30 Sep 2021

Semi-Annual Progress Report #9

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

UTC Semi-Annual Progress Report #9

GRANT NO: 69A3551747126
GRANT PERIOD: 11/30/16 – 09/30/23
REPORTING PERIOD: 04/1/2021 – 09/30/2021

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
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EIN Number:	436003859
Recipient Identifying Number:	00055082
Report Term or Frequency:	Semi-annual
Submission Date:	October 30, 2021

Signature of Submitting Official: 10/29/2021

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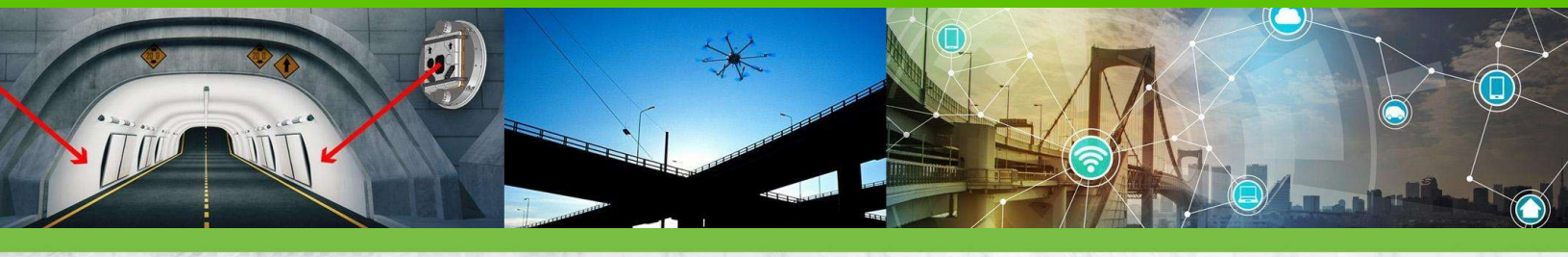
Inspecting and Preserving Infrastructure through Robotic Exploration (INSPIRE)

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



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1. ACCOMPLISHMENTS

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

Center's Mission and Goals

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

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

Research Objectives

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

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

Education Objectives

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

1. To develop new education materials related to advanced sensing and robotic technologies, such as real-world examples and cases that can reinforce the learning objectives of current curriculums, and interdisciplinary topics for senior design/capstone projects that can promote cooperative learning among students from various disciplines;
2. To create new opportunities for knowledge expansion and skill training on non-traditional civil engineering subjects, such as sensing, NDE, and bridge inspection and maintenance with robotics, which can enrich existing civil engineering programs or non-degree certificate programs; and
3. To connect students with transportation industries and professionals through center meetings, annual transportation research board (TRB) meetings, an international conference, and the external advisory committee.

Workforce Development Objectives

Two workforce development objectives are set and achieved through various outreach activities and close collaborations with professional organizations such as the Missouri Local Technical Assistance

Program (LTAP) and the Center for Worker Education (CWE), New York:

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

Technology Transfer Objectives

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

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

Diversity Objectives

Two diversity objectives are set:

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

1.B - What Was Accomplished under These Goals?

To support the technology transfer goal, an accompanying seven-state pooled-fund study No. TPF-5(395): Traffic Disruption-free Bridge Inspection Initiative with Robotic Systems was initiated on August 1, 2019. During the last reporting period, the pooled-fund study progressed in two tasks for bridge selection and sensor calibration. Specifically, selection of steel-girder bridges in the state of New York, Virginia and Wisconsin, and prestressed concrete girder bridges in Georgia, Texas, and California was being finalized for field tests starting this summer. In Missouri, both groups of girder bridges would be tested. Sensor calibration started with infrared cameras on a reinforced concrete slab with embedded artificial defects or simulated delamination. Both heating and water cooling were applied during the test to understand how rapidly and accurately the cameras can respond.

Bi-monthly meetings were held with Principal Investigators (PIs) to provide open lines of communication within the Center, and to share important news and announcements with the research team. PIs provide research progress updates and submit written quarterly reports to the Center.

