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) Quarter 3 (July 1 – September 30, 2023) **X** Quarter 4 (October 1 – December 31, 2023)	
Project Title: Robust wireless skin sensor networks for long-term fatigue crack monitoring of bridges		
Project Manager: Khyle Clute	**Phone:** 239-1471	**E-mail:** khyle.Clute@iowadot.us
Project Investigator: Simon Laflamme	**Phone:** 294-3162	**E-mail:** laflamme@iastate.edu
Lead Agency Project ID:	**Other Project ID (i.e., contract #** Addendum 736	**Project Start Date:** May 15, 2020
Original Project End Date: May 14, 2023	**Contract End Date:** May 14, 2024	**Number of Extensions:** 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)	$400,069	95% of Phase I

Quarterly Project Statistics:

Total Project Expenses This Quarter	Total Amount of Funds Expended This Quarter	Percentage of Work Completed This Quarter
$19,755		

Project Description:

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

- TAC meeting on Dec 13th 2022.
- ISU started to write the final report for the TPF, and continued to work closely with USC on archiving key results in relevant academic journals.
- KU conducted tests on the new sensor board integrated with Xnode technology, aiming to wirelessly collect data from the SEC sensor.The Xnode was subjected to vibration to activate its event-triggering data collection feature for the SEC sensor. Upon being powered on, the sensor board automatically undergoes a balancing and shunt calibration process, which lasts approximately 40 seconds. After 40 seconds, displacement was applied to a steel plate, allowing it to undergo free vibration. This free vibration data was then automatically recorded by the Xnode and transmitted to cloud storage through the Gateway node. The figure below illustrates a specific recorded signal, with a zoomed-in view on the right.

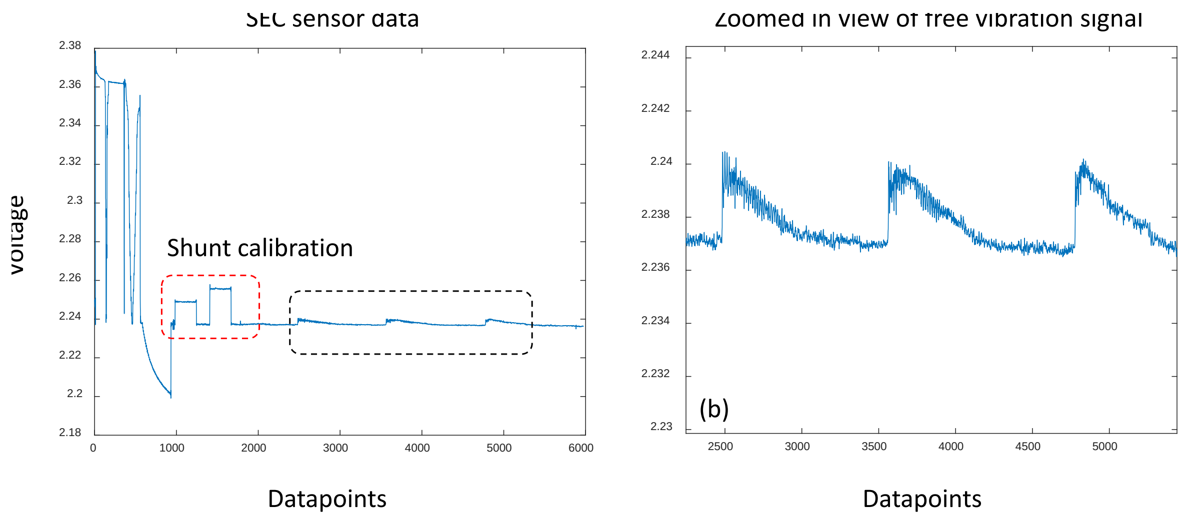
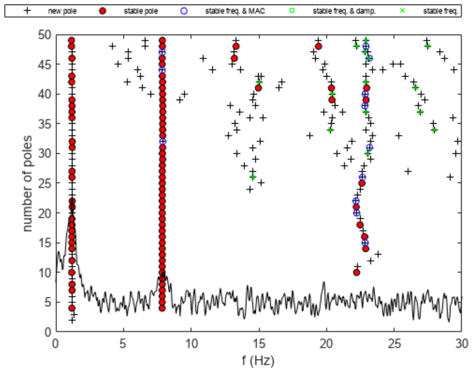


