TRANSPORTATION POOLED FUND PROGRAM
QUARTERLY PROGRESS REPORT

Lead Agency (FHWA or State DOT): ____IOWA DOT____

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 # *TPF-5(449)*	**Transportation Pooled Fund Program - Report Perio** Quarter 1 (January 1 – March 31, 2023) Quarter 2 (April 1 – June 30, 2023) X Quarter 3 (July 1 – September 30, 2023) Quarter 4 (October 1 – December 31, 2023)

Project Title:
Robust wireless skin sensor networks for long-term fatigue crack monitoring of bridges

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Lead Agency Project ID:	**Other Project ID (i.e., contract #**	**Project Start Date:**
	Addendum 736	May 15, 2020
Original Project End Date:	**Contract End Date:**	**Number of Extensions:**
May 14, 2023	May 14, 2024	1 extension granted to May 2024

Project schedule status:
x On schedule □ On revised schedule □ Ahead of schedule □ Behind schedule

Overall Project Statistics:

Total Project Budget	**Total Cost to Date for Projec**	**Total Percentage of Work Completed**
$ 540,000 (Phase I)	$380,314	93% of Phase I

Quarterly Project Statistics:

Total Project Expenses This Quarter	**Total Amount of Funds Expended This Quarter**	**Percentage of Work Completed This Quarter**
$119,626		

Project Description:

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

- TAC meeting on Dec 13th 2022.
- ISU produced a 3-minute video describing the main outcomes of the pooled fund project. The video will be shared with other DOTs in an effort to obtain additional funds to pursue the other planned phases of the project. The video is posted here: https://youtu.be/5ENHpKL1nhk
- KU tested new sensor boards supplied by UA for auto balancing and shunt calibration. The experimental setup is presented in the figure below. The oscilloscope probes were attached to sensor board to monitor the auto balancing process and initial 50-60 seconds data was captured using NIDAQ system for shunt calibration data. Results of balanced signal and shunt calibration are presented in the following figure.