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

Table 1. A summary of research progress

Topic	Major Activities	Specific Objectives	Significant Results	Key Outcomes
SN	1. Complete. 2. Complete. 3. Complete. 4. Complete. 5. Prepare and review a final report. 6. Complete a student exchange between Gorgia Tech and UNR to integrate the ultrasonic transducer with a climbing robot. 7. Prepare laboratory specimens to test and evaluate NDT methods. 8. Prepare and test a significant number of Fe-C coated long period fiber gratings sensors.	1. Complete. 2. Complete. 3. Complete. 4. Complete. 5. Develop and publish a high-quality report on research findings and results. 6. Develop an ultrasonic system for automated measurement of thickness in steel plates. 7. Identify five effective NDT and hyperspectral imaging methods for freeze-thaw (F-T) damage assessment. 8. Develop a probability of detection (POD) for steel corrosion monitoring.	1. Complete. 2. Complete. 3. Complete. 4. Complete. 5. A linear increase of characteristic reflectance with Cl- content up to 0.8 wt.%. 6. A verifiable accuracy during ultrasonic thickness measurement at a grid of 19 locations on a rusty steel specimen. 7. Effective indicators of F-T induced degradation by ultrasonic pulse velocity and electrical resistivity. 8. Consistent sensing trend but with a significant variation.	1. Complete. 2. Complete. 3. Complete. 4. Complete. 5. Hyperspectral imaging for steel rebar corrosion and chloride ion Cl- concentration. 6. A success of couplant application, transducer mounting, thickness measurement and data transmission. 7. Effect of degree of saturation on material properties characterized. 8. Preliminary PODs determined from two methods and compared.
AS	1. N/A. 2. Prepare and review a final report. 3. N/A. 4. Test manual flight control of the 2nd BIRDS prototype to satisfaction. 5. Test two climbing robots on a highway bridge for real-time defect detection based on deep learning. 6. Integrate a MEMS microphone into the sliding rail of an Impact-Rover for sounding data collection and analysis. 7. Demonstrate horizontal aerial manipulation using an Avatar-Drone.	1. N/A. 2. Develop and publish a high-quality report on research findings and results. 3. N/A. 4. Develop a hybrid flying and traversing unmanned vehicle for bridge inspection. 5. Validate the robot mobility and learning algorithm in practical application. 6. Develop an impact sounding system and analysis algorithm for detection of defects in concrete bridges. 7. Develop a drone that can take actions both vertically and horizontally in a laboratory condition.	1. N/A. 2. Successful demonstration of robot prototypes in laboratory and field. 3. N/A. 4. A glitch of Realsense camera causing a sudden loss of communication link during flight test. 5. Reliable collection of optical images and GPR data from the bridge deck. 6. K-means method effective in detecting and visualizing voids on a contour 2D map. 7. Horizontal aerial manipulation as effective as vertical manipulation when benefiting from gravitational force.	1. Complete. 2. Climbing robots tested on steel members and bridges. 3. Complete. 4. Further ROS improvement needed for girder detection and flight control. 5. A multi-directional bicycle robot tested for steel inspection. 6. An Impact-Rover system with K-means machine learning for defect detection. 7. Avatar-Drone integration for aerial drilling and debris cleaning via a hose.

	8. Test the mobility of a four-vacuum-cup TreeFrog robot to enable its climbing on column surface for scour monitoring.	8. Develop a real-time scour monitoring technique with a robot-mounted soner and altimeter.	8. Initial success on suction mechanism tested to ensure sufficient force.	8. A prototype of a climbing robot based on vacuum cup suction mechanism.
IM	1. N/A 2. Complete. 3. Integrate various components into a smart sounding data collection and recording system for defect detection in hollow structures.	1. N/A 2. Complete. 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.	1. N/A 2. Complete. 3. Microphone shielded from the sounding tool for high quality data collection and good defect classification.	1. Withdrawn. 2. Complete. 3. Near completion of a sound device prototype with integrated individual components.
RR	1. Create methods to utilize bridge inspection data to analyze and update assessment of bridge performance. 2. Collect and label data and images for corrosion condition classification from deep learning.	1. Evaluate the effect of inspection parameters on the predicted performance and resilience of bridges. 2. Support bridge management decision from imagery data based on learning the state of corrosion degradation.	1. Computational and experimental verification on the effect of scour in various soil types. 2. Successful collection of images using a high-definition camera on a DJI Air Mavic 2 drone.	1. A set of fragility curves and risk updates based on scour data at foundation. 2. Labelbox used to label data for both corrosion detection and quantification.
WD	1. Complete. 2. Develop a simulated bridge generation engine to diversify training scenarios. 3. Design training exercises to teach human operators to work with the simulated robotic team to accomplish a bridge inspection task. 4. Select a web software platform to implement the developed deep learning tool for image segmentation and object detection.	1. Complete. 2. Develop a Simulation Training And Control System (STACS 2) with robot routing plans. 3. Develop a training and control interface for human operators to oversee a team of autonomous bridge inspection robots. 4. Prototype an interactive web system that guides and assists users in robot-based inspection video analytics.	1. Complete. 2. Automated generation of truss bridges. 3. Development of an Euler-cycles based representation of MinMax k-Chinese postman problem. 4. Django language in Python for the development of web interactive system.	1. Complete. 2. The first version of the STACS environment. 3. A bridge builder to automatically generate training scenarios. 4. Functions and features of the developed deep learning tool reviewed.

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

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

In this reporting period, the INSPIRE UTC directly involved 10 faculty, 2 post doc, 12 graduate students, and 9 undergraduate students in civil engineering, electrical engineering, mechanical engineering, computer science, and engineering management and system engineering through its research and administrative programs with 16 on-going projects. The INSPIRE team includes 4 female participants.

The INSPIRE UTC continued to offer courses that are relevant to the research activities among consortium partners. For example, Dr. Hongyan Ma taught undergraduate course Mechanics of Materials, which attracted 65 and 64 students in Spring and Fall semesters, respectively. Dr. Ma also offered graduate course Characterization and Modeling of Cement-based Materials, attracting 6 students. Dr. Chen offered the graduate course Structural Dynamics and Earthquake Engineering in

Winter 2021 at Missouri S&T, which attracted 9 graduate students. Dr. Chen offered another graduate course Structural Health Monitoring in Fall 2021 at Missouri S&T, which attracted 4 graduate students.

