as DOT and industry. Both undergraduate and graduate students have participated in all phases of the project. They have been trained through hands-on design, fabrication, prototyping and programming of the robots.

Dr. Iris Tien of Georgia Institute of Technology is impacting transportation workforce development through continued graduate student advising for work for the Bridge Resilience Assessment with INSPIRE Data project. This project has provided training in communication of research results in the form of preparing, editing, and revising manuscripts for publication; and provided training in the form of oral presentations to research groups on the results of the research work and oral presentations at conferences to audiences of researchers and practitioners across the U.S.

Dr. Yang Wang of Georgia Institute of Technology worked with one female graduate student on transportation-related research with faculty associated with the INSPIRE UTC.

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

COVID-19 Impact on Research Approach

The City College of New York campus has been closed since early March 2020 due to the rapid development of the COVID-19 crisis. Students cannot conduct laboratory tests on our sounding tool or GPS and location setup accuracy. Students are currently working from home by using their laptops. Computational work related to data analysis, product design, and paper writing is still in progress.

Dr. Genda Chen's campus allowed for student access to laboratory as soon as students in any laboratory meet mask and 6-ft-distance requirements. Students may thus have to access to laboratory in a shifted schedule.

Dr. Hung La's campus is mainly in telework mode with partial access to machine shops, laboratory spaces, facilities, and equipment. Students supported on this project are continuing with computational work and only have partial access to the lab and facility to perform physical work.

Dr. Sushil Louis' campus is partially open, but most students remain in telework mode with occasional visits to campus labs, facilities and equipment.

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

COVID-19 Impact on Research Progress Delay

During COVID-19 period, computational modeling and simulation work at the INSPIRE UTC continues with little impact. But most of experimental works are on hold or impacted with limited access.

Dr. Anil Agrawal of The City College of New York (CCNY)'s work progress has been affected by the final semester exams of his student unrelated to COVID.

Dr. Genda Chen from Missouri University of Science and Technology is slightly delayed due to the limited student access to any laboratory at the same time.

Dr. Hung La from the University of Nevada Rene is limited for work related to hardware integration, robot part manufacturing, robot test and validation due to COVID-19 safety requirements.

Dr. Sushil Louis from the University of Nevada Reno is limited for work related to hardware integration or investigation of workforce training software.

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

COVID-19 Impact on Research Expenditure

Research students and faculty are paid on appointment based on the expected work to be completed. In general, work efficiency of the research projects is at approximately 75%. For all INSPIRE projects, the completion of the scopes during the COVID-19 period remains uncertain.

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

Nothing to report.

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

Nothing to report.