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UTC Semi-Annual Progress Report #7

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Inspecting and Preserving Infrastructure through Robotic Exploration (INSPIRE)

NSPIR

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



Submitted to:	U.S. Department of Transportation (USDOT) Office of the Assistant Secretary for Research and Technology (OST-R)	
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1. ACCOMPLISHMENTS

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

Center's Mission and Goals

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

The overarching goals of the center in five years are to transform in at least two demonstration cases from manual to automated inspection and preservation of bridges with sensors, nondestructive evaluation (NDE) devices, multi-modal unmanned vehicles, and data logistics, thus providing cost-effective, consistent, and reliable solutions in bridge condition assessment and maintenance, and to develop diverse transportation workforces mastering the advanced technologies.

Research Objectives

To achieve the center's goals, three research objectives of the center are set:

- 1. To explore, develop, validate, and demonstrate standardized-integrated measurement technologies, decision-making tools, data logistics, and autonomous systems to facilitate the field inspection and maintenance of bridges;
- 2. To develop, validate, and demonstrate methods of robot-enabled resilience analysis and intervention technologies (retrofit and repair) of bridges; and
- 3. To develop innovative tools and methods for the next-generation transportation workforce training and the general public education.

Education Objectives

Three education objectives are set and achieved through degree-granting programs with transportation components and transportation non-degree programs:

- 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;
- To create new opportunities for knowledge expansion and skill training on non-traditional civil engineering subjects, such as sensing, NDE, and bridge inspection and maintenance with robotics, which can enrich existing civil engineering programs or non-degree certificate programs; and
- 3. To connect students with transportation industries and professionals through center meetings, annual transportation research board (TRB) meetings, an international conference, and the external advisory committee.

Workforce Development Objectives

Two workforce development objectives are set and achieved through various outreach activities and close collaborations with professional organizations such as the Missouri Local Technical Assistance Program (LTAP) and the Center for Worker Education (CWE), New York:

- 1. To raise the public awareness of changes from adopting advanced technologies and attract new entrants from varying pipelines into transportation-related majors; and
- 2. To apply the robot simulator and video games developed as part of the research portfolio for a rapid and innovative workforce training of both current and prospective transportation workforces.

Technology Transfer Objectives

Three technology transfer objectives are set and achieved through various technology showcases to end users and perspective workforce:

- 1. To work in partnership with end users to facilitate technology transfer, including state and local governments, non-profit entities, and private enterprises, and assist them in mastering and implementing the developed technologies such as sensors, robots, and image analysis tools;
- 2. To protect intellectual properties with patent applications through the technology transfer and economic development offices and actively seek their licensing with small businesses such as InnovBot LLC; and
- 3. To disseminate research results through high quality peer-reviewed journals, conference proceedings, seminars/workshops/short courses, and exhibitions at TRB annual meetings and other national/international conferences.

Diversity Objectives

Two diversity objectives are set:

- 1. To broaden underrepresented minority participation through direct involvement of two minority institutions; and
- 2. To recruit and retain female and traditionally underrepresented minority students in close collaboration with special programs such as the activities of the Student Diversity, Outreach and Women's Programs office at Missouri S&T.

1.B - What Was Accomplished under These Goals?

The INSPIRE UTC held its annual meeting virtually on August 3-4, 2020. Activities included technical research presentations by major university member principal investigators and an INSPIRE UTC executive business meeting. Highlighted topics included the new Educational Module Lecture Series on each completed research topic presented by Major university members at the City College of New York, Georgia Institute of Technology, Missouri S&T, University of Nevada-Las Vegas and the University of Nevada-Reno for undergraduate students from community colleges. This initiative is targeted as a pipeline of workforce development in the area of transportation infrastructure inspection. Other topics included were updates on recent developments with the seven-state pooled-fund study and a virtual graduate poster session.

The accompanying seven-state pooled-fund study No. TPF-5(395): Traffic Disruption-free Bridge Inspection Initiative with Robotic Systems was progressed in two tasks for bridge selection and fabrication of a combined flying and traversing robot, named BIRDS. Specifically, steel-girder bridges in the state of New York, Virginia and Wisconsin, and prestressed concrete girder bridges in Georgia, Texas, and California would be tested. In Missouri, both groups of girder bridges would be tested. The finite element model of the hybrid unmanned vehicle was established to understand the aerodynamic stability as the vehicle approaches a bridge girder. This understanding can help develop an effective and practical navigation strategy of the BIRDS in application, providing foundation for workforce training in vehicle operation. Bi-monthly meetings were held with Principal Investigators (PIs) to provide open lines of communication within the Center, and to share important news and announcements with the research team. PIs provide research progress updates, and submit written quarterly reports to the Center.

Table 1 summarizes the major progress made in each of the research topics: sensing and nondestructive evaluation (SN), autonomous systems (AS), inspection and maintenance (IM), retrofit and resilience (RR), and workforce development (WD). Progress evaluation is done in terms of major activities, specific objectives, significant results and key outcomes/achievements.

