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** **x** Quarter 1 (January 1 – March 31, 2023) Quarter 2 (April 1 – June 30, 2023) 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		
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 31, 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)	$330,422	92% of Phase I

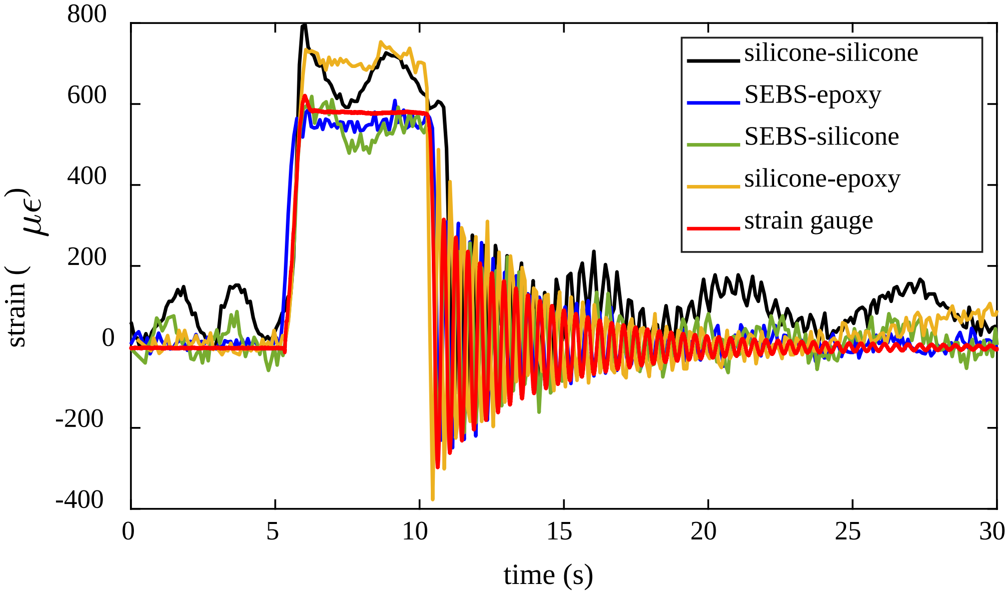
Quarterly Project Statistics:

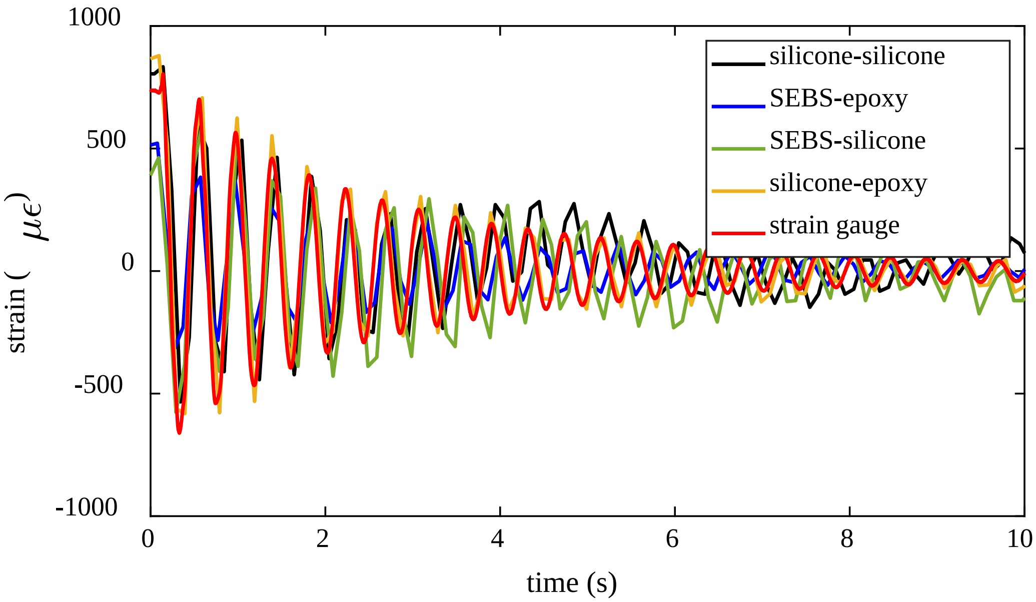
Total Project Expenses This Quarter	Total Amount of Funds Expended This Quarter	Percentage of Work Completed This Quarter
$69,734		

Project Description:

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

- TAC meeting on Dec 13th 2022.
- ISU studied the paintable version of the SEC made of silicone. Vibration tests were performed on a simply-supported plate. The objective was to compare strain measured by the paintable SEC ("silicone-silicone"), versus traditional traditional sensor (SEBS-epoxy), an epoxied version of the paintable SEC ("silicone-epoxy"), and the traditional sensor adhered with a layer of silicone instead of epoxy ("SEBS-silicone"). Both plots below show typical results. Overal, the paintable sensor showed performance comparable to that of the strain gauge, yet is more noisy. More research is required to refine the fabrication process and deployment procedure.





