30 Sep 2022

Semi-Annual Progress Report #11

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

UTC Semi-Annual Progress Report #11

GRANT NO: 69A3551747126
GRANT PERIOD: 11/30/16 – 09/30/23
REPORTING PERIOD: 04/01/2022 – 09/30/2022

Submitted to:	U.S. Department of Transportation (USDOT) Office of the Assistant Secretary for Research and Technology (OST-R)
Submitted by:	The Curators of the University of Missouri on behalf of Missouri University of Science and Technology, 202 Centennial Hall, Rolla, MO 65409
Center Director Name and Contact Information:	Dr. Genda Chen, P.E. Email: inspire-utc@mst.edu; Tel: 573-341-6114
DUNS:	8048837670000
EIN Number:	436003859
Recipient Identifying Number:	00055082
Report Term or Frequency:	Semi-annual
Submission Date:	October 31, 2022

Signature of Submitting Official:

Dr. Kamal Khayat, Interim Vice Chancellor of Research and Innovation, research@mst.edu; 573-341-4134

Inspecting and Preserving Infrastructure through Robotic Exploration (INSPIRE)

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

TABLE OF CONTENTS

1. ACCOMPLISHMENTS

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

Center's Mission and Goals

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

The overarching goals of the center in five years are to transform in at least two demonstration cases from manual to automated inspection and preservation of bridges with sensors, nondestructive evaluation (NDE) devices, multi-modal unmanned vehicles, and data 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 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 of the center 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 degree 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 of the center 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 training of both current and prospective transportation workforces.

Technology Transfer Objectives

Three technology transfer objectives of the center 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 of the center 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-5, extracting from the first column (Topic SN) and the second column (the project number 5).

Table 1. A summary of research progress

Topic	Major Activities	Specific Objectives	Significant Results	Key Outcomes
SN	5. Conduct laboratory tests of steel-bar embedded mortar cubes with three water-to-cement ratios in corrosive environment. 6. Calibrate the *Martlet* ultrasonic device and compare its performance with a thickness measurement gauge. 7. Complete the collection of NDT data and compressive strength of different mix proportions. 8. Collect data and summarize the results and findings on the probability of detection (POD) in monitoring.	5. Develop a hyperspectral imaging method for evaluating chloride ion concentration and steel bar corrosion. 6. Improve the accuracy of measurement from the Martlet ultrasonic device for thickness in steel plates. 7. Identify the parameters of mixture and primary/ secondary NDTs for AI training. 8. Prepare a final technical report on the probability of detection (POD) in steel corrosion monitoring.	5. A linear increase of characteristic reflectance with Cl- content up to 0.8 wt.%. 6. More accurate than the gauge in measurement of 10 out of 14 0.175"-1" thick specimens. 7. Over 300 data including factors of NDT results and F-T induced degradation. 8. Unconservative use of sensor data in structural heath monitoring without considering the POD.	5. Hyperspectral imaging for steel rebar corrosion and chloride ion Cl- concentration. 6. A real-time localization system of robot and thickness measurement. 7. Hyperspectral images for the evaluation of F-T induced damage. 8. Two methods developed and compared for the determination of POD in practice.

AS	4. Identify the sources of rocking in the hybrid flying and traversing unmanned vehicle. 5. Equip a bicycle-like robot with an ultrasonic thickness sensor and a RGB camera for detection of steel corrosion. 6. Develop an App for the interactive impact echo-based thickness calculation and the visualization of results. 7. Complete initial flight tests of aerial hosing to clean a mixture of commercially-sold dirt and water. 8. Set a sonar in a horizontal or vertical direction and deploy it near the wall of a swimming pool with a flat or sloped bottom. 9. Complete hosing-drone flight tests for the verification-and-validation of underlying drone dynamics	4. Improve the stability of the hybrid vehicle for bridge inspection through autotuning function. 5. Develop localization and motion planning algorithms of the bicycle-like robot for accurate measurement. 6. Investigate various deep learning models to detect subsurface defects (voids, honeycombs, and delamination. 7. Develop computer vision algorithms to gage dirt removal progress and performance. 8. Understand sonar acoustic reflection patterns from multiple objects in the swimming pool. 9. Implement tele-impedance feedback in a simulator to improve drone stability through scenario studies.	4. Effective autotuning during simulations, which must be validated in flight. 5. Successful test and validation on the Synchronization of the robot pose with ultrasonic data. 6. Validation of the deep learning models using the data collected from in-house slabs. 7. Drone stabilized using visual-inertial odometry while hosing water. 8. Potential effect of turbulent water surface on multiple reflections of acoustic waves. 9. Knowledge from gantry testing-and-evaluation to improve flight behavior in the simulator.	4. Autonomous clamping while in flight achieved in laboratory tests. 5. A multifunctional bicycle robot tested for steel member inspection. 6. An Impact-Rover robot (V2) with omnidirectional wheels for acoustic tests. 7. Controlling of nozzle kick-back analogous with stabilization of a classic cart-trolley. 8. Acoustic reflection patterns related to sonar orientation and distance to various objects. 9. Design trade-offs among diameter, mass, and number of rotors for desired water pressure.
IM	3. Synchronize sounding data and tracking videos with wireless communication between the GPS rover and the base station.	3. Develop a sound device of speaker, microphone, tracking camera, and RTK GPS for inspection of the underside of a bridge deck and pier surfaces.	3. Autonomous synchronization between sounding data and tracking videos with programing.	3. Slow yet accurate connection established between GPS rover and the base station.
RR	2. Train a Mask R-CNN with 133 images for the detection of surface and section loss.	2. Remove background noises via 3D modeling, common object cleaning, color thresholding.	2. Background noise making the R-CNN inaccurate in output prediction.	2. Detectable surface and section loss when low in background noise.
WD	4. Implement keyword-based search for bridges to be studied.	4. Develop a search engine based on key words from a dataset.	4. Effective keywords used in National Bridge Inventory.	4. Functions tested in a web-interactive platform.

