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Semi-Annual Progress Report #10

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

UTC Semi-Annual Progress Report #10

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Submitted by:	The Curators of the University of Missouri on behalf of Missouri University of Science and Technology, 202 Centennial Hall, Rolla, MO 65409
Center Director Name and Contact Information:	Dr. Genda Chen, P.E. Email: inspire-utc@mst.edu; Tel: 573-341-6114
DUNS:	8048837670000
EIN Number:	436003859
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Dr. Kamal Khayat, Interim Vice Chancellor of Research and Innovation, research@mst.edu; 573-341-4134

Inspecting and Preserving Infrastructure through Robotic Exploration (INSPIRE)

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

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

1.B - What Was Accomplished under These Goals?

To support the research objectives, major progress was made in each of the research topics: sensing and nondestructive evaluation (SN), autonomous systems (AS), inspection and maintenance (IM), retrofit and resilience (RR), and workforce development (WD). As summarized in Table 1, the progress is evaluated in terms of major activities, specific objectives, significant results, and key outcomes.

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. Continue to finalize a final report. 6. Replace gel couplant with two potential elastomer couplants to improve ultrasonic test performance.	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.	1. Complete. 2. Complete. 3. Complete. 4. Complete. 5. A linear increase of reflectance with Cl-content up to 0.8 wt.%. 6. An elastomer couplant that fills gel right before the transducer providing a practical solution.	1. Complete. 2. Complete. 3. Complete. 4. Complete. 5. Hyperspectral imaging for steel corrosion and Cl-concentration. 6. A success of couplant application and transducer miniaturization.

Topic	Major Activities	Specific Objectives	Significant Results	Key Outcomes
	7. Characterize concrete specimens with hyperspectral imaging. 8. Develop a length-at-detection method for the determination of probability of detection (POD).	7. Identify effective NDTs and hyperspectral imaging for freeze-thaw (F-T) damage assessment. 8. Develop a probability of detection (POD) for steel corrosion monitoring at 95% confidence level.	7. Free water decrease until damage is induced by F/T cycles. 8. Consistency in distribution models leading to good POD calculation.	7. A database of data collected from integrated NDTs and imaging. 8. The assessment of detection result quality and reliability.
AS	1. Complete. 2. Revise a final report. 3. Complete. 4. Fine tune the flight control algorithm to exclude the effect of drone rotation during flight. 5. Test two climbing robots on a highway bridge for real-time defect detection based on deep learning. 6. Design and fabricate a robust sliding mechanism hosting both impact echo and sounding modules. 7. Complete gantry-based testing of an aerial hose task with a force-torque sensor and fluid flow sensors attached. 8. Assemble and test a sonar operation system for riverbed survey when immersed in water via a climbing robot.	1. Complete. 2. Develop and publish a report on research findings and results. 3. Complete. 4. Develop a hybrid flying and traversing unmanned vehicle for bridge inspection. 5. Provide the already built climbing robot with an autonomous inspection capability. 6. Modify impact sounding hardware and software for effective detection of subsurface defects. 7. Develop a drone that conduct bridge cleaning tasks with high pressure water through a water hose system. 8. Develop a real-time scour monitoring technique with a robot-mounted sonar and altimeter.	1. Complete. 2. Demonstration of robot prototypes in laboratory and field. 3. Complete. 4. Removal of drone angular motion improving drone controllability. 5. Redesigned robot validated to traverse smoothly on curve surfaces. 6. Solenoid impact mechanism, sensor, and microphone amplifier. 7. Reaction forces identified and a compensator designed in simulation. 8. Initial success on the operation of the sonar system tested to ensure water depth measurement.	1. Complete. 2. Climbing robots tested on steel bridges. 3. Complete. 4. Observer and controller collocation for flight stability. 5. Multi-directional bicycle robot tested for steel inspection. 6. Impact Rover with K-means machine learning for defect detection. 7. A debris cleaning drone with a hose helps engineers maintain bridges effectively. 8. A robot-mounted sonar system for riverbed survey and water depth determination.
IM	1. Withdrawn. 2. Complete. 3. Modify the impact sounding tube for effective isolation of the microphone from direct sound from the speaker.	1. Withdrawn. 2. Complete. 3. Develop a system of speaker, microphone, tracking camera, and RTK GPS for inspection of bridge decks and piers.	1. Withdrawn. 2. Complete. 3. Data fusion, GPS and Realsense tracking synchronization for better accuracy and efficient mapping.	1. Withdrawn. 2. Complete. 3. A visual device with simultaneous localization and mapping improvement.
RR	1. Create methods to utilize bridge inspection data to analyze and update assessment of bridge performance. 2. Collect and label images for deep learning of corrosion condition in bridge classification.	1. Evaluate the effect of inspection parameters on the predicted performance and resilience of bridges. 2. Support bridge inspection 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. Collection of images from three bridges and additional 774 images.	1. A set of fragility curves and risk updates based on scour data at foundation. 2. Label data for both corrosion detection and quantification.
WD	1. Complete. 2. Prepare a final report for the first version of Simulation Training And Control System (STACS).	1. Complete. 2. Develop STACS with robot routing plans and optimization for bridge inspection.	1. Complete. 2. Route optimization and automated generation of truss bridges.	1. Complete. 2. The first version of STACS with route optimization and truss generation.

