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, 2022) **x** Quarter 4 (October 1 – December 31, 2022)
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, 2023	**Number of Extensions:**

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)	$300,213	90% of Phase I

Quarterly Project Statistics:

Total Project Expenses This Quarter	**Total Amount of Funds Expended This Quarter**	**Percentage of Work Completed This Quarter**
$36,356		

Project Description:

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

- TAC meeting on Dec 13th 2022.
- ISU refined the fabrication process of silicone-based SECs for direct-paintable applications. Sensors were produced and characterized in a laboratory environment. The figure below compares free-vibration data from an SEC bounded to a fiberglass plate directly on a painted conductive solution, vs the silicone-based SEC that can be directly painted. Data showed that the silicone SEC is more noisy.

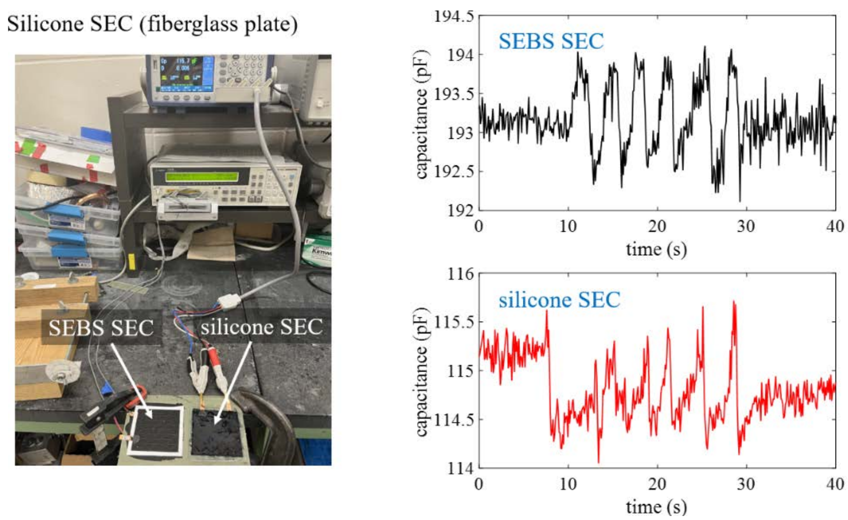


Figure: comparison of directly adhered SEC and painted silicone SEC

- ISU refined the fabrication process by incorporating PELCO conductive glue. Additional tests were performed on the plate and capacitance data compared against strain data measured by a strain gauge. A typical time series is shown below. Results show good agreement between both sensors.

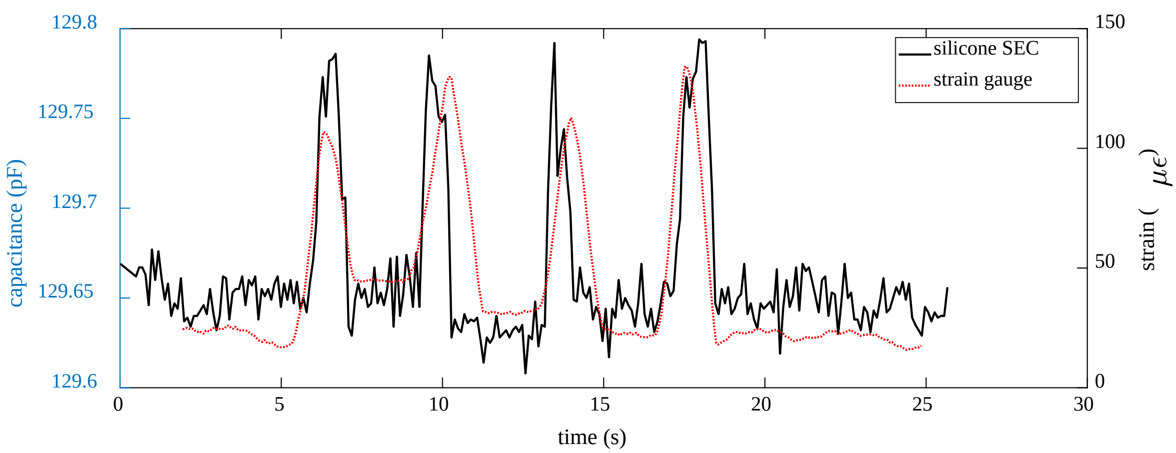


Figure: comparison of silicone SEC vs strain gauge data

- KU fixed the power issue on the bridge; the wireless sensor network is now working very well. Measurement threshold fhas been increased for even-trigger sensing mode to save power.
- KU investigated the new sensor boards and Wheatstone bridge using the laboratory specimen shown in the Figure below. The laboratory specimen contains four new SECs and two strain gauges.