1.D - How Have the Results Been Disseminated?

The research results from various projects were disseminated through multiple venues, including Invited Presentations, Journal and Conference papers, Biannual Newsletters, Quarterly Webinars, open-source public project repository and Education and Outreach Activities.

Invited Presentations at Universities and Professional Meetings without Publications

1. Genda Chen. "Robot-assisted Bridge Inspection and Maintenance – a Futuristic Perspective," Annual Infrastructure Advancement Institute Meeting, September 27-29, 2021.
2. Genda Chen. "Extended Opportunities through Cross-disciplinary Training: Robot-assisted Bridge Preservation," Chi Epsilon meeting at Missouri University of Science and Technology, September 7, 2021.
3. Genda Chen. "Robot-assisted Bridge Inspection and Maintenance," Southeast University, Nanjing, China, July 26, 2021.

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 13,000 people through the Center's listserv, and are made available online at https://inspire-utc.mst.edu/news/. An INSPIRE UTC Newsletter (Vol. 5, No. 1) was published in Spring 2021 and included three technical articles related to INSPIRE research:

- *The Importance of Accounting for Soil Effects in Risk Assessments of Bridges Subject to Scour, Dr. Iris Tien, Georgia Institute of Technology*
- *Assistive Intelligence: A Collaboration between Human and Artificial Intelligence for Segmenting Bridge Elements from Inspection Video Data, Dr. Ruwen Qin, Missouri University of Science and Technology (moved to Stony Brook University since September 1, 2020)*
- *Synchro-Squeezed Adaptive Wavelet Analysis for Effective Extraction of Features from Nonstationary Data Series, Dr. Genda Chen, Missouri University of Science and Technology*

Quarterly Webinars

The INSPIRE UTC hosts quarterly webinars. Overall, 17 INSPIRE webinars have engaged more than 1,135 people from 48 US States and 51 different countries, including Australia, Brazil, Canada, China, Germany, India, Italy, Mexico, Portugal, Serbia, Sweden, Switzerland, United Kingdom, and the US. On average, 53% of the participants are from academia, 20% are from industry, 18% are from Government, and 9% are unknown. Note that the updated statistics during this report period is unavailable due to unexpected changes in Zoom meeting setup to enhance security.

Two webinars were presented in this reporting period, and engaged more than 385 participants:

1. Fiber Optic Sensor Based Corrosion Assessment in Reinforced Concrete Bridge Elements and Metal Pipelines was presented on June 16, 2021 by Dr. Genda Chen from Missouri University of Science and Technology, Rolla, MO.
2. Image-Based Bridge Defect Detection and Monitoring Technologies was presented on September 14, 2021 by Dr. Jian Zhang from Southeast University, China.

Education and Outreach Activities

Dr. Genda Chen's team at Missouri S&T demonstrated robotics and remote sensing technologies to 27 K-12 students, including many girls, during the Jackling Introduction to Engineering Summer Camp on June 22 and July 12, 2021. An INSPIRE UTC team led by Dr. Liujun Li, Research Associate Professor at the Center for Intelligent Infrastructure, flew a drone that carries both RBG and infrared cameras around a 3-story Emerson building with a green roof of plants arranged in pattern of a flower. This flight demonstration showed several optical and thermal imaging applications in civil, architectural, and environmental engineering programs, including building envelope inspection, green roof energy efficiency, and plant heat stress assessment. The participants observed the difference in temperature among the green roof, white roof, and black roof and intuitively learned the heat stress condition of different objects, such as plants, air condition fans, cooling pipelines, and building structures.

Dr. Paul Oh's team at the University of Nevada-Las Vegas (UNLV) continues to work with the neighboring Clark County Las Vegas Public Library in the Saturday K-12 Programs. Lesson plans include computer-aid-design (CAD), 3D printing, and embedded controllers (Arduino). Due to COVID-19, these programs are being held online. Additionally, the team continues to serve institutional outreach programs, namely Upward Bound. This program is UNLV's outreach to middle schoolers. Each Saturday (09:00-15:00), the team conducts hands-on STEM labs. These labs include drone (programming), augmented reality (projection mapping), and embedded control (Arduino). Due to COVID-19, these programs are also being held online.

Dr. Genda Chen introduced extended opportunities through cross-disciplinary training: robot-assisted bridge preservation to about 20 Chi Epsilon students who are members of the national civil engineering honor society at Missouri S&T. Dr. Chen shared his outlook on the impact of Industry 4.0 technologies (e.g., the Internet of Things, artificial intelligence, and robotics) on civil engineering job opportunities and illustrated the shortage of workforce in construction sector that masters the modern technologies. Students who are well trained in interdisciplinary engineering will position themselves for more and better-paid employment opportunities.

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 on-going research projects awarded by the INSPIRE UTC.

Table 2. A summary of planned research activities

Topic	Project Title	Planned Activities
SN	Autonomous Ultrasonic Thickness Measurement by a Magnet-Wheeled Robot	• Test wireless Martlet thickness measurements with a Linux server for better software integration with commanding of the mobile robot. • Identify and acquire an alternative couplant to gel couplant for improved adhesive. • Add a tri-axial accelerometer to the ultrasonic Martlet device for improved measurement accuracy.
	Health Inspection of Concrete Pavement and Bridge Members Exposed to Freeze-Thaw Service Environments	• Extend and characterize the degree of saturation from 50% to 90% using hyperspectral imaging. • Correlate the reflectance from hyperspectral imaging to electrical conductivity to understand the effect of freeze-thaw cycling on strength degradation. • Extend nondestructive tests to early ages and severely degraded concrete to broaden the database.