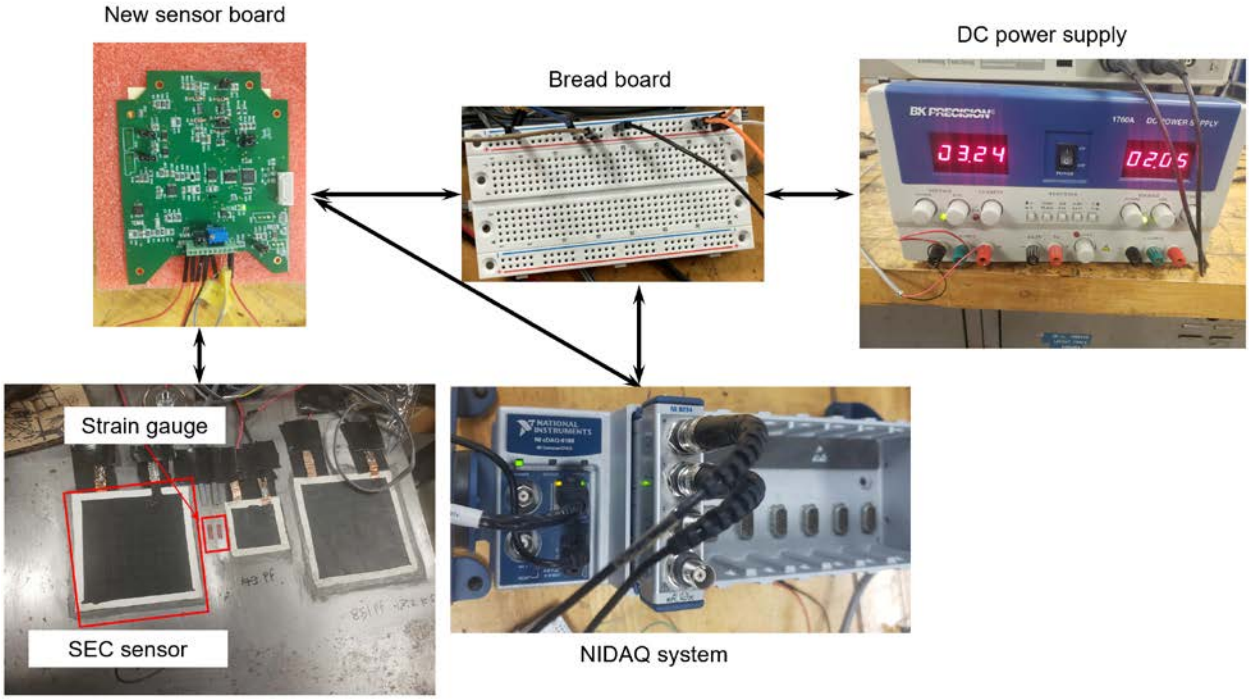


Figure: Test setup of SEC sensor, sensor board, power supply, and DAQ system

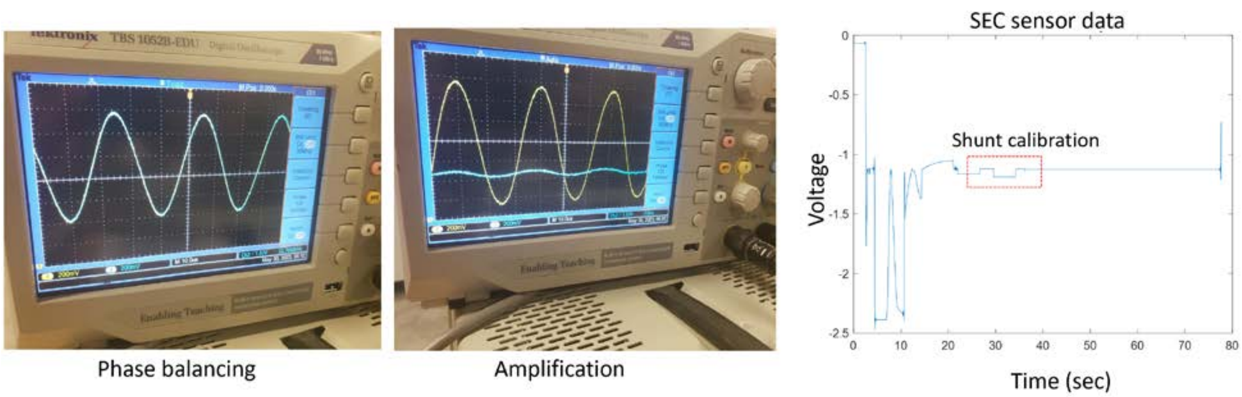


Figure: Phase balancing, amplification, and shunt calibration

Once the balancing and calibration processes were confirmed as completed, data for free vibration was collected using both the SEC sensor and strain gauge. To induce free vibration, an initial displacement was applied to the steel platform, allowing it to vibrate freely. The signals obtained from both the SEC sensor and the strain gauge were recorded and are plotted in the figure below.

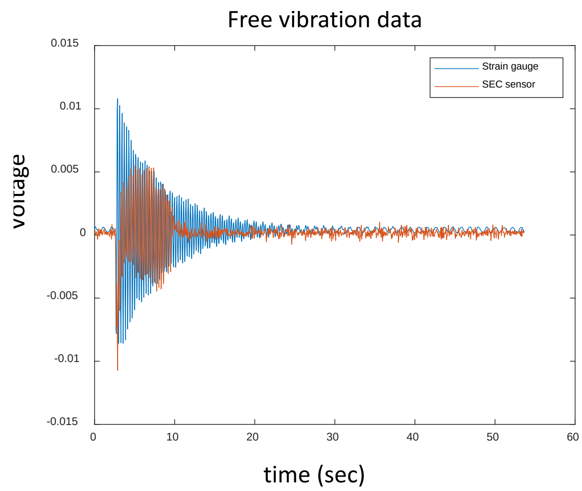
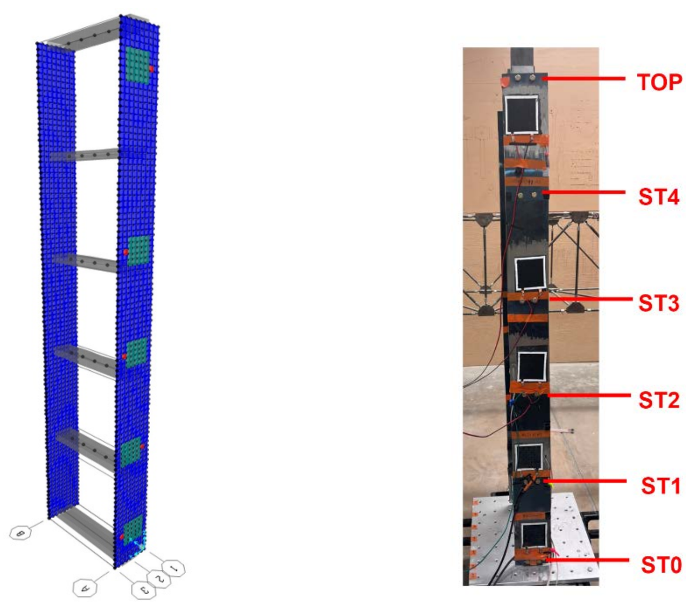


