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Scalable Thin Film Sensor for Damage Detection and Localization

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ABSTRACT
Damage detection and localization on very large surfaces, including wind turbine blades, aircraft wings, and bridge girders, is a difficult task. Most of readily available structural health monitoring solutions do not scale up due to technical and/or economic constraints. The authors have recently developed a soft elastomeric capacitor (SEC), which transduces strain into a measurable change in capacitance. The fabrication process of an SEC is simple, and is based on an inexpensive polymer matrix and nanoparticles, which makes the technology highly scalable and ideal for monitoring strain over large surfaces. Deployed in a network configuration, the SEC has the capacity to detect and localize damage over a global surface, analogous to biological skin. In this paper, we discuss the fundamental features that enables scalability of the sensor, and provide an example that leverages this scalability to detect and localize damage on a surface, here a fatigue crack. We also present preliminary results on the development of an in-house dedicated data acquisition systems for large-scale implementations.

KEYWORDS: *Soft elastomeric capacitor; thin film sensor; fatigue crack; strain gauge; sensor network*

1. INTRODUCTION

Detection and localization of damage on mesosurfaces is a complex task due to the scale of geometries under consideration. Off-the-shelf technology are difficult to scale up due to technical and/or economic constraints. A solution is to deploy dense arrays of sensors. For instance, piezoelectric wafer active sensors (PWAS) networks have been proposed for detecting and localizing fatigue cracks [1-2], as well as networks of fiber optics-based technologies [3-4]. Others have studied the deployment of carbon nanotube networks to detect changes in local damages over a global area [5-7].

Alternatively, it is possible to leverage recent technological advances and discoveries in the field of flexible electronics and conductive polymers in order to develop large sensors tailored to mesosurface applications. Such sensing technologies are termed large-area electronics (LAE). Their sensing principle can be analogous to biologic skin, in the sense that an array of LAE can be capable of detecting local changes over a global area. State-of-the-art research in LAE includes large sensing sheets of strain gauges [8, 9], resistance-based thin-films [10–13] and capacitance-based sensors for strain [14], pressure [15], triaxial force [16], and humidity [17, 18] measurements.

While promising at mesoscale monitoring, some LAE may be difficult to produce in large volumes. In particular, there is a trade-off between the cost of a conductive filler used in the making of an LAE and the electromechanical sensitivity of the sensor, and the utilization of high conductivity nanoparticles, such as carbon nanotubes, often leads to a complex fabrication process due to the difficult dispersion of the particles [19].

To address these limitations, the authors have recently proposed a highly scalable LAE for strain measurement of mesosurfaces [20]. The LAE is a soft elastomeric capacitor (SEC) fabricated using inexpensive materials and a simple fabrication process. In this paper, the high scalability potential of the SEC is presented, and its application to damage detection and localization demonstrated. The main contribution of this article is the development of a dedicated readout circuit (ROC) enabling large-scale deployment of the novel sensing system. This particular ROC is capable of measuring very small changes in capacitance at a high precision, over a large number of capacitors. Its design is based on a relaxation oscillator and a negative impedance circuit. The output is a square wave with the capacitance data encoded on the period of the wave.

The paper is organized as follows. Section 2 discusses the salient features of the SEC that enable high scalability, and provides its electromechanical model for completeness. Section 3 demonstrates an application, which consists of detection and localization of a fatigue crack using a network of SEC. Section 4 presents the ROC and provides preliminary results obtained with this dedicated electronics. Section 5 concludes the paper.

2. SCALABLE SENSOR

This section describes the salient features that provides the SEC with a high scalability, including the inexpensive materials used in its fabrication and the fabrication process. The electromechanical model of the SEC is also provided, for completeness.