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 in different disciplines at partner institutions. Non-degree education programs such as conferences and meetings with industrial participants (sometimes advisors) were initiated, such as the 8th World Conference on Structural Control and Monitoring (8WCSCM).

To support the workforce development objectives, graduate students and professionals were exposed to the technologies developed at the INSPIRE UTC through virtual 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, 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 by completing the inspection of 36 bridges in the state of Missouri, Wisconsin, and Virginia. An inspection crew of three people operated commercial drones (e.g., Elise2, Skydio2, Phantom4, and Anafi Parrot), 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 and graduate students as well as 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 9 faculty, 7 post docs and research faculty, 22 graduate students, and 22 undergraduate students in civil and architectural engineering, computer science, electrical and computer engineering, and mechanical engineering through 14 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 K7-12 from 25 states in the U.S., academics, and industry. These venues include Biannual Newsletters, Education and Outreach Events, Invited Presentations, Journal and Conference Initiatives, and Quarterly Webinars.

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 14,221 people through the Center's listserv and are made available online at https://inspire-utc.mst.edu/news/. An INSPIRE UTC Newsletter (Vol. 6, No. 1) was published in Spring 2022, including three technical articles related to INSPIRE research:

1. *VR Operator Training for Robot-Assisted Bridge Inspection, Mr. Brian Dedeurwaerder, University of Nevada - Reno*
2. *Human-Embodied Drones for Mobile Manipulation in Bridge Inspection and Maintenance, Dr. Dongbin Kim, University of Nevada - Las Vegas*
3. *When AR Meets Bridge Inspection: From Bridge to Cloud, Dr. Liujun Li, formerly of Missouri University of Science and Technology*

Education and Outreach Events

1. On June 8, 2022, the INSPIRE UTC at Missouri S&T participated in the robotics camp with the Kummer Center for STEM Education. The INSPIRE UTC demonstrated climbing robot and augmented reality technologies through physical and video shows. A total of 54 students attended the camp at Rolla, MO.
2. On July 13, 2022, the INSPIRE UTC at Missouri S&T hosted five 8th grade students as part of the Jackling Introduction to Engineering summer camp activities. The students were introduced with the INSPIRE UTC Bridge Inspection Robot Deployment Systems (BIRDS) -a platform to support field inspection. The BIRDS includes HoloLens, a Tello drone, and a

custom-made climbing robot on steel members. These hardware platforms are equipped with multiple sensors, including RGB, infrared, and hyperspectral cameras as well as LiDAR scanners. These sensors can help efficiently inspect aging bridges for defect detection such as corrosion, crack, and other deterioration. The students had hands-on experience on flying a Tello drone and observing virtual bridge inspection through HoloLens in a digital world.

3. On July 19-21, 2022, the INSPIRE UTC at Missouri S&T hosted outreach activities for approximately 69 students from Aerospace Summer Camp. The outreach was divided into three sessions that were participated by 25, 24, and 20 students, respectively. The students were given a glimpse of the research activities conducted at the INSPIRE UTC, including several types of unmanned aircraft systems (drones), robots, and equipment. They were presented a variety of equipment at the center including a large 3-D printer, a Tello drone, a Phantom4 drone, a Skydio2 Pro drone, an Elios2 drone, a "drilling" drone, a "BIRDS" drone, and a climbing robot. After the presentation, the students were demonstrated how to fly a Tello drone and provided with individual hands-on experience opportunities. Some students tried the Intelligence Flight mode, one of which involves flipping maneuver.
4. On September 23, 2022, the INSPIRE UTC at Missouri S&T hosted a "Traffic Jam" Workshop for 28 middle school (7th and 8th grade) students as part of the 21st "Expanding Your Horizons" event. The students were evenly divided into two groups with 14 students each. The Workshop was organized in two parts. In the first part, the students were demonstrated how to operate a car simulator by accelerating, braking, and turning the car when encountering traffic lights, and driving backward when stuck. In the second part, the students played five online games that were related to the "Traffic Jam" topic, including Dilemma Zone, Design Road Curves, Time-Space Invaders, Transporters, and Road Crush. In the Dilemma Zone game, students were required to stop at a green light within the min and max green light time. In the Design Road Curves game, students would adjust the radius and superelevation so that the vehicle would stay on the road while making a smooth turn at high speed. In the Time-Space Invader game, students would adjust the offset time so that vehicles being trapped at a red light (indicated as costs) would be minimum. In the Transporters game, students would plan a region to connect houses and shopping zones with different roads without causing traffic congestion. In the Road Crush game, students would design a pavement with four types of materials, which is strong enough to support the traffic.
5. On September 27-28, 2022, the INSPIRE UTC at Missouri S&T participated in the Geo-Resolution 2022 annual symposium followed with a student poster competition co-sponsored by the National Geospatial-Intelligence Agency (NGA) and Saint Louis University (SLU). The INSPIRE UTC played a significant role in the recently-established Taylor Geospatial Institute (TGI). Led by SLU, TGI is a consortium of eight research institutions that share their expertise and critical research facilities, including Missouri S&T. TGI received 40 posters from students at the consortium member institutions on a wide range of research topics connected to geospatial science. Pengfei Ma, a Ph.D. student under the supervision of Dr. Genda Chen, represented the INSPIRE UTC and the Center for Intelligent Infrastructure (CII) at the 2022 poster competition. He presented his research project on the use of hyperspectral imaging for pipeline gas leakage detection using the degree of vegetation stress. Pengfei won the 2nd place and received a $750 award and certificate. All the submitted posters and their accompanying videos are available on the TGI website (https://taylorgeospatial.org/geo-resolution-2022-poster-session/).
6. 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, and 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.

Invited Presentations

1. Jizhong Xiao. "Robotic Inspection and 3D GPR Imaging of Concrete Structure," 11th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-11), Montreal Canada, August 11, 2022.