Figure: Free vibration data captured from SEC sensor and strain gauge using new sensor board

- UA conducted initial simulations and experimental tests on an existing shear building sensor network to investigate an possible data fusion method to reduce the noise from SEC network by adding a few low-noise strain gauges, particularly to improve output-only modal ID quality in terms of strain mode shapes. The following are the simulation and experimental setups of 5-SEC network of a shear building on a shake table.



a. Simulation in SAP2000 b. Experimental setup

Figure: Shear Building Sensor Network Setup

The NEXT-ERA method that uses cross-correlation functions between strain gauge signals (response) and SEC signals (response) is employed for output-only modal identification. The obtained mode shapes in the simulation setup show improved accuracy when additional strain gauge is utilized, compared to one when only SECs are used. The experimental results showed the promise of this method.

- USC began the deployment of SECs on a concrete bridge to detect and monitor cracks. Two flat SECs and one corrugated SEC were deployed alongside three resistance strain gauges (BDI strain transducer) on the bridge. The first figure below illustrates the bridge layout and the placement of these sensors. To assess traffic on the bridge, vehicle activity was observed over a 6-minute period, during which data was collected from all the sensors. In the second figure below, data from the three strain transducers are presented, with noticeable spikes indicating the times when light vehicles passed over the bridge. In the third figure below, on the other hand, depicts the data collected from the three SECs. Notably, the SECs did not identify light vehicle passages, likely because the strain induced by vehicles on the bridge was relatively low. Previous studies have shown that SECs are most effective for strains exceeding 25 microstrain. USC plans to conduct further investigations to enable the SEC to detect larger loadings on the bridge. Additionally, USC is in the process of setting up a Data Acquisition System (DAQ) from Arizona, which will be used in conjunction with the SECs on the bridge.

Figure: The bridge and the deployed sensors under the bridge.

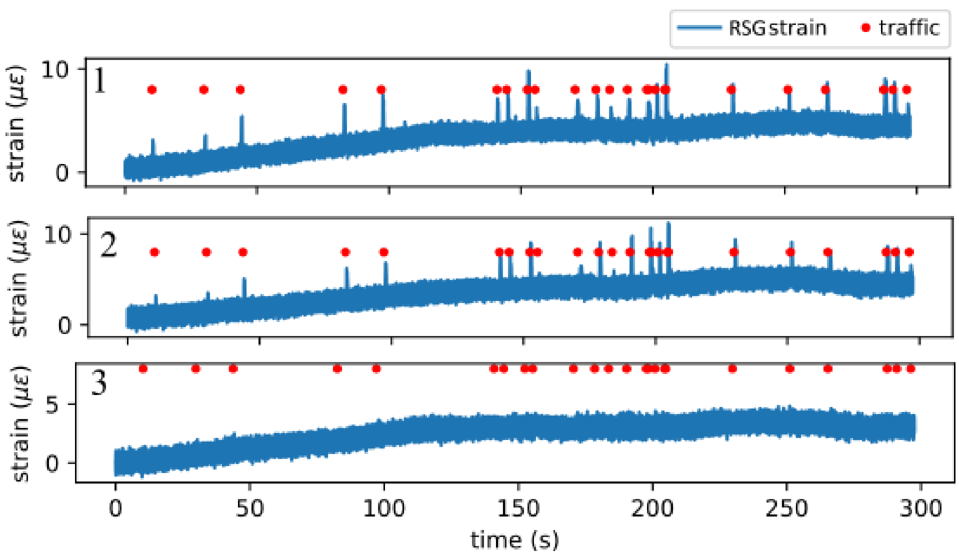


Figure: Illustrates the data collected from the three strain transducers.

