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Semi-Annual Progress Report #13

Missouri University of Science and Technology
Inspire - University Transportation Center

UTC Semi-Annual Progress Report #13

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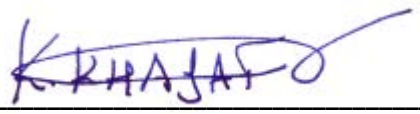

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1. ACCOMPLISHMENTS

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 are approaching 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 analytics, 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 analytics, 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 general public education.

Education Objectives

Three education objectives are set:

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:

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 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 University of Science and Technology (Missouri S&T).

1.B - What Was Accomplished under These Goals?

To support the research objectives, major progress was made in each of the research topics: sensing and nondestructive evaluation (SN), autonomous survey (AS), inspection and maintenance (IM), retrofit and resilience (RR), and workforce development (WD). As summarized in Table 1, the progress is evaluated in terms of major activities, specific objectives, significant results, and key outcomes for each ongoing project. For example, the first project in Table 1 is designated as SN-6, extracting from the first column (Topic SN) and the second column (the project number 6).

Table 1. A summary of research progress

Topic	Major Activities	Specific Objectives	Significant Results	Key Outcomes
SN	6. Test a new solar charging and ultrasonic testing system including two more pulser boards. 7. Continue to draft the final report of this two-year project. 8. Continue to test transparent MXene for easy coating and improved sensing. 9. Set up Q-fog tests to validate hyperspectral imaging performance for steel- corrosion analysis.	6. Provide more stable power supply to ultrasonic devices and multiple sensor nodes. 7. Summarize approaches, experimental setups, and research findings. 8. Improve the reliability of corrosion sensors for steel mass loss measurement. 9. Develop a rapid condition assessment tool for multilayered coating on steel members.	6. The 12V solar battery voltage is reduced to 7V for stable power of Martlet system. 7. Both nondestructive tests & hyperspectral imaging are effective. 8. Preliminary results show consistent sensitivity to some degree. 9. Hyperspectral images include information on coating and substrate condition.	6. The Martlet wireless sensing device becomes more stable. 7. Hyperspectral images include F-T damage information. 8. Three sensors are encapsulated in tube for short- and long-term monitoring. 9. Hyperspectral imaging is a rapid and effective tool for coating assessment.

AS	4. Build and test a new prototype for hybrid flying and traversing operation in application. 5. Implement SLAM on an inspection robot and calibrate LiDAR and stereo camera. 6. Develop an iPad App for motion control of climbers and visualization of inspection results. 7. Prepare and submit the draft final report currently under review. 8. Acquire and receive a 3D sonar for 3D riverbed reconstruction. 9. Continue to improve the cable-driven parallel robot.	4. Create a multifunctional hybrid platform to support tele-inspection in high quality. 5. Develop a reliable field-grade bicycle-like robot with both sensing and actuating mechanisms. 6. Improve the vertical mobility of a GPR-rover and the GPR detectability of internal defects. 7. Summarize approaches, experimental setups, and research findings. 8. Map riverbed to create 3D reconstruction and understand scouring. 9. Test the cable-driven parallel robot with a telescopic mast.	4. Previous tests on two highway bridges indicate robust flight and data collection. 5. Real-time video streams are used to guide navigation of the climbing robot. 6. The two-chamber robot carries two GPR antennas (GP880 and Flex NX). 7. A human-drone interface with haptics is tested. 8. A multi-beam sonar is assembled with its ROV being assembled. 9. Smartphone App is used to compute drone waypoints.	4. A design of hybrid flying and traversing vehicles is prototyped. 5. Two publications appear and the start-up Air Corp website is launched. 6. The integrated system is tested successfully at a bridge site. 7. The drilling drone is transferred to the INSPIRE Center. 8. A multi-beam sonar in water provides 3D information. 9. A model for LEG's bi-stable properties is derived.
IM	3. Modify the Graphical User Interface to support automatic data collection and visualization. 4. Explore photogrammetric and Gaussian splatting approaches for 3D reconstruction. 5. Revise the final report of this project and update a journal manuscript.	3. Integrate the new software package into the early sounding device for data collection. 4. Develop an efficient procedure and model for 3D reconstruction of bridges. 5. Develop technical performance criteria and evaluation metrics.	3. Data are collected smoothly through the new App as confirmed in lab tests. 4. Visual images from multiple drone fights are stitched for a complete bridge view. 5. Virtual collaboration is implemented in AR/VR environment.	3. The new interface is greatly simplified to enhance data handling efficiency. 4. Synchronized multimodal images enable a 3D bridge reconstruction. 5. AR immerses several inspectors in virtual collaboration.
RR	2. Collect, cleanse, label, and apply data in computer vision and machine learning.	2. Improve computer vision and machine learning for corrosion effects from RGB images.	2. A framework of data process and analysis is created to support bridge inspection.	2. Image processing, computer vision, and accuracy evaluation modules are tested.
WD	4. Develop instructional neural networks with a reconfigurable architecture.	4. Guide and assist users to learn fundamentals of video data analytics using machine learning.	4. Modular blocks of a neural network are combined for a learning task.	4. A large dataset and machine learning modules are developed.