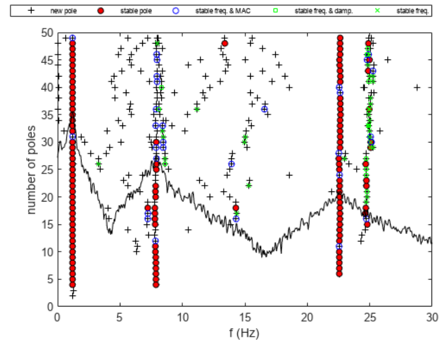
Figure: Recorded Signal from SEC Sensor Using Xnode Technology

From the figure, it's evident that the recorded signal effectively captured the shunt calibration process, which is crucial for converting the voltage signal into actual capacitance. The two plateaus in the signal are critical in estimating the voltage variation resulting from a 3pF change in the SEC sensor. However, the sensor board did not adequately capture the free vibration. In the experiment, a total of three consecutive free vibrations were applied. The data from the SEC sensor appears to have significant drift embedded in the data, which may be filtered out through post-processing.

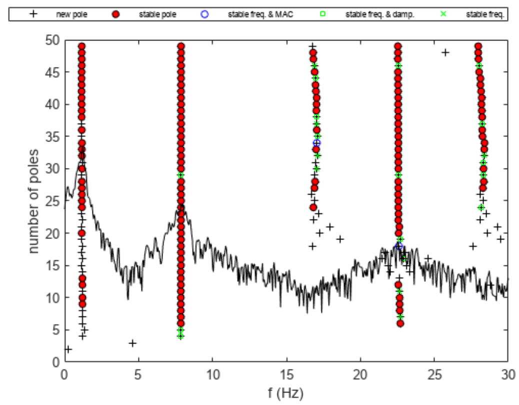
- UA team developed a finite element model for a cantilever plate setup on a shake table in ANSYS to conduct a simulation study on the cross-correlation-based system identification method. The objective is to use a heterogeneous sensor network of low-noise strain gauges in a SEC network to improve output-only strain-based modal ID quality while taking advantage of the SEC network. For that reason, the cross-correlation between strain gauge signal and SEC signal is used as an impulse response in NExT-ERA-based modal analysis. The obtained natural frequencies and mode shapes from modal analysis show higher accuracy when only one strain gauge is utilized in a 5-SEC network. A comparison shown in the figure below shows that when using only SEC, the 3rd natural frequency could not be estimated. On the other hand, by using only 1 strain gauge signal along with 5 SEC signals, we could estimate all first three natural frequencies distinctively.



a. Only using a 5 SEC network



b. Using only 5 strain gauges



c. Using 1 strain gauge and 5 SEC (proposed cross-correlation method)

Figure: Stabilization diagram obtained from output-only strain-based modal

- USC initiated the deployment of Soft Elastomeric Capacitors (SECs) on a bridge for crack detection and monitoring. To support long-term SEC deployment, the development of a deployable data acquisition system (DAQ) was prioritized. This compact DAQ, capable of storing capacitance data, comprises a sensor board from the University of Arizona, a data logger, and a battery, as illustrated in the Figure below. The DAQ's functionality was verified through a quasi-static laboratory test, with the resulting capacitance data also presented in the Figure. This system will be operational for data collection from the bridge through the first quarter of 2024.