1. Develop a localization 1. Characterize field 1. Two magnet 1. Implement algorithm for more than one performance of two positioning obtained of one sm	tation art
algorithm for more than one performance of two positioning obtained of one sm	art
	are
smart rocks deployed in close magnets/smart rocks for through field tests. rock at th	2
distance and continue with bridge scour monitoring. 2. N/A. Rubidoux	Bridge.
field validation tests. 2. N/A. 3. Consistent strain 2. Complete	
2. N/A. 3. Understand the potential measurements from 3. Steel tube	
3. Evaluate the coupled effect interference between grating and packaged	
of long period fiber gratings grating and scattering scattering sensors. sensors for	r life
and distributed fiber optic sensors. 4. Harmonic power in cycle corr	osion
sensors. 4. Develop and optimize a microwave monitorin	g.
4. Compare microwave SAR Vivaldi antenna and a nonlinear 4. Cross range	e and
imaging method, microwave double-ridged horn measurement resolution	of SAR
resonance method, and antenna, and investigate proportional to the images aff	ected
microwave nonlinear the nonlinear effect of insulation thickness. by antenn	a beam
SN measurement for their ability distributed rebar on 5. Droplet tests giving for delam	nation
to detect corrosion effects. corrosion detectability. generally consistent detection.	
5. Develop a test protocol to 5. Characterize steel corrosion degree, 5. Hyperspec	tral
characterize the features of samples with droplet and 6. ADC board tested to imaging for	r steel
steel structures. immersion tests using be functional with corrosion	
6. Integrate advanced wireless hyperspectral images, satisfactory detection	
sensing technologies into a 6 Develop a functional high-	and a
robot platform for speed ADC board between the ADC new version	n of
autopomous ultrasonic metal consisting of a high-rate chin and the huffer nulse board	d with
thickness measurement ADC chin a memory 7 None to report 12V nowe	
7 None to report hugger and a parallel-to- 8 None to report supply tes	ed
8 None to report serial converter successful	v
7 None to report 7 Not vet st	,. arted
8. None to report. 8. Not yet st	arted.
1 N/A $1 N/A$ $1 N/A$ $1 Complete$	
2. Design and build a prototype 2. Transfer the climbing 2. A compact and 2. Parts orde	red
of climbing robot for field robot technology into robust design of and being	
tests. practice as part of the robot prototype assemble	l for
3. Design a new climbing robot field test facility to be 3. Computer field test	p.
on a larger footprint of developed at the Center, simulation 3. A new dev	ign of
concrete as required to host 3. Develop robust robots to demonstrating robot that	is
a sliding mechanism for a provide vertical mobility satisfactory results computat	onally
AS solenoid-based impact for field deployment and 4. Successful field tests demonstr	ated (
sounding device.	
4. Assemble 2 nd prototype of a concrete surface manual switches 4. Hardware	design
hybrid vehicle for field testing 4. Develop a solar-nowered between flying and and fabric	ation
and develop navigation and mobile test facility for traversing modes complete	
control software for flight field tests at bridge sites 5 Development for 5 A bounda	v
automation 5. Provide the built climbing ontimization of detection	,
5 Test and validate houndary robot with an motion planning algorithm	and a
detection algorithm for an algorithms to motion planning algorithms to	anning

Table 1- A summary of research progress



Торіс	Major Activities	Specific Objectives	Significant Results	Key Outcomes
	autonomous navigation of the robot.	autonomous inspection capability.	determine the best path of the robot on	algorithm for optimal path of
	 6. Produce small parts of a new climbing robot with 3D printing and large mechanical parts by the 3rd party vendors. 7. Augmented-reality operator control of the drone's manipulator. 8. Complete one design with vacuum suction of a climbing robot on column surfaces for scour monitoring. 	 6. Develop a field deployable robot for data collection on create bridges and other infrastructure. 7. Develop a human-in-the- loop control strategy for aerial manipulation tasks such as deck-hosting and hole-drilling. 8. Develop a real-time scour monitoring technique with a robot-mounted sonner and altimeter. 	 a steel surface. 6. Piezoelectric accelerometers used to record impact echo for the detection of subsurface flaws. 7. Human-drone interaction for hole-drilling tests. 8. Suction mechanism tested to ensure sufficient force. 	 climbing. 6. Reinforced concrete slabs built with embedded defects for echo tests. 7. Aerial drilling using haptic feedback. 8. A complete design of climbing robot.
IM	 N/A Combine empirical mode decomposition and power- spectral density analyses to extract useful features of sounding data from hammer. Develop two different configurations of smart sounding tool for defect detection in hollow structures. 	 N/A Develop a fusion strategy of features extracted from multiple analysis tools. Develop an approach to rate the condition of concrete members based on measurements from robot-mounted sensors (speaker and camera). 	 N/A Empirical mode decomposition effective to eliminate noise from captured data. Individual components of the sounding tool tested for their compatibility and efficiency. 	 Withdrawn. Defect contour of an inspected concrete slab for rapid decision- making. GPS, tracking camera, MEMS microphone, and Bluetooth speaker tested functional.
RR	 Develop a new method to update bridge fragility curves with new inspection data. None to report. 	 Analyze and update the assessment of bridge performance. None to report. 	 Conjugate Bayesian inference as an analytical- computational approach achieving stable fragility results. None to report. 	 Faster convergence and higher accuracy with fewer analyses achieved. Not yet started.
WD	 Prepare a final report with two distinctive tasks to assist engineers in segmenting important images from video and analyzing images to support decision-making. Improve a genetic algorithm with a parallelized implementation to run on graphic cards for an existing real-world bridge. None to report. None to report. 	 Create a framework of training engineers and policy makers on the use of image analysis for bridge inspection. Develop and iterate the 2nd prototype of the Simulation Training And Control System (STACS 2) with optimal robot routing. None to report. None to report. 	 Deep learning effective in segmenting and detecting critical components from a bridge. Near-optimal inspection routes achieved for less than 10 robots. None to report. None to report. 	 Technology transfer training for one student and one post doc at the INSPIRE Center. New control algorithms and models for a flying robot and a climbing robot. Not yet started. Not yet started.
Note:	to address the 1 st researc	h objective; the 2 nd	objective; and	the 3 rd objective.