2.1 Materials

The material selection in the fabrication of the SEC was conducted to ensure scalability and mechanical robustness. The dielectric of the sensor is composed of a styrene-ethylene/butylene-styrene (SEBS) polymer matrix filled with PDMS-coated titanium dioxide (TiO_2) particles. SEBS (VTC Elastoteknik AB) is a block copolymer widely used for medical applications, because of its purity, softness, elasticity, and strength [21]. Titania (TPL) is an inorganic particle characterized by a high dielectric permittivity that increases the permittivity and durability of the SEBS matrix [22]. The dielectric of the SEC is sandwiched between two electrodes fabricated from SEBS filled with carbon black (CB) particles. CB particles type Printex XE-2B (Orion Engineered Carbons) are selected due to their low cost and high structure (minimum oil absorption 380 cc/100g), which facilitates higher conductivity [23]. The utilization of the same polymer matrix (SEBS) for both the electrodes and dielectric results in a strong mechanical bond between the layers that constitute the SEC.

2.2 Fabrication Process

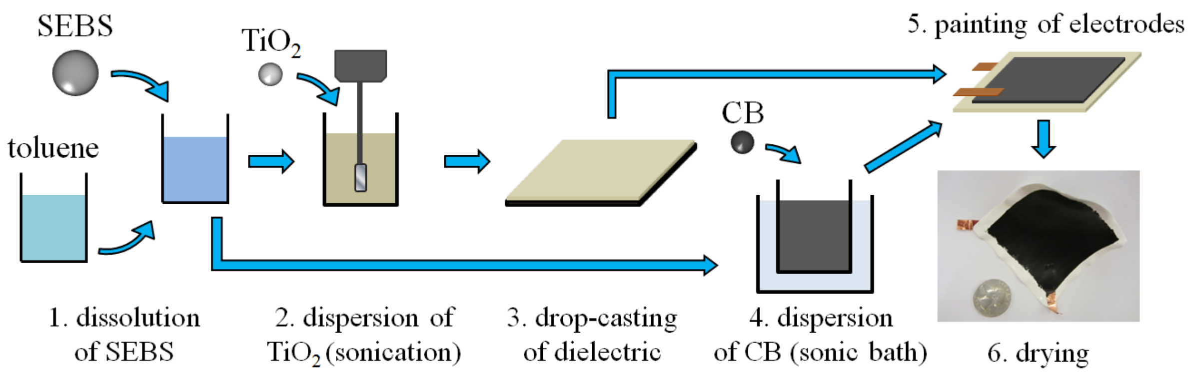


Figure 2.1 Drop-cast fabrication process of an SEC

The SEC is hand-fabricated using a drop-cast process. This particular process is illustrated in Figure 2.1 and described in details in Ref. [24]. Briefly, the SEBS is dissolved in toluene (step 1, Figure 2.1), and TiO_2 dispersed in the solution via sonication (step 2, Figure 2.1). After, the SEBS+TiO_2 mix is drop-casted on a glass plate and allowed to dry (step 3, Figure 2.1). Meanwhile, CB is dispersed in a second SEBS solution using a sonication bath (step 4, Figure 2.1). The resulting conductive paint is applied onto both sides of the dried dielectric and copper tapes embedded to create mechanical connections to the data acquisition system (step 5,

Figure 2.1) and finally let dry (step 6, Figure 2.1). Step 6 in Figure 2.1 shows the picture of an SEC measuring 75 x 75 mm^2 (3 x 3 in^2).

The drop-cast process has shown to be cost-effective in a research laboratory environment. An alternative fabrication process termed melt-mixing has also been investigated to enable large-scale fabrication. The investigation of the fabrication process is presented in Ref. [25]. In summary, the melt-mixing process facilitates further the fabrication process, but necessitates a heated shear mixer. It also eliminates the need for toluene, but requires a surfactant (Si-69) to provide a homogeneous dispersion.