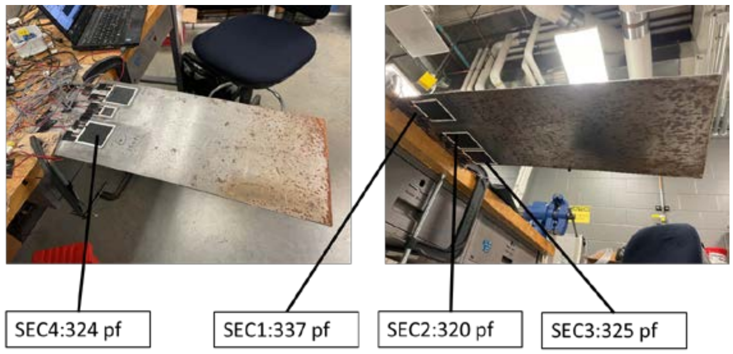


Figure: The specimen (cantilever steel plate) with new SECs and strain gauges.

One of the strain gauges was connected with NI-DAQ for comparison purposes, while the other one was connected with the new Wheatstone bridge. The test was run by applying a load at the tip of the cantilever steel plate, and data was recorded. The figure below compares the time histories of the strains obtained from NI-DAQ and the new Wheatstone bridge. The time histories are almost identical, indicating the effectiveness of the new Wheatstone bridge. The response from the SECs will be measured during the next quarter and data analyzed.

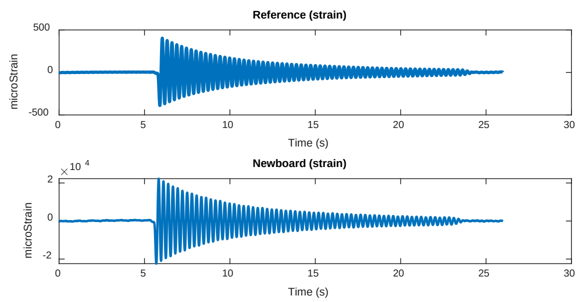


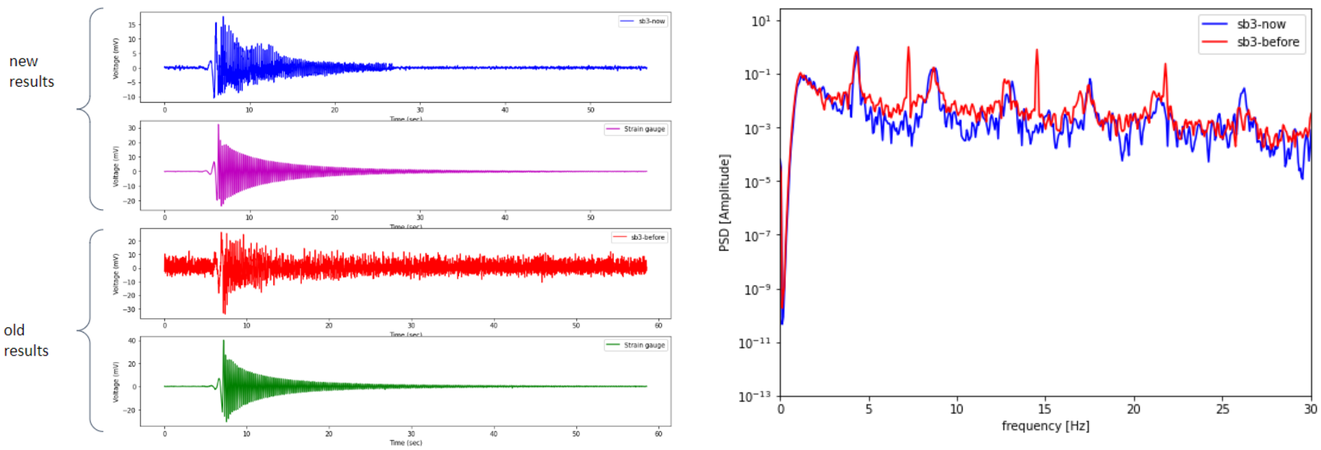
Figure: the time histories of the strains from NI-DAQ and the new Wheatstone bridge.

- UA received the shop-manufactured 15 sensor boards. The following shows is a sample of the manufactured boards. After initial testing it was found that most of the boards were having issues related to ADC not working properly. Replacing the ADC solved the problem.

Figure: one manufactured board.