Topic	Major Activities	Specific Objectives	Significant Results	Key Outcomes
	3. Design training exercises to teach human operators to work with the simulated robotic team to accomplish a bridge inspection task. 4. Select web software to implement deep learning tool for image segmentation and object detection.	3. Develop a training and control interface for human operators to oversee inspection robots in STACS-2 environment. 4. Prototype an interactive web system to aid in robot-based inspection video analytics.	3. Climbing robots traversing bridge members for defect detection with drone confirmation. 4. Django language in Python for the development of web interactive system.	3. A bridge builder to automatically generate training scenarios with climbing robots. 4. Functions and features of the deep learning tool reviewed.

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

To support the education objectives, courses related to the theme of the INSPIRE UTC were offered in different disciplines at partner institutions. Non-degree education programs such as conferences and meetings with industrial advisors were initiated.

To support the workforce development objectives, graduate students and professionals were exposed to the technologies developed at the INSPIRE UTC. Hands-on training modules were developed to help participants learn the concept, design, and fabrication of various hardware and use software to simulate sensing and assessment during inspection and develop strategies during maintenance.

To support the technology transfer objectives, an accompanying seven-state pooled-fund study No. TPF-5(395): Traffic Disruption-free Bridge Inspection Initiative with Robotic Systems was initiated on August 1, 2019. During the last reporting period, the pooled-fund study progressed in training of several drones to be used in field tests. An inspection crew of three people were being trained to operate commercial drones (e.g., Elise2, Skydio2, Phantom4) and custom-made robots (e.g., the BIRDS on girder bridges and the climbing robot on steel bridges).

To support the diversity objectives, laboratory demonstrations, hands-on practices, and other outreach activities were offered to college students in collaboration with minority student organizations and K-6 to K-12 students. Undergraduate and graduate students working on the INSPIRE UTC projects served as models and mentors for the young participants.

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

The INSPIRE UTC directly involved 9 faculty, 6 post docs and research faculty, 15 graduate students, and 11 undergraduate students in civil engineering, computer engineering, computer science, electrical engineering, engineering management and system engineering, and mechanical engineering through 13 on-going research projects.

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.

Biannual Newsletters

The INSPIRE UTC publishes biannual newsletters to disseminate research information and enhance public understanding of Center activities. INSPIRE newsletters are distributed to over 13,350 people through the Center's listserv and are made available online at https://inspire-utc.mst.edu/news/. An

INSPIRE UTC Newsletter (Vol. 6, No. 1) will be published in Spring 2022, including three technical articles related to INSPIRE research:

- *When AR Meets Bridge Inspection, Dr. Liujun Li, Missouri S&T*
- *VR Operator Training for Robot Assisted Bridge Inspection, Dr. Sushil Louis, University of Nevada, Reno*
- *Human-Embodied Drones for Mobile Manipulation in Bridge Inspection and Maintenance, Dr. Paul Oh, University of Nevada, Las Vegas*

Education and Outreach Activities

- The INSPIRE UTC at Missouri S&T supported the 2021 Boy Scout Jamboree Event in Missouri. On October 2, 2021, the biennial Boy Scout Jamboree Event since 2019 was held at the Lake of the Ozarks scout reservation that is the camping home of the Boy Scout of America Great Rivers Council. This event is committed to help scouts, students and adults to understand business, manufacturing and production, leadership, marketing, creativity, and most importantly how to serve the community using what they learn. The Jamboree event attracted 280 participants, totaling over 300 people on camp including staff and volunteers. The INSPIRE UTC Center presented and demonstrated innovative robot-assisted bridge inspection technologies via live demos, videos, and hands-on practices by Scouts. The Scouts and their parents learned our research background, practical applications, and the process of training and operating the advanced robots/drones.
- The INSPIRE UTC at Missouri S&T hosted a workshop for National Society of Black Engineers Precollege Initiatives. On February 18, 2022, the precollege initiatives attracted a group of 13 high school students. The workshop aimed at getting students excited with hands-on experience on a driving simulator in different simulated game environments. The simulated environments include different scenarios such as urban, rural, and mountain driving conditions. Before the hands-on practice, the students were asked for several questions, including why we need a car simulator, how a car simulator is built, how challenging it is to drive in different traffic and weather conditions, and how to make a career out of a car simulator while having fun with video games.
- The INSPIRE UTC at Missouri S&T hosted 6th to 8th graders from Houston, Missouri. On February 28, 2022, 13 middle school students visited the INSPIRE UTC. Andrew Rawlings, a senior in mechanical engineering and an undergraduate research assistant at the INSPIRE UTC introduced ongoing research activities including the exploration and development of robotic (both flying and climbing) technologies for next-generation bridge inspection. Each middle school student then flew drones to gain hands-on experience.
- The INSPIRE UTC at Missouri S&T hosted 8th graders from Newburg, Missouri. On March 14, 2022, a group of 19 students were on their field trip to visit the INSPIRE UTC. The goal of the workshop is to give a sense of the diverse engineering research that the center is conducting with the hope to spark their STEM interests. This time the INSPIRE UTC demonstrated a climbing robot and Tello drones. The climbing robot which was designed to climb structural steel frames via its magnetic mechanism, is also able to carry optical and thermal cameras for steel frame inspections. Besides recreational purposes, the Tello drones are used to do drone initial training as well as superficial bridge inspections. Each student operated the climbing robot and flew a Tello drone. Andrew Rawlings, a senior in mechanical engineering and an undergraduate research assistant at the INSPIRE UTC, demonstrated how to flip a drone while flying. The teacher of the 8th graders also showed great interest in the INSPIRE UTC research.