2.3 Electromechanical Model

The electromechanical model mapping a change in the SEC capacitance ΔC to a change in its strain is as follows

$$\frac{\Delta C}{C_0} = \frac{1}{1-\nu}(\varepsilon_x + \varepsilon_y) \tag{1}$$

with

$$C_0 = e_0 e_r A/h_d \tag{2}$$

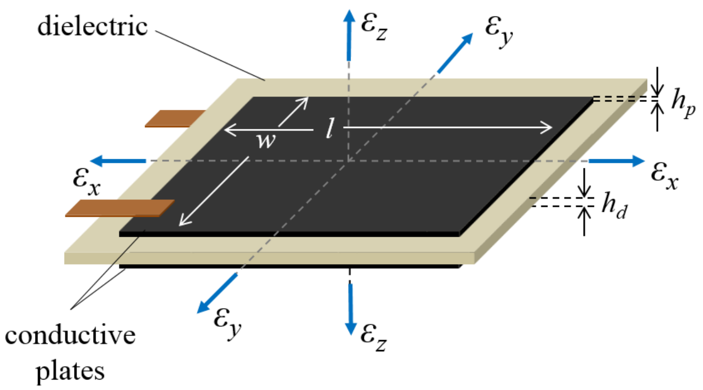


Figure 2.2 Schematic representation of an SEC

where ε_x and ε_y are the in-plane strains as shown in Figure 2.2, $\nu \approx 0.49$ is the Poisson ratio of the polymer, e_0 is the vacuum permittivity, e_r the polymer relative permittivity, $A = w \cdot l$ the initial sensor area with initial width w and length l, and h_d the initial height of the dielectric. The gauge factor can be approximated as $\lambda = 1/(1-\nu) \approx 2$. This formulation assumes that the material is incompressible and under plane stress ($\sigma_z = 0$). A derivation of the electromechanical model and a discussion on the additive strain measurement $(\varepsilon_x + \varepsilon_y)$ feature is provided in Ref. [26].

3. LARGE-SCALE APPLICATION EXAMPLE

The SEC has been designed to be deployed in network configurations. Applications include damage detection, diagnosis, prognosis, and strain and deflection map reconstruction. In this section, results from a previous investigation on fatigue crack detection and localization [27] are summarized.

The experimental procedure consisted of deploying the SECs onto the surface notched steel specimens subjected to a fatigue load. The specimens were fabricated with a width of 6 in to accommodate four SEC of dimensions 38 x 38 mm^2 (1.5 x 1.5 in^2). Data from the SEC were acquired continuously using an off-the-shelf data acquisition system (ACAM PCap01) during dynamic loading of the plate. Test specimens were visually inspected to monitor the formation of a fatigue crack and its development, and pictures taken using a Canon T2i DSLR camera 18.0-megapixel. These pictures were post-processed using a pixel count to determine the crack length and width and correlated with the SEC signal to determine whether the fatigue crack was detectable. The test configuration is shown in Figure 3.1, and times series results plotted in Figure 3.2(a) along with a picture of the cracked specimen (Figure 3.2(b)). Only sensor 1 (Figure 3.1(b)) has an observable increase in its time series measurements. This demonstrates that the network was capable of both detecting and localizing the fatigue crack.

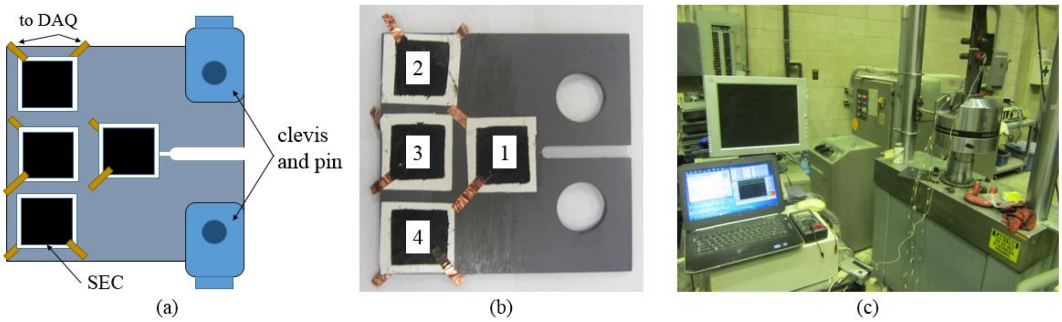


Figure 3.1 Test configuration: (a) schematic; (b) picture of the specimen; and (c) picture of the configuration