Journal and Conference Initiatives

1. On June 5-8, 2022, the INSPIRE UTC participated in the 8th World Conference on Structural Control and Monitoring (8WCSCM, http://www.8wcscm.org/), Orlando, Florida. Sponsored by the U.S. Panel on Structural Control and Monitoring of which the INSPIRE UTC Director Genda Chen served as the Vice President, the Conference was organized by Dr. Hae-Bum "Andrew" Yun and Dr. F. Necati Catbas from the University of Central Florida. The INSPIRE UTC had a significant presence at this premier conference that has been held every four years. Led by Dr. Genda Chen, INSPIRE UTC Director, an INSPIRE UTC team of Drs. Liujun Li, Zhenhua Shi, Haibin Zhang, Bo Shang, Tarutal Mondal, and Yanping Zhu from Missouri S&T attended this conference. INSPIRE UTC Co-Director, Dr. Yang Wang from Georgia Institute of Technology, and a former INSPIRE UTC faculty investigator, Dr. Ruwen Qin from Stony Brook University, were also among the crowd. Dr. Chen was invited to chair a keynote session. Drs. Chen and Wang co-organized a technical session on INSpecting and Preserving Infrastructure through Robotic Exploration (INSPIRE). Overall, the INSPIRE UTC affiliates made eight presentations.
    a. Mondal T. G. and Jahanshahi M. R. "Vision-based Autonomous Inspection of Reinforced Concrete Buildings Leveraging RGB-D Fusion."
    b. Li, L., and Chen, G. "Mixed Reality Interface of Geospatial Data towards Efficient, Effective, and Reliable Bridge Inspection."
    c. Li, L., Chen, G. and Shang B. "Mixed Reality Enabled Digital Twin for Robot-Assisted Bridge Element Inspection and Maintenance."
    d. Otsuki, Y., Lander, P., and Wang, Y. "Field Validation of a Compact Martlet Wireless Ultrasonic Thickness Measurement System."
    e. Shi, Z., Shang, B., Zhang, H., Li, L., Chen, G. "Evaluation of User-friendliness of Several Unmanned Aircraft Systems for Bridge Inspection."
    f. Zhang, C., Karim, M., Yin, Z., and Qin, R. "A Deep Neural Network for Multiclass Bridge Element Parsing in Inspection Image Analysis."
    g. Zhang, H., Jiao, P., Li, L., Shi, Z., Shang, B., and Chen, G. "Delamination Detection of Concrete Bridge Deck through UAV-based Infrared Thermography."
    h. Zhu, Y., and Chen, G. "Cable Force Monitoring by Distributed Fiber Optic Sensor with Two Installation Schemes."
2. On June 20-23, the INSPIRE UTC participated in the 30th Research Symposium sponsored by the American Society of Nondestructive Testing (ASNT), St. Louis, Missouri. INSPIRE UTC Director Genda Chen in collaboration with Dr. Glenn Washer from the University of Missouri – Columbia organized an INSPIRE UTC session entitled "Recent Advances on Nondestructive Evaluation of Bridges." INSPIRE UTC Co-Directors Yang Wang and Hung La made a presentation on Autonomous Ultrasonic Thickness Measurement using a Steel Climbing Mobile Robot Integrated with Martlet Wireless Sensing.

Quarterly Webinars

Overall, 21 INSPIRE UTC quarterly webinars have engaged 2068 people from 48 US States and 51 different countries, including Austria, Bangladesh, Brazil, Canada, China, France, Germany, Japan, Switzerland, Thailand, United Kingdom, and the US. On average, 39% of the participants are from academia, 18% are from industry, 23% are from Government, and 21% are unknown.

In the reporting period, two webinars were presented, attracting 243 (57+186) participants:

1. Intelligent Human-Infrastructure Interfaces for Inspectors and Decision-makers was presented on June 21, 2022, by Dr. Fernando Moreu from University of New Mexico, Albuquerque, NM.
2. Reliability of Bridge Inspection Technologies was presented on September 13, 2022, by Dr. Glenn Washer from University of Missouri (Mizzou), Columbia, MO.

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	• Design a prototype brushing mechanism. • Install an autonomous long-term ultrasonic thickness measurement system on a steel girder bridge near LaGrange, GA.
	7. Health Inspection of Concrete Pavement and Bridge Members Exposed to Freeze-Thaw Service Environments	• Correlate the reflectance from hyperspectral imaging to electrical conductivity to understand the F-T cycling effect on strength degradation. • Develop a deep learning model to relate various NDT test data with the strength of concrete including the F-T cycling effect.
	8. Probability of Detection in Corrosion Monitoring with Fe-C Coated LPFG Sensors	• Prepare a final report based on Years 4 and 5 studies. • Evaluate the conservatism of the traditional sensing method without considering the probability of detection for Fe-C coated LPFG sensors.
AS	4. Bridge Inspection Robot Deployment Systems (BIRDS)	• Improve stability of the hybrid vehicle when approaching a bridge. • Prepare a final report for the 1st and 2nd prototypes of the hybrid vehicle.
	5. Nondestructive Data Driven Motion Planning for Inspection Robots	• Prototype a multiple-sensor deployment mechanism on a bicycle-like robot and test and validate the design in laboratory. • Design a high-load bicycle-like robot for deployment on bridges.
	6. A Field Deployable Wall-Climbing Robot for Bridge Inspection using Vision and Impact Sounding Techniques	• Collect more impact sounding and impact echo data on concrete slabs. • Investigate impact sounding and echo analytics and improve the AR-enabled user graphical interface to visualize subsurface defects. • Integrate vision-based positioning with automatic sampling without marks.
	7. Augmenting Bridge Inspection with Augmented Reality and Haptics-based Aerial Manipulation	• Prepare a final report based on the Year 4 study. • Revise the final report based on the review feedback from the INSPIRE UTC. • Disseminate the results through conference and journal publications.
	8. Robot-assisted Underwater Acoustic Imaging for Bridge Scour Evaluation	• Summarize swimming pool test results to understand the sonar principle. • Simplify the TreeFrog climbing robot design into a single cup supported side-scan sonar and altimeter in a tethered operation.
	9. Integration of Aerial Manipulation, Haptics-based Human-in-the-Loop Control, and Augmented Reality for Bridge Deck Hosing	• Defend a doctoral dissertation on the hosting drone. • Integrate tele-impedance force-feedback into the hosing drone using haptic gloves and AR/VR headsets. • Test and validate the performance of the hosing drone in a gantry system. • Validate the hosing drone for open field tests for dirt cleaning.