- The INSPIRE UTC at the University of Nevada-Las Vegas (UNLV with Dr. Paul Oh's team) continued to work with the neighboring Clark County Las Vegas Public Library in the Saturday K-12 Programs. Lesson plans included computer-aid-design (CAD), 3D printing, and embedded controllers (Arduino). Due to COVID-19, these programs are being held online. Additionally, the team continued to serve institutional outreach programs, namely Upward Bound. This program has been a primary UNLV's outreach event 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).

Invited Presentations

1. Genda Chen. "Robot-assisted Bridge Inspection and Maintenance," International Workshop on Civil Digital Transformation and Beyond, KAIST, Korea, November 19, 2021.
2. Genda Chen. "Robot-Assisted Bridge Inspection and Maintenance," Transportation Research Board (TRB) Webinar on Robot-Enabled Sensing and Augmented Learning (RE-SEAL) for Bridge Inspection on March 29, 2022.
3. Hung (Jim) La. "Climbing Robots for Steel Bridge Inspections," Transportation Research Board (TRB) Webinar on Robot-Enabled Sensing and Augmented Learning (RE-SEAL) for Bridge Inspection on March 29, 2022.
4. Hongyan Ma. "Advances in Materials for Sustainable Infrastructure: Eco-Efficient Cements, Concrete Durability and Demolition Waste Management," School of Civil Engineering, Tianjin University (Online Webinar), December 28, 2021.
5. Hongyan Ma. "Carbon-Negative Upcycling of Solid Wastes in Construction Materials," Missouri Department of Natural Resources Solid Waste Forum, Jefferson City, MO, February 16, 2022.

Quarterly Webinars

The INSPIRE UTC hosts quarterly webinars. To date, the INSPIRE UTC has presented 19 webinars. The participants for two webinars during the pandemic were not recorded unexpectedly. Thus, the total number of participants was estimated based on those shown online during the webinars. Overall, the 19 webinars engaged approximately 1,825 participants from 44 US States and 15 different countries and regions, 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. The two webinars presented in this reporting period engaged 212 participants (137 for the first + 75 for the second webinar):

1. Hyperspectral Imaging and Data Analytics for Civil Infrastructure Inspection was presented on December 14, 2021, by Dr. Genda Chen from Missouri S&T, Rolla, MO.
2. Toward Dexterous Aerial Manipulation Using Embodied Human-Intelligence for Bridge Inspection and Maintenance was presented on March 16, 2022, by Dr. Dongbin Kim from University of Nevada, Las Vegas.

Transportation Research Board (TRB) Webinar

1. Genda Chen. "Robot-Enabled Sensing and Augmented Learning (RE-SEAL) for Bridge Inspection", Transportation Research Board (TRB), Washington, D.C., March 29, 2022. This webinar was organized on behalf of four standing committees: AKB40 (Testing and Evaluation of Transportation Structures), AKT40 (Structures Maintenance), AKT50 (Bridge and Structures

Management), and AKT60 (Bridge Preservation). This webinar attracted 320 registrations of which 244 at peak participated in the webinar. It includes three presentations:

a. Dr. Genda Chen from Missouri S&T on Robot-Assisted Bridge Inspection and Maintenance
b. Dr. Hung (Jim) La from the University of Nevada, Reno, on Climbing Robots for Steel Bridge Inspections
c. Dr. Fernando Moreu from the University of New Mexico on Augmented Learning through Augmented Reality and Artificial Intelligence

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

Research projects will continue in the five research categories as described in Table 1. No change will be made to the approved plan. Planned research activities are summarized in Table 2 for each of the active research projects awarded by the INSPIRE UTC.

