TRANSPORTATION POOLED FUND PROGRAM
QUARTERLY PROGRESS REPORT

Lead Agency (FHWA or State DOT): ____Kansas 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 #	**Transportation Pooled Fund Program - Report Period:**
TPF-5(328)	☐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:
Strain-based Fatigue Crack Monitoring of Steel Bridges using Wireless Elastomeric Skin Sensors

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Lead Agency Project ID:	**Other Project ID (i.e., contract #):**	**Project Start Date:**
RE-0699-01		**9/2015**
Original Project End Date: **Multi-year project**	**Current Project End Date:** **8/31/2018**	**Number of Extensions:** **N.A.**

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	Total Percentage of Work Completed
$405,000	**$ 9,059.76**	**5%**

Quarterly Project Statistics:

Total Project Expenses This Quarter	Total Amount of Funds Expended This Quarter	Percentage of Work Completed This Quarter
$ 9,059.76	**$ 9,059.76**	**5%**

Project Description:
The main objective of this proposed research is to *provide state DOTs a practical and cost-effective long-term fatigue crack monitoring methodology using* ***a wireless elastomeric skin sensor network***. This research is intended to demonstrate the value-added of fatigue crack monitoring of steel bridges using wireless skin sensors over the traditional bridge inspection.

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

1. Project Kickoff Meeting:

The project kickoff meeting was held on October 5, 2015 via teleconference. Participants include Justin Ocel (FHWA), Ping Lu (IaDOT), Guozhou Li (PennDOT), Lianxiang Du (TxDOT), Wes Kellogg (OkDOT), Karl Johnson (MnDOT), Tom Koch (NCDOT), Simon Laflamme (ISU), Hongki Jo (U of Arizona), William Collins (KU), Caroline Bennett (KU), Xiangxiong Kong (KU), and Jian Li (KU).

2. Site visit to Iowa State University:

The project team paid the first site visit to Iowa State University on November 5 and 6, 2015. The KU team (Jian Li, Caroline Bennett, William Collins, and Xiangxiong Kong) and UA team (Hongki Jo) had meetings and technical discussions with ISU team (Simon Laflamme) and IaDOT representatives (Ping Lu and Michael Todsen). The group also toured Dr. Laflamme's laboratory where the Soft Elastomeric Capacitor (SEC) sensors are fabricated and other facilities at ISU.

3. ISU progress:

Fatigue crack sensors are to be produced with an approximate thickness of 200-400 μm to enhance the mechanical robustness under harsh environment. The anticipated number of sensors is 150 to 200.

Soon after the project began, the manufacturer of titania used in the production of the sensor stopped selling the nanofiller that had previously been used in manufacturing the sensors. ISU found another supplier. The new titania showed different dielectric properties, which resulted in lower initial capacitance values C_0. While there was no initial requirement on C_0, it was agreed that maintaining a value in the ranges of 800 to 1000 pF was more important than the agreed thickness. ISU reduced the thickness of the sensors in order to compensate for the lower permittivity of the new titania. It is now in the range 100-200 μm.

Table 1 – produced sensors

Sensor	Date cast:	Capacitance (pF)	Dielectric Thickness (mm)	std dev
1	11/29/2015	926	0.182	0.0085
2	11/29/2015	959	0.159	0.0101
3	11/29/2015	942	0.169	0.0055
4	11/29/2015	868	0.187	0.0184
5	12/1/2015	975	0.159	0.0104
6	12/1/2015	852	0.174	0.0080
7	12/1/2015	883	0.175	0.0108
8	12/1/2015	877	0.172	0.0078
9	12/1/2015	860	0.173	0.0047
10	12/1/2015	921	0.161	0.0114
11	12/16/2015	897	0.169	0.0156
12	12/16/2015	900	0.169	0.0086
13	12/16/2015	876	0.178	0.0231
14	12/16/2015	875	0.171	0.0039
15	12/16/2015	870	0.159	0.0097
16	12/16/2015	815	0.179	0.0076
17	12/17/2015	888	0.168	0.0106
18	12/17/2015	830	0.173	0.0089
19	12/17/2015	855	0.167	0.0067
20	12/17/2015	839	0.179	0.0076
21	12/17/2015	907	0.158	0.0071
22	12/17/2015	868	0.162	0.0097
23	12/17/2015	807	0.172	0.0075
24	12/18/2015	857	0.176	0.0070
25	12/18/2015	851	0.172	0.0091
26	12/18/2015	951	0.142	0.0047
27	12/18/2015	882	0.158	0.0082
28	12/18/2015	916	0.159	0.0061
29	12/18/2015	879	0.166	0.0052
30	12/18/2015	822	0.181	0.0039