IM	3. "Smart Sounding System" for Autonomous Evaluation of Concrete and Metallic Structures	• Optimize the tube shape to improve sound flow and reduce weight by developing and analyzing a finite element model of the sounding device. • Develop a program with graphical user interface for real-time analysis and evaluation of damage condition in bridge structures.
	4. QA/QC Guidelines on Drone-based Remote Sensing for Bridge Element Inspection	• Identify actionable inspection activities and procedures in route planning, sensor measurement, ground truth selection, and statistical analysis. • Outline assessment matrices and best practices for drone-based imaging.
	5. Mixed Reality for Beyond Visual Line-of-Sight Bridge Inspection Using Robot-Assisted Nondestructive Evaluation	• Develop a framework of mixed reality-based bridge inspection for beyond-visual-line-of-sight (BVLOS) elements. • Integrate a NDE device into a climbing robot for remote bridge element inspection.
RR	2. Data-Driven Risk-Informed Bridge Asset Management and Prioritization across Transportation Networks	• Evaluate more background removal methods. • Evaluate texture extraction for structural corrosion detection using Sobel filters, Canny edge detection, and entropy. • Determine percent area of elements or bridges affected by steel corrosion.
WD	4. An Interactive System for Training and Assisting Bridge Inspectors in Inspection Video Data Analytics	• Increase the dataset of bridges inspected under the pooled-fund study. • Train web-based learning modules to master cross-disciplinary knowledge and fundamental skills of analytics. • Develop a 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. INSPIRE UTC Presentation to Missouri Bridge Conference audiences, Columbia, MO on October 19, 2022. The aim of this presentation is to introduce the INSPIRE UTC programs, innovations, and technology transfers to practitioners.
2. INSPIRE UTC Quarterly Webinar on December 13, 2022, on Structural Inspection Automation: Research Challenges and 3D machine vision techniques by Dr. ZhiQiang Chen from the University of Missouri-Kansas City, MO.

2. PARTICIPANTS & COLLABORATING ORGANIZATIONS

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

Consortium Collaborators

The consortium members of the INSPIRE UTC include:

- Missouri University of Science and Technology (Missouri S&T) - 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 https://www.buzzfile.com/business/Air-Corp-732-668-8112
- Ameren Corporation, St. Louis, MO https://corporateofficeheadquarters.org/ameren-corporation/

- Clark County Las Vegas Library, Las Vegas, NV https://lvccld.org
- California Department of Transportation, Sacramento, CA https://dot.ca.gov
- Colorado Department of Transportation, Denver, CO https://www.codot.gov
- Georgia Department of Transportation, Atlanta, GA www.dot.ga.gove
- Geophysical Survey System, Inc. (GSSI), Nashua, NH https://www.geophysical.com
- InnovBot LLC, New York, NY http://www.innovbot.com/theme/users
- Iowa State University, Ames, IA https://www.iastate.edu
- Mid-America Transportation Center, Lincoln, NE https://matc.unl.edu
- Missouri Department of Transportation, Jefferson City, MO http://www.modot.org
- Nevada Department of Transportation, Carson City, NV https://www.nevadadot.com/
- New York Department of Transportation, Albany, NY https://www.dot.ny.gov
- Paul D. Thompson Consulting Services, Bellevue, WA www.pdth.com
- Rice University, Houston, TX https://ceee.rice.edu
- Stony Brook University, Stony Brook, NY 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, Austin, TX https://www.txdot.gov
- Turner Fairbanks Highway Research Center of FHWA, McLean, VA https://highways.dot.gov/research
- Virginia Department of Transportation, Richmond, VA https://www.virginiadot.org/
- Wisconsin Department of Transportation, Madison, WI 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/national-society-of-black-engineers
- Research Support Services/MinerFly Team https://itrss.mst.edu/minerfly/
- Scholars Mine https://scholarsmine.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?

- Dr. Genda Chen's team at Missouri S&T 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 the INSPIRE UTC.
- Dr. Paul Oh's team at the University of Nevada, Las Vegas, has a Phase 3 task order contract with Tesla's Reno-based Gigafactory that officially began January 2022. This task order is

independent of Dr. Oh's INSPIRE UTC project. However, there is some overlap technologically, e.g. augmented reality (AR) and robots are used to help monitor sites and manipulate objects. Hence, this UNLV-Tesla collaboration is mentioned and would likely give the INSPIRE added visibility.

- Dr. Jizhong Xiao's team at the City College of New York accessed Geophysical Survey System Inc. (GSSI)'s test pit to collect ground penetrating radar (GPR)/impact sounding data and InnovBot LLC to construct concrete slabs buried with pipes and boxes to simulate defects (voids, delamination, honeycomb) at different sizes and depths. InnovBot LLC has received an NSF grant "SBIR Phase II: 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.