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

To support the education objectives, courses related to the theme of the INSPIRE UTC were offered at partner institutions, such as CIV_ENG5208: Structural Dynamics at Missouri S&T as impact-echo tests involves the dynamic response of a structure, which attracts 17 full-time and part-time students.

To support the workforce development objectives, graduate students and professionals were exposed to the technologies developed at the INSPIRE UTC through quarterly webinars or in-person gatherings. Hands-on training modules from completed research projects were developed to help participants learn the concept, design, and fabrication of various hardware and use software to simulate sensing and assessment during inspection and/or develop strategies during maintenance.

To support the technology transfer objectives, the accompanying seven-state pooled-fund study No. TPF5(395): Traffic Disruption-free Bridge Inspection Initiative with Robotic Systems progressed by further processing the imagery collected from 45 bridges in the state of Virginia, Wisconsin, Georgia,

Missouri, and Texas. An inspection crew of three people operated commercial drones (e.g., Elios3), custom-integrated drones (e.g., Headwall DJI M600, and Geodetic DJI M600), and custom-made robots (e.g., climbing robot on steel bridges).

To support the diversity objectives, laboratory demonstrations, hands-on practices, and other outreach activities were offered to college students in collaboration with minority student organizations and K-7 to K-12 students. Undergraduate, graduate students, and post-doctoral fellows working on the INSPIRE UTC projects served as models and mentors for the young participants.

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

The INSPIRE UTC directly involved 8 faculty, 10 post docs, 23 graduate students, and 13 undergraduate students in civil and architectural engineering, computer science, electrical and computer engineering, and mechanical engineering through 15 on-going research projects.

1.D - How Have the Results Been Disseminated?

The research results from various projects were disseminated through multiple venues for audiences from K7-K16 students, governments, academia, and industry. These venues include Biannual Newsletters, Education and Outreach Events, Invited Presentations, Journal and Conference Initiatives, and Quarterly Webinars.

Invited Presentations:

1. Dr. Jizhong Xiao was invited to give a talk at ASNT2023, the annual conference of American Society of Nondestructive Testing on October 24, 2023, in Houston, TX. The title of the invited talk is “Robotic Inspection of Infrastructure Using Vision, GPR and Impact-Echo Sensors”.

Biannual Newsletters

The INSPIRE UTC publishes biannual newsletters to disseminate research information and enhance public understanding of Center activities. INSPIRE newsletters are distributed to 14,572 people through the Center’s listserv and are made available online at https://inspire-utc.mst.edu/news/. An INSPIRE UTC Newsletter (Vol. 7, No. 2) was published in Fall 2023, including one research article related to INSPIRE research:

1. Mullti-dimensional digital twin in the built environment prepared by Genda Chen, INSPIRE UTC Director.

Quarterly Webinars

Overall, 27 INSPIRE UTC quarterly webinars have engaged 4,698 people from 49 US States and 58 different countries, including Australia, Brazil, Canada, China, Czech Republic, Finland, France, Germany, Hong Kong, Italy, Japan, Kyrgyzstan, Mexico, Netherlands, Pakistan, Portugal, Romania, Russia, Spain, Sweden, Switzerland, Thailand, Turkey, United Kingdom, and the US. On average, 38% of the participants are from academia, 19% are from industry, 14% are from Government, and 29% are unknown. In the reporting period, two webinars were presented, attracting 452 online participants:

1. Multidimensional Digital Twin in the Built Environment to Support Multifunctional Modeling for Broader Impacts was presented on December 4, 2023, by Dr. Genda Chen from Missouri University of Science and Technology.
2. Multi-User Collaboration in Augmented Reality for Beyond-Visual-Line-of-Sight Bridge Inspection Using Robotic Platforms was presented on March 27, 2024, by Dr. Genda Chen from Missouri University of Science and Technology.