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

In this reporting period, the INSPIRE UTC directly involved 10 faculty, 4 post docs, 28 graduate students, and 12 undergraduate students in civil engineering, electrical engineering, mechanical engineering,

computer science, and engineering management and system engineering through its research program with 24 projects.

1.D - How Have the Results Been Disseminated?

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

Invited Presentations:

 J.L. Feng, L. Yang, H.Y. Wang, Y.F. Song, J.Z. Xiao, "GPR-based Subsurface Object Detection and Reconstruction Using Random Motion and DepthNet," Presented at the 2020 IEEE International Conference on Robotics and Automation (ICRA2020), June 1, 2020. (invited session)

Biannual Newsletters

The INSPIRE UTC publishes biannual newsletters to disseminate research information and enhance public understanding of Center activities. INSPIRE newsletters are distributed to more than 7,500 people through the Center's listserv, and are made available online at https://inspire-utc.mst.edu/news/. An INSPIRE UTC Newsletter (Vol. 4, No. 1) was published in Spring 2020 and included three technical articles related to INSPIRE research:

- Failure Investigation of the Cardinal Raul Silva Henriquez Steel-Girder Bridge During the 2010 Chile Earthquake, Dr. Genda Chen, Missouri S&T
- Lesson Learned from the Failure of The Steel Strut of Paseo Suspension Bridge, Dr. Genda Chen, Missouri S&T
- March 2018 Collapse of the Pedestrian Bridge in Miami, Florida, Dr. Anil Agrawal, the City College of New York

Quarterly Webinars

The INSPIRE UTC hosts quarterly webinars. Overall, 13 INSPIRE webinars have engaged more than 750 people from 44 US States and 15 different countries, including Australia, Brazil, Canada, China, Germany, India, Italy, Mexico, Portugal, Serbia, Sweden, Switzerland, Taiwan, United Kingdom, and the US. On average, 56% of the participants are from academia, 21% are from industry, 18% are from Government, and 5% are unknown.

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

- 1. Mobile Manipulating Drones was presented on June 17, 2020 by Dr. Paul Oh, Mechanical Engineering, University of Nevada-Las Vegas.
- 2. UAV-Enabled Measurement for Spatial Magnetic Field of Smart Rocks in Bridge Scour Monitoring was presented on September 14, 2020 by Dr. Genda Chen, Missouri S&T.

Education and Outreach Activities

Dr. Paul Oh's team at the University of Nevada-Las Vegas (UNLV) continues to work with the neighboring Clark County Las Vegas Public Library in the Saturday K-12 programs. Lesson plans include computer-aid-design (CAD), 3D printing, and embedded controllers (Arduino). Due to COVID-19, these programs were held online. Additionally, the team serves institutional outreach programs, namely Upward Bound. This program is UNLV's outreach to middle school students. Each Saturday, the team conducts hands-on STEM labs which include drone programming, augmented reality

projection mapping, and embedded control Arduinos. Due to COVID-19, these programs were also held online.

1.E - What Do You Plan to Do during the Next Reporting Period to Accomplish the Goals?

Research projects will continue in the five research topics 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.