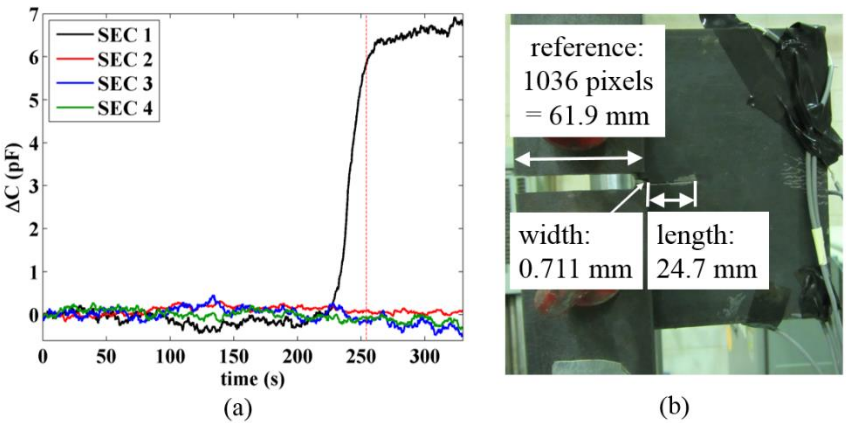


Figure 3.2 Typical test result: (a) time series measurements; and (b) picture of the cracked specimen

4. DEDICATED ELECTRONICS

This section presents recent research developments in a dedicated method of measuring small changes in capacitance while greatly increasing the overall sensitivity of the sensing system. The choice of an ROC based on a relaxation oscillator and a negative impedance circuit was motivated by robustness and minimal part count, along with stability over large temperature and operating conditions. The minimal part count is invaluable to extend this system to large sensor arrays with each sensor only requiring a single silicon chip, four passive components and a digital potentiometer. The period of the output signal is easy to measured quickly and accurately with most microcontrollers such as an MSP430, allowing for easy multiplexing of large arrays of sensors to a single microcontroller. In what follows, the proposed ROC is described, and preliminary results are presented.

4.1 Proposed ROC

The proposed ROC measures capacitance through the waveform generated by the relaxation oscillator. The SEC provides the required capacitance value to relaxation oscillator. To provide higher circuit sensitivity a negative impedance circuit is combined with the relaxation oscillator circuit to remove the sensor's base capacitance, allowing the remaining capacitance values to be used as the capacitor of the relaxation oscillator. The circuit produces a square wave, the period of which is related to the measured capacitance. The negative impedance value is settable through a potentiometer, used to calibrate the system to a specific sensor. Figure 4.1 is the schematic of the ROC.

