Project – Scope of Work

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

Principal Investigator

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Research Objective

Fatigue-induced cracks are of great concern to the Departments of Transportation. An important number of bridges in the country are fracture critical bridges that are vulnerable to fatigue cracks due to the brittle nature of their failure modes. Localizing and monitoring fatigue cracks is critical for determining retrofitting and maintenance plans. However, the localization process is difficult. This process is typically conducted via visual inspections, and sometime leveraging nondestructive evaluation techniques. Both methods require an inspector to be involved, are time consuming, and do not guarantee that a fatigue crack would be discovered on-time.

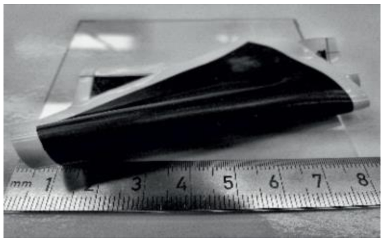
Figure 1. Elastomeric Sensing Skin

A solution is to deploy sensors, but the commercially available solutions do not allow for the discovery of new fatigue cracks, because these sensors are relatively very small in comparison to the geometries (i.e., girders) to be monitored. The recent pooled fund effort TPF-5(328)[1] conducted research on leveraging a large skin-type sensor (Fig. 1) that could easily be deployed over large areas in order to localize and monitor fatigue cracks. The research project was successful in demonstrating the capability of the technology both in a laboratory environment and in the field. The overarching objective of this proposed project is to enable large-scale deployments in the United States by addressing further essential development needs uncovered during the previous research to achieve more robust, accurate, and flexible crack monitoring using the wireless skin sensor network.

Research Team

The proposed research will be conducted by the same team that successfully completed the previous pooled fund project TPF-5(328). It includes Iowa State University (ISU, lead: Simon Laflamme), the University of Kansas (KU, lead: Jian Li), and the University of Arizona (UA, lead: Hongki Jo). ISU has expertise in sensor development and soft materials, KU has expertise in field deployment and steel fatigue, and UA has expertise in data acquisition (DAQ) and transmission.

Work Plan

The work plan is divided into three main research tasks. Task 1 is to deploy the sensing system in the field and collect data. Task 2 is to develop the integrated sensing system. Task 3 is to formulate algorithms and models. The project's schedule is illustrated in Table 1. It is anticipated to run over a period of five years. The schedule is separated into six deliverables listed Table 2 and three research phases listed in Table 3. Tables 2 and 3 also list approximate costs for each deliverables and phases. Phase 1 (P1) is expected to run over the first three years of the project with an approximated budget of \$550,000. It consists of developing and validating a second generation sensing system (the first generation sensing system is the outcome from TPF-5(328)). Generation II will require the digitalization of the sensing board and development of signal processing algorithms for crack detection based on realistic field data deployment strategies (deliverables D1-D4). Phase 2 (P2) is expected to run over one year subsequent to the completion of P1, with an approximated budget of \$250,000. It consists of

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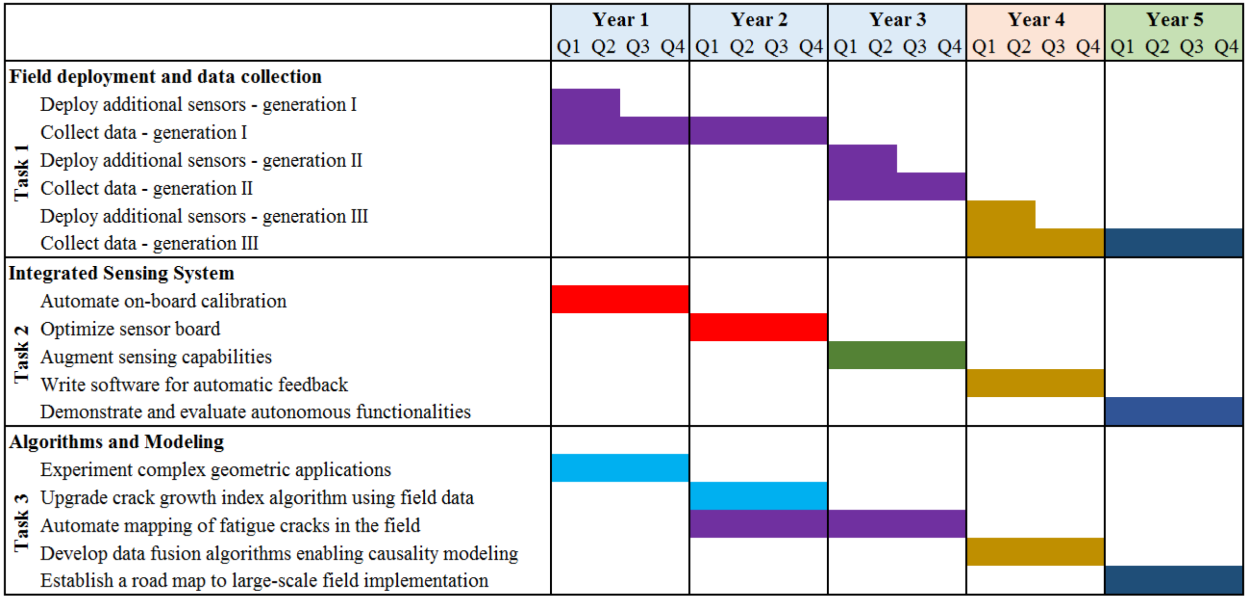
[1] TPF-5(328) *Strain-based fatigue crack monitoring of steel bridges using wireless elastomeric skin sensors*. Participating states: Kansas (lead), Iowa, Minnesota, North Carolina, Oklahoma, Pennsylvania, Texas.