Topic	Project Title	Planned Activities		
	Autonomous Ultrasonic	• Continue to improve the communication reliability between the ADC chip and		
	Thickness Measurement by a	the memory buffer.		
	Magnet-Wheeled Robot	• Finalize the design of printed circuit board for final evaluation.		
		Integrate the final PCB with the UNR robot.		
	Health Inspection of Concrete	Establish a spectra library of components involved in concrete exposed to		
	Pavement and Bridge	Freeze-Thaw environments (especially deicing chemicals)		
SN	Members Exposed to Freeze-	• Develop the correlation between the hyperspectral signatures and the degree		
	Thaw Service Environments	of saturation of concrete.		
	Probability of Detection in	• Standard test specimens and experimental designs will be prepared to provide		
	Corrosion Monitoring with Fe-C	relevant cases to sensors' field applications in steel reinforced concrete (RC)		
	Coated LPFG Sensors	structures.		
		The proposed statistical methods will be validated to determine the largest		
		mass loss with 90% probability of detection at a 95% lower confidence level.		
	Bridge Inspection Robot	Design and prototype a hybrid flying and traversing unmanned vehicle for		
	Deployment Systems (BIRDS)	inspection of girder bridges and for deployment of climbing robots.		
		• Develop technical specifications of the vehicle for flying, traversing, and their		
		transition performance.		
	Nondestructive Data Driven	Utilize the previously developed boundary detection algorithm, deep learning		
	Motion Planning for Inspection	method, and hidden Markov model to classify different steel structure shapes		
	Robots	for a robot to safely navigate and transit on steel bridges.		
		Continue to investigate the deployment of the robot in actual steel bridges to		
		achieve its autonomy.		
	A Field Deployable Wall-	Investigate solutions to eliminate the limitations of the current impact		
	Climbing Robot for Bridge	sounding mechanism.		
	Inspection using vision and	Investigate impact sounding and/or impact echo instruments to be outfitted		
AS		on a robot for structural integrity testing.		
	Augmenting Bridge Inspection	Conduct field tests of a virtual reality controlled dual-arm manipulator like an		
	with Augmented Reality and	Avatar drone.		
	Haptics-based Aerial	• Task the manipulator with the stacking and unstacking of items (i.e., boxes).		
	Manipulation			
	Robot-assisted Underwater	Design and prototype a dual-chamber climbing robot that can move on the		
	Acoustic imaging for Bridge	curve/flat surfaces of RC piers.		
	Scour Evaluation	Integrate the side-scan sonar and the altimeter with the climbing robot, and		
		test the system's maneuverability and stability as well as the sensors'		
		performance in application settings.		
	Data-Driven Risk-Informed	Create classes of bridges based on collected inspection data.		
	Bridge Asset Management and	Define measures of similarity across bridges.		
	Prioritization across			
	Transportation Networks			
	Autonomous Functions for	Optimize the components of an electronic sounding tool for damage detection is both associate and exetable structure and the structure of the structur		
RR	Autonomous Evaluation of	in both concrete and metallic structures, such as shallow delamination in		
	Structures	concrete decks and cracks in steel beams.		
	Structures			

Table 2- A summary of planned research activities



Topic	Project Title	Planned Activities		
		• Integrate the new "smart-sounding system" with the VSLAM technology for mapping and data collection.		
	Simulation Training to Work with Bridge Inspection Robots	 Investigate algorithms for simulation control and mapping of multiple inspection robots within the same software system. Integrate routing optimization into the simulation system to reduce human operator fatigue and improve monitoring. 		
WD	An Interactive System for Training and Assisting Bridge Inspectors in Inspection Video Data Analytics	 Create web-based learning modules for trainees to master cross-disciplinary knowledge and fundamental skills of analytics. Develop an inspection data analytics tool to assist inspectors in processing and analyzing inspection video data for the condition assessment of bridges. 		
Note:	to address the 1 st resea	earch objective; the 2 nd objective; and the 3 rd objective.		

Other Planned Initiatives

- 1. After-school activities include Robotics Programs in surrounding areas of Rolla, MO (Newburg, Dent and Belle/Vichy).
- FIRST Lego League teams in Phelps and Dent County will compete throughout the school year. FLL Junior teams (K-4) and Pre-K-1st—Vienna Kindergarten joined as part of a major expansion to the competition, made possible with UTC grant funding.
- 3. Kaleidoscope Discovery Center will host the Missouri Future City Competition. The virtual event will be held on Saturday, February 27, 2021 with judging to take place virtually.

2. PARTICIPANTS & COLLABORATING ORGANIZATIONS

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

Consortium Collaborators

The consortium members of this University Transportation Center remain the same as proposed originally. But one project was subcontracted to Dr. Reza Zoughi in Iowa State University and completed during this reporting period due to his move from Missouri University of Science and Technology to Iowa State University. The complete list of members includes:

- City College of New York New York, NY
- East Central College Union, MO
- Georgia Institute of Technology Atlanta, GA
- Lincoln University Jefferson City, MO
- Missouri University of Science and Technology Rolla, MO (lead institution)
- Ozarks Technical College Springfield, MO
- St. Louis Community College St. Louis, MO
- University of Colorado at Boulder Boulder, CO
- University of Nevada-Las Vegas Las Vegas, NV
- University of Nevada at Reno Reno, NV

External Collaborators

- California Department of Transportation https://dot.ca.gov
- Clark County Las Vegas Library https://lvccld.org
- Colorado Department of Transportation <u>www.codot.gov</u>
- Geophysical Survey System, Inc. (GSSI) <u>https://www.geophysical.com</u>

