TRANSPORTATION POOLED FUND PROGRAM
QUARTERLY PROGRESS REPORT

Lead Agency (FHWA or State DOT): _Missouri Department of Transportation_________________

INSTRUCTIONS:
Project Managers and/or research project investigators should complete a quarterly progress report for each calendar quarter during which the projects are active. Please provide a project schedule status of the research activities tied to each task that is defined in the proposal; a percentage completion of each task; a concise discussion (2 or 3 sentences) of the current status, including accomplishments and problems encountered, if any. List all tasks, even if no work was done during this period.

Transportation Pooled Fund Program Project #	**Transportation Pooled Fund Program - Report Period:**
TPF-5(395)	☐ Quarter 1 (January 1 – March 31) ☐ Quarter 2 (April 1 – June 30) ☒ Quarter 3 (July 1 – September 30) ☐ Quarter 4 (October 1 – December 31)

Project Title: Traffic Disruption-free Bridge Inspection Initiative with Robotic Systems

Name of Project Manager(s):	**Phone Number:**	**E-Mail:**
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Lead Agency Project ID: S064101S	**Other Project ID (i.e., contract #):** TR202004	**Project Start Date:** August 1, 2019
Original Project End Date: July 31, 2024	**Current Project End Date:** July 31, 2024	**Number of Extensions:** 0

Project schedule status:
☐ On schedule ☐ On revised schedule ☐ Ahead of schedule ☒ Behind schedule

Overall Project Statistics:

Total Project Budget	Total Cost to Date for Project	Percentage of Work Completed to Date
$725,000	$447,206.94	70%

Quarterly Project Statistics:

Total Project Expenses and Percentage This Quarter	Total Amount of Funds Expended This Quarter	Total Percentage of Time Used to Date
$447,206.94 and (40.7%)	$18,191;.83	83%

Note that the University of Missouri has recently implemented a new PI grant reporting system. The latest monthly report I received in December of 2021 includes expenditure up to November 30, 2021. For convenience, I will report expenditure up to one month prior to the progress report date. For example, the December 31, 2021, report includes expenditures till November 30, 2021.

Also note that this month's expenditure includes correction from the previous two years for research engineer's salary.

Project Description:

Bridge inspection often requires the use of heavy lifting and access equipment, thus increasing operation time and direct costs. When access to the inspected area must be made from bridge decks, the indirect costs associated with road closure multiply. In such a case, travelers are frustrated with traffic congestion and, both the travelers and inspectors are subject to a safety concern on high volume highways. Moreover, visual inspection is quite subjective and often inconsistent. It is thus of economic, psychological and social importance to develop an alternative platform for faster, safer, cheaper, and consistent bridge inspection with minimum impact on traffic flow.

The INSPIRE University Transportation Center (https://inspire-utc.mst.edu) at Missouri University of Science and Technology has been focused on the development of advanced technologies to aid in bridge inspection and maintenance. Specifically, structural crawlers, unmanned aerial vehicles (UAVs), and multimodal unmanned vehicles will provide a mobile platform for in-depth inspection of elevated bridges. In particular, a special multimodal unmanned vehicle, named Bridge Inspection Robot Deployment Systems (BIRDS), will be developed to combine both the driving capabilities of crawlers and the flying capabilities of UAVs into one system for bridge inspection.

At the INSPIRE Center, microwave and hyperspectral images will be developed to assess concrete delamination and steel corrosion of reinforced concrete (RC) bridges. Together with other existing technologies such as impact echo, impact sounding, and infrared images, they will provide a suite of measurement tools and methods for the nondestructive evaluation (NDE) of structural damage and deterioration conditions in RC and steel bridges. Innovative sensors such as UAV-based smart rocks for scour monitoring, integrated point and distributed optical fiber systems for strain and corrosion monitoring, and coupled antenna systems for strain and crack monitoring will provide mission-critical data, such as the maximum scour depth, corrosion-induced steel mass loss, and live load induced strains in order to normalize the NDE data taken over time at spatially distributed points.