	Probability of Detection in Corrosion Monitoring with Fe-C Coated LPFG Sensors	• Analyze the test data collected from Fe-C coated long period fiber gratings (LPFG) sensors using the length-at-detection and random effect generalization methods. • Compare the probability of detection for Fe-C coated LPFG sensors using the two methods.
AS	Bridge Inspection Robot Deployment Systems (BIRDS)	• Test manual traversing capability of the hybrid vehicle. • Continue to develop an autonomous transition scheme from flying to traversing mode of operation. • Document technical specifications and development of the vehicle for flying, traversing, and their transition performance.
	Nondestructive Data Driven Motion Planning for Inspection Robots	• Develop and validate deep learning-based visual defect detection algorithms for real-time implementation on the climbing robot. • Continue to build a complete navigation framework that utilizes the previously developed boundary detection algorithm, deep learning method, and hidden Markov model to classify different steel structure shapes. • Continue to investigate the deployment of the robot in actual steel bridges to achieve its autonomy and classification of various structural shapes.
	A Field Deployable Wall-Climbing Robot for Bridge Inspection using Vision and Impact Sounding Techniques	• Assemble and integrate impact sounding and echo devices into the impact-rover robot. • Develop a mover-stop-sample operation procedure for the impact-rover robot, lowering the impact echo device to be in direct contact with the surface, triggering the solenoid impactor, and collecting echo and acoustic sounding data. • Continue to integrate vision-based positioning into the automatic collection of data to make the robotic sampling much faster than manual data collection.
	Augmenting Bridge Inspection with Augmented Reality and Haptics-based Aerial Manipulation	• Use pressure washers rated at 4000 psi to mimic application in bridge maintenance. • Strengthen the damaged systems integrated sensor test rig with higher torque motors. • Resume hosing testing and evaluation and analyze hose splines from the motion capture system.
	Robot-assisted Underwater Acoustic Imaging for Bridge Scour Evaluation	• Conduct an initial test of the four vacuum cups supported TreeFrog robot on a masonry wall. • Finalize and order the side-scan sonar and the altimeter for integration with the TreeFrog climbing robot. • Implement multi-threading in ROS for thread communication, debugging tools, and visualization tools, each thread implemented in Python/C.
IM	"Smart Sounding System" for Autonomous Evaluation of Concrete and Metallic Structures	• Establish RTK GPS wireless communication between a base station and the impact-rover to achieve accurate location. • Configure and control a Realsense tracking camera with Raspberry Pi to achieve portability and easy integration with the sounding device. • Collect microphone array data and apply signal processing (beamforming) to achieve the unidirectional response by avoiding surrounding noise.
RR	Data-Driven Risk-Informed Bridge Asset Management and Prioritization across Transportation Networks	• Label images for corrosion classification. • Train learning algorithms with the collected and labeled datasets to detect and characterize corrosion. • Perform image segmentation using Matterport Mask-RCNN and evaluate the accuracy of the learning algorithms.
WD	Simulation Training to Work with Bridge Inspection Robots	• Continue to integrate generated trusses into five training scenarios with n flying and k climbing inspection robots and evaluate their utility for workforce training. • Continue to develop a c# version of genetic algorithm router for better integration into scenario generation and execution. • Continue to create a template ROS bridge to a robot to make the developed technique generalizable to other robots for monitoring and control in STACS.

	An Interactive System for Training and Assisting Bridge Inspectors in Inspection Video Data Analytics	• Create web-based learning modules for trainees to master cross-disciplinary knowledge and fundamental skills of analytics. • Develop an inspection data analytics tool to assist inspectors in processing and analyzing inspection video data for the condition assessment of bridges.

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

Other Planned Initiatives

1. Invention Jamboree for Boy Scouts of America, Organized by Great Rivers Council, October 1-3, 2021.
2. Two Technical Sessions at the 13th International Workshop on Structural Health Monitoring (IWSHM 2021) organized by INSPIRE UTC researchers Drs. Genda Chen and Yang Wang from Missouri University of Science and Technology and Georgia Tech, respectively, December 7-9, 2021.
3. INSPIRE UTC Webinar on *Hyperspectral Imaging and Data Analytics for Civil Infrastructure Inspection* to be presented by Dr. Genda Chen, Missouri University of Science and Technology, December 14, 2021.