deploying the Generation III sensing system, which includes on-board software capable of notifying infrastructure operators with fatigue crack alarms (deliverable D5). Phase 3 (P3) is expected to run over one year subsequent to the completion of P2, with an approximated budget of $200,000. It consists of validating the autonomous functionalities of Generation III (deliverable D6). The scope of work is discussed in details in what follows.

Table 1 – Project Schedule



		Year 1				Year 2				Year 3				Year 4				Year 5			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Field deployment and data collection																					
Task 1	Deploy additional sensors - generation I	🟪	🟪																		
	Collect data - generation I	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪												
	Deploy additional sensors - generation II									🟪	🟪										
	Collect data - generation II									🟪	🟪	🟪	🟪								
	Deploy additional sensors - generation III													🟨	🟨						
	Collect data - generation III													🟨	🟨	🟨	🟨	⬛	⬛	⬛	⬛
Integrated Sensing System																					
Task 2	Automate on-board calibration	🟥	🟥	🟥	🟥																
	Optimize sensor board					🟥	🟥	🟥	🟥												
	Augment sensing capabilities									🟩	🟩	🟩	🟩								
	Write software for automatic feedback													🟨	🟨	🟨	🟨				
	Demonstrate and evaluate autonomous functionalities																	⬛	⬛	⬛	⬛
Algorithms and Modeling																					
Task 3	Experiment complex geometric applications	🟦	🟦	🟦	🟦																
	Upgrade crack growth index algorithm using field data					🟦	🟦	🟦	🟦												
	Automate mapping of fatigue cracks in the field					🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪								
	Develop data fusion algorithms enabling causality modeling													🟨	🟨	🟨	🟨				
	Establish a road map to large-scale field implementation																	⬛	⬛	⬛	⬛

Table 2 – Project deliverables and approximated costs

Deliverables			Cost
D1	End of Y2	Final algorithm characterizing sensor behavior	$ 100,000
D2	End of Y2	Digital wireless DAQ	$ 75,000
D3	End of Y3	Automated fatigue crack detection	$ 325,000
D4	End of Y3	Multivariate digital wireless DAQ	$ 50,000
D5	End of Y4	Automated alarm for fatigue crack detection & prognostics	$ 250,000
D6	End of Y5	Validated system and road map to large-scale field implementation	$ 200,000

Table 3 – Project phases and approximated costs

Phases		Cost
P1	Deliverables D1-D4 (3 years): Validated generation II sensing system	$ 550,000
P2	Deliverable D5 (1 year): Deployed generation III with alarm software	$ 250,000
P3	Deliverable D6 (1 year): Validated generation III and road map	$ 200,000

Task 1: Field deployment and data collection (lead: KU)

KU will be responsible for the deployment of sensing systems, and for the collection and storage of data. The test steel bridge is the same as used in TPF-5(328). It is part of the I-70 highway near Kansas City, Kansas, at the intersection of the N. 57th Street. Based on the recent two inspections performed in 2013 and 2017, multiple locations on the bridge was subject to fatigue damage, typically at web-gap regions in the cross-frame-to-girder connections. An exterior girder was selected for the sensing system installation, which included two fatigue-susceptible regions (Figure 2). Based on the inspection reports and the marks on the structural surface, two fatigue cracks can be found in this region including: 1) a horizontal crack initiated between the flange and the web (Crack 1); and 2) a horizontal crack in the web (Crack 2). Both cracks propagated between the inspection periods.