Table 2. A summary of planned research activities

Topic	Project Title	Planned Activities
SN	Autonomous Ultrasonic Thickness Measurement by a Magnet-Wheeled Robot	• Test thickness measurements with a Linux server for better integration. • Develop 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	• Characterize the degree of saturation from 50% to 90% using hyperspectral imaging. • Correlate the reflectance with 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 test data collected from Fe-C coated long period fiber gratings (LPFG) sensors using length-at-detection and random effect generalization methods. • Compare the probability of detection for Fe-C coated sensors.
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. • Integrate the previously developed boundary detection algorithm, deep learning method, and hidden Markov model to classify steel structure shapes. • Deploy the robot in steel bridges to achieve its autonomy and classification.
	A Field Deployable Wall-Climbing Robot for Bridge Inspection using Vision and Impact Sounding Techniques	• Integrate impact sounding and echo devices into the impact-rover robot. • Develop a move-stop-sample operation procedure for the impact-rover robot. • 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 bridge maintenance. • Strengthen the 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 a test of four vacuum cups supported robot on a masonry wall. • Integrate a side-scan sonar and an altimeter into the 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. • 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	• 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	• Integrate generated trusses into five training scenarios with n flying and k climbing inspection robots and evaluate their utility for workforce training. • Develop a c# version of genetic algorithm router for better integration into scenario generation and execution. • Create a template ROS bridge to a robot to make the developed technique generalizable to other robots for monitoring and control in STACS.
	An Interactive System for Training and Assisting Bridge Inspectors in Inspection Video Data Analytics	• Create web-based learning modules for trainees to master cross-disciplinary knowledge and fundamental skills of analytics. • Develop an inspection data analytics tool to assist inspectors in processing and analyzing inspection video data for the condition assessment of bridges.

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

Other Planned Initiatives

1. INSPIRE UTC Presentation to 7th graders from Bourbon, MO on May 2, 2022. The aim of this presentation is to get middle school students excited with STEM education and transportation engineering as their career path.
2. INSPIRE UTC Special Session at the 8th World Conference on Structural Control and Monitoring (8WCSCM), Orlando, FL on June 5-8, 2022. Drs. Genda Chen and Yang Wang organized a session on the development of mobile platforms for infrastructure inspection and maintenance.
3. INSPIRE UTC Special Session at the 30th Research Symposium Organized by the American Society for Nondestructive Testing, St. Louis, MO on June 20-23, 2022. Drs. Genda Chen and Glenn Washer organized a session on recent advances on nondestructive evaluation of bridges.
4. INSPIRE UTC Quarterly Webinar on June 21, 2022 on Intelligent Human-Infrastructure Interfaces for Inspectors and Decision-makers by Dr. Fernando Moreu in structural engineering from the University of New Mexico at Albuquerque. This seminar will challenge traditional conversations about digital twins and machine learning in a paradigm for smart cities transformation centered in new human-infrastructure interfaces.
5. INSPIRE UTC Annual Meeting in August of 2022. The aim of the annual meeting is to promote collaboration among principal investigators from different institutions, promote student interaction with transportation professionals from state DOTs and private industry, and report progress and performance and receive feedback from the External Advisory Committee.

2. PARTICIPANTS & COLLABORATING ORGANIZATIONS

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

Consortium Collaborators

The consortium members of the INSPIRE UTC include:

- Missouri University of Science and Technology (Missouri S&T) - Rolla, MO (lead institution)
- City College of New York - New York, NY
- Georgia Institute of Technology - Atlanta, GA
- University of Nevada-Las Vegas - Las Vegas, NV

- University of Nevada at Reno - Reno, NV
- East Central College - Union, MO
- Lincoln University - Jefferson City, MO
- Ozarks Technical College - Springfield, MO
- St. Louis Community College - St. Louis, MO

External Collaborators

- Air Corp, Reno, NV https://www.buzzfile.com/business/Air-Corp-732-668-8112
- Ameren Corporation, St. Louis, MO https://corporateofficeheadquarters.org/ameren-corporation/
- Clark County Las Vegas Library, Las Vegas, NV https://lvccld.org
- California Department of Transportation, Sacramento, CA https://dot.ca.gov
- Georgia Department of Transportation, Atlanta, GA www.dot.ga.gove
- Geophysical Survey System, Inc. (GSSI), Nashua, NH https://www.geophysical.com
- InnovBot LLC, New York, NY http://www.innovbot.com/theme/users
- Iowa State University, Ames, IA https://www.iastate.edu
- Mid-America Transportation Center, Lincoln, NE https://matc.unl.edu
- Missouri Department of Transportation, Jefferson City, MO http://www.modot.org
- Nevada Department of Transportation, Carson City, NV https://www.nevadadot.com/
- New York Department of Transportation, Albany, NY https://www.dot.ny.gov
- Paul D. Thompson Consulting Services, Bellevue, WA www.pdth.com
- Rice University, Houston, TX https://ceee.rice.edu
- Stony Brook University, Stony Brook, NY https://www.stonybrook.edu/
- Technology Entrepreneur Center, Inc., St. Louis, MO https://downtowntrex.org/
- Tesla Gigafactory, Reno, NV https://www.tesla.com/gigafactory
- Texas Department of Transportation, Austin, TX https://www.txdot.gov
- Turner Fairbanks Highway Research Center of FHWA, McLean, VA https://highways.dot.gov/research
- Virginia Department of Transportation, Richmond, VA https://www.virginiadot.org/
- Wisconsin Department of Transportation, Madison, WI https://wisconsindot.gov/Pages/home.aspx