Education and Outreach Activities

1. On October 13, 2023, the Center for Intelligent Infrastructure (CII) as an umbrella organization to the INSPIRE UTC hosted 11 middle school girls and exposed them to emerging transportation infrastructure solutions in which women can play a significant role through STEM education. Specifically, the students witnessed the first hand on how infrastructure inspection will be aided by robotic exploration and augmented reality (AR) visualization through three sessions: (1) a powerpoint presentation for the introduction to CII, (2) a tour of the CII's three state-of-the-art lab facilities (REAL, VIRTUAL, and autonomous vehicles), and (3) three hands-on interactive activities. CII showcased bridge inspection using various drones (Tello drone, Geodetic, Phantom 4 drone, Skydio 2 Pro drone, Elios 3), augmented reality (AR) interaction with virtual bridges, additive manufacturing (3D-printing), CII invented robots, and driving simulator. The students were curious about how much time it took to program the augmented reality devices and how the digital content was created. The three hands-on experience involved the driving simulator and two Microsoft Hololens collaborations. The driving simulator seemed to capture the high interest of students as they actively and enthusiastically participated in all scheduled activities.
2. On October 14, 2023, the CII visited the Lake of Ozarks and hosted scouts of various ages with the intent of orienting them to robotic applications in infrastructure inspection. The CII showcased ground robot teleoperation aided by AR in addition to drone flight and control. The students' interest varied from digital content creation, slider-based navigation of the robot using AR, the duration of robot development, and the payload that can be handled by the robot. The demos involved Hololens 2 robotic teleoperation and drone operation. The drone flight seemed to excite attendees the most. CII research engineer Zhenhua Shi and CII post-doctoral fellow Joel Runji guided the students throughout these activities while enjoying the joyful moments shared with the participants.
3. On November 8, 2023, the CII welcomed and hosted 30 middle and high school students in two groups of 15 each. The intent of this event was to get the students excited with STEM education by demonstrating what a future STEM professional could mean for them. Specifically, the students got familiarized with infrastructure inspection aided by robotic exploration and AR visualization. Two separate introductory and walk-through sessions and a combined demo session were organized. The introductory session included a PowerPoint presentation on CII's major activities, a tour of the CII's three state-of-the-art lab facilities, and three hands-on interactive activities. For example, bridge inspections using Tello, Geodetic, Phantom 4, Skydio 2 Pro, and Elios 3 drones and using AR interaction with virtual bridges were highlighted. The students were curious about deployment time for various drones, sensors mounted on various drones, and drone interaction with the AR devices. In particular, the driving simulator for autonomous vehicles peaked the attendees' interest.
4. On January 11, 2024, the CII gave a lab tour to two KEEN visitors: Dr. Ranen McLanahan, a program director for the Kern Family Foundation, and Dr. Curtis Abel, the executive director of innovation and entrepreneurship at Worcester Polytechnic Institute (WPI). Specifically, they visited the Visual Inspection Research and Training Using Augmented Learning (VIRTUAL) Lab and Autonomous Vehicles Lab. The VIRTUAL Lab features high-performance computers for virtual reality and augmented reality, and a drone net for customized-drone development environment. The Autonomous Vehicle Lab features various uncrewed aircraft vehicles (UAVs) including DJI Phantom4, Skydio2+, DJI M600, Elios 2, and Elios 3. When in the VIRTUAL Lab, Dr. Abel mentioned that WPI also has a Gaming Lab featuring software development and the

promotion of collaboration among different departments across the campus. Dr. McLanahan asked if images are the main data that the drones collect. Besides regular RGB pictures and videos, the drones can collect thermal, LiDAR, and Hyperspectral data.

5. On February 22, 2024, the CII held an outreach event meant to celebrate the National Engineering week for approximately 31 students in three groups of 8, 14, and 9, respectively. The participants were drawn from homeschoolers in New Haven, Franklin Co, and Viburnum. The CII showcase began with a PowerPoint presentation to introduce CII's main activities, was followed by a tour of three state-of-the-art lab facilities, and ended with three hands-on interactive activities. Specifically, drone-assisted bridge inspection, AR interaction with virtual bridges, additive manufacturing (3D-printing), and hybrid flying and traversing robots were highlighted. The students were excited with various activities and asked how long it takes to create a drone, how much commercial drones cost, what are the regulatory requirements to fly a drone (e.g., drone registration, pilot permit, flight height, flying time), and whether the CII had any accidents using the heavy Geodetics drone. The students were enthusiastic with flying Tello drones and wearing Microsoft HoloLens 2 glasses to see both virtual and real worlds. The CII tour was given by Mr. Joshua Ghilino, an undergraduate student in computer science, Dr. Joel Runji, a post-doctoral fellow in mechanical engineering, and Dr. Zhenhua Shi, a research engineer in civil engineering).
6. Dr. Jizhong Xiao's team mentored four high school interns for Bergen County Academies' senior experience program. The student interns spent every Wednesday at CCNY Robotics Lab to conduct hands-on research in the Fall 2023 and Spring 2024 semesters.

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. Like Table 1, Table 2 includes the same notation for each project. For example, the first project in Table 2 is designated as SN-6, extracting from the first column (Topic SN) and the second column (the project number 6).

Table 2. A summary of planned research activities

Topic	Project Title	Planned Activities
SN	6. Autonomous Ultrasonic Thickness Measurement by a Magnet-Wheeled Robot	• Summarize the test results and findings in a final project report. • Prepare a final data report, data files, and an educational module on a science topic related to this project for general educational purpose.
	7. Health Inspection of Concrete Pavement and Bridge Members Exposed to F-T Environments	• Summarize the test results and findings in a final project report. • Prepare a final data report, data files, and an educational module on a science topic related to this project for general educational purpose.
	8. Probability of Detection in Corrosion Monitoring with Fe-C Coated LPFG Sensors	• Summarize the test results and findings in a final project report. • Prepare a final data report, data files, and an educational module on a science topic related to this project for general educational purpose.
	9. Hyperspectral Imaging and Analysis for Steel Paint Condition Assessment	• Prepare a Q-fog corrosion cyclic test of various coating samples designed with a different combination of parameters. • Conduct the fog test and analyze the test results for corrosion severity.
AS	4. Bridge Inspection Robot Deployment Systems (BIRDS)	• Test and validate the performance of the BridgeBot prototype – a hybrid flying and traversing vehicle to support multimodal sensing.
	5. Nondestructive Data Driven Motion Planning for Inspection Robots	• Summarize the test results and findings in a final project report. • Prepare a final data report, data files, and an educational module on a science topic related to this project for general educational purpose.
	6. A Field Deployable Wall-Climbing Robot for Bridge	• Summarize the test results and findings in a final project report.