The sensor's production schedule was set to 15 sensors per month starting November 2015. The objective of 30 sensors by December 31st was attained. They are listed in Table 1. Technical support from ISU (Task 3) is being provided to KU on a continuous basis, as well as discussion and feedback (Task 4).

4. UA Progress:

The University of Arizona team has been focused on the design, implementation, and testing of the data acquisition (DAQ) board for the SEC sensor. The DAQ board is used for converting capacitance change of the sensors produced by strain change under deformations caused by cracking, into readable analog voltage signals, so that the Imote2 platform can digitize and wirelessly transmit the signals for further processing. Two types of AC Wheatstone bridge have been employed and simulated for function verification. The board has been fabricated for Imote2 platform and its performance has been partially tested. At this point, the DAQ board shows a sensitivity of 303 mV/pF and RMS noise as low as 5mV (0.0165pF) with conventional capacitors (variable).

5. KU Progress:

Before the wireless DAQ board becomes ready from the UA team, the KU team has been utilizing an off-the-shelf wired data acquisition system (PCAP02) to take capacitance readings from the SEC sensor. To enhance data quality and minimize the noise level of measurement, improvements have been made by trimming down all the wires in the aluminum housing, and using a surface mount ceramic capacitor as the reference capacitor. Test results showed that the modifications reduced the noise levels and improved signal stability.

Several compact tension (CT) specimens have been fabricated for small scale testing to monitor fatigue cracks using the SEC sensor under cyclic loading. A Crack Opening Displacement (COD) gauge has been purchased and calibrated for measuring real-time fatigue crack growth of the specimen during testing. These tests are part of the small-scale validation tests for the SEC sensors for in-plane fatigue crack detection.

Anticipated work next quarter:

ISU: The objective of the next quarter is to produce 45 additional sensors, for a total of 75 sensors. The production of sensors will continue until KU provides results from testing, which could lead to additional optimization (Task 2). Technical support (Task 3) will continue to be provided to KU, as well as discussion and feedback (Task 4).

UA: Focus will be placed more on improving the noise performance and resolution of the DAQ board by optimizing the board circuitry. The performance of the DAQ system will be tested with the SEC skin sensors to be used for fatigue crack monitoring. The goal is to be able to measure a capacitance change of 1 pF with noise level under 5%, such that fatigue crack can be detected in early stage (< 1 in).

KU: Small scale testing will be carried out using CT specimens. Both capacitance change and crack size will be continuously measured during the tests. The tests with CT specimens don’t have the same constraint that real bridge elements have; therefore, focus will be placed on loading protocols for the CT specimens to make sure realistic fatigue cracks are generated.

Significant Results:

1. Design of the DAQ system for wireless sensing platform:

The block diagram of the DAQ system is shown in Fig. 1. The DAQ system consists two parts: the first part is the capacitive strain sensor board (C-strain Board) to convert the capacitance (strain) change from the skin sensor into analog voltage, and the second part is SHM-DAQ board of the Imote2 which digitizes the analog voltages. Fig. 2 shows the PCB design and the fabricated prototype of the C-Strain board.

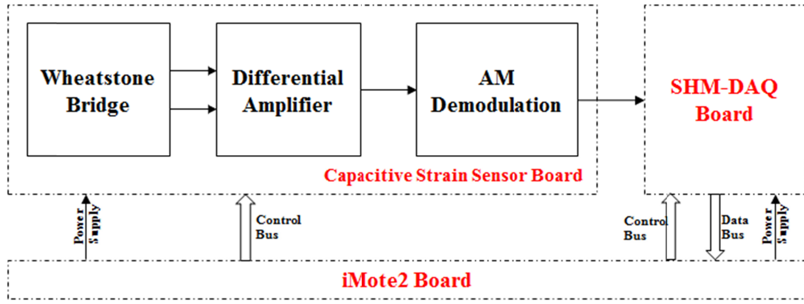


Fig. 1 Diagram of the DAQ system.