Internal Partners at Missouri S&T

- Center for Intelligent Infrastructure https://cii.mst.edu
- Curtis Law Wilson Library/Scholars' Mine http://scholarsmine.mst.edu/
- Department of Civil, Architectural and Environmental Engineering https://care.mst.edu/
- Department of Computer Science https://cs.mst.edu
- Department of Engineering Management and Systems Engineering https://emse.mst.edu/
- EdTech Connect https://edtechconnect.mst.edu/
- Kummer Center for STEM Education https://stemcenter.mst.edu/
- National Society of Black Engineers https://mst.campuslabs.com/engage/organization/national-society-of-black-engineers
- Research Support Services/MinerFly Team https://itrss.mst.edu/minerfly/
- Scholars Mine https://scholarsmine.mst.edu
- Society of Hispanic Professional Engineers https://mst.campuslabs.com/engage/organization/society-of-hispanic-professional-engineers
- Student Diversity Initiatives http://sdi.mst.edu/

- System and Process Assessment Research (SPAR) Laboratory https://spar.mst.edu

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

Dr. Paul Oh's team of the University of Nevada, Las Vegas, has a Phase 3 task order contract with Tesla's Reno-based Gigafactory starting January 2022. Although independent of this INSPIRE UTC project, this task order has some overlap technologically, such as augmented reality (AR) to help monitor sites and manipulate objects. Hence, this UNLV-Tesla collaboration would give the INSPIRE UTC added visibility.

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 buried with pipes and boxes to simulate defects (voids, delamination, honeycomb) at different sizes and depth. InnovBot LLC has received an NSF grant "SBIR Phase II: Robotic Inspection and Data Analytics to Localize and Visualize the Structural Defects of Civil Infrastructure" and subcontracted some research and development work to the City College of New York Robotics Lab.

3. OUTPUTS

3.A - Publications, Conference Papers, and Presentations

Journal Publications

1. Amjadian, M., Agrawal, A.K., Silva, C.E. and Dyke, S.J. "Experimental Testing and Validation of the Dynamic Model of a Magneto-solid Damper for Vibration Control," Mechanical Systems and Signal Processing, Vol. 166, Paper No, 108479, March 2022. https://doi.org/10.1016/j.ymssp.2021.108479
2. Bate, B., Chen, X., Chen, C., Ma, H., Zhu, J., Cao, J., Chen, J., Khayat, K., and Zhang, S. "Setting Times of Early-Age Mortars Determined from Evolution Curves of Poisson's Ratio," MDPI Materials, Vol. 15, No. 3, p. 853, January 23, 2022. https://doi:10.3390/ma15030853
3. Cao, R., Agrawal, A.K., El-Tawil, S. and Wong, W. "Data Filtering in Vehicle–Bridge Impact Simulations: Evaluation of Different Force Filtering Methods and Recommendations," ASCE Journal of Bridge Engineering, Vol. 26, No. 12, pp. 04021094, December 2021. https://doi.org/10.1061/(ASCE)BE.1943-5592.0001806
4. Cao, R., El-Tawil, S., Agrawal, A.K. and Wong, W. "Performance and Capacity Assessment of Concrete Barriers Subject to Lateral Loading," ASCE Journal of Bridge Engineering, Vol 26, No. 12, pp. 04021090. December 2021. https://doi.org/10.1061/(ASCE)BE.1943-5592.0001789
5. Chen, X., Wang, X., Wang, H., Agrawal, A.K., Chan, A.H.C., and Cheng, Y. "Simulating the Failure of Masonry Walls Subjected to Support Settlement with the Combined Finite-discrete Element Method," Journal of Building Engineering, Vol. 43, pp. 102558, November 2021. https://doi.org/10.1016/j.jobe.2021.102558
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Books or Other Non-periodical One-time Publications – Conference Papers

1. Agrawal, A.K. and Amjadian, M. "Seismic Component Devices," in Innovative Bridge Design Handbook, pp: 637-662, Publisher: Butterworth-Heinemann, January 01, 2022.
2. Hoxha, E., Feng, J., Sanakov, D., and Xiao, J. "Robotic Inspection and Characterization of Subsurface Defects on Concrete Structures Using Impact Sounding and Impact Echo Techniques," 13th International Workshop on Structural Health Monitoring (IWSHM), Palo Alto, CA, USA, March 15-17, 2022 (workshop cancelled but accepted paper published in proceedings).
3. Jiao, P., Shang, B., Li, L. and Chen, G. "The Ceiling Effect and Flight Insight of Unmanned Aerial Vehicles during Proximity Inspection of Bridges via Computational Fluid Dynamics Modeling and Simulations," 13th International Workshop on Structural Health Monitoring (IWSHM), Palo Alto, CA, USA, March 15 - 17, 2021 (workshop cancelled but accepted paper published in proceedings).
4. Motley, C., Nguyen, S., and La, H.M. "Design of a High Strength Multi-Steering Climbing Robot for Steel Bridge Inspection," 2022 IEEE/SICE International Symposium on System Integration (SII), Narvik, Norway, January 8-12, 2022.
5. Pham, A.Q., La, A.T., Chang, E. and La, H.M. "Flying-climbing Mobile Robot for Steel Bridge Inspection," 2021 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR), pp. 230-235, New York, USA, October 25, 2021. doi: 10.1109/SSRR53300.2021.9597676
6. Pham, A.Q., Motley, C., Nguyen, S., and La, H.M. "A Robust and Reliable Climbing Robot for Steel Structure Inspection," 2022 IEEE/SICE International Symposium on System Integration (SII), Narvik, Norway, January 8-12, 2022.
7. Otsuki, Y, Lander, P, and Wang, Y. "Field Validation of a Compact Martlet Wireless Ultrasonic Thickness Measurement System," 13th International Workshop on Structural Health Monitoring (IWSHM), Palo Alto, CA, USA, March 15 - 17, 2021 (workshop cancelled but accepted paper published in proceedings).
8. Singandhupe, A. and La, H.M. "Single Frame Lidar Stereo Camera Calibration Using Registration of 3D Planes," IEEE International Conference on Robotic Computing, Taichung, Taiwan, November 15-17, 2021.