2. PARTICIPANTS & COLLABORATING ORGANIZATIONS

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

Consortium Collaborators

The consortium members of this University Transportation Center are:

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

External Collaborators

- Air Corp, Reno, NV https://www.buzzfile.com/business/Air-Corp-732-668-8112
- 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 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 – a Spinoff Company out of the CCNY Robotics Lab, 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, Department of Civil and Environmental Engineering, Houston, TX https://ceee.rice.edu
- Stony Brook University, Stony Brook, NY https://www.stonybrook.edu/
- Tesla Gigafactory, Reno, NV https://www.tesla.com/gigafactory
- Texas Department of Transportation, Austin, TX https://www.txdot.gov
- TranSystems Corporation, Kansas City, MO www.transystems.com
- 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/
- Educational Technology http://edtech.mst.edu/
- Research Support Services/MinerFly Team https://itrss.mst.edu/minerfly/
- Student Diversity Initiatives http://sdi.mst.edu/
- System and Process Assessment Research (SPAR) Laboratory https://spar.mst.edu

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

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

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

Dr. Hongyan Ma's team gave a seminar at the Missouri Department of Transportation to discuss potential collaboration.

Dr. Paul Oh's team hosted a visit of Dr. Bo Shang from Missouri University of Science and Technology to spend time replicating and verifying-and-validating MM-UAV (i.e. a prove-on study) The University of Nevada, Las Vegas officially began a Phase 2 task order contract with Tesla's Reno-based Gigafactory in March 2020 with researchers using robots for building inspection. This task order is independent of this INSPIRE UTC project. However, there are some synergetic technical activities e.g. Augmented Reality and robots used to monitor sites and manipulate objects. Hence, this UNLV-Tesla collaboration will likely give INSPIRE UTC an added visibility.

Dr. Iris Tien's team has collaborated with the department of Civil and Environmental Engineering at Rice University.

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

Dr. Jizhong Xiao's team of the City College of New York accessed Geophysical Survey System Inc. (GSSI)'s test pit to collect ground penetrating radar (GPR)/impact sounding data and InnovBot LLC to construct concrete slabs with buried pipes and boxes to simulate defects (voids, delamination, honeycomb) at different sizes and depths. InnovBot LLC has received a NSF grant "SBIR Phase I: Robotic Inspection and Data Analytics to Localize and Visualize the Structural Defects of Civil Infrastructure" and subcontracted some research and development work to the City College of New York Robotics Lab.

3. OUTPUTS

3.A - Publications, Conference Papers, and Presentations

Journal Publications

1. **A.K. Agrawal**, G. Washer, S. Alampalli, X. Gong, and R. Cao. "Evaluation of the Consistency of Bridge Inspection Quality in New York State," Journal of Civil Structural Health Monitoring 11(5): 1393-1413, Published online: August 25, 2021.
2. **A.K. Agrawal**, G. Washer, S. Alampalli, X. Gong, and R. Cao. "Evaluation of the Consistency of Bridge Inspection Ratings in New York State," Journal of Infrastructure Systems 27(3): 04021016, Published online: May 11, 2021.
3. R. Cao, **A.K. Agrawal**, S. El-Tawil, and W. Wong. "Performance-based Design Framework for Concrete Barriers Subjected to Truck Collision," Journal of Bridge Engineering 26(8), August 2021.
4. R. Cao, **A.K. Agrawal**, S. El-Tawil, and W. Wong. "Overheight Impact on Bridges: A Computational Case Study of the Skagit River Bridge Collapse," Engineering Structures 237: 112215, June 15, 2021.
5. X. Chen, H. Wang, AHC Chan, **A.K. Agrawal**, and Y. Cheng. "Collapse Simulation of Masonry Arches Induced by Spreading Supports with the Combined Finite–discrete Element Method," Computational Particle Mechanics 8: 721–735, July, 2021.
6. Jacob Hale and **Suzanna Long**. "A Time Series Sustainability Assessment of a Partial Energy Portfolio Transition," *Energies 2021*, 14, 141; https://doi.org/10.3390/en14010141. Invited Special Issue on Integrated Approaches for Enterprise Sustainability. Special Issue Editor: Dr. Patrycja Habek.
7. E. Hoomaan, **A.K. Agrawal**, N. Davis, and F. Jalinoos. "Risk of Reuse in Highway Bridge Foundations," Journal of Infrastructure Systems 27(4): 04021043, September 23, 2021.
8. Pu Jiao, Yang Song, Jennifer Leopold, and **Genda Chen**. "Graph-Based Analysis of COVID-19 Transmission Using State- and County-Based Location Exposure Index." Biostatistics and Biometrics 10(3): 555789, June 2021. DOI: 10.19080/BBOAJ.2021.10.5557789.
9. Muhammad Monjurul Karim, Ruwen Qin, **Genda Chen**, and Zhaozheng Yin. "A Semi-supervised Self-training Method to Develop Assistive Intelligence for Segmenting Multiclass Bridge Elements from Inspection Videos." *Structural Health Monitoring*, 1-18, May 2021, https://doi.org/10.1177/14759217211010422.
10. M. Khanjani, D. Westenberg, A. Kumar, and **H. Ma**. "Tuning Polymorphs and Morphology of Microbially Induced Calcium Carbonate: Controlling Factors and Underlying Mechanisms," ACS Omega 6(18): 11988-12003. doi: 10.1021/acsomega.1c00559, April 2021.
11. S. Mondal, A. Welz, A. Rownaghi, B. Wang, **H. Ma**, F. Rezaei, A. Kumar, and M. Okoronkwo. "Investigating the Microstructure of High-calcium Fly Ash-based Alkali-activated Material for

Aqueous Zn Sorption," Environmental Research 198: 110484. doi: 10.1016/j.envres.2020.110484, July 2021.