INSPECTING AND PRESERVING INFRASTRUCTURE THROUGH ROBOTIC EXPLORATION

- Georgia Department of Transportation www.dot.ga.gove
- InnovBot LLC a Spinoff Company out of the CCNY Robotics Lab
- Mid-America Transportation Center <u>https://matc.unl.edu</u>
- Missouri Department of Transportation <u>http://www.modot.org</u>
- Nevada Department of Transportation https://www.nevadadot.com/
- New York Department of Transportation <u>https://www.dot.ny.gov</u>
- Paul D. Thompson Consulting Services <u>www.pdth.com</u>
- Rice University, Department of Civil and Environmental Engineering https://ceee.rice.edu
- Stony Brook University <u>https://www.stonybrook.edu/</u>
- Tesla Gigafactory, Reno, NV <u>https://www.tesla.com/gigafactory</u>
- Texas Department of Transportation https://www.txdot.gov
- TranSystems Corporation <u>www.transystems.com</u>
- Turner Fairbanks Highway Research Center of FHWA, McLean, VA <u>https://highways.dot.gov/research</u>
- Virginia Department of Transportation <u>https://www.virginiadot.org/</u>
- 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 <u>http://scholarsmine.mst.edu/</u>
- Department of Civil, Architectural and Environmental Engineering <u>https://care.mst.edu/</u>
- Department of Computer Science <u>https://cs.mst.edu</u>
- Department of Engineering Management and Systems Engineering <u>https://emse.mst.edu/</u>
- Educational Technology http://edtech.mst.edu/
- Research Support Services/MinerFly Team https://itrss.mst.edu/minerfly/
- Student Diversity Initiatives http://sdi.mst.edu/

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

Georgia Institute of Technology collaborated with the Department of Civil and Environmental Engineering at Rice University.

Geophysical Survey System Inc. (GSSI) granted the CCNY team to access their test pit to collect GPR/impact sounding data.

InnovBot LLC has received a NSF grant "SBIR Phase I: Robotic Inspection and Data Analytics to Localize and Visualize the Structural Defects of Civil Infrastructure" and will subcontract some research and development work to the City College of New York Robotics Lab.

The University of Nevada-Las Vegas officially began a Phase 2 task order contract with Tesla's Renobased Gigafactory in March 2020. This task order is independent of this INSPIRE project. However, there is some overlap technologically e.g. AR and using robots to monitor sites and manipulate objects.

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

3. OUTPUTS

3.A - Publications, Conference Papers, and Presentations

Journal Publications

- 1. N.T. Davis, E. Hoomaan, **A.K. Agrawal**, M. Sanayei, and F. Jalinoos. "Foundation Reuse in Accelerated Bridge Construction." Journal of Bridge Engineering 24(10): 05019010, October 2019; https://doi.org/10.1061/(ASCE)BE.1943-5592.0001455.
- X.D. Chen, H.F. Wang, A.H. Chan, and A.K. Agrawal. "Dynamic Failure of Dry-joint Masonry Arch Structures Modelled with the Combined Finite–discrete Element Method." Computational Particle Mechanics 7(5): 1017-1028, 2019; https://doi.org/10.1007/s40571-019-00297-2.
- X. Chen, A.K. Agrawal, S. El-Tawil, X.C. Xu, R. Cao, and W. Wong. "Inelastic Behavior of a Bridge Bent Subjected to Truck Impact: Experimental and Computational Study." Engineering Structures 199(5): 109543, November 2019; https://doi.org/10.1016/j.engstruct.2019.109543.
- K.T. Tran, F. Jalinoos, T.D. Nguyen, and A.K. Agrawal. "Evaluation of Bridge Abutment with Ultraseismic Waveform Tomography: Field Data Application." Journal of Nondestructive Evaluation 38(4): 95, December 2019; https://doi.org/10.1007/s10921-019-0631-4.
- F. Jalinoos, M. Amjadian, A.K. Agrawal, C. Brooks, and D. Banach. "Experimental Evaluation of Unmanned Aerial System for Measuring Bridge Movement." Journal of Bridge Engineering 25(1): 04019132, January 2020; https://doi.org/10.1061/(ASCE)BE.1943-5592.0001508.
- R. Cao, S. EI-Tawil, and A.K. Agrawal. "Miami Pedestrian Bridge Collapse: Computational Forensic Analysis." Journal of Bridge Engineering 25(1): 04019134, January 2020; https://doi.org/10.1061/(ASCE)BE.1943-5592.0001532.
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- C. Liu, M.T. Qaseer, and R. Zoughi. "Influence of Antenna Pattern on Synthetic Aperture Radar Resolution for NDE Applications." IEEE Transactions on Instrumentation and Measurement, September 2020; https://doi 10.1109/TIM.2020.3026122.

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

- 1. Y. Zhang, and I. Tien. "Fragility Curve Updating Using Inspection Data and Dynamic Analysis with Application to Corroded Bridges." ASCE Engineering Mechanics Institute Conference (EMI) and Probabilistic Mechanics and Reliability Conference (PMC), published.
- 2. Y. Zhang, and I. Tien. "Robust Risk Assessment of Reinforced Concrete Columns with Short Lap Splices through Regularization." ASCE Engineering Mechanics Institute Conference (EMI) and Probabilistic Mechanics and Reliability Conference (PMC), published.
- C. Liu, M.T. Al Qaseer, and R. Zoughi. "Influence of Antenna Pattern on Synthetic Aperture Radar Resolution for NDE Applications." IEEE Transactions on Instrumentation and Measurement (Early Access) DOI 10.1109/TIM.2020.3026122.