- UA improved some bridge balancing features for the new boards. In the earlier version of the automated board, the full range of digital potentiometer was not used, but covered only quite narrow range of nominal capacitance of the SEC. If the SEC nominal capacitance is around 50 pf higher or lower than the reference capacitance, early version could result in the out-of-balance of the bridge, which may cause significant noise issue. The software code is updated to include the two-step balancing (i.e. coarse and fine balancing) to cover a wider SEC nominal capacitance range without sacrificing the balancing precision.
- The second update was associated with some unexpected harmonic noisy peaks (around 7 hz, 15 hz, 21 hz), which were visible during the free vibration test. UA found that powering down the microcontroller after

balancing and calibration (a sleep code is added at the end of bal&cal) eliminates the noisy peaks and reduces the noise level significantly. The following shows a comparison between before and after the sleep code was implemented in the operating software.



- USC investigated the performance of painted SEC and epoxy-adhered SEC on steel joints in response to slight offsets at the joints. The Figure below shows the response of the painted SEC (a), epoxy-adhered SEC (b), and compares the variation in capacitance (c). The epoxy-adhered SEC was shown to be more stable and sensitive when compared to the painted-on SEC.

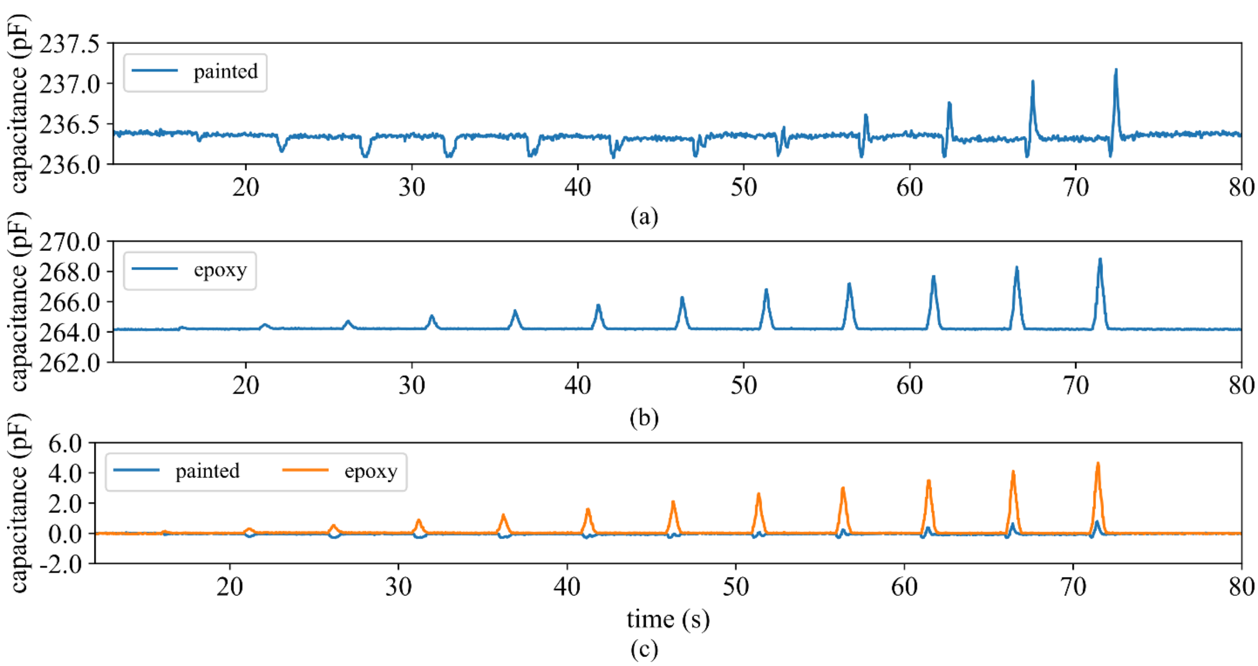


Figure: Capcitance change from joint displacement of angle bar measured by : (a) painted SEC, and; (b) epoxy-adhered SEC.

Anticipated work next quarter:

- ISU will improve the silicone-based designed for directly paintable SECs.
- KU will work with the Arizona team to improve results using the new sensor boards and deploy the new sensor boards to the field when they become ready.
- KU plans to remove the SECs on the bridge and measure the current crack lengths.
- UA will continue testing the new boards, including on the building testbed.
- USC will continue testing painted SECs with mixes prepared by ISU.

Significant Results:

- Paintable SEC mix showed great promise at replacing the SEC mix.
- Wireless sensor network on the bridge is now fully operational, and data are successfully being collected.
- Bridge balancing has been improved over a wide range of nomial capacitance of SECs, and the problem with harmonics has been mitigated.

Products (pooled fund sponsoring acknowledged):

Journal Publications (published/in press)

[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

[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