12. Son Nguyen and **Hung M. La**. "A Climbing Robot for Steel Bridge Inspection," *Journal of Intelligent and Robotic Systems* 102(75), July 2021.
13. J. Qin, J. Qian, X. Dai, C. You, **H. Ma**, and Z. Li. "Effect of Water Content on Microstructure and Properties of Magnesium Potassium Phosphate Cement Pastes with Different Magnesia-to-phosphate Ratios," Journal of the American Ceramic Society 104(6): 2799-2819. doi: 10.1111/jace.17695, June 2021.
14. X. Sun, W. Liao, A. Kumar, K. Khayat, Z. Tian, and **H. Ma**. "Multi-level Modeling of Thermal Behavior of Phase Change Material Incorporated Lightweight Aggregate and Concrete," Cement and Concrete Composites 122: 104131. doi: 10.1016/j.cemconcomp.2021.104131, September 2021.
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19. Yanping Zhu, Yang Zhang, Xingliang Li, and **Genda Chen**. "Finite Element Model to Predict Structural Response of Predamaged RC Beams Reinforced by Toughness-improved UHPC under Unloading Status." *Engineering Structures* 235: 112019, May 15, 2021.
20. Yanping Zhu, Matthew Klegseth, Yi Bao, Matthew S. Hoehler, Lisa Choe, and **Genda Chen**. "Distributed Fiber Optic Measurements of Strain and Temperature in Long-span Composite Floor Beams with Simple Shear Connections Subjected to Compartment Fires," *Fire Safety* Journal 121: 103275, May 2021.

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

1. Rahul Dubey and **Sushil Louis**. "Evolving Potential Field Parameters for Deploying UAV-based Two-hop Wireless Mesh Networks," *Proceedings of the Genetic and Evolutionary Computation Conference (GECCO-21)*, pg. 311-312, ACM, July 10-14, 2021
2. Jinglun Feng, Liang Yang, Ejup Hoxha, Diar Sanakov, Stanislav Sotnikov and **Jizhong Xiao**. "GPR-based Model Reconstruction System for Underground Utilities Using GPRNet." In 2021 *IEEE International Conference on Robotics and Automation (ICRA)*, May 30-June 5, 2021.
3. Jinglun Feng, Hua Xiao, Ejup Hoxha, Haiyan Wang, Yifeng Song, Liang Yang, and **Jizhong Xiao**. "Automatic Impact-sounding Acoustic Inspection of Concrete Structure", *10th International Conference on Structural Health Monitoring of Intelligent Infrastructure Advanced Research and Real-world Applications (SHMII-10)*, Porto, Portugal, June 30 – July 2, 2021, Porto, Portugal.
4. Jacob Hale and **Suzanna Long**. "Transitioning Power Generation to Renewable Portfolios," Proceedings of the IISE Annual Conference and Expo 2021, June 2021. (Invited Session)

5. Jacob Hale, **Suzanna Long**, Steven Corns, and Cihan 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)
6. Jason C. Hollan and **Suzanna Long**. "Disaster Planning in the Age of Pandemics," Proceedings of the IISE Annual Conference and Expo 2021, June 2021.
7. Dongbin Kim and **Paul Y. Oh**. "Toward Avatar-Drone: A Human-Embodied Drone for Aerial Manipulation," International Conference on Unmanned Aerial Systems (ICUAS), Athens, Greece June 15-18, 2021.
8. Yu Otsuki, Peter Lander, and **Yang Wang**. "Ultrasonic Thickness Measurement using the Martlet Wireless Sensing System," Proceedings of the IEEE 2021 International Instrumentation & Measurement Technology Conference, Glasgow, Scotland, May 17-20, 2021.
9. Y. Otsuki, D. Li, X. Dong, and **Y. Wang**. "SMU - an open-source MATLAB package for structural model updating." Proceedings of the 10th International Conference on Bridge Maintenance, Safety and Management (IABMAS), Sapporo, Japan, April 11-18, 2021.
10. Kripash Shrestha, Rahul Dubey, Ashutosh Singandhupe, **Sushil Louis** and **Hung La**. "Multi Objective UAV Network Deployment for Dynamic Fire Coverage," Proceeding of IEEE Congress on Evolutionary Computation, June 28- July 1, 2021.
11. Y. Zhang and **Iris Tien**. "Fragility Curve Updating Using Inspection Data and Dynamic Analysis with Application to Corroded Bridges," 2021 *ASCE Engineering Mechanics Institute Conference (EMI)*, New York, NY, May 25-28, 2021.
12. Y. Zhang and **Iris Tien**. "Robust Risk Assessment of Reinforced Concrete Columns with Short Lap Splices through Regularization," *Probabilistic Mechanics and Reliability Conference (PMC)*, New York, NY, May 25-28, 2021.