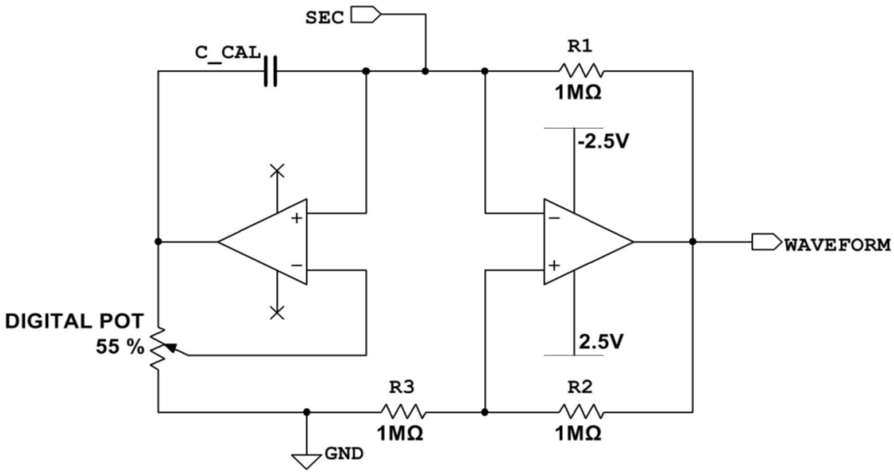


Figure 4.1 Schematic of the readout circuit

The known capacitor is set to have a capacitance C_1. This capacitance is determined by a calibration capacitor C_{cal} and the tuning of the digital potentiometer k. For convenience, a change of variable is used such that $x = 1/k$. The capacitance value of C_1 is calculated using

$$C_1 = (1 - 256x)C_{\mathrm{cal}} \tag{3}$$

The relaxation oscillator was selected due to its high stability over a wide operating range of passive component values and ease to measure square wave output. The periodicity of a relaxation oscillator is selected by tuning the R and C values of the passive components. By selecting all resistors to have the same value, a duty cycle of 50% is achieved. For a basic relaxation oscillator the period of the output waveform is

$$T = 2\ln(3)\,RC \tag{4}$$

and the period of the output waveform resulting from a change in capacitance ΔC is

$$\begin{aligned} T(\Delta C) &= 2\ln(3)\,R(C_0 + \Delta C + C_1) \\ &= 2\ln(3)\,R(C_0 + (1 - 256x)C_{\mathrm{cal}}) + 2\ln(3)\,R\Delta C \\ &= T_0 + G\Delta C \end{aligned} \tag{5}$$

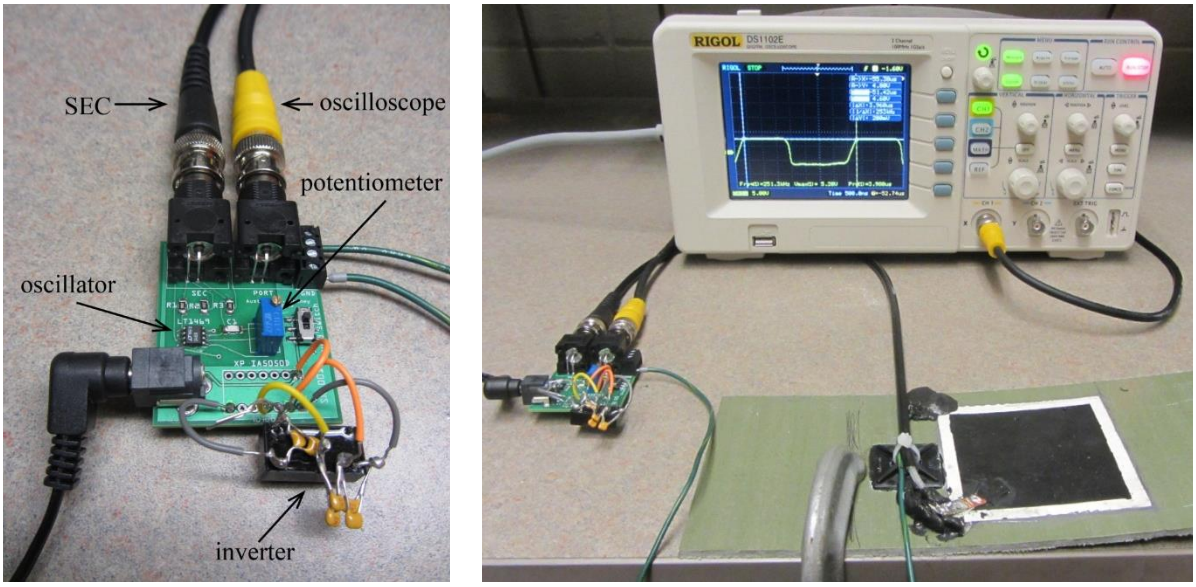
with

$$G = 2\ln 3\,R \tag{6}$$

where T_0 is the nominal period of the output waveform when no additional capacitance is present from the sensor, and G is the gain multiplier of the change in measured capacitance. The sensitivity of the system is maximized when G becomes large, which is achieved by maximizing the value of R, and when T_0 becomes minimized by selecting x and C_{cal} such that $C_0 + (1 - 256x)C_{\mathrm{cal}}$ is minimized. Because x is related to the set point of an eight-bit digital potentiometer, it much be selected such that $x = 1/k\,, k \in \mathbb{Z}, 0 \leq k < 256$.