- The wireless sensor installed on a steel highway bridge in Kansas City, KS, has been working well, and the data has been continuously collected.

- KU has been continuing to collect and analyze data from the wireless sensors. Specifically, up-to-date CGI from mid-March 2022 to mid-march 2023 was computed for fatigue crack monitoring. The mean and standard deviation of the CGIs are shown in the figure below. Overall, the CGIs remain constant, showing that the crack size remains constant.

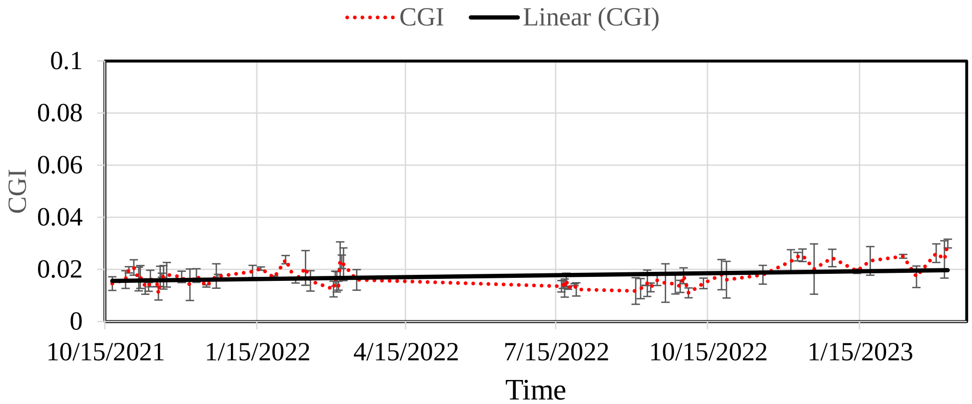
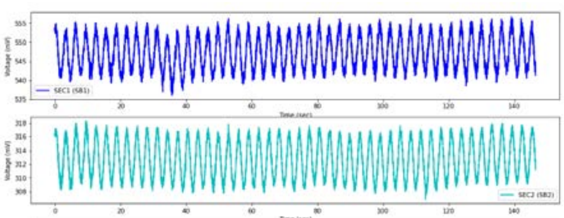
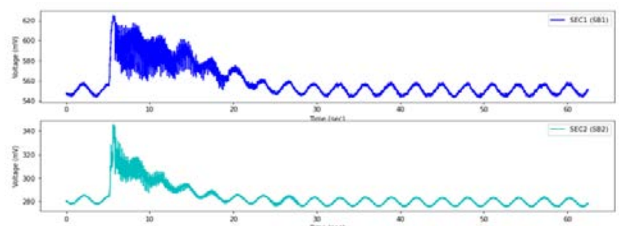


Figure: The mean and standard deviation of the CGI from mid-March 2022 to mid-March 2023.

- KU started to investigate the impact of the environment, such as temperature, on CGI. The daily average temperatures for the monitoring period were obtained from the Weather Ground website, specifically from the station of Kansas City, MO, Weather History. The station is near the steel highway bridge containing the wireless sensors.
- UA addressed the unexpected noise issue during the simultaneous test of multiple sensor boards/SECs. A low-frequency harmonic waves have always been seen in the signal if multiple sensor boards were tested simultaneously. With the more number of sensor boards were used, the more harmonic waves with higher frequencies were observed. The figures below show the presence of low-frequency waves during simultaneous tests of two and three sensor boards respectively.



a) Two SEC signals during a static test (no excitation)



b) Two SEC signals during a dynamic test (free vibration)

Figure: Two SEC signals when the sensor boards are being tested simultaneously (before)