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

- Advanced Robotics and Automation Laboratory: https://ara.cse.unr.edu
- Center for Intelligent Infrastructure: https://cii.mst.edu
- INSPIRE University Transportation Center: https://inspire-utc.mst.edu
- Research in Progress Database: https://rip.trb.org/
- Evolutionary Computing Systems Laboratory: https://ecsl.cse.unr.edu/projects/bridge_inspection/index.html
- Open Source STACS Software: https://github.com/sushillouis/Stacs (main and Pronto2 branches)

3.C - New Technologies or Techniques

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

- Dr. Anil Agrawal's team developed a single MEMS microphone with acoustic shield and foam.
- Dr. Genda Chen's team developed a climbing robot mimicking the movement of a tree frog for scour monitoring with a sonar and an altimeter.
- Dr. Genda Chen's team developed a comprehensive sensor calibration framework and procedure for visible, thermal, and hyperspectral imagers as well as LiDAR scanners.
- Dr. Hung La's team introduced a novel concept of robotic sensing, localization and navigation in a confined space or complex steel structure.
- Dr. Paul Oh's team developed a drone-mounted arm to inspect, maintain and repair bridges for tasks like deck-hosing and hole-drilling.

- Dr. Iris Tien's team developed a simplified analysis to update bridge risk assessment under corrosion conditions and better understood the expected performance of bridge piles under scour conditions.
- Dr. Yang Wang's team integrated an ultrasonic device into a climbing robot for measuring the thickness of steel surfaces and developed a new sensor board for acceleration measurement along with the ultrasonic thickness measurement on the same Martlet device.
- Dr. Jizhong Xiao's team provided a robotic (Impact-Rover) solution to generate and analyze the impact sounding data for nondestructive evaluation of underground defects.

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

- "Robotic Device for Providing Vertical Mobility", U.S. Patent No. 11029692, issued on June 08, 2021. Inventors: Jizhong Xiao, Kenshin Ushiroda, Guoyong Yang, SaiadiVishnu Saniegepalli, and Yifeng Song.

3.E – Other Products, such as Data or Databases, Physical Collections, Audio or Video Products, Application Software or NetWare, Analytical Models, Educational Aids, Courses or Curricula, Instruments, Equipment, or Research Materials

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

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

3.F - INSPIRE Research Outputs Performance Metrics

Research Outputs - Performance Measures	Cumulative Total
1. At least 5 journal publications and books per investigator/year	6.4
2. At least 15 keynote/invited presentations delivered at national and international conferences in 5 years	29
3. 4 webinars/year	5.8/Year
4. 2 NDE/sensor prototype in 5 years	2
5. 1 robotic training simulator in 5 years	1

4. OUTCOMES

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

Dr. Anil Agrawal's team improved the isolation of microphone from receiving direct sound from the speaker.

Dr. Genda Chen's team improved the girder detection algorithm during flight tests of the BIRDS.

Dr. Hung La's team improved deep learning-based visual defect detection algorithms for deployment on a climbing robot for real-time inspection of a structural surface.

Dr. Hongyan Ma's team characterized the degree of saturation of cement pastes and concrete with a hyperspectral camera.

Dr. Sushil Louis' team improved the previous genetic algorithm with parallelized implementation to run on graphics cards and caching, and then improved the first version of the Simulation Training And Control System software, named STACS 2 that can now generate truss bridges automatically.

Dr. Paul Oh's team improved the design, test, and evaluation of an Avatar-Drone for its verification and validation.

Dr. Jizhong Xiao's team improved the K-Means method for the feature clustering of sounding data. The first spectral moment (centroid) and the second spectral moment (standard deviation) are among the most significant features that help interpolate sounding data.

4.B – INSPIRE Research Outcomes Performance Metrics

Research Outcomes – Performance Measures	Cumulative Total
1. 1 recommended Federal policy change on bridge inspection frequency	0
2. At least 1 manual of practice related to inspection/preservation with mobile robots in 5 years (recommended policy change for inspection protocol)	1

5. IMPACTS

5.A - The Effectiveness of the Transportation System

Dr. Anil Agrawal's team and their work will improve the efficiency of current defect detection for concrete structures by developing automated impact sounding tools. A software module in MATLAB will facilitate the implementation of the approach for practical applications. The program will also seek to replace the traditional mechanical-impact devices, such as the hammer, with much more controllable electronic-sounding devices.

Dr. Genda Chen's team and their work on a hybrid flying and traversing vehicle 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. More importantly, the hybrid vehicle will provide a stationary platform for high-quality data collection towards a more reliable assessment of the condition of bridge elements.

Dr. Hung La's team and their work on the sensing, localization, and navigation of a climbing robot will enable automated bridge inspection and evaluation in a crowd space. 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 deterioration in steel bridges.

Dr. Sushil Louis' team and their work on the STACS 2 software in game environment with automatic generations of training scenarios of bridges and robot routings will enable future inspectors (human operators) to work with the simulated robotic team to accomplish a bridge inspection task.

Dr. Hongyan Ma's team and their work on hyperspectral imaging and other nondestructive evaluation will develop a deeper understanding of the mechanism of freeze-thaw cycling induced damages to concrete and an effective method for the damage evaluation.

Dr. Paul Oh's team and their work on the design, development, and deployment of aerial manipulators in an augmented reality will enable future engineers to conduct local maintenance work of bridges standing on ground.

Dr. Iris Tien's team and their work on an accurate corrosion assessment of bridges based on drone-collected imagery data will improve the assessment of bridge performance and risk.