	Inspection using Vision and Impact Sounding Techniques	• Prepare a final data report, data files, and an educational module on a science topic related to this project for general educational purpose.
	7. Augmenting Bridge Inspection with Augmented Reality and Haptics-based Aerial Manipulation	• Summarize the test results and findings in a final project report. • Prepare a final data report, data files, and an educational module on a science topic related to this project for general educational purpose.
	8. Robot-assisted Underwater Acoustic Imaging for Bridge Scour Evaluation	• Scan the riverbed of the selected bridges in the state of Missouri. • Analyze the collected sonar images to understand the profile of the riverbed around a bridge pier in water.
	9. Integration of Aerial Manipulation, Haptics-based Human-in-the-Loop Control, and Augmented Reality for Bridge Deck Hosing	• Conduct LEG's modelling and experimental confirmation. • Summarize the test results and findings in a final project report. • Prepare a final data report, data files, and an educational module on a science topic related to this project for general educational purpose
IM	3. "Smart Sounding System" for Autonomous Evaluation of Concrete and Metallic Structures	• Summarize the test results and findings in a final project report. • Prepare a final data report, data files, and an educational module on a science topic related to this project for general educational purpose.
	4. QA/QC Guidelines on Drone-based Remote Sensing for Bridge Element Inspection	• Develop an efficient, robust framework of 3D bridge reconstruction. • Develop an effective and efficient approach for hyperspectral horizontal imaging and image processing.
	5. Mixed Reality for Beyond Visual Line-of-Sight Bridge Inspection Using Robot-Assisted Nondestructive Evaluation	• Summarize the test results and findings in a final project report. • Prepare a final data report, data files, and an educational module on a science topic related to this project for general educational purpose.
RR	2. Data-Driven Risk-Informed Bridge Asset Management and Prioritization across Transportation Networks	• Summarize the test results and findings in a final project report. • Prepare a final data report, data files, and an educational module on a science topic related to this project for general educational purpose.
WD	4. An Interactive System for Training and Assisting Bridge Inspectors in Inspection Video Data Analytics	• Summarize the test results and findings in a final project report. • Prepare a final data report, data files, and an educational module on a science topic related to this project for general educational purpose.

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

Other Planned Initiatives

1. Participation in the CUTC Summer Meeting on June 10-12, 2024 in South Padre Island, Texas, USA.
2. Presentation at the USDOT Future of Transportation Summit on August 13-15, 2024 in Washington DC, USA.
3. Presentation at the Georg Nemetschek Institute Symposium and Expo on September 10-12, 2024 in Munich, Germany.

2. PARTICIPANTS & COLLABORATING ORGANIZATIONS

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

Consortium Collaborators

The consortium members of the INSPIRE UTC 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

External Collaborators

- Air Corp, Reno, NV https://www.buzzfile.com/business/Air-Corp-732-668-8112
- Ameren Corporation, St. Louis, MO https://corporateofficeheadquarters.org/amerencorporation/
- 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 https://www.innovbot.com/
- 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/
- Technology Entrepreneur Center, Inc., St. Louis, MO https://downtowntrex.org/
- 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/
- EdTech Connect https://edtechconnect.mst.edu/
- Kummer Center for STEM Education https://stemcenter.mst.edu/
- National Society of Black Engineers https://mst.campuslabs.com/engage/organization/nationalsociety-of-black-engineers
- Research Support Services https://itrss.mst.edu/
- Society of Hispanic Professional Engineers https://mst.campuslabs.com/engage/organization/society-of-hispanic-professional-engineers

- 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?

1. Dr. Genda Chen's team at Missouri S&T has been working actively with the Kaleidoscope Discovery Center, Rolla, MO, on various robotic competition activities for K6-K12 students.
2. Dr. Paul Oh's team at the University of Nevada, Las Vegas, has been working with Tesla's Reno-based Gigafactory that officially began in January of 2022.
3. Dr. Iris Tien's team has collaborated with the Department of Civil and Environmental Engineering at Rice University.
4. Dr. Yang Wang's team is partnered with Dr. Hung La's team from UNR. Dr. Hung La's team has provided the mobile robot for integration.
5. Dr. Jizhong Xiao's team at the City College of New York conducted a successful field test of Great-Wall-Climbing Robot (GWCR-03) on the Congress Street Bridge, Troy, NY on December 15, 2023.
6. Dr. Jizhong Xiao's team at the City College of New York has participated in a pilot study with Stantec Inc. and NY/NJ Port Authority to analyze the video image data collected by drones to inspect the Bayonne Bridge, NJ.
7. Dr. Jizhong Xiao's team at the City College of New York has worked with the inspection team of Stantec Inc. to collect GPR data using Omni-GPR-Rover ground robot on FDR drive bridge, New York City.