- 4. J. Hale, **S. Long**, S. Corns, and C. Dagli. "A Computational Intelligence Approach to Transitioning an Electricity Portfolio." Proceedings of the IISE Annual Conference and Expo 2020, New Orleans, LA, June 2020. (invited session)
- J.L. Feng, L. Yang, H.Y. Wang, Y.F. Song, J.Z. Xiao, "GPR-based Subsurface Object Detection and Reconstruction Using Random Motion and DepthNet," Presented at the 2020 IEEE International Conference on Robotics and Automation (ICRA2020), June 1, 2020. (invited session)

Final Technical Reports of Projects

- 1. C. Liu, M.T. Al Qaseer, and **R. Zoughi**. Microwave Camera for Concrete Delamination and Steel Corrosion Detection. Final Report No. INSPIRE-006, June 30, 2020.
- 2. **R.W. Qin**, G.D. Chen, Z.Z. Yin, M.M. Karim, and T.Y. Zhao. A Training Framework of Robotic Operation and Image Analysis for Decision-Making in Bridge Inspection and Preservation. Final Report No. INSPIRE-007, July 31, 2020.
- F. Jalinoos, A.K. Agrawal, C. Brooks, M. Amjadian, D. Banach, E.J. Boren, R.J. Dobson, T.M. Ahlborn. "Post-hazard Engineering Assessment of Highway Structures Using Remote Sensing Technologies." FHWA-HIF-20-004. Federal Highway Administration, Office of Infrastructure Research and Development, United States.

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

- Advanced Robotics and Automation Laboratory: <u>https://ara.cse.unr.edu</u>
- Center for Intelligent Infrastructure: <u>https://cii.mst.edu</u>
- Evolutionary Computing Systems Laboratory: <u>https://ecsl.cse.unr.edu/projects/bridge_inspection/index.html</u>
- INSPIRE University Transportation Center: <u>https://inspire-utc.mst.edu</u>
- Missouri University of Science and Technology Scholars' Mines: <u>https://scholarsmine.mst.edu/</u>
- Research in Progress Database: <u>https://rip.trb.org/</u>

3.C - New Technologies or Techniques

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

- Dr. Genda Chen's team successfully tested the second prototype of a hybrid flying and traversing vehicle for flight capability in open field, and developed the software required to make it an autonomous system in a test unmanned aerial vehicle.
- Dr. Anil Agrawal's team has extended the sounding data analysis procedure to filtering of highfrequency noise in theoretical and experimental data from high speed impact of trucks on bridge piers and barriers. This will be a significant publication impacting many broad areas of engineering requiring complex explicit finite element simulations using software such as LS-DYNA.
- Dr. Hung La's team has tested and validated the boundary detection algorithm for autonomous navigation of the steel climbing robot on several steel structures setup in the lab.
- Dr. Sushil Louis' team has developed new control algorithms and modelled a flying inspection robot and a climbing robot. These generalized models can be modified to simulate the physics of robots being designed as part of the INSPIRE project. They also developed a new version of the open source STACS software on Github at <u>https://github.com/sushillouis/Stacs</u>. This serves as a resource for INSPIRE and other projects related to autonomy and bridge inspection.

- Dr. Paul Oh's team developed two drone-mounted arms to inspect, maintain and repair bridges. The resulting aerial manipulation demonstrated tasks like deck-hosing and hole-drilling. Also created was a virtual reality headset and Unity software environment.
- Dr. Iris Tien's team has been advancing a method to more efficiently update fragility assessments with inspection data. The method is based on conjugate Bayesian inference, thus combining an analytical approach with computational approaches to perform fragility assessment. They also developed a new approach that enables a more comprehensive assessment of the performance of scoured bridges than previously possible. The verification using a combination of multiple approaches shows confidence in the results of the developed approaches in assessing the vulnerability of scoured bridges.
- Dr. Yang Wang's team has developed a new high-speed ADC board that mainly consists of the high-rate ADC chip, a memory buffer, and a parallel-to-serial converter. The evaluation circuits for each component of the ADC board have been built on breadboards. The performance of individual components have been verified. In addition, Dr. Yang Wang's team has developed a new version of the pulser board. The latest version directly accepts the 12V power supply that will come from the UNR robot. In addition, through four corner sockets, the latest version can conveniently stack up on top of the Martlet motherboard, providing a compact overall dimension.
- Dr. Jizhong Xiao's team has produced a CAD model of a new climbing robot design that has a larger robot base to host a sliding mechanism that drive the solenoid-based impact sounding device along a straight line, which facilitates the data collection at multiple points. In addition, Dr. Jizhong Xiao's team has produced an impacting mechanism that is used to generate sounding data for the NDE of delamination.
- Dr. Reza Zoughi's team has improved upon aspects of high-frequency synthetic aperture radar (SAR) imaging as it directly relates NDE applications such as bridge deck delamination and corrosion in rebar detection. This study has involved the influence of antenna beamwidth and the influence of antenna pattern on SAR image sidelobe level.

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

- Jizhong Xiao submitted a provisional patent application on "Method and Apparatus for Automatic GPR Data Collection and GRR Imaging." Inventors: Jizhong Xiao, Jinglun Feng and Liang Yang, Provisional #63/031,977, May 29, 2020.
- Genda Chen's team submitted a provisional patent application on "3D Printing Configurable Reinforced for Concrete Structures." Inventors: Chenglin Wu, Genda Chen, Dimitri Feys, and Guirong Yan, Case 19MST044: Provisional #62/994,543, March 25, 2020.
- Genda Chen's team submitted a provisional patent application on "A Miniature, Micrometer-Accuracy, 3D Position-to-Optical Displacement Sensor." Inventors: Genda Chen, Jie Gao, and Steve Guo, Case 20MST036: Provisional #63/069,170, August 24, 2020.