The goals of this pooled-fund initiative are to engage closely with several state Departments of Transportation (DOTs) in the early stage of technology development at the INSPIRE University Transportation Center, and leverage the center resources to develop case studies, protocols, and guidelines that can be adopted by state DOTs for bridge inspection without adversely impacting traffic. The initiative involves the integration, field demonstration and documentation of a robotic system of structural crawlers, UAVs, BIRDS, NDE devices, sensors, and data analytics. Depending on the interest of participating DOTs, the objectives of this initiative include, but are not limited to:

- Development of inspection/operation protocols for various types of bridges with the robotic system integrated into current practice.
- Comparison and correlation of bridge deck inspections from the top and bottom sides of decks to understand the reliability of traffic disruption-free bridge inspection from the underside of decks.
- Design and technical guidelines of measurement devices on a robotic platform for the detection of surface and internal damage/deterioration in structural elements, and for the change in lateral support of foundations.
- Data fusion and analytics of measurements taken from various imaging and sensing systems for consistency and reliability.
- Development of best practices on bridge inspection using the robotic system.

To achieve the above objectives, the following tasks are proposed:

1. Bridge selection for manual and automated inspections. Develop a selection protocol of bridges that are appropriate for both manual visual inspection and automated NDE. Thus, the performance of robot-based NDE can be compared with the current practice of visual inspection. The main parameters considered in this selection include span length, bridge type, accessibility, and importance. For example, river-crossing bridges may be inspected in great depth with advanced technologies, while simple highway bridges with easy access may not require any robotic platform during inspection.
2. Operation of multimodal unmanned systems. Develop a field test facility (e.g., recreational vehicle for a three-person crew) of the robotic system, including the BIRDS equipped with two infrared cameras (e.g., dual-sensor FLIR DuoTM Pro) and one impact sounding/echo device for RC elements, and a structural crawler for other bridge elements. The inspection crew will consist of a research engineer in bridge inspection and maintenance, a research assistant professor in system integration and robotics, and a rotating graduate student intern.
3. Correlation of top and bottom deck inspections. Due to gravity, deterioration on the bottom surface (a safety issue) is more critical than that on the top surface (a serviceability concern). On the bottom side of a bridge deck, deterioration such as concrete cracking, concrete delamination, and reinforcement steel corrosion are easier to detect from underside of the deck. The detection results derived from inspections above and below the deck will be compared to understand their correlation or complementary nature.

4. NDE and sensing integration into visual inspection. Develop preliminary guidelines to test NDE devices, such as hyperspectral and microwave cameras, for surface mechanical and electrochemical features as well as internal corrosion condition of steel reinforcing bars in RC elements, and test in-line fiber optic sensors for simultaneous measurement of strain, temperature, and mass loss in cross section of the reinforcing bars. Normalize/calibrate the NDE test results with those of a few pre-installed fiber optic sensors in structural behavior assessment. All the detected deterioration with measurement data are compared with visual inspection results to understand and quantify the improvement in probability of detection compared to the current practice of inspection.
5. Case studies with a representative bridge inventory. Develop an inventory of geographically-distributed test bridges and conduct case studies to implement and demonstrate NDE devices and sensors for the detection of surface and internal damage and deterioration in structural elements, and implement and demonstrate UAV-based smart rocks with embedded magnets for the scour monitoring of bridges. Up to nine (9) highway bridges/year in three (3) age groups or one long-span bridge/year from each participating state will be tested starting in the 2nd year. Store and maintain curated data within six months of their collection at the Scholars' Mine of Missouri University of Science and Technology. Share the data with the INSPIRE University Transportation Center investigators and, upon approval of state DOTs, the public as appropriate.
6. Protocol and guideline modification. Evaluate and refine as needed the protocols and guidelines of field tests for disruption-free bridge inspections after three (3) years of field operation. Imaging and sensing data are fused together to improve the detectability of problem areas with reduced capacity. The test results and corresponding visual inspection results are evaluated and summarized in a mid-term report, based on the probability of detection for structural damage/ deterioration and the improvement of visual inspection practice of bridges.
7. Limited release of protocols, guidelines, and criteria. Conduct a beta version rollout of the protocols, guidelines, and performance criteria at the INSPIRE University Transportation Center and the Missouri Local Technical Assistance Program (LTAP) in 4th and 5th years. As part of this rollout, workshops on the workforce development with the developed protocols, guidelines, and field demonstration technologies are conducted. Upon request, in-house workshops are held at participating states once a year.
8. Final reporting and curation of main findings. Prepare and publish a final report on the protocols, guidelines, and performance criteria of field tests with the robotic system at the end of 5th year. Store and maintain curated data and the final report at the Scholars' Mine of Missouri University of Science and Technology. Share the data and the report with the INSPIRE University Transportation Center investigators and, upon approval of state DOTs, the public as appropriate.