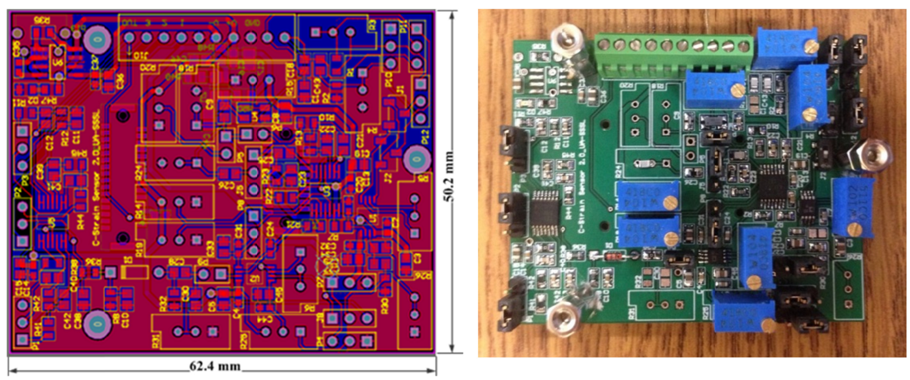


Fig. 2 PCB design and the fabricated C-strain board.

2. Simulation results of the C-strain Board of the DAQ system.

The C-strain board employs an AC Wheatstone bridge and AM demodulation circuitries. Fig. 3 shows the AC Wheatstone bridge and the external excitation AC source waveform currently used in the C-strain board. Fig. 4 shows the demodulation and low-pass filter (LPF) circuitry and the simulation result of the final output of the C-strain board.

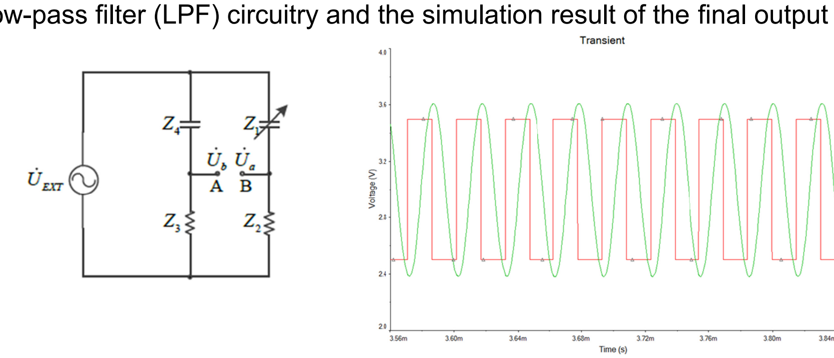


Fig. 3 The AC Wheatstone bridge and the waveforms used in C-Strain board.

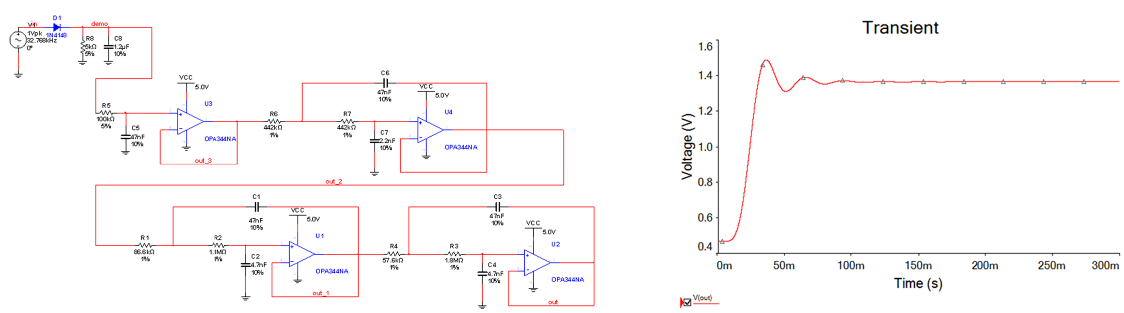


Fig. 4 Part of C-strain circuitry and the simulation result of the finally output of the circuitry.