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

Video Products

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

Final Data Reports of Projects

- 1. Genda Chen. UAV-enabled Measurement for Spatial Magnetic Field of Smart Rocks in Bridge Scour Monitoring, April 31, 2020.
- 2. Anil Agrawal. Quantitative Bridge Inspection Ratings Using Autonomous Robotic Systems, June 30, 2020.
- 3. Reza Zoughi. Microwave Camera for Concrete Delamination and Steel Corrosion Detection, June 30, 2020.
- 4. Ruwen Qin. A Training Framework of Robotic Operation and Image Analysis for Decision-Making in Bridge Inspection and Preservation, July 31, 2020.

Educational Modules

- 1. Genda Chen. Long Period Fiber Grating based Fiber Optic Sensor for Deterioration Detection in Reinforced Concrete Structures, April 31, 2020.
- 2. Reza Zoughi. Microwave Materials Characterization and Imaging for Structural Health Monitoring, June 30, 2020.
- 3. Ruwen Qin. Bridge Inspection Video Data Analysis for Achieving Data-driven Asset Management, July 31, 2020.

3.F - INSPIRE Research Outputs Performance Metrics

Research Outputs - Performance Measures		Cumulative Total
1.	At least 5 journal publications and books per investigator/year	4.25
2.	At least 15 keynote/invited presentations delivered at national	29
	and international conferences in 5 years	
3.	4 webinars/year	4/Year
4.	2 NDE/sensor prototype in 5 years	4
5.	1 robotic training simulator in 5 years	3

4. OUTCOMES

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

Dr. Genda Chen's team has advanced the process, techniques, and skills of building hybrid flying and traversing vehicles. The second prototype was tested successful in open field.

Dr. Hung La's team has optimized motion planning to determine the best path for a robot to transit efficiently between various parts of a steel structure.

Dr. Sushil Louis' team has developed new functionality in STACS software to perform a mock inspection task to train human operators, and students in future technologies, techniques, and skills required for automated bridge inspection with autonomous robots.

Dr. Iris Tien's team has developed a new method to update bridge fragility curves with new inspection data that is more computationally efficient than existing approaches. Bridge fragility curves provide assessments of bridge safety and risk under varying loads. They also built bridge models and evaluated their performance under non-uniform scour as a result of a combined earthquake and flood event.

Dr. Yang Wang's team has developed a new high-speed ADC board that mainly consists of the high-rate ADC chip, a memory buffer, and a parallel-to-serial converter. Evaluation circuits for each component of

the ADC board have been built on breadboards. The performance of individual components has been verified. They also have improved the communication between the new high-rate ADC chip and the memory buffer. The circuits laid on a breadboard now demonstrate reliable and acceptable performance with all connections.

Dr. Reza Zoughi's team has improved upon synthetic aperture radar (SAR) imaging techniques for NDE applications. These improvements have furthered understanding of the SAR imaging technique and its applicability to NDE of concrete structures.

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	0
	robots in 5 years (recommended policy change for inspection protocol)	

5. IMPACTS

5.A - The Effectiveness of the Transportation System

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

Dr. Genda Chen's work on smart rocks will enable real-time monitoring of bridge scour during a flood event since smart rocks can be deployed at riverbed in the proximity of bridge piers and survive harsh environments. His work on corrosion sensors allows the obtainment of ground true corrosion data for many NDE methods such as ground penetrating radars.

Dr. Anil Agrawal's work on automated impact sounding tools will improve the efficiency of current defect detection for concrete structures. A software module in MATLAB will facilitate the implementation of the approach for practical applications. The sounding devices are easy to be implemented in robotic systems, such as unmanned aerial vehicles (UAVs).

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.

Dr. Yang Wang's work on an innovative robotic sensing technology enables an autonomous collection of corrosion induced thickness of steel bridge members by the ultrasonic method.

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

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

Dr. Hung La's team is currently working on a SBIR proposal to request for funding to support this startup company – Automated Inspection Robots (AIR) Corp. Dr. Jizhong Xiao founded InnovBot LLC as a CUNY spin-off company, which can potentially develop a new product as a complete, self-contained robotic NDE tool with vertical mobility that carries an RGB-D camera, GPR sensor and impact sounding device to detect surface flaws and subsurface defects. InnovBot LLC is dedicated to the commercialization of wall-climbing robot technologies.

5.C - The Body of Scientific Knowledge

Dr. Genda Chen's team works towards the understanding of aerodynamics of a UAV in proximity of a bridge. In particular, the ceiling effect as the UAV approaches the bridge is examined in great detail using computational fluid mechanics. This understanding may shed light on a novel attachment mechanism of an UAV on the surface of a solid object.

Dr. Hung La's team introduced novel concepts of robotic sensing, localization and navigation in confined space or complex steel structure. The proposed rigorous magnetic force analysis can serve as a framework to calculate and design different types of steel inspection robots in the future.