Final Technical Reports of Projects

1. Agrawal, A.K., Amjadian, M. and Nassif, H. "Energy Harvesting for Self-Powered Sensors for Smart Transportation Infrastructures", Connected Cities for Smart Mobility toward Accessible and Resilient Transportation Center (C2SMART), November 1, 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
- Evolutionary Computing Systems Laboratory: https://ecsl.cse.unr.edu/projects/bridge_inspection/index.html
- INSPIRE University Transportation Center: https://inspire-utc.mst.edu
- Open Source STACS Software: https://github.com/sushillouis/Stacs
- Research in Progress Database: https://rip.trb.org/
- Scholars Mine: https://scholarsmine.mst.edu

3.C - New Technologies or Techniques

- Dr. Genda Chen's team at Missouri S&T discovered that the use of angular motion as feedback

in control algorithm made a quadcopter less stable during flight tests. The team thus developed and fine tuned a collocated observer and controller technique to stabilize the drone motion.

- Dr. Hung La's team at the University of Nevada, Reno, developed a rigorous magnetic force analysis of magnet-wheeled climbing robots for bridge inspection in a confined space within complex steel structures.
- Dr. Sushil Louis' team at the University of Nevada, Reno, developed a new algorithm of generating and optimizing multiple robot paths on the surface of steel members or along bridge members.
- Dr. Hongyan Ma's team at Missouri S&T developed an inventory and database of standardized samples for hyperspectral imaging features under various deterioration conditions.
- Dr. Paul Oh's team at the University of Nevada, Las Vegas, developed a novel rotorcraft that can carry a water hose and provide high pressure jet flow to clean critical bridge components.
- Dr. Yang Wang's team at Georgia Institute of Technology developed an innovative robotic sensing technology that allows an autonomous ultrasonic measurement of the thickness of steel bridge members.
- Dr. Jizhong Xiao's team at City College of New York developed a solenoid, microphone, and piezoelectric sensor solution with a robust sliding mechanism for enhanced impact sounding and echo tests to collect acoustic and vibration signals automatically.

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

1. Nothing to Report during this Reporting Period

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

- Dr. Genda Chen at Missouri S&T, USDOT RD&T UTC Video Forum on Artificial Intelligence: https://www.transportation.gov/utc/usdot-rdt-utc-video-forums
- Dr. Dongbin Kim at the University of Nevada, Las Vegas, INSPIRE UTC Quarterly Webinar on *Toward Dexterous Aerial Manipulation using Embodied Human-Intelligence for Bridge Inspection and Maintenance*, which was recorded and stored at Missouri S&T's Scholars Mine Data Repository Site: https://scholarsmine.mst.edu/inspire_webinars/19/
- Dr. Genda Chen at Missouri S&T, INSPIRE UTC Quarterly Webinar on *Hyperspectral Imaging and Data Analytics for Civil Infrastructure Inspection*, which was recorded and stored at Missouri S&T's Scholars Mine Data Repository Site: https://scholarsmine.mst.edu/inspire_webinars/18/
- Dr. Sushil Louis at the University of Nevada, Reno, Open Source STACS Software on Github that serves as a public project repository resource for INSPIRE UTC and other projects related to autonomy and bridge inspection: https://github.com/sushillouis/Stacs

Final Data Reports from INSPIRE UTC Projects

1. Genda Chen. Hyperspectral Imaging and Data Analytics for Civil Infrastructure Inspection, January 4, 2022.
2. Jizhong Xiao. Autonomous Wall-climbing Robots for Inspection and Maintenance of Concrete Bridges, March 28, 2021.

Educational Modules from INSPIRE UTC Projects

1. Genda Chen. Hyperspectral Imaging and Data Analytics for Civil Infrastructure Inspection, January 4, 2022.
2. Jizhong Xiao. Senior Design Projects on Robotic Inspection of Infrastructure, April 1, 2021.