4.2 Preliminary Results

The ROC was laid out on a printed circuit board, shown in Figure 4.2(a), and tested at taking measurements from the SEC. The experimental configuration, shown in Figure 4.2(b), consisted of measuring the frequency following a change in capacitance of the SEC provoked by strain. The SEC was deployed onto the top surface of a clamped beam, and a constant upwards displacement applied at the tip of the beam. Before increasing the upwards displacement, the plate displacement was taken back to 0 (i.e. flat), to ensure measurement stability. The capacitance of the SEC was also independently measured using an LCR bridge.



(a) (b)

Figure 4.2 (a) Picture of the ROC; and (b) test configuration

Figure 4.3 is a plot of the measured changes in frequency Δf versus the measured change in capacitance ΔC. The ROC exhibits linearity with respect to capacitance, and has a sensitivity of 750 Hz/pF. The unstrained capacitance value of the SEC is 637.0 pF, where a change in 1 pF corresponds to approximately 1121 με using Equation (2).

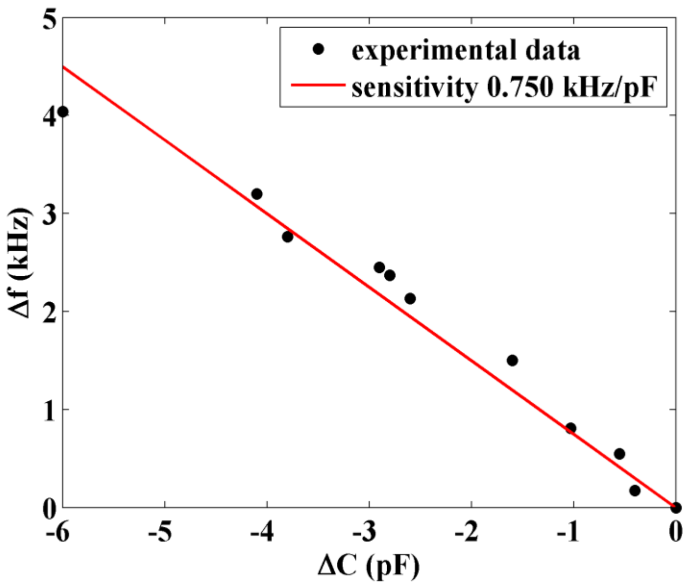


Figure 4.3 Change in frequency versus change in capacitance

5. CONCLUSION

In this paper, a highly scalable LAE has been presented. The LAE consists of an SEC, fabricated using inexpensive materials and simple fabrication process. An application to damage detection and localization has been provided, where it was demonstrated that a network of SEC can successfully diagnose and locate a fatigue crack on a steel specimen. The SEC is a promising technology at monitoring strain over mesosurfaces.

Results from existing research on a dedicated data acquisition system have been presented. The ROC is a relaxation oscillator, capable of measuring very small changes in capacitance. The ROC has been laid out on a circuit board, and used to measure the change in capacitance in an SEC subjected to strain. Results showed that the measured frequency from the ROC was had a close to linear dependence on capacitance, with a sensitivity of 750 Hz/pF.

Future work includes the development of a data logger to continuously log measurements at high frequencies, and the comparison with off-the-shelf capacitance data acquisition systems. The development of a dedicated circuitry will enable large-scale applications by providing inexpensive and accurate measurement solutions for dense arrays of SECs.