3. OUTPUTS

3.A - Publications, Conference Papers, and Presentations

Journal Publications

1. R. Cao, X. Zuo, A.K. Agrawal, S. El-Tawil, and W. Wong. "Evaluating the Performance of Protection Beams Subject to Overheight Vehicular Impacts Using Analytical and Machine Learning–Based Methods," ASCE Journal of Bridge Engineering 28(12): 04023091, December 2023. https://doi.org/10.1061/JBENF2.BEENG-5984
2. G.D. Chen, I. Alomari, W.Z. Taffese, Z.H. Shi, M.H. Afsharmovahed, T.G. Mondal, and S. Nguyen. "Multifunctional Models in Digital and Physical Twinning of the Built Environment — A University Campus Case Study," Smart Cities 7(2): 836-858, March 26, 2024. https://doi.org/10.3390/smartcities7020035
3. Q. Chen, H.F. Wang, S. El-Tawil, A.K. Agrawal, B. Bhattacharya, and W. Wong. "Behavior of a network tied-arch bridge subjected to sudden hanger loss scenarios," ASCE Journal of Bridge Engineering 29(1): 05023010, January 2024. https://doi.org/10.1061/JBENF2.BEENG-6328
4. B. Hament and P. Oh. "High Pressure Hosing-Drone Dynamics and Controls," Journal of Intelligent Robot System 109(90), December 2023. https://doi.org/10.1007/s10846-023-01954-8
5. Y.Q. Li, Y. Li, H.Y. Ma, and J.Q. Li. "The hydration, microstructure, and mechanical properties of vaterite calcined clay cement (VC3)," Cement and Concrete Research 175: 107374, January 1, 2024. DOI: https://doi.org/10.1016/j.cemconres.2023.107374
6. P.F. Ma, W.Y. Liao, Y. Zhuo, H.Y. Ma, Y.P. Zhu, and G.D. Chen. "Characterization of Alkali-silica Reaction (ASR) Products and C-S-H Using SWIR Spectroscopy for Nondestructive Detection of ASR," Construction and Building Materials 416: 135207, February 16, 2024.

https://doi.org/10.1016/j.conbuildmat.2024.135207
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8. P.F. Ma, Y. Zhuo, G.D. Chen, and J.G. Burken. "Natural Gas Induced Vegetation Stress Identification and Discrimination from Hyperspectral Imaging for Pipeline Leakage Detection," Remote Sensing 16(6): 1029, March 14, 2024. https://doi.org/10.3390/rs16061029
9. S.T. Nguyen, K.T. La, and H.M. La. "Agile robotic inspection of steel structures: A bicycle-like approach with multisensor integration," Journal of Field Robotics 41: 396–419, November 23, 2023. https://doi.org/10.1002/rob.22266
10. Z.H. Shi, Y.M. Mohammed, N. Uddin, and G.D. Chen. "A vehicle-bridge interaction model considering contact patch size and vehicle self-generated excitation – A theoretical study," Engineering Structures 298: 117079, January 1, 2024. https://doi.org/10.1016/j.engstruct.2023.117079
11. W.Z. Taffese, Y.P. Zhu, and G.D. Chen. "Utilizing ensemble learning in the classifications of ductile and brittle failure modes of UHPC strengthened RC members," Archives of Civil and Mechanical Engineering 24(2): 1-24, April 2024. https://doi.org/10.1007/s43452-024-00897-7
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14. H.F. Wang, Q. Chen, A.K. Agrawal, S. El-Tawil, B. Bhattacharya, and W. Wong. "Performance of a Long-Span Suspension Bridge Subjected to Sudden Single Suspender Loss," ASCE Journal of Bridge Engineering 28(11): 05023006, November 2023. https://doi.org/10.1061/JBENF2.BEENG-6108
15. H.B. Zhang, X.Z. Yuan, G.D. Chen, and P. Lomonaco. "Performance of SMART Shear Keys in Concrete Bridges under Tsunami Loading: an Experimental Study," ASCE Journal of Structural Engineering 150(1), October 24, 2023. https://doi.org/10.1061/JSENDH.STENG-12517
16. Y. Zhuo, P.F. Ma, C.R. Guo, and G.D. Chen. "Probability of Detection for Corrosion-induced Steel Mass Loss Using Fe-C Coated LPFG Sensors," Structural Health Monitoring, February 14, 2024. https://doi.org/10.1177/14759217241227229

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

1. F. Jalinoos, A.K. Agrawal, E. Hoomaan, R.E. Crowder, and J. Descour. "Substructure Condition Evaluation of the Willow Valley Creek Bridge Using Geophysical Logging Methods," Report No. FHWA-HRT-23-080, Federal Highway Administration, 2023.
2. N. Kosanovic, J.C. Vaz, and P.Y. Oh. "Biomimetic Real-Time Multimodal Tactile Perception and Haptics for Telepresence Humanoids," IEEE International Conference on Advanced Robotics (ICAR), Abu Dhabi, UAE, December 2023.
3. P.D. Ogunjinmi and G.D. Chen. "Bridge Scour Depth Prediction using Ensemble Machine Learning Models," SPIE Smart Structures + Nondestructive Evaluation, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems Conference, Long Beach, CA, March 24-28, 2024.

4. R. Panik, K. Watkins, and I. Tien. "Bicycle Exposure Models Using Bayesian Updating," 11th International Cycling Safety Conference, The Hague, the Netherlands, November 15-17, 2023.
5. H.B. Zhang, Z.H. Shi, D. Edwards, and G.D. Chen. "UAV-based Active Infrared Thermography for Concrete Defects Detection," presented at the 12th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-12), October 19-22, 2023, Hangzhou, P.R. China.
6. J.C. Vaz, N. Kosanovic, B.S. Kim, and P.Y. Oh. "Real-Time Joint Trajectory Optimization and Predictive Safety Filtering for Telepresence Avatar Robotics," IEEE International Conference on Advanced Robotics (ICAR), Abu Dhabi, UAE, December 2023.