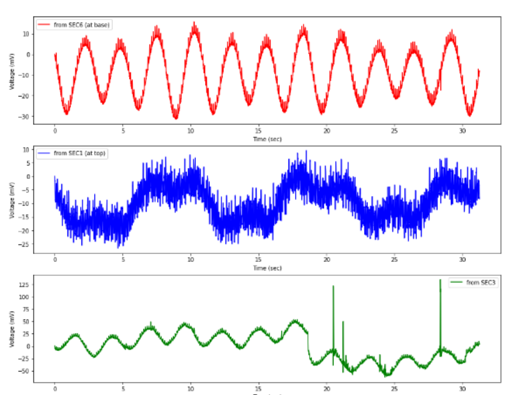
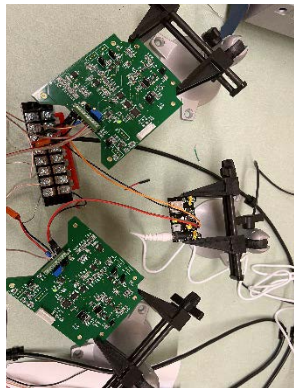


Figure: Three SEC signals during a static test (no excitation) when the sensor boards are being tested simultaneously (before)

The issue was resolved by replacing the grounding interface from a breadboard to a screw terminal, of which the breadboard was being used as an interface to connect all the ground points to earth ground. The reason may be attributed to the fact that the breadboard may provide some poor connection of ground wires and possible EM interference, while the screw terminal provide the complete connection of the wires. Below are three different test setups for the simultaneous test of the sensor boards i.e. two sensor boards with separate battery power supplies, two sensor boards with common power supply, and three sensor boards with common power supply.

a) Separate battery power supply for 2 boards

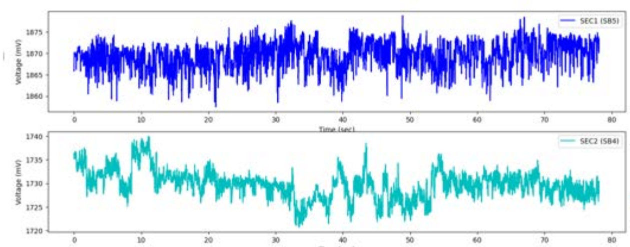


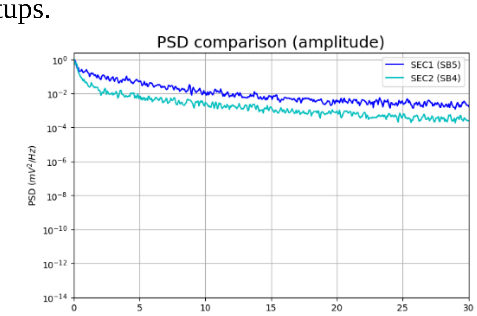
b) Common DC power supply for 2 boards

c) Common DC power Supply for 3 boards

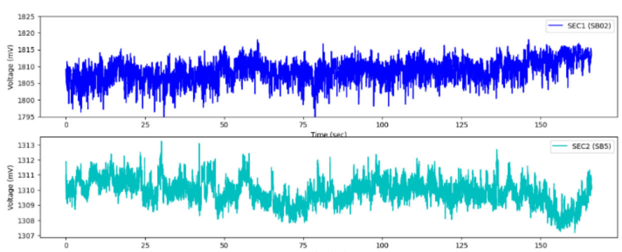
Figure: Different test setup for the simultaneous test of sensor boards

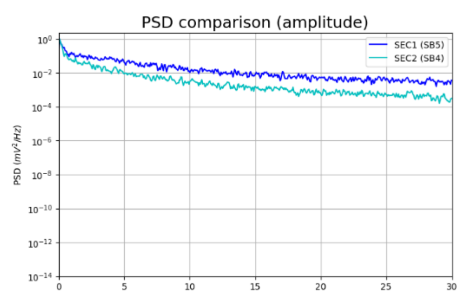
The below time history and frequency plots show that there is no unwanted harmonic noise present during the simultaneous test of sensor boards in different test setups.