Dr. Sushil Louis' team mapped a multi-robot bridge inspection to the well-known and computationally intractable MinMax K-Chinese postman problem. The solution to the problem will give back to the operations research community and other engineering disciplines impacting work in logistics, scheduling, and other routing problems in fields from VLSI design to mathematics.

Dr. Yang Wang's team developed new knowledge regarding the dual-mode antenna sensing technology and autonomous ultrasonic thickness measurement technology for bridge monitoring.

Dr. Jizhong Xiao's team developed image processing algorithms on the impact sounding technology developed in collaboration with Dr. Anil Agrawal for detection of delamination.

Dr. Reza Zoughi's team improved SAR imaging techniques by determining optimal measurement technique and system parameters. The new development was corroborated by performing numerical simulations.

5.D - Transportation Workforce Development

Dr. Genda Chen of Missouri University of Science and Technology launched a pooled-fund study with seven state departments of transportation. Field tests will be conducted to validate NDE and sensing technologies that are implemented in a mobile testing facility through drones. At the same time, field test results and process will be used as part of the technology training program for professionals.

Dr. Hung La of University of Nevada Reno continued to develop robot-assisted infrastructure inspection concepts and apply them into the current robotics courses: CPE470/670-Autonomous Mobile Robots; CS791-Special Topics on Robotics, and CS455/655-Mobile Sensor Networks. Both undergraduate and graduate students have fully participated all phases of the project. They have been trained through hands-on design, fabrication, prototyping and programming of the robots.

Dr. Sushil Louis of the University of Nevada Reno began to develop test cases in the STACS training software to teach human operators to use the software, and train them to oversee a team of robots during a bridge inspection task. The training task should be a good representation of a real-world bridge inspection, utilizing a team of heterogeneous robots for a cooperative inspection of bridges. This will help workforce development and skills training and refreshing.

Dr. Paul Oh's team continues to develop aerial manipulation and human-in-the-loop controls that would augment the performance of bridge workers with new tools.

Dr. Ruwen Qin of Missouri University of Science and Technology developed a workforce training tool involving machine learning algorithms which will become a mode of work for future transportation workforce.

Dr. Iris Tien's team is contributing transportation workforce development through continued graduate student advising for work for the Bridge Resilience Assessment with INSPIRE Data project. This project has provided opportunities for training in communication of research results in the form of preparing, editing, and revising manuscripts for publication, and training on oral communication in the form of oral presentations to research groups and conference audiences across the U.S.

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

Dr. Jizhong Xiao's project on climbing robots in the City College of New York, continues to inspire innovation and support the training of future workforce from traditionally underrepresented students at the College to meet the critical national need for sustainable infrastructure.

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	0
	inspection that requires the use of heavy lifting equipment.	
2.	At least 5 patents generated in 5 years and at least 1 associated	6
	technology applied in practice.	

6. CHANGES/PROBLEMS

6.A - Changes in Approach and Reasons for Change

COVID-19 Impact on Research Approach

All project investigators continued to maximize their student time in conducting computational modeling and simulation even though most laboratories were opened up in summer 2020. All partner institutions implemented social distance and mask requirements while working in laboratory. As a result, experimental work has been slowly picking up since June, 2002. Most, if not all, project meetings are virtual through Zoom or other platforms. Face-to-face meetings remain limited. As an example, the University of Nevada Reno campus partially opened in summer 2020. Due to the recent uptick in cases, most students have gone back to work from home, and occasionally visited to campus laboratories, facilities, and equipment.

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

COVID-19 Impact on Research Progress Delay

In general, computational modeling and simulation work continues with little impact. But most of experimental works are delayed. The strategy taken by all investigators is to maximize the use of student and faculty time in executing as many research tasks as practically feasible.

Dr. Chen's team worked in laboratories with reduced capacity. Students had to take turn to be in the laboratories to carry out research. More importantly, students had to be working individually in most of time due to social distancing requirements. Lacking group dynamic support slowed down the research progress in general.

Dr. Hung La of the University of Nevada Reno limited all work related to hardware integration, robot part manufacturing, robot test and validation.

Dr. Sushil Louis of the University of Nevada Reno slowed down hardware integration or the investigation of workforce training software in laboratory.

Dr. Yang Wang's campus shut down all non-essential research labs from March to July, causing the hardware development for the project to be delayed.

Dr. Jizhong Xiao's team had limited access to the Grove School of Engineering building at the City College of New York. They managed to print small parts in their lab and resourced third party vendors for the fabrication of large mechanical parts.

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

COVID-19 Impact on Research Expenditure

Research assistants and faculty are paid based on their continued appointments. In general, work efficiency of the research projects is at approximately 50%. For all INSPIRE projects, the completion of the scopes during the COVID-19 period remains uncertain. The mitigation approach that all investigators take is to extend computational work and simulations as time permits, while completing as many experimental tasks as possible within physical constraints during this period.

On the other hand, all investigators have delayed expenditures on buying hardware and software. More importantly, the costs budgeted for organizing special sessions on behalf of the INSPIRE UTC and attending conferences (e.g., the 2020 ASCE Structures Congress, St. Louis) were not spent due to its cancellation associated with COVID-19. Even so, all investigators still made efforts to limit expenditures within 10% allowable variation in every major category.

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.