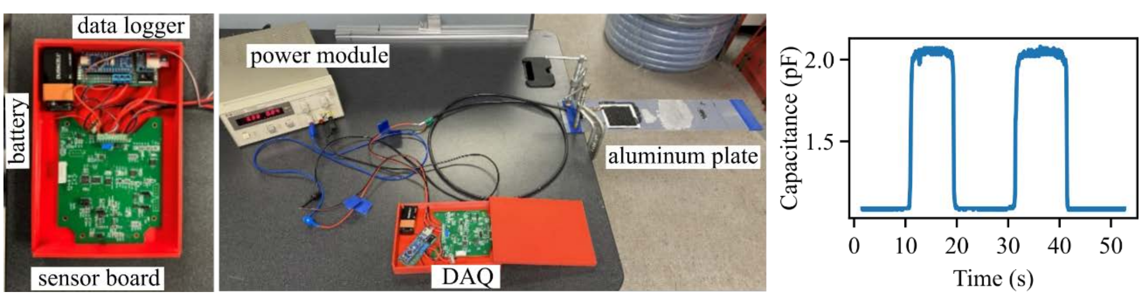


Figure: DAQ along with typical test results.

- USC also initiated a study on the efficacy of SECs on various types of concrete surfaces to understand how surface texture affects SEC measurements. The study involves testing SECs on concrete surfaces with different finishes, including grooved, indented, rough, and smooth textures, as depicted in the Figure below. This research is slated to continue through the first quarter of 2024, aiming to provide insights into the adaptability of SEC technology across diverse concrete surface conditions.

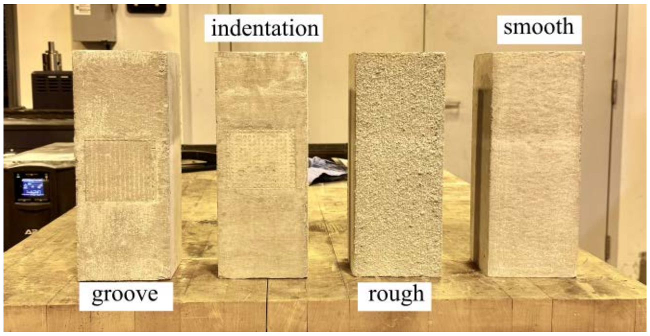


Figure: Different concrete surface textures under test.

Anticipated work next quarter:
- ISU will continue working on the TPF report.
- KU will conduct further investigation into the breakout box and the new sensor board regarding the drift in the data.
- UA will continue testing the sensor network on both the simulated and experimental setups of the cantilever plate and later on the shear building setup.
- USC will deploy the SECs with the DAQ from Uof Arizona on the bridge.

Significant Results:
- The amplification, phase balancing as well as shunt calibration were executed exceptionally well when Xnode and breakout box were used in conjunction with the new sensor board.
- The recorded signals from SEC sensor through the breakout box and the Xnode wireless sensor platform appear to capture the free vibration data but include some drift in the signal.
- Simulation results from the finite element model of the cantilever plate setup on the shake table show prominence of the proposed cross-correlation method of a heterogenous sensor network of few strain-gauges in a network of SEC to improve system ID quality.

Products (pooled fund sponsoring acknowledged):

Journal Publications

[12] Vereen, A., Downey, A. R., Sockalingam, S., & Laflamme, S. (2023). Validation of large area capacitive sensors for impact damage assessment. *Measurement Science and Technology*, *35*(3), 035106.

[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

[8] Liu, H., Kollosche, M., Laflamme, S., and Clarke, D. (2023, September). Elastomeric transducers for electric and optic sensing performance for an in-situ Structural Health Monitoring. In *Multifunctional Materials and Metamaterials I*. IWSHM.

[7] Taher, S. A., Li, J., Jeong, J. H., Laflamme, S., Jo, H., Bennett, C., Collins, W., Liu, H., Downey, A.. & Shaheen, M. (2022, April). Long-term field monitoring of fatigue cracks for steel bridges with wireless large-area strain sensors. In *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2022* (Vol. 12046, pp. 20-28). SPIE.

[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

[9] Nishat, T, Jo, H, Li, J, Laflamme, S, Downey, A, Bennett, C, Collins, W, Taher, S, Liu, H. (2023) Investigation of heterogeneous strain data fusion for output-only system identification. Engineering Mechanics Institute Conference, Atlanta, Georgia, June 6-9

[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