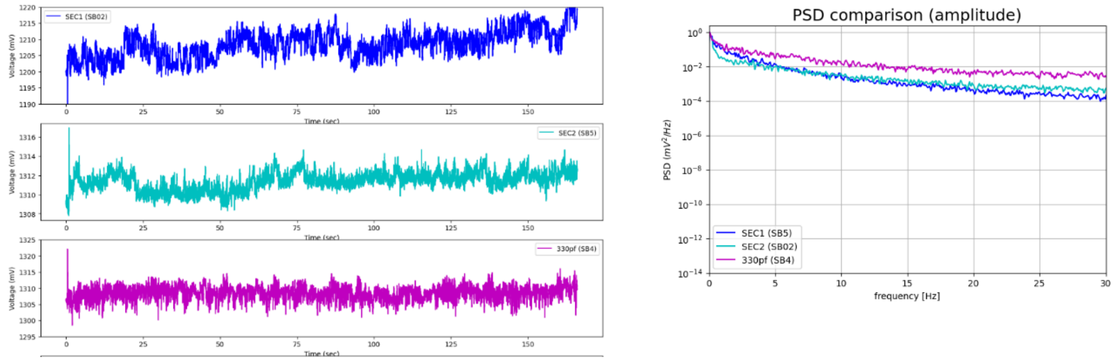


a) Separate battery power supply for 2 boards





b) Common DC power supply for 2 boards



c) Common DC power supply for 3 boards

Figure: Time histories and power spectral plots of SEC signal during the simultaneous test of sensor boards with no excitation (current)

- UA addressed the frequency differences of two strain gauges (one connected to the sensor board and the other as a reference connected to the NIDAQ module)

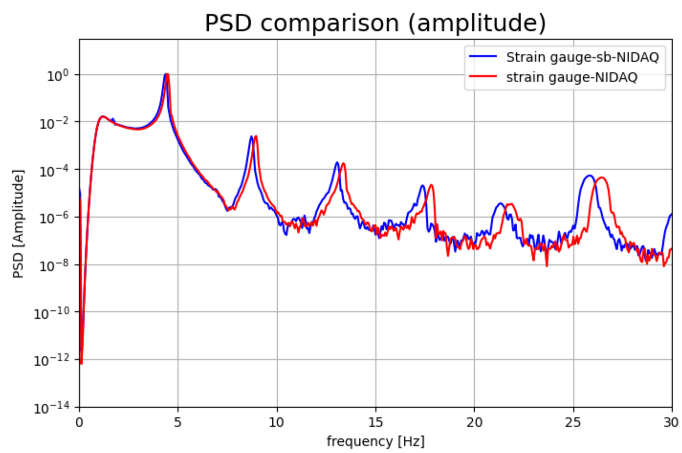


Figure: The power spectral of two strain gauges (before)

It was found that the frequency difference was due to the different clock speeds of two different NIDAQ modules. By utilizing the same clock, the issue could be resolved. Figure below shows the perfectly synchronized strain gauge frequencies with no time delay.

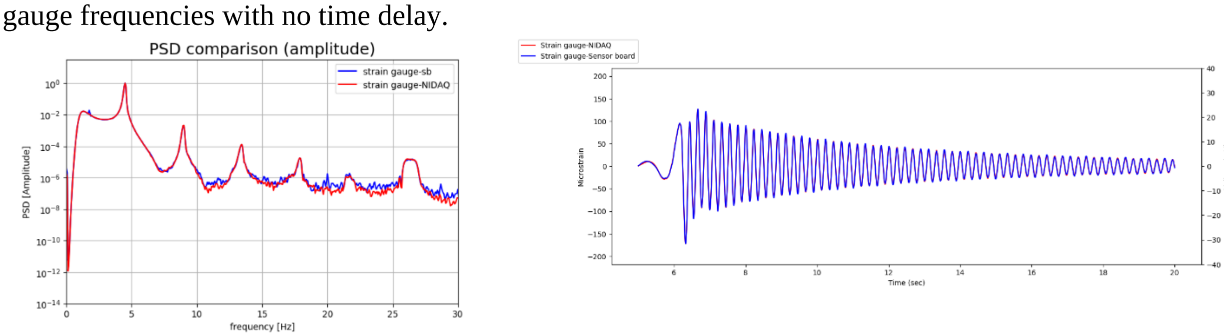


Figure: The power spectral and time histories of two strain gauges (current)

- USC began testing the extended SEC with an extra layer of SEBS on concrete for crack monitoring and quantification. This preliminary test used unreinforced concrete to detect cracks using the sensor. The concrete specimen was loaded using the four-point bending shown in the figure below and displaced to 0.01, 0015, and 0.02 inches using the dynamic testing system. Digital image correlation was also used on the surface of the SEC during the loading process to monitor strain. The displacement against capacitance change on the SEC and the corresponding strain values from the SEC and DIC were recorded.