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

- Advanced Robotics and Automation (ARA) Lab: https://ara.cse.unr.edu
- Center for Intelligent Infrastructure: https://cii.mst.edu
- Evolutionary Computing Systems Laboratory: https://ecsl.cse.unr.edu/projects/bridge_inspection/index.html
- INSPIRE University Transportation Center: https://inspire-utc.mst.edu
- Open Source STACS Software: https://github.com/sushillouis/Stacs
- Research in Progress Database: https://rip.trb.org/
- Scholars Mine: https://scholarsmine.mst.edu

3.C - New Technologies or Techniques

- Dr. Anil Agrawal's team at City College of New York developed a remotely-operated device to facilitate impact sounding (IS) tests on the substructures of bridges on ground.
- Dr. Genda Chen's team at Missouri S&T developed a new, more stable attachment scheme for its invented hybrid drone with cascaded flying and traversing capabilities, which will enhance the quality of data collected from the underside of bridge decks.
- Dr. Hung La's team at the University of Nevada, Reno, developed an integration platform of nondestructive testing devices, navigation strategies, and data analytics to support tele-inspection of bridges.
- Dr. Paul Oh's team at the University of Nevada, Las Vegas, explored a telescopic tool to access crowded areas from a cable driven robot for inspections in industrial factories and potentially junction areas of a few roads.
- Dr. Iris Tien's team developed a deep learning approach to detect and quantify corrosion deterioration in steel girder bridges, taking the color and texture of steel surfaces and other factors into account.
- Dr. Yang Wang's team at Georgia Institute of Technology validated in field conditions an autonomous ultrasonic measurement of the thickness of steel bridge members by installing it on a climbing robot in collaboration with Dr. Hung La's group.
- Dr. Jizhong Xiao's team at City College of New York developed a few data analytics algorithms to detect defects and classify reinforced concrete slabs from the data set collected from nondestructive tests, such as ground penetrating radar (GPR), impact sounding (IS), and impact echo (IE).

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

- Dr. Genda Chen's team at Missouri S&T submitted a patent application for a hybrid flying and

traversing vehicle that enable high-quality data collection on a stationary platform.
- Dr. Hung La's team at UNR discussed with the start-up company, AIR Corp, to license the SEAL robot.

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, two INSPIRE UTC quarterly webinars were video recorded and stored at Missouri S&T's data repository site – https://scholarsmine.mst.edu/inspire_webinars.

- Dr. Genda Chen from Missouri University of Science and Technology, Multidimensional Digital Twin in the Built Environment to Support Multifunctional Modeling for Broader Impacts, which was recorded on December 4, 2023, and stored at Missouri S&T's Scholars Mine Data Repository Site: https://scholarsmine.mst.edu/inspire_webinars/25/
- Dr. Genda Chen from Missouri University of Science and Technology, Multi-User Collaboration in Augmented Reality for Beyond-Visual-Line-of-Sight Bridge Inspection Using Robotic Platforms , which was recorded on March 27, 2024, and stored at Missouri S&T's Scholars Mine Data Repository Site: https://scholarsmine.mst.edu/inspire_webinars/26/

3.F - INSPIRE Research Outputs Performance Metrics

Research Outputs - Performance Measures	Cumulative Total
1. At least 5 journal publications and books per investigator/year	5.5
2. At least 15 keynote/invited presentations delivered at national and international conferences in 5 years	27
3. 4 webinars/year	4/Year
4. 2 NDE/sensor prototype in 5 years	3
5. 1 robotic training simulator in 5 years	1

4. OUTCOMES

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

- Dr. Anil Agrawal's team developed a portable sounding device that can improve the efficiency of current substrate defect detection for concrete structures. Once fully demonstrated in field applications, the controllable electronic-sounding device can potentially replace traditional mechanical-impact devices, such as a hammer.
- Dr. Genda Chen's team developed a new method of drone attachment on the bottom flange of bridge girders to allow high-quality data collection from the underside of bridge decks with poor light conditions and no GPS signals. The new attachment uses completely a vertical support mechanism instead of a combination of friction and vertical support mechanism previously used in earlier prototypes.
- Dr. Hung La integrated surface brush cleaning, couplant gel application, and ultrasonic thickness measurement functions into a compact bicycle-like climbing robot for steel girder corrosion detection and quantification in collaboration with Dr. Yang Wang. This integrated system enables autonomous measurement of the steel plate thickness of bridges.