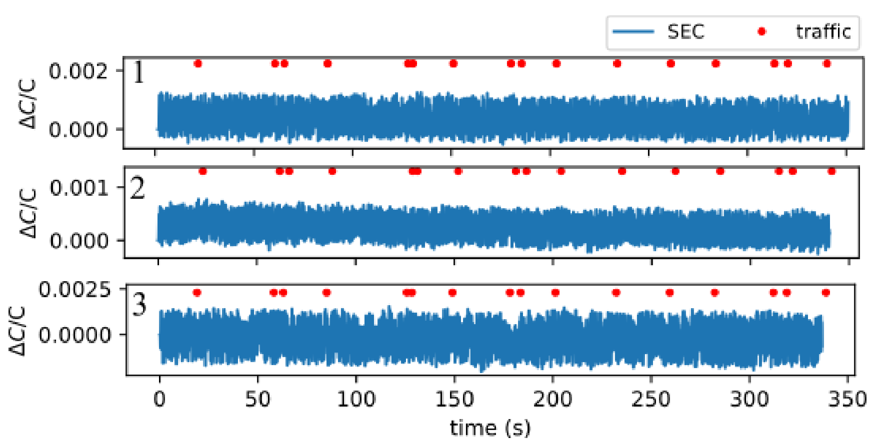


Figure: Data collected from the three SECs

Anticipated work next quarter:

- ISU will start working on a promotional video for the pooled fund project.
- KU will continue to collect and analyze data from wireless sensors.
- UA will continue testing the sensor network on both the experimental setups i.e., cantilever plate and shear building.
- USC will deploy the SECs with the DAQ from Arizona on the bridge.
- USC will continue to investigate cracks in concrete with SEC.

Significant Results:

- A 4-minute video summarizing results of the pooled-fund project.
- The amplification, phase balancing as well as shunt calibration were executed exceptionally well.
- The recorded signals from SEC sensor and strain gauge using new sensor board demonstrated proficiency of new sensor board in accurately collecting capacitance-based signals from SEC sensors.

Products (pooled fund sponsoring acknowledged):

Journal Publications

[11] Liu, H., Laflamme, S., and Kollosche, M., *Paintable Silicone-Based Corrugated Soft Elastomeric Capacitor for Area Strain Sensing*, Sensors. (2023)

[10] Liu, H., Laflamme, S., Li, H., Downey, A., Bennett, C., Collins, W., Ziehl, P., Jo, H., and Todsen, M., *Sensing Skin Technology for Fatigue Crack Monitoring of Steel Bridges: Laboratory Development, Field Validation, and Future Directions*, International Journal of Bridge Engineering and Management, invited inaugural contribution.

[9] Liu, H., Kollosche, M., Laflamme, S., Clarke, D. *Multifunctional Soft Stretchable Strain Sensor for Complementary Optical and Electrical Sensing of Fatigue Cracks*, Smart Materials and Structures (2023).

[8] Ogunniyi, E., Vereen, A., Downey, A., Laflamme, S., Li, J., Bennett, C., Collins, W., Jo, H., Henderson, A., and Ziehl, P. *Investigation of Electrically Isolated Capacitive Sensing Skins on Concrete to reduce Structure/Sensor Capacitive Coupling*, Measurement Science and Technology, 34(5), (2023).

[7] Liu, H., Laflamme, S., Taher, S., Jeong, J.-H., Li, J., Bennet, C., Collins, W., Eisenmann, D., Downey, A., Ziehl, P., Jo, H., *Investigation of Soft Elastomeric Capacitor for the Monitoring of Large Angular Motions*, Materials Evaluation (in press).

[6] Taher, S. A., Li, J., Jeong, J. H., Laflamme, S., Jo, H., Bennett, C., Collins, W. & Downey, A. R. (2022). Structural Health Monitoring of Fatigue Cracks for Steel Bridges with Wireless Large-Area Strain Sensors. *Sensors*, *22*(14), 5076.

[5] Jeong, J. H., Jo, H., Laflamme, S., Li, J., Downey, A., Bennett, C., Collins, W., Taherand, S., Liu, H. & Jung, H. J. (2022). Automatic control of AC bridge-based capacitive strain sensor interface for wireless structural health monitoring. *Measurement*, *202*, 111789.