Dr. Yang Wang's team and their work on an innovative robotic sensing technology that can autonomously perform ultrasonic thickness measurement on steel bridge members will have potential to be adopted in deterioration evaluation of aging bridges.

Dr. Jizhong Xiao's team and their work on robotic hardware and nondestructive evaluation as well as data analysis will improve vertical mobility of robots to reach difficult-to-access areas. For example, vision-based positioning and localization will enable 3D ground penetrating radar (GPR) imaging, impact sounding, and impact echo analysis over a target area.

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

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

Dr. Jizhong Xiao's team developed 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. This new product will expand the capabilities of the start-up company InnovBot LLC, a CUNY spin-off company founded by Prof. Xiao that dedicated to the commercialization of the wall-climbing robot technologies.

5.C - The Body of Scientific Knowledge

Dr. Genda Chen's team works towards an in-depth understanding of remote sensing with dual-sensor FLIR Duo Pro R640 Infrared camera and Nano-Hyperspec camera as well as different LiDAR scanners. The understanding of imaging mechanisms from various devices helps acquire high-quality inspection data when installed on a UAV.

Dr. Hung La's team works towards a novel integration of sensing, localization, and navigation technologies into a robotic system that can greatly reduce inspection time, improve inspector safety, and quantify/increase the accuracy in condition assessment of bridge elements.

Dr. Paul Oh's team further understands the mechanism, characteristics, and behavior of Avatar-Drone, an integrated outcome of multiple disciplines like robotics, haptics, augmented reality, and construction automation.

Dr. Hongyan Ma's team helps understand the effectiveness of nondestructive testing and hyperspectral imaging for the evaluation of freeze-thaw degradation which could make pavement and bridges more durable and safer by warning before non-repairable damage takes place.

Dr. Iris Tien's team begins to explore machine learning for image detection and segmentation. Once successful, the learning algorithms will make inferences on the structural states and associated risks of varying bridge assets with a goal to increase the safety, reliability, and resilience of transportation infrastructure.

Dr. Jizhong Xiao's team identified effective features for internal defect detection of reinforced concrete slabs from 3D GPR imaging, impact sounding, and impact echo technologies.

5.D - Transportation Workforce Development

Dr. Genda Chen of Missouri University of Science and Technology provided diverse training opportunities of 9 undergraduate (including 2 female), 5 graduate students, 2 post docs, and 2 professional staff researchers on interdisciplinary research topics involving civil engineering, computer science, electrical engineering, and mechanical engineering. This school of students and scholars will contribute the much-needed workforce related to the remote sensing and data analytics in transportation infrastructure. Dr. Chen also integrated some of the research findings on embedded and remote sensing technologies into a graduate course: CIV ENG6001 Structural Health Monitoring. Dr. Chen's team also demonstrated robotic technologies to the K-12 students through various outreach activities such as Jackling Summer Program and Boy Scout of America's camp.

Dr. Hung La of University of Nevada Reno introduced automated infrastructure inspection concepts using robots into the current robotics courses: CPE470/670-Autonomous Mobile Robots; CS791-Special Topics on Robotics, and CS455/655-Mobile Sensor Networks. Dr. Hung is developing a new advanced robotics course: CPE471/671 Advanced Robotics, and its curriculum has been submitted and under review by the UNR Curriculum committee. Additionally, Dr. Hung has organized several lab open day events to generate robotic interests to both local elementary and high school students as well as DOT and industry. Both undergraduate and graduate students have participated in all phases of the project. They have been trained through hands-on design, fabrication, prototyping and programming of the robots.

Dr. Paul Oh of University of Nevada Las Vegas continues to work with aerial manipulation and human-in-the-loop control which would augment the performance of bridge workers with new tools. Dr. Oh introduced the design and operation of autonomous vehicles to the K-12 and general public through regular Library Project on Saturday.

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

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

Dr. Jizhong Xiao's of City College of New York's project directly supported graduate students and involved undergraduates in the R&D activities through senior design, summer internship, and master projects.

5.E - INSPIRE Impacts Performance Metrics

Research Impacts – Performance Measures	Cumulative Total
1. At least 50% reduction of the total cost of a traditional in-depth bridge inspection that requires the use of heavy lifting equipment.	0
2. At least 5 patents generated in 5 years and at least 1 associated technology applied in practice.	5

6. CHANGES/PROBLEMS

6.A - Changes in Approach and Reasons for Change

COVID-19 Impact on Research Approach

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

Dr. Hung La's campus is partially in telework mode with partial access to our machine shop, laboratory space, facilities, or equipment. Students supported on this project are continuing with computational work and only partial access to the lab and facility to perform physical work. Due to COVID-19, some work related to hardware integration, robot part manufacturing, robot test and validation has been limited as well as expenditures on buying robotic, sensor and other related components.

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

COVID-19 Impact on Research Progress Delay

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

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

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

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

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

COVID-19 Impact on Research Expenditure

Research students and faculty are paid on appointment based on the expected work to be completed. In general, work efficiency of the research projects is at approximately 75%. As soon as the COVID-19 clears completely, the INSPIRE team will move forward with project activities at full speed, catching up some of the lost time during the COVID-19 period.

Dr. Hung La changed expenditures related to buying robotic, sensor, and other related components.

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.