- Dr. Hongyan Ma's team improved the understanding of concrete characterization directly from hyperspectral images for the change of free water content before damage is induced by F/T cycles. The team also developed an artificial intelligence tool to relate the nondestructive testing data to the strength of concrete.
- Dr. Paul Oh's team developed a cable-driven parallel robot (CDPR) for double-deep rack inventory inspection, which was demoed at Tesla's Reno Gigafactory. The double-deep rack environment shares many structural and occlusion properties as bridge decks at road conjunction bottle necks. This efficient and cost-effective approach could potentially replace the manual laborious process of cleaning surfaces.
- Dr. Iris Tien's research developed a way for inspectors to evaluate corrosion degradation on bridges using UAV- and drone-collected imagery data without putting bridge inspectors potentially in a harmful way to conduct bridge inspections in hard-to-reach places.
- Dr. Jizhong Xiao's team developed deep learning algorithms to detect and classify subsurface defects in reinforced concrete slabs from the data collected from ground penetrating radar, impact sounding, and impact echo installed on a ground robot. The acoustic signals are enhanced with a microphone through signal amplification and ambient noise isolation.

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)	1

A manual of practice for inspection and maintenance using mobile robots are being reviewed. Once field tests progress in summer 2024 with the pooled-fund study No. TPF-5(395), a close-distance inspection with a robotic arm tapping on bridge members will be explored and compared with human inspection results.

5. IMPACTS

5.A - The Effectiveness of the Transportation System

- Dr. Anil Agrawal's work will improve the efficiency of current subsurface defect detection in reinforced concrete structures by developing an automated impact sounding tool. The device will be used by the inspector to evaluate the subsurface delamination of bridge decks and can be especially utilized for the elevated regions where conventional detection devices cannot reach. A software module will facilitate the implementation of the approach for practical applications and will make the process more convenient. The device can perform fast and effective subsurface defect detection over concrete surfaces.
- Dr. Genda Chen's work on hybrid vehicles that can fly around and/or autonomously engage with a bridge girder will enable bridge inspection from the underside of bridge decks with no impact on traffic on roadways. With this new capability, bridges can be safely inspected in augmented reality and beyond the visual line of sight even after the vehicles run out of battery power unexpectedly. This capability is especially important for river-crossing long-span bridges where many components underneath the bridge deck cannot be seen on the bridge deck. Such inspections would be safer, cheaper, faster, and more consistent.

- Dr. Hung La's work will contribute to 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. The team introduced novel concepts of robotic sensing, localization and navigation in confined space or complex steel structure, which advance the existing work and provide the research community a new and implementable tool to enable automated bridge inspection and evaluation process.
- Dr. Hongyan Ma's work on freeze-thaw cycling induced damage to concrete structure may establish a database with distinct features for adoption by transportation communities. The robot-assisted hyperspectral imaging can be scaled up in real-world applications for fresh concrete strength and chloride content monitoring.
- Dr. Paul Oh's work on aerial manipulators will augment the performance of bridge maintenance workers with human-in-the-loop control of tasks such as debris cleaning and crack sealing. The testing-and-evaluation and verification-and-validation platforms are unique in the aerial manipulation research area. Hence, they can provide tools for a larger drone community.
- Dr. Iris Tien's work on accurate corrosion assessment of bridges based on drone-collected imagery data will help assess steel bridge deterioration rapidly. Specifically, both color and texture are included in deep learning for corrosion severity classification. Their goal is to translate the corrosion results to assessments of bridge performance and risk.
- Dr. Yang Wang's work will result in an innovative robotic sensing technology that can autonomously performs ultrasonic thickness measurement on steel bridge members. The sensing technology has the potential to be adopted in bridge monitoring practices.
- Dr. Jizhong Xiao's work on robotic hardware and data analysis software will likely increase the knowledge base and tackle the robotic inspection challenges on a wide range of infrastructure. The impact sounding technology will provide an alternative way for the detection of subsurface defects. The R&D results may lead to a complete, self-contained robotic evaluation tool with vertical mobility that carries an RGB-D camera, GPR sensor and impact sounding device to detect surface flaws and subsurface defects.

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

- Dr. Hung La established Automated Inspection Robots (AIR) Corp., a start-up company in January of 2020.
- Under Dr. Jizhong Xiao's direction, InnovBot LLC, a CUNY spin-off company, received an NSF award: SBIR Phase-II: "Robotic Inspection and Data Analytics to Localize and Visualize the Structural Defects of Civil Infrastructure", 6/15/2022-5/31/2024. Data are collected from an RGB-D camera, ground penetrating radar, and impact sounding device.

5.C - The Body of Scientific Knowledge

- Dr. Anil Agrawal's team's research indicates that the sounding device has potential to introduce a new defect detection method using sounds as an excitation. Due to its portability and accessibility to elevated regions such as the underside of bridge decks, it can become a good option for defect detection.
- Dr. Genda Chen's team developed a probability of detection theory (size-of-defect-at-detection or SODAD) for steel corrosion evaluation using Fe-C coated long period fiber optic (LPFG) sensors. The data taken from an LPFG sensor are partially correlated at a fixed location. The

proposed SODAD accounted for the correlation of sensor data accurately. It is easy to apply as it is based on two random variables with clear physical meaning.

- Dr. Hongyan Ma's team helps understand the effectiveness of nondestructive testing and hyperspectral imaging for the evaluation of freeze-thaw degradation which, by alerting before non-repairable damage takes place, could make pavement and bridges more durable and safer.
- Dr. Iris Tien's team improved the methods of image processing and machine learning. The data types are significantly different from existing datasets, presenting more difficult problems for these algorithms to solve.
- Dr. Hung La's team introduced novel concepts of robotic sensing, localization, and navigation in confined spaces or complex steel structures. Rigorous magnetic force analysis provides a design baseline for different types of steel inspection robots to ensure safety.
- Dr. Paul Oh's drones with aerial manipulation arms have advanced the design theory of counter-reaction effects in different applications, such as water jet streaming in a surface cleaning task.
- Dr. Jizhong Xiao's team developed a concrete spalling and crack dataset that includes over 3,000 images with pixel-level labeling and their augmentation by image flipping, rotation, and sub-cropping for training and validation of CNN-based visual inspection algorithms.