[4] Liu, H., Laflamme, S., Li, J., Bennett, C., Collins, W. N., Eisenmann, D. J., Downey, A., Ziehl, P. & Jo, H. (2022). Investigation of textured sensing skin for monitoring fatigue cracks on fillet welds. *Measurement Science and Technology*, *33*(8), 084001.

[3] Liu, H., Laflamme, S., Li, J., Bennett, C., Collins, W. N., Downey, A., Ziehl, P, & Jo, H. (2021). Soft elastomeric capacitor for angular rotation sensing in steel components. *Sensors*, *21*(21), 7017.

[2] Liu, H., Laflamme, S., Zellner, E. M., Aertsens, A., Bentil, S. A., Rivero, I. V., & Secord, T. W. (2021). Soft Elastomeric Capacitor for Strain and Stress Monitoring on Sutured Skin Tissues. *ACS sensors*, *6*(10), 3706-3714.

[1] Liu, H., Laflamme, S., Li, J., Bennett, C., Collins, W., Downey, A., ... & Jo, H. (2021). Investigation of surface textured sensing skin for fatigue crack localization and quantification. *Smart Materials and Structures*, *30*(10), 105030.

Conference Proceedings

[6] Vereen, A. B., Downey, A., Sockalingam, S., & Laflamme, S. (2022, April). Large area capacitive sensors for impact damage measurement. In *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2022* (Vol. 12046, pp. 115-120). SPIE.
[5] Smith, C., & Downey, A. R. (2023). Additively Manufactured Flexible Hybrid Electronic Sensor for Discrete Fatigue Crack Detection. In *AIAA SCITECH 2023 Forum* (p. 2417).
[4] Ogunniyi, E. A., Liu, H., Downey, A. R., Laflamme, S., Li, J., Bennett, C., Collins, W., Jo, H. & Ziehl, P. (2023, April). Soft elastomeric capacitors with an extended polymer matrix for strain sensing on concrete. In *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2023* (Vol. 12486, pp. 262-270). SPIE.
[3] Liu, H., Laflamme, S., Zellner, E. M., Bentil, S. A., Rivero, I. V., Secord, T. W., & Tamayol, A. (2021, May). Corrugated Compliant Capacitor towards Smart Bandage Application. In *2021 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)* (pp. 1-6). IEEE.
[2] Vereen, A. B., Downey, A., Sockalingham, S., Ziehl, P., LaFlamme, S., Li, J., & Jo, H. (2021, March). Monitoring impact damage in composites with large area sensing skins. In *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2021* (Vol. 11591, pp. 336-344). SPIE.
[1] Liu, H., Laflamme, S., Li, J., Bennett, C., Collins, W., Downey, A., & Jo, H. (2021, March). Experimental validation of textured sensing skin for fatigue crack monitoring. In *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2021* (Vol. 11591, pp. 345-351). SPIE.

Invited Presentations

[8] Soft Sensing Technology for Fatigue Crack Discovery and Monitoring, University of Perugia, Seminar of the Intl Doctoral Program in Civil and Env. Eng., Nov. 11th 2022.
[7] *Tianjin University*, Tianjin, China, "Advanced sensing and computer vision for civil infrastructure monitoring and inspections. " November 10, 2022.
[6] Liu, H., Laflamme, S., Li, J., Bennett, C., Collins, W., Downey, A., Ziehl, P., & Jo, H., Robust Wireless Skin Sensor Networks for Long-Term Fatigue Crack Monitoring of Bridges, Mid-Continent Transportation Research Symposium, Ames, IA, Sept. 15 2022.
[5] *Harbin Institute of Technology*, Harbin, China, "Advanced sensors and computer vision for civil infrastructure monitoring and inspections. " August 1, 2022.
[4] *Shenzhen University*, Shenzhen, China, "Advanced sensors and computer vision for civil infrastructure monitoring and inspections. " January 4, 2022.
[3] *The SIR Frontiers Seminar Series, South China University of Technology*, Guangzhou, China, "Advanced sensors and computer vision for civil infrastructure monitoring and inspections. " August 12, 2021.
[2] Field Deployable Textured Sensing Skin for Monitoring of Surface Strain, webinar (Department of Civil & Environmental Engineering), U. Mass. Lowell, April 19th 2021.
[1] Field Deployable Sensing Skin for Monitoring of Surface Strain, webinar, Electric Power Research Institute, Nov 5th 2020.

Circumstance affecting project or budget (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). N/A