3. Preliminary test results of the DAQ system.

Based on the design and simulation, a prototype of the C-strain sensor was developed and tested at the University of

Arizona. Fig. 5 shows the test field. Fig. 6 gives waveforms of the test results which show the amplitude change according to adding the 6.8 pF capacitance. By using the configuration in Fig. 5, the linearity was demonstrated for the C-strain sensor according to the preliminary test results shown in Fig. 7. In the test, 330pF nominal capacitance was used, and the capacitance change was +1 pF to +6.8 pF (change lower than 3%). Test results show the sensitivity of the C-strain sensor about 303mV/pF. Following noise tests show the RMS noise can be as low as 5mV (0.0165pF).

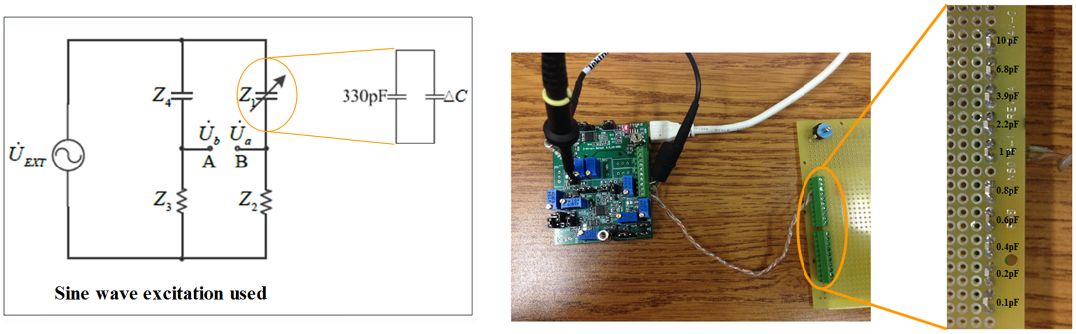


Fig. 5 Test setup for the C-strain sensor (left is the AC Wheatstone bridge configuration used in the sensor for the test).

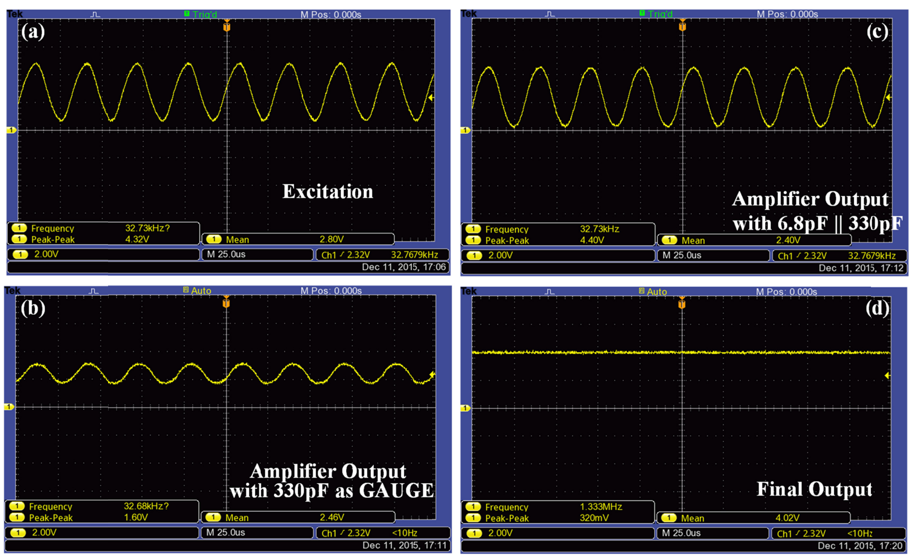


Fig. 6 Test results for the C-Strain Sensor with 330 pF as the nominal capacitance for the AC Wheatstone bridge. (a) external excitation signal; (b) the amplifier output without capacitance change; (c) the amplifier output with 6.8 pF capacitance change; (d) the final output with 6.8 pF capacitance change.