3. OUTPUTS

3.A - Publications, Conference Papers, and Presentations

Journal Publications

1. Amjadian, M., Agrawal, A. K., & Nassif, H. H. "Development of An Analytical Method for Design of Electromagnetic Energy Harvesters with Planar Magnetic Arrays," Energies, Vol. 15, No. 10, 3540, May 12, 2022. https://doi.org/10.3390/en15103540
2. Bai, H., Guo, D., Wang, W., Tan, X., Yan, M., Chen, G., and Bao, Y. "Experimental Investigation on Flexural Behavior of Steel-concrete Composite Floor Slabs with Distributed Fiber Optic Sensors," Journal of Building Engineering, May 17, 2022. https://doi.org/10.1016/j.jobe.2022.104668
3. Feng, J., Yang, L., Hoxha, E., and Xiao, J. "Improving 3D Metric GPR Imaging Using Robotic Data Collection and DNN-based Processing," IEEE Sensors Journal, April 04, 2022, https://doi.org/10.1109/JSEN.2022.3164707
4. Guo, C., Fan, L., and Chen, G. "Magnet-assisted Hybrid EFPI/FBG Sensor for Internal Corrosion Monitoring of Steel Pipelines," Optical Fiber Technology, Vol. 73, September 21, 2022. https://doi.org/10.1016/j.yofte.2022.103064
5. Lapeyre, J., Ponduru, S., Okoronkwo, M., Ma, H., and Kumar, A. "Hydration of High Alumina Calcium Aluminate Cements with Carbonate and Sulfate Additives," Journal of Thermal Analysis and Calorimetry, Vol. 147, pp. 5575-5587, 2022. https://doi.org/10.1007/s10973-021-10939-4
6. Li, D., and Wang, Y. "Constrained Unscented Kalman Filter for Parameter Identification of Structural Systems," Structural Control and Health Monitoring, Vol. 29, No. 4, e2908, April 2022. https://doi.org/10.1002/stc.2908
7. Li, H., Agrawal, A. K., Chen, X., Ettouney, M., and Wang, H. "A Framework for Identification of the Critical Members for Truss Bridges through Nonlinear Dynamic Analysis," Journal of Bridge Engineering, Vol. 27, No. 8, 04022060, August 2022.
8. Lu, H., Sun, X., and Ma, H. "Anti-washout Concrete: an Overview. Construction and Building Materials," Vol. 344, Paper No. 128151, 2022. https://doi.org/10.1016/j.conbuildmat.2022.128151
9. Manhães, P., Araruna, J., Chen, G., Anderson, N., Pereira, E., and Silva, F. "The Use of GPR to Investigate Steel Fiber Distribution on the Mechanical Behavior of FRC," Construction and Building Materials, Vol. 344, Paper No. 128248, June 4, 2022. https://doi.org/10.1016/j.conbuildmat.2022.128248
10. Mondal, T., and Chen, G. "Artificial Intelligence in Civil Infrastructure Health Monitoring - Historical Perspectives, Current Trends, and Future Visions," Frontiers in Built Environment,

August 31, 2022. https://doi.org/10.3389/fbuil.2022.1007886

11. Oh, K., Ma, H., Yi, H., Kou, R., Vollero, D., Schmidenberg, D., and Qiao, Y. "Structural Parts Based on Municipal-Solid-Waste Incineration Ashes," Waste Management, Vol. 150, pp. 185-190, 2022. https://doi.org/10.1016/j.wasman.2022.07.004
12. Otsuki, Y., Lander, P., Dong, X., and Wang, Y. "Formulation and Application of SMU - an Open-Source MATLAB Package for Structural Model Updating," Advances in Structural Engineering, Vol. 25, NO. 4, pp. 698-715, January 21, 2022. https://doi.org/10.1177/13694332211022066
13. Qin, J., Dai, F., Ma, H., Dai, X., Li, Zhen, Jia, X., and Qian, J. "Development and Characterization of Magnesium Phosphate Cement Based Ultra-high Performance Concrete," Composites Part B: Engineering, Vol. 234, Paper No. 109694. https://doi.org/10.1016/j.compositesb.2022.109694
14. Wang, H., Chen, Q., Agrawal, A. K., El-Tawil, S., Bhattacharya, B., and Wong, W. "Dynamic Response and Progressive Collapse of a Long-Span Suspension Bridge Induced by Suspender Loss," Journal of Structural Engineering, Vol. 148, NO. 6, 05022001, June 2022.
15. Yan, C., Ma, H., Luo, Z., Zhou, X., and Wang, L. "Influence of Phosphorus Sources on the Compressive Strength and Microstructure of Ferronickel Slag-based Magnesium Phosphate Cement," Materials, Vol. 15, No. 5, p. 1965. https://doi.org/10.3390/ma15051965
16. Yang, L. Li, B., Feng, J., Yang, G., Chang, Y., Jiang, B., and Xiao, J. "Automated Wall-climbing Robot for Concrete Construction Inspection," Journal of Field Robotics, September 21, 2022, https://doi.org/10.1002/rob.22119
17. Zhang, J., Kang, Z., Hou, D., Dong, B., and Ma, H. "Wavelet Power and Shannon Entropy Applied to Acoustic Emission Signals for Corrosion Detection and Evaluation of Reinforced Concrete," ES Materials and Manufacturing, Vol. 16, pp. 46-55. https://doi.org/10.30919/esmm5f554
18. Zhang, J., Zhang, M., Dong, B., and Ma, H. "Quantitative Evaluation of Steel Corrosion Induced Deterioration in Rubber Concrete by Integrating Ultrasonic Testing, Machine Learning and Mesoscale Simulation," Cement and Concrete Composites, Vol. 128, Paper No. 104426. https://doi.org/10.1016/j.cemconcomp.2022.104426
19. Zhao, Y., Zhang, J., Qiao, G., Hou, D., Dong, B., and Ma, H. "Enhancement of Cement Paste with Carboxylated Carbon Nanotubes and Poly(vinyl alcohol)," ACS Applied Nano Materials, Vol. 5, No. 5, pp. 6877-6889, 2022. https://doi.org/10.1021/acsanm.2c00875
20. Zhu, Y. and Chen, G. "Rayleigh Scattering Based, Thermal Deformation Measurement along Steel Bars at High Temperature," Journal of Infrastructure Intelligence and Resilience, Vol. 1, No. 1, July 3, 2022. https://doi.org/10.1016/j.iintel.2022.100002