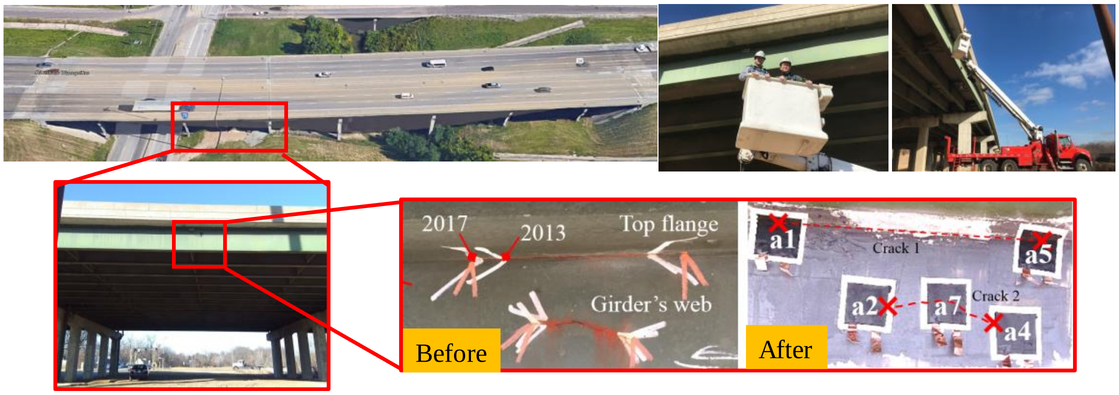


Figure 2: I-70 Bridge in Kansas with sensor network currently deployed

Task 1 is divided into six subtasks:

- Task 1.1: Deploy additional sensors – Generation I.

KU will deploy additional sensors on the bridge to increase the size of the monitored area using the technology developed in TPF-5(328)

- Task 1.2: Collect data – Generation I.

KU will collect and store data from the Generation I system, and will maintain the sensor network.

- Task 1.3: Deploy additional sensors – Generation II.

KU will deploy an updated sensor network (Generation II) on the bridge based on deliverables D1-D4.

- Task 1.4: Collect data – Generation II.

KU will collect and store data from the Generation II system, and will maintain the sensor network.

- Task 1.5: Deploy additional sensors – Generation III.

KU will deploy an updated sensor network (Generation III) with complete autonomous capabilities based on deliverable D5.

- Task 1.6: Collect data – Generation III.

KU will collect and store data from the Generation III system, and will maintain the sensor network.

Task 2: Integrated Sensing System (lead: UA)

UA will be responsible for the development of an improved design for the wireless DAQ hardware and software for multi-channel sensing of dynamic capacitance on a single board with automated on-board calibration capability.

Task 2 is divided into five subtasks:

- Task 2.1: Automate on-board calibration.

UA will develop improved circuit design and software for automated Wheatstone bridge balance and shunt calibration to convert dynamic capacitance change of the SEC into analog voltage signal.

- Task 2.2: Optimize sensor board.

UA will optimize the DAQ board design to provide multi-channel dynamic capacitance sensing capability with a single board. The entire circuit design will be re-configured to accommodate multi-channel signal process within minimized circuit footprint.

- Task 2.3: Augment sensing capabilities.

UA will add a regular (i.e. resistive-type) strain sensing circuit in the wireless DAQ board to provide a reference data (e.g., information on load input) for the fatigue crack growth index (CGI) generation. Optimal signal amplification circuit will be implemented for effective resolution of low-level strain signal without saturating the DAQ bandwidth.

- Task 2.4: Write software for automatic feedback.

UA will write software that will pre-process CGI and load input using results from Task 3.4 enabling the transmission of automatic feedback to infrastructure operators in the form of alarms.

- Task 2.5: Demonstrate and evaluate autonomous functionalities.

Led by UA, the research team will demonstrate the autonomous functionality of the sensing system, and study data across the three generations of sensing systems to evaluate and quantify performance.

Task 3: Algorithms and modeling (lead: ISU)

ISU will be responsible for the development of algorithms and models enabling links from sensor data to decision making.

Task 3 is divided into five subtasks:

- Task 3.1: Experiment complex geometric applications.

ISU will conduct laboratory experiments to characterize the signal of sensors installed in complex geometries, such as welds under out-of-plane distortion. The characterized signal will be used to update the CGI algorithm.

- Task 3.2: Upgrade crack growth index algorithm using field data.

ISU and KU will develop an algorithm to automate the process of extracting vehicle-induced data from field data that was found to be contaminated with low-amplitude noise. This will produce more reliable CGIs.

- Task 3.3: Automate mapping of fatigue cracks in the field.

ISU and KU will develop an algorithm for the automatic mapping of CGIs in the field based on results from tasks 3.1 and 3.2. An important output of Task 3.3 will be visualization tools showing the distribution of cracks over a monitored area, along with their gravity.

- Task 3.4: Develop data fusion algorithms enabling causality modeling.

ISU will use data from the additional sensing capabilities developed under Task 2.3 along with the CGIs to formulate models that will learn crack growth causalities directly from the spatio-temporal data. These models will be used in the development of autonomous alarms by providing a level of forecasting capability.

- Task 3.5: Establish a roadmap to large-scale field implementation.

Led by ISU, the research team will leverage discoveries from the project along with validation results from Task 2.5 to provide a roadmap to large-scale field implementation.