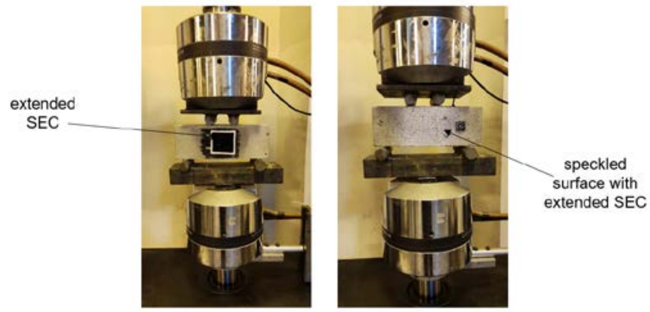
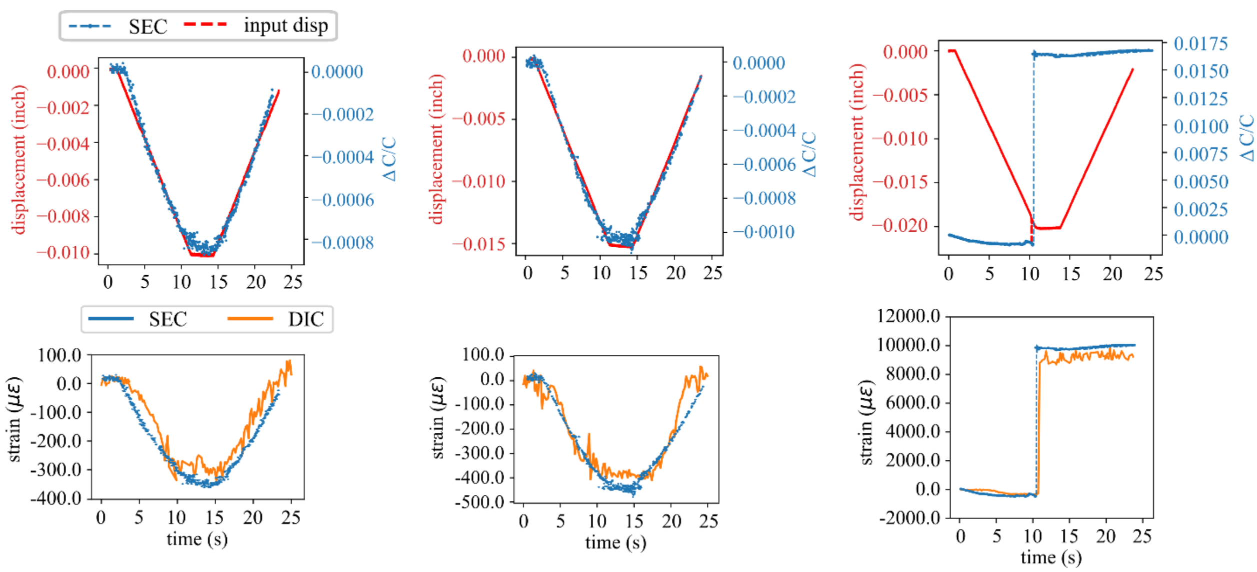


Figure: Loading setup for the concrete specimen

Results reported below show that the SEC responds well to loading, as seen in the similarity in strain by the SEC and DIC. During the 0.02-inch displacement, the specimen cracked at about 0.018-inch displacement, seen in the jump at around 11 secs, the crack point in figure c.



(a) 0.01 inch displacement
no crack

(b) 0.015 inch displacement
no crack

(c) 0.02 inch displacement
crack formed

Figure: Results showing capacitance change and strain data from loading at (a) 0.01 displacement; (b) 0.015 displacement, and; (c) 0.02 displacement where crack occured

Anticipated work next quarter:

- ISU will keep improving the silicone-based designed for directly paintable SECs.
- KU will continue to collect and analyze data from the wireless sensors.
- KU will continue to investigate the impact of the environment, such as temperature, on CGI.
- UA will continue testing the sensor boards, including on the building testbed.
- USC will continue investigation on concrete using the upgraded SEC.

Significant Results:

- Paintable SEC mix characterized.
- Issues associated with the sensor board have been resolved.
- Up-to-date CGI now available.

Products (pooled fund sponsoring acknowledged):
Journal Publications

[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
Corinne Smith and Austin R.J. Downey. Additively manufactured flexible hybrid electronic sensor for discrete fatigue crack detection. In AIAA SCITECH 2023 Forum. American Institute of Aeronautics and Astronautics, jan 2023. doi:10.2514/6.2023-2417

[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