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

1. Dedeurwaerder, B., Louis, S., Liu, S., and Harris, N. "Routing for Bridge Inspecting Robots Using a Metaheuristic Genetic Algorithm," The Genetic and Evolutionary Computation Conference Companion, Boston, MA, United States, July 9-13, 2022.
2. Hament, B. and Oh, P. "A Pressure Washing Hosing-Drone – Mitigating Reaction Forces and Torques," 2022 International Conference on Unmanned Aircraft Systems (ICUAS), pp. 468-477, Dubrovnik, Croatia, June 21-24, 2022. https://doi.org/10.1109/ICUAS54217.2022.9836101.
3. Hoxha, E., Feng, J., Sanakov, D., and Xiao, J. "Robotic Inspection and Characterization of Subsurface Defects on Concrete Structures Using Impact Sounding and Impact Echo Techniques," 13th International Workshop on Structural Health Monitoring (13IWSHM), Palo Alto, CA, United States, March 15-17, 2022.
4. Lander, P., Fahed, N., and Wang, Y. "Martlet Wireless Sensing System for Full Scale Bridge Weigh-in-motion," SPIE 12046 on Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems, Long Beach, CA, United States, March 6-10, 2022.

5. Li, L., and Chen, G. "Mixed Reality Interface of Geospatial Data towards Efficient, Effective, and Reliable Bridge Inspection," 8th World Conference on Structural Control and Monitoring (8WCSCM), Orlando, FL, United States, June 5-8, 2022.
6. Li, L., Chen, G. and Shang B. "Mixed Reality Enabled Digital Twin for Robot-Assisted Bridge Element Inspection and Maintenance," 8th World Conference on Structural Control and Monitoring (8WCSCM), Orlando, FL, United States, June 5-8, 2022.
7. Li, Z., Zhou, X., Ma, H., and Hou, D. Advanced Concrete Technology, 624 pp., 2nd Ed., Wiley, Hoboken, NJ, September 2022, ISBN: 978-1-119-80619-6 (e-book).
8. Otsuki, Y., Lander, P., and Wang, Y. "Field Validation of a Compact Martlet Wireless Ultrasonic Thickness Measurement System," 8th World Conference on Structural Control and Monitoring (8WCSCM), Orlando, FL, United States, June 5-8, 2022.
9. Otsuki, Y., Nguyen, S.T., La, H.M., and Wang, Y. "Autonomous Ultrasonic Thickness Measurement using a Steel Climbing Mobile Robot Integrated with Martlet Wireless Sensing," 30th ASNT Research Symposium, St. Louis, MO, United States, June 20-23, 2022.
10. Otsuki, Y., Lander, P., and Wang, Y. "Ultrasonic Thickness Measurement Using the Martlet Wireless Sensing System," 2021 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), Glasgow, Scotland, May 17-20, 2021.
11. Otsuki, Y., Li, D., Dong, X., and Wang, Y. "SMU - an Open-source MATLAB Package for Structural Model Updating," 10th International Conference on Bridge Maintenance, Safety and Management (IABMAS), Sapporo, Japan, April 11-18, 2021.
12. Shi, Z., Shang, B., Zhang, H., Li, L., Chen, G. "Evaluation of User-friendliness of Several Unmanned Aircraft Systems for Bridge Inspection," 8th World Conference on Structural Control and Monitoring (8WCSCM), Orlando, FL, United States, June 5-8, 2022.
13. Zhang, H., Jiao, P., Li, L., Shi, Z., Shang, B., and Chen, G. "Delamination Detection of Concrete Bridge Deck through UAV-based Infrared Thermography," 8th World Conference on Structural Control and Monitoring (8WCSCM), Orlando, FL, United States, June 5-8, 2022.
14. Zhu, Y., and Chen, G. "Cable Force Monitoring by Distributed Fiber Optic Sensor with Two Installation Schemes," 8th World Conference on Structural Control and Monitoring (8WCSCM), Orlando, FL, United States, June 5-8, 2022.

Final Technical Reports of Projects

1. Louis, S.J. "Developing a Robotic Simulator and Video Games for Professional and Public Training," Final Technical Report INSPIRE - 011, Tier 1 INSPIRE University Transportation Center, September 30, 2022.
2. Louis, S.J. "Simulation Training to Work with Bridge Inspection Robots," Final Technical Report INSPIRE - 013, Tier 1 INSPIRE University Transportation Center, September 30, 2022.

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
- 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. Genda Chen's team at Missouri S&T discovered that the 90% detectable, upper-confidence-bound corrosion-induced mass loss at 95% confidence level based on Fe-C coated fiber optic corrosion sensors is underestimated by over 50% when sensors' data are assumed independent.
- Dr. Hung La's team at the University of Nevada, Reno, developed a bicycle-like climbing robot that is versatile enough to move around the surface of most structural steel members and integrated the robot localization into the application of gel coupling and ultrasonic sensing for a successful thickness measurement.
- Dr. Sushil Louis' team at the University of Nevada, Reno, developed a new algorithm of generating and optimizing multiple robot paths along or on the surface of steel members.
- Dr. Hongyan Ma's team at Missouri S&T developed a deep learning model to relate nondestructive test data to the strength of concrete under various freeze-thaw cycling effects.
- Dr. Paul Oh's team at the University of Nevada, Las Vegas, developed a novel algorithm to control kickback action in a rotorcraft that can carry a water hose and provide high pressure jet flow to clean critical bridge components.
- Dr. Yang Wang's team at Georgia Institute of Technology developed an autonomous ultrasonic measurement of the thickness of steel bridge members by installing it on a climbing robot.
- Dr. Jizhong Xiao's team at City College of New York developed a solenoid, microphone, and piezoelectric sensor solution with a robust sliding mechanism for enhanced impact sounding and echo tests to collect acoustic and vibration signals automatically.