5.D - Transportation Workforce Development

Direct Training of Undergraduate Students through Hands-on Research and Administrative Tasking

1. Collin Brockman in mechanical engineering, Missouri S&T
2. Zahir Castrejon in mechanical engineering, University of Nevada, Las Vegas
3. Akshay Dave in mechanical engineering, University of Nevada, Las Vegas
4. Joshua Ghilino in computer science, Missouri S&T
5. Ross Kreager in civil engineering, Georgia Institute of Technology
6. Ziyu (Kevin) Lai in computer science, Missouri S&T
7. Shreya Mocherla in computer science, Missouri S&T
8. Ryan Swan in mechanical engineering, Missouri S&T
9. Son Tran in mechanical engineering, University of Nevada, Las Vegas
10. Nicholas Ward in computer science and engineering, University of Nevada, Reno
11. Drew Wellen in electrical engineering, Missouri S&T
12. Armaun Zargari in mechanical engineering, University of Nevada, Las Vegas
13. David Kirakosian in electrical engineering, the City College of New York

Direct Training of Graduate Students through Hands-on Research

1. Habib Ahmed in computer science and engineering, University of Nevada, Reno
2. Ibrahim Alomari in civil engineering, Missouri S&T
3. Harry Ashimatey in civil engineering, Georgia Institute of Technology
4. Kangyi Cai in civil engineering, Missouri S&T
5. Rezwana Hafiz in civil engineering, Missouri S&T
6. Blake Hament in mechanical engineering, University of Nevada, Las Vegas
7. Yang He in electrical and computer engineering, City College of New York
8. Hana Herndon in civil engineering, Georgia Institute of Technology
9. Tamjid Hossain in computer science and engineering, University of Nevada, Reno
10. Ejup Hoxha in electrical and computer engineering, City College of New York
11. Deepak Kumar in civil engineering, City College of New York

12. Peter Ogunjinmi in civil engineering, Missouri S&T
13. Chuong Le in computer science and engineering, University of Nevada, Reno
14. Pengfei Ma in civil engineering, Missouri S&T
15. Mohammad Afsharmovahed in civil engineering, Missouri S&T
16. Ali Salem in electrical and computer engineering, City College of New York
17. Diar Sanakov in electrical and computer engineering, City College of New York
18. Adarsh Sehal in computer science and engineering, University of Nevada, Reno
19. Zhengbo Wang in civil engineering, Georgia Institute of Technology
20. Andrew Washburn in computer science and engineering, University of Nevada, Reno
21. Tamanna Yasmin in computer science and engineering, University of Nevada, Reno
22. Ying Zhuo in civil engineering, Missouri S&T
23. Cesar Gilberto Hernandez Montiel in electrical engineering, City College of New York

Direct Training of Postdoctoral Fellows and Research Engineers through Hands-on Research

1. Dr. Bo Shang in electrical engineering, City College of New York
2. Dr. Tarutal Gosh Mondal in civil engineering, Missouri S&T
3. Dr. Guna Manogaran in computer science, Missouri S&T
4. Dr. Son Nguyen in Computer Science, Missouri S&T
5. Dr. Kevin Romans in physics, Missouri S&T
6. Dr. Joel Runji in mechanical engineering, Missouri S&T
7. Dr. Ritesh Sharma in computer science, Missouri S&T
8. Dr. Zhenhua Shi in civil engineering, Missouri S&T
9. Dr. Woubishet Taffese in civil engineering, Missouri S&T
10. Dr. Sanaz Vajedian in geological engineering, Missouri S&T

Direct Training of Undergraduate and Graduate through Course Work

Dr. Hung La started to introduce 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. La is developing a new advanced robotics course: CPE471/671 Advanced Robotics, and its curriculum has been approved by the University of Nevada - Reno Curriculum Committee. This CPE471/671 course is being offered in Fall 2023.

Representatives in the Following Organizations Exposed to the INSPIRE UTC Advanced Technologies

1. Ameren Corporation
2. California Department of Transportation
3. Georgia Department of Transportation
4. Missouri Department of Transportation
5. Nevada Department of Transportation
6. New York Department of Transportation
7. Texas Department of Transportation
8. Virginia Department of Transportation
9. Wisconsin Department of Transportation
10. Paul D. Thompson Consulting Services
11. Technology Entrepreneur Center, Inc.
12. Tesla Gigafactory

13. Turner Fairbanks Highway Research Center, Federal Highway Administration
14. Stantec Inc.

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

Once field tests continue till summer 2024 with the pooled-fund study No. TPF-5(395), robot-assisted bridge inspection will be compared with the conventional visual inspection to understand cost saving.

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

One-year no-cost extension was approved for the INSPIRE UTC to complete ongoing projects.

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

Nothing to report.