3.F - INSPIRE Research Outputs Performance Metrics

Research Outputs - Performance Measures	Total
1. At least 5 journal publications and books per investigator/year	6.2
2. At least 15 keynote/invited presentations delivered at national and international conferences in 5 years	24
3. 4 webinars/year	4/Year
4. 2 NDE/sensor prototype in 5 years	3
5. 1 robotic training simulator in 5 years	1

4. OUTCOMES

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

- Dr. Anil Agrawal's team isolated the microphone from receiving direct sound from the speaker to achieve better classification of deterioration in concrete bridge deck.
- Dr. Genda Chen's team introduced a collocated observer and controller algorithm with linear motion input only for stable flights of a hybrid flying and traversing robot when manually controlled.
- Dr. Hung La's team improved a bicycle climbing robot that can smoothly move side-way on curve surfaces as tested in a real-world steel bridge.
- Dr. Sushil Louis' team matched the simulated climbing robots with the INSPIRE UTC robot prototypes in terms of sensing, assessment, and data management in bridge inspection.
- Dr. Hongyan Ma's team characterized concrete specimens directly from hyperspectral images for the change of free water content before damage is induced by F/T cycles.
- Dr. Paul Oh's team developed a reproducible method that reflects the amount of dirt removed from a bridge to measure the performance of aerial hosing for bridge element cleaning.
- Dr. Iris Tien's team developed skills to label the existence/location of corrosion, pitting/uniform corrosion, extent of corrosion, and the level of corrosion.
- Dr. Yang Wang's team developed a design procedure to optimize the placement of gel for effective ultrasonic tests while maintaining the stability of a carrying robot.
- Dr. Jizhong Xiao's team designed and fabricated a robust sliding mechanism to host both impact sounding and echo modules for collecting acoustic and vibration signals automatically with an enhanced microphone to amplify acoustic signals and insolate ambient noises.

4.B - INSPIRE Research Outcomes Performance Metrics

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

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

5. IMPACTS

5.A - The Effectiveness of the Transportation System

Dr. Genda Chen's work on hybrid vehicles that can fly around and/or climb on bridge elements will enable bridge inspection from the underside of bridge decks and substructures with minimum or no impact on traffic on roadways. Such inspections would be safer, cheaper, and faster as well as more consistent in inspection results from remote sensing and nondestructive evaluation. Currently autonomous engagement of a hybrid vehicle with a bridge girder is being developed.

Dr. Hung La's work on a bicycle robot with magnet wheels and propellers that can fly to bridge sites and move along the surface of steel elements will enable automated bridge inspection and evaluation process. Once installed with nondestructive evaluation devices, this robot will serve as a new mobile inspection tool that is cost effective and easy to deploy.

Dr. Sushil Louis' work on Simulation Training And Control System (STACS) in game environment with training scenario generations and robot routings will lay a framework and foundation for future inspectors/operators to get trained with simulated bridge inspection with robots.

Dr. Hongyan Ma's work on the nondestructive evaluation of freeze-thaw cycling induced damages to concrete structure will establish a database with distinct features for potential adoption by transportation communities in bridge deterioration assessment.

Dr. Paul Oh's work on the design, development, and deployment of aerial manipulators will augment the performance of bridge maintenance workers with human-in-the-loop control of tasks such as debris cleaning and crack sealing.

Dr. Yang Wang's work on a robot-assisted ultrasonic steel thickness measurement technology will enable an automated inspection of steel bridges for the deterioration level of corrosion. This technology has the potential to be adopted in bridge monitoring practices.

Dr. Jizhong Xiao's work on visual simultaneous localization and mapping (V-SLAM) and the vision-based positioning method will enable 3D GPR imaging, impact sounding, and impact echo analysis on a target area of interest. These technologies can be adopted to potentially detect subsurface defects.

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

Dr. Hung La's team prepared a SBIR proposal and requested funding to support Automated Inspection Robots (AIR) Corp., a start-up company established in January of 2020. The INSPIRE UTC provided a strong leverage to the growth of the company.

Dr. Jizhong Xiao's work on a self-contained robotic nondestructive evaluation system with vertical mobility and an RGB-D camera, GPR, and impact sounding device enhanced and accelerated the development and validation of market-ready technologies to support InnovBot LLC, a CUNY spin-off company. The INSPIRE UTC provides a strong leverage and support letter for the company to successfully secure a recent SBIR grant from National Science Foundation.

5.C - The Body of Scientific Knowledge

Dr. Anil Agrawal's team worked towards the understanding of robot-induced sound used either as a source of impact sounding or noise to be filtered out from a separate impact sounding source for an efficient detection of hidden defects in concrete structures. Data analysis methods such as Hilbert-Huang Transformation and power spectral density were investigated for this application.

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

Dr. Genda Chen's team contributed to the detection and control algorithms of hybrid vehicles that can fly around and traverse on bridge members. These models lay a solid foundation for further innovation of hybrid vehicles that function like inspection platforms and promote adoption in engineering practice.

Dr. Hung La's team developed a magnetic force analysis of magnet-wheeled climbing robots for steel bridge inspection. This procedure and process enables further investigation with the use of various nondestructive evaluation methods.

Dr. Sushil Louis' team developed an improved understanding on the optimal strategy for the work balance among k climbing robots in the formulation of Minimax k-Chinese Postman Problem (MMk-CPP). This understanding will impact operation research and nonlinear optimization community.