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

1. Genda Chen, Jie Gao, and Chuanrui Guo. "A Miniature, Micrometer-Accuracy, 3D Position-to-Optical Displacement Sensor," Provisional Patent Application No. 63/069,170 filed on August 24, 2020, PCT Application No. PCT/US2021/047234 filed on August 24, 2021, and Utility Application No. 17/919,158 filed on October 14, 2022.
2. Genda Chen, Alec Reven, Bo Shang, Zhenhua Shi, Liujun Li, and Boyang Li. "Unmanned Vehicle Having Flight Configuration and Surface Traverse Configuration," Provisional Patent Application No. 63/409.522, September 23, 2022.
3. Chenglin Wu, Genda Chen, Dimitri Feys, and Guirong Yan. "3D Printing Configurable Reinforcement for Concrete Structures," Provisional Application No. 62/994,543 filed on March 25, 2020, PCT Application No. PCT/US2021/24146 filed on March 25, 2021, and Utility Application No. 17/797,342 filed on August 3, 2022.
4. Jizhong Xiao, Guoyong Yan, and Yifeng Song. "Method and Apparatus to Clean Wind Turbine Blades," U.S. Patent No. 11,378066, issued on July 5, 2022.

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. Fernando Moreu from the University of New Mexico, *Intelligent Human-infrastructure Interfaces for Inspectors and Decision-makers*, which was recorded on June 21, 2022, and stored at Missouri S&T's Scholars Mine Data Repository Site: https://scholarsmine.mst.edu/inspire_webinars/20/

- Dr. Glenn Washer from the University of Missouri - Columbia, *Reliability of Bridge Inspection Technologies*, which was recorded on September 13, 2022, and stored at Missouri S&T's Scholars Mine Data Repository Site: https://scholarsmine.mst.edu/inspire_webinars/21/

3.F - INSPIRE Research Outputs Performance Metrics

Research Outputs - Performance Measures	Total
1. At least 5 journal publications and books per investigator/year	7.6
2. At least 15 keynote/invited presentations delivered at national and international conferences in 5 years	24
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 proved effective in detecting the delamination of concrete slabs with artificial defects. The sounding data collected and the tracking videos from a camera are synchronized through software integration for a real-time assessment of potential structural damage.
- Dr. Genda Chen's team developed the Random Effect Generalization method for the determination of the POD for Fe-C coated fiber optic corrosion sensors. The corrosion level at 90% POD was underestimated by more than 12.5% from the traditional statistical regression approach. For the upper confidence bound corrosion level at 95% confidence level, the traditional approach was unconservative by as much as over 50% in comparison with the Random Effect Generalization.
- Dr. Hung La's team developed a synchronized bicycle-like robot localization, surrounding surveillance, and ultrasonic thickness measurement strategy. Such a strategy allows an autonomous measurement of steel plate thickness in real-world steel bridges.
- Dr. Sushil Louis' team matched the simulated climbing robots with the INSPIRE UTC robot prototypes in terms of sensing, assessment, and data management in bridge inspection.
- 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 reproducible method that reflects the amount of dirt removed from a bridge to measure the performance of aerial hosing for bridge element cleaning. The method involves the use of a mixture of water and commercially sold dirt. This method more accurately captured the type of dirt build-up found on bridges.
- Dr. Iris Tien's team developed various approaches for background removal from images in order to improve the predictability of the proposed deep learning method when applied to filed obtained images and videos.
- Dr. Yang Wang's team developed a design procedure to optimize the placement of gel for effective ultrasonic tests while maintaining the stability of a carrying robot. Together with Dr. Hung La's team, Dr. Wang's team developed a highly integrated platform for robot

localization, surrounding surveillance, and thickness measurement.

- Dr. Jizhong Xiao's team designed and fabricated a robust sliding mechanism to host both impact sounding and echo modules for collecting acoustic and vibration signals automatically with an enhanced microphone to amplify acoustic signals and insolate ambient noises.

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

Once field tests progress in 2022 – 2023 with the pooled-fund study No. TPF-5(395), a condition/risk-based policy to change a bridge inspection frequency will be explored and a manual of practice for inspection and maintenance using mobile robots will be developed.

5. IMPACTS

5.A - The Effectiveness of the Transportation System

- Dr. Anil Agrawal's work on sounding devices that can automate impact sounding tests and data collection may replace an impact hammer with a more controllable electronic-sounding device.
- 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. Such inspections would be safer, cheaper, faster, and more consistent.
- Dr. Hung La's work on robotic sensing, localization, and navigation in a confined space of a steel (truss) bridge will ultimately enable automated bridge inspection for fracture critical members.
- Dr. Sushil Louis' work on game environment for training scenario generations and robot routings will lay a foundation for inspector/operator training with simulated bridges and robots.
- 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.
- 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.
- Dr. Yang Wang's work on a robot-assisted ultrasonic steel thickness measurement technology will enable an automated inspection of steel bridges for the deterioration level of corrosion.
- Dr. Jizhong Xiao's work on vision-based positioning will enable 3D GPR imaging, impact sounding, and impact echo analysis on a target area of interest.

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

- Dr. Hung La's team submitted an NSF-SBIR Phase I proposal in May 2022 to support Automated Inspection Robots (AIR) Corp., a start-up company established in January of 2020.
- Dr. Jizhong Xiao's work on a robotic nondestructive evaluation system with vertical mobility and an RGB-D camera, GPR, and impact sounding device enhanced and accelerated the development and validation of market-ready technologies to support InnovBot LLC, a CUNY spin-off company.

5.C - The Body of Scientific Knowledge

- Dr. Genda Chen's team developed a POD theory for steel corrosion evaluation using Fe-C coated

long period fiber optic (LPFG) sensors. The data taken from an LPFG sensor are partially correlated. The proposed Length-at-Detection and Random Effect Generalization methods accounted for the correlation of sensor data and made the 90% POD upper mass loss bound at 95% confidence level over 50% larger than the traditional results.