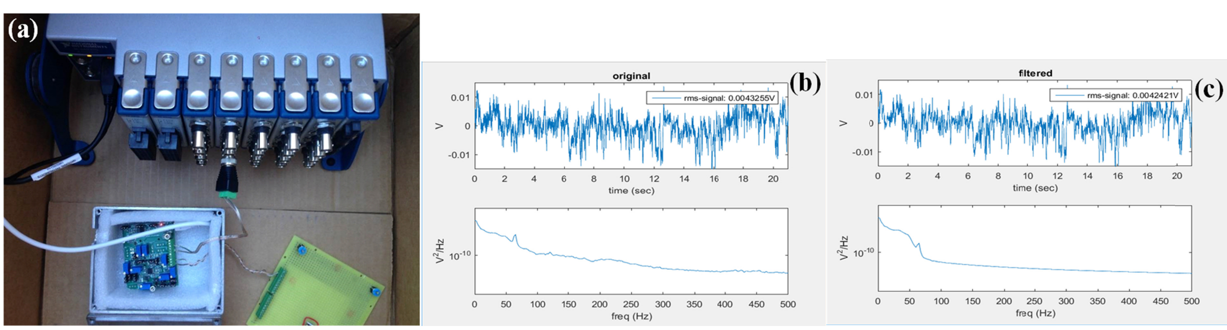
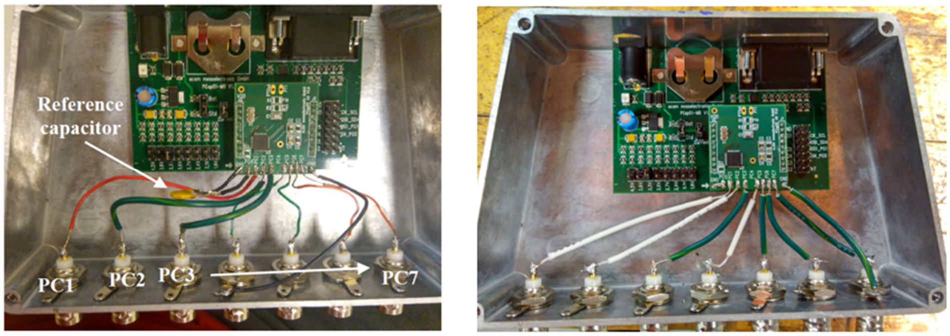


Fig. 7 Noise test for the C-strain sensor. (a) test setup; (b) the rms noise results; (c) the rms noise results with LPF applied.

3. Improvement of the off-the-shelf DAQ system

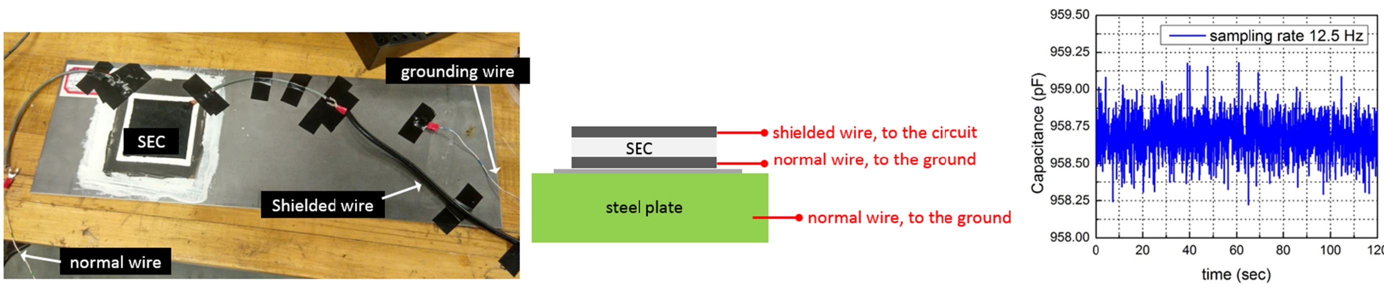
As mentioned previously, while the wireless DAQ board is under development by the UA team, the KU team currently focuses on using an off-the-shelf data acquisition system (PCAP02) to measure the capacitance reading of the SEC sensor. To enhance the data quality and minimize the noise level of measurement, improvements have been made by trimming down all the connecting wires in the aluminum housing, and using a surface mount ceramic capacitor as the reference capacitor (Fig. 8).



(a) (b)

Fig. 8 (a) former and (b) updated DAQ setup with the PCAP02 board

The performance of the updated data acquisition system is tested (Fig. 9a and 9b). The result indicates that the updated DAQ system is able to generate a more stable measurement. In addition, the noise level of the signal is about 0.5 pF, which is much lower than the previous tests.



(a) (b) (c)

Fig. 9 (a) test setup; (b) schematic of sensor connections; and (c) a sample measurement

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

None.