Dr. Paul Oh's research provided an unprecedented understanding of how a rotorcraft works with a hose discharging water in the horizontal direction – an asymmetrical multi-degree dynamic system with a significant horizontal force to counteract during the flight of the rotorcraft. A human-embodied rotorcraft was also developed through haptics in an augmented reality.

Dr. Iris Tien's team's developed machine learning algorithms to inference structural states of bridges and associated risks from images and quantify the effect of corrosion on risk assessment and facilitate prioritization and comparison of expected bridge performance for potential repair and retrofit solutions.

Dr. Jizhong Xiao's team proposed a new design and implementation of solenoid impact mechanism on vacuum-based climbing robots with data analysis software. The vision-based positioning method will enable 3D GPR imaging, impact sounding, and impact echo analysis for detection of subsurface defects.

5.D - Transportation Workforce Development

Direct Training of Undergraduate Students through Hands-on Research

1. Maria Alvarado in civil engineering, Missouri S&T
2. Derek Edwards in mechanical engineering, Missouri S&T
3. Shawn Faulkingham in aerospace engineering, Missouri S&T
4. Rueil Manzambi in computer science, Missouri S&T
5. Daniel Mcdonald in electrical and computer engineering, Missouri S&T
6. Ava Ramljak in electrical and computer engineering, Missouri S&T
7. Andrew Rawlings in mechanical engineering, Missouri S&T
8. Joseph Ressel in mechanical engineering, Missouri S&T
9. Jonathan Saelens in electrical and computer engineering, Missouri S&T
10. Nicholas Ward in computer science and engineering, University of Nevada, Reno
11. Mathew Weiss in mechanical engineering, Missouri S&T

Direct Training of Graduate Students through Hands-on Research

1. Ibrahim Alomari in civil engineering, Missouri S&T
2. Jinglun Feng in electrical and computer engineering, City College of New York
3. Rezwana Binte Hafiz in civil engineering, Missouri S&T
4. Blake Hament in mechanical engineering, University of Nevada, Las Vegas
5. Hana Herndon in civil engineering, Georgia Institute of Technology
6. Ejup Hoxha in electrical and computer engineering, City College of New York
7. Pu Jiao in civil engineering, Missouri S&T
8. Dongbin Kim in mechanical engineering, University of Nevada, Las Vegas
9. Deepak Kumar in civil engineering, City College of New York
10. Pengfei Ma in civil engineering, Missouri S&T
11. Cadence Motley in computer science and engineering, University of Nevada, Reno
12. Thanh Son Nguyen in computer science and engineering, University of Nevada, Reno
13. Yu Otsuki in civil engineering, Georgia Institute of Technology
14. Yanping Zhu in civil engineering, Missouri S&T
15. Ying Zhuo in civil engineering, Missouri S&T

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

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

Direct Training of Undergraduate and Graduate through Course Work

1. In Fall 2021 and Spring 2022, Dr. Hongyan Ma trained 64 undergraduate students in CIV ENG 3116 Construction Materials, Properties and Testing, including a module of nondestructive tests for concrete strength evaluation.
2. In Fall 2021, Dr. Genda Chen trained 4 graduate students in CIV ENG 6001 Structural Health Monitoring in civil engineering, Missouri S&T, including topics such as remote sensing and data analytics in transportation infrastructure.
3. In Spring 2022, Dr. Hung La trained 57 undergraduate students and five (5) graduate students in CPE 470/670 Autonomous Mobile Robots in electrical and computer engineering, the University of Nevada, Reno.
4. In Spring 2022, Dr. Iris Tien trained 30 graduate students in CEE 8813 Data Analytics for Civil and Environmental Engineering Systems in civil engineering, Georgia Institute of Technology, providing in-depth knowledge and application of a range of data analytics methods and techniques for the analysis of civil and environmental systems, such as monitoring, assessment, and control of transportation systems.

Professionals Exposed to the INSPIRE UTC Advanced Technologies

1. Ameren Corporation
2. California Department of Transportation
3. Georgia Department of Transportation
4. Missouri Department of Transportation

5. Nevada Department of Transportation
6. New York Department of Transportation
7. Texas Department of Transportation
8. Virginia Department of Transportation
9. Wisconsin Department of Transportation
10. Paul D. Thompson Consulting Services
11. Technology Entrepreneur Center, Inc.
12. Tesla Gigafactory
13. Turner Fairbanks Highway Research Center, Federal Highway Administration

5.E - INSPIRE Impacts Performance Metrics

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

Once field tests start in summer of 2022 with the pooled-fund study No. TPF-5(395), robot-assisted bridge inspection will be compared with the conventional visual inspection to understand cost saving.

6. CHANGES/PROBLEMS

6.A - Changes in Approach and Reasons for Change

Nothing to report.

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

Dr. Anil Agrawal's team recently realized that integration of different components is more complicated than expected. Their workability and compatibility must be investigated before they can be assembled.

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 during the COVID-19 period is **estimated** at **90**%. 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.

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.