- Dr. Hung La's team developed a magnetic force analysis of magnet-wheeled climbing robots for steel bridge inspection. This procedure and process enables further investigation with the use of various nondestructive evaluation methods.
- Dr. Sushil Louis' team developed an optimal strategy for the work balance among k climbing robots in the formulation of Minimax k-Chinese Postman Problem (MMk-CPP). This understanding will impact operation research and nonlinear optimization community.
- Dr. Paul Oh's research provided an unprecedented understanding of how a rotorcraft works with a hose discharging water in the horizontal direction – an asymmetrical multi-degree dynamic system with a significant kickback force to counteract during the flight of the rotorcraft.
- Dr. Jizhong Xiao's team proposed a solenoid impact mechanism on vacuum-based climbing robots with data analysis software. The vision-based positioning method will enable 3D GPR imaging, impact sounding, and impact echo analysis for detection of subsurface defects.

5.D - Transportation Workforce Development

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

1. Maria Alvarado in civil engineering, Missouri S&T
2. Daniel Bloom in electrical and computer engineering, City College of New York
3. Sean Boland in computer science, Missouri S&T
4. Zahir Castrejon in mechanical engineering, University of Nevada, Las Vegas
5. Akshay Dave in mechanical engineering, University of Nevada, Las Vegas
6. Derek Edwards in mechanical engineering, Missouri S&T
7. Timothy Headrick in computer science, Missouri S&T
8. Dawson Jobe in mechanical engineering, Missouri S&T
9. Ziyu (Kevin) Lai in computer science, Missouri S&T
10. Rueil Manzambi in computer science, Missouri S&T
11. Daniel Mcdonald in electrical and computer engineering, Missouri S&T
12. Toni (Ava) Ramljak in electrical and computer engineering, Missouri S&T
13. Andrew Rawlings in mechanical engineering, Missouri S&T
14. Joseph Ressel in mechanical engineering, Missouri S&T
15. Elizabeth Rozhanskiy in civil engineering, Missouri S&T
16. Jonathan Saelens in electrical and computer engineering, Missouri S&T
17. Brandyss Sherman-Hall in electrical and computer engineering, Missouri S&T
18. Eric Ssesanga in civil engineering, Missouri S&T
19. Son Tran in mechanical engineering, University of Nevada, Las Vegas
20. Nicholas Ward in computer science and engineering, University of Nevada, Reno
21. Matthew Weiss in mechanical engineering, Missouri S&T
22. Armaun Zargari in mechanical engineering, University of Nevada, Las Vegas

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. Jinglun Feng in electrical and computer engineering, City College of New York
4. Rezwana Binte Hafiz in civil engineering, Missouri S&T
5. Blake Hament in mechanical engineering, University of Nevada, Las Vegas
6. Yang He in electrical and computer engineering, City College of New York
7. Hana Herndon in civil engineering, Georgia Institute of Technology
8. Tamjid Hossain in computer science and engineering, University of Nevada, Reno
9. Ejup Hoxha in electrical and computer engineering, City College of New York
10. Deepak Kumar in civil engineering, City College of New York
11. Chuong Le in computer science and engineering, University of Nevada, Reno
12. Pengfei Ma in civil engineering, Missouri S&T
13. Cadence Motley in computer science and engineering, University of Nevada, Reno
14. Thanh Son Nguyen in computer science and engineering, University of Nevada, Reno
15. Yu Otsuki in civil engineering, Georgia Institute of Technology
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. Andrew Washburn in computer science and engineering, University of Nevada, Reno
20. Tamanna Yasmin in computer science and engineering, University of Nevada, Reno
21. Yanping Zhu in civil engineering, Missouri S&T
22. Ying Zhuo in civil engineering, Missouri S&T

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

1. Dr. Dongbin Kim in mechanical engineering, University of Nevada, Las Vegas
2. Dr. Liujun Li in mechanical engineering, Missouri S&T
3. Dr. Tarutal Gosh Mondal in civil engineering, Missouri S&T
4. Dr. Bo Shang in electrical engineering, Missouri S&T
5. Dr. Zhenhua Shi in civil engineering, Missouri S&T
6. Dr. Haibin Zhang in civil engineering, Missouri S&T
7. Dr. Yanping Zhu in civil engineering, Missouri S&T

Direct Training of Undergraduate and Graduate through Course Work

1. In Spring 2022, Dr. Hung La trained 57 undergraduate students and five (5) graduate students in CPE 470/670 Autonomous Mobile Robots in electrical and computer engineering, the University of Nevada, Reno.
2. In Spring 2022, Dr. Hongyan Ma trained 32 undergraduate students in CIV ENG 3116 Construction Materials, Properties and Testing in civil engineering, Missouri University of Science and Technology. In Fall 2022, Dr. Ma trained 11 undergraduate and graduate students in CIV ENG 5113 Composition and Properties of Concrete/6801 Advanced Concrete Science and Technology, including a module of nondestructive tests for concrete strength evaluation.
3. In Spring 2022, Dr. Iris Tien trained 30 graduate students in CEE 8813 Data Analytics for Civil and Environmental Engineering Systems, Georgia Institute of Technology, covering a range of data analytics methods and techniques for the analysis of civil and environmental systems, such as monitoring, assessment, and control of transportation systems.
4. In Spring 2022, Dr. Jizhong Xiao trained 10 undergraduate students in EE598.66 Senior Design II and 3 graduate students in EE G7501 Advanced Mobile Robots. In Fall 2022, Dr. Xiao trained 9 undergraduate students in EE598.67 Senior Design I and 9 graduate students in EE G5501

Introduction to Robotics in electrical engineering, the City College of New York.

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

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 2023 and 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

Nothing to report.

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.