The performance period of this project will be August 1, 2019, to July 31, 2024 for five years. Table 1 details the specific schedule of this project by year. The kickoff (K) meeting, mid-term (M) report, draft (D) report/deliverables, and final (F) report/deliverables are marked on the project schedule. The final report will be due by the contract termination date.

Table 1 Project Schedule by Year

Task	**Year**				
	1	**2**	**3**	**4**	**5**
1. Bridge selection for manual and automated inspections	K				
2. Operation of multimodal unmanned systems					
3. Correlation of top and bottom deck inspections					
4. NDE and sensing integration into visual inspection					
5. Case studies with a representative bridge inventory					
6. Protocol and guideline modification			M		
7. Limited release of protocols, guidelines, and criteria					
8. Final reporting and curation of main findings					D F

Notes:
K Kickoff meeting at the beginning of this contract
M Mid-term report due at the end of 3 years
D Draft report/deliverables due 60 days prior to the contract termination date
F Final report/deliverables due by the contract termination date

Progress this Quarter (includes meetings, work plan status, contract status, significant progress, etc.):

Between July 1 and September 30, 2023, the following activities took place:

- Task 2. Initial tests on horizontal hyperspectral imaging began indoor and outdoor.
- Task 5. Stitching and visualization of multimodal images such as RGB, LiDAR, Infrared, and Hyperspectral continued for inspected bridges. RGB provides an overview of the inspected bridges. LiDAR includes three-dimensional coordinate geospatial information for construction of digital bridges. Thermal images provide a way to understand the defect in substrates. Hyperspectral images include material information on the surface of infrastructure members and systems.
- Task 6. A draft mid-term report was being revised.

Anticipated work next quarter:

During the next quarterly, the following activities are expected to take place:

- Task 1. Continue to communicate with New York DOTs for bridge drawings for inspection planning.
- Task 2. Understand how line scanning images can be stitched to an overall spatial image after horizontal hyperspectral imaging.
- Task 5. Continue to summarize and update the field test protocol using drones for bridge inspection following the guidelines in the AASHTO Manual for Bridge Element Inspection.
- Task 6. Finalize the mid-term report and share with the participating state DOTs. Continue to populate the center's data curation and repository system with more bridge data. Review and standardize the collected data with simple post-processing, such as labeling, hyperspectral imaging to be used to detect abnormality from machine learning, and 3D reconstruction of bridge models to be used in virtual reality.

Significant Results:

During this report period, preliminary results from horizontal hyperspectral imaging were obtained. First, LiDAR data show no difference between horizontal and vertical scanning. Second, hyperspectral data consist of two parts: spatial image and spectrum. The spatial image was distorted in horizontal direction due to unknown reasons. But the spectrum for each pixel remains meaningful. As such, the main challenge is how to rectify spatial images after stitching from multiple line scanning.

Circumstance affecting project or budget. (Please describe any challenges encountered or anticipated that might affect the completion of the project within the time, scope and fiscal constraints set forth in the agreement, along with recommended solutions to those problems).

The project currently moves forward at full speed. But due to the previous impacts of COVID-19, communication challenge with two state DOTs, delayed or interrupted appointment of the research engineer, the overall project was delayed for about one year.

Potential Implementation:

Once the field mobile testing facility is fully developed, some of the advanced technologies developed at the INSPIRE University Transportation Center will be tested and demonstrated at bridge sites in participating states. Pilot/inspector training for automated tele-inspection will be provided to participating state DOTs free of charge.