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REFERENCES

1. L. Yu, V. Giurgiutiu, P. Ziehl, D. Ozevin, and P. Pollock. (2010). Steel bridge fatigue crack detection with piezoelectric wafer active sensors. In *SPIE Smart Structures and Materials & Nondestructive Evaluation and Health Monitoring.* **76471Y**.
2. M. Gresil, L. Yu, Y. Shen, and V. Giurgiutiu. (2013). Predictive model of fatigue crack detection in thick bridge steel structures with piezoelectric wafer active sensors. *Smart Structures and Systems*, **12:2**, 097-119.
3. H. Tsuda, J.-R. Lee, Y. Guan, and J. Takatsubo. (2007). Investigation of fatigue crack in stainless steel using a mobile fiber bragg grating ultrasonic sensor. *Optical Fiber Technology*. **13:3**, 209-214.
4. D.C. Lee, J.J. Lee, I.B. Kwon, and D.C. Seo. (2001). Monitoring of fatigue damage of composite structures by using embedded intensity-based optical fiber sensors. Smart materials and structures, **10:2**, 285.
5. L. Gao, E.T. Thostenson, Z. Zhang, J.-H. Byun, and T.-W. Chou. (2010). Damage monitoring in fiber-reinforced composites under fatigue loading using carbon nanotube networks. *Philosophical Magazine*, **90:31-32**, 4085-4099.
6. D'Alessandro, A., Ubertini, F., Materazzi, A. L., Laflamme, S., & Porfiri, M. (2014). Electromechanical modelling of a new class of nanocomposite cement-based sensors for structural health monitoring. *Structural Health Monitoring*. **14:2**, 137-147.
7. F. Ubertini, L. Materazzi, A. D'Alessandro, & S. Laflamme. (2014). Natural frequencies identification of a reinforced concrete beam using carbon nanotube cement-based sensors. *Engineering Structures*. **60**, 265-275.
8. Hu Y *et al.* (2014). Large-scale sensing system combining large-area electronics and CMOS ICs for structural-health monitoring. *IEEE J. Solid-State Circuits* **49,** 513–23.
9. Tung S, Yao Y and Glisic B. (2014). Sensing sheet: the sensitivity of thin-film full-bridge strain sensors for crack detection and characterization *Meas. Sci. Technol.* **25,** 075602.
10. Gao L, Thostenson E T, Zhang Z, Byun J-H and Chou T-W. (2010). Damage monitoring in fiber-reinforced composites under fatigue loading using carbon nanotube networks. *Phil. Mag.* **90,** 4085–99.
11. Kang I, Schulz M J, Kim J H, Shanov V and Shi D. (2006). A carbon nanotube strain sensor for structural health monitoring. *Smart Mater. Struct.* **15,** 737.
12. Loh K J, Kim J, Lynch J P, Kam N W S and Kotov N A. (2007). Multifunctional layer-by-layer carbon nanotube– polyelectrolyte thin films for strain and corrosion sensing. *Smart Mater. Struct.* **16,** 429.
13. Srivastava R K *et al.* (2011). The strain sensing and thermal–mechanical behavior of flexible multi-walled carbon nanotube/polystyrene composite films. *Carbon.* **49,** 3928–36.
14. Suster M, Guo J, Chaimanonart N, Ko W H and Young D J. (2006). A high-performance MEMS capacitive strain sensing system. *J. Microelectromech. Syst.* **15,** 1069–77.
15. Lipomi D J *et al* (2011). Skin-like pressure and strain sensors based on transparent elastic films of carbon nanotubes. *Nat. Nanotechnol.* **6,** 788–92.
16. Dobrzynska J A and Gijs M. (2013). Polymer-based flexible capacitive sensor for three-axial force measurements *J. Micromech. Microeng.* **23,** 015009.
17. Harrey P, Ramsey B, Evans P and Harrison D. (2002). Capacitive-type humidity sensors fabricated using the offset lithographic printing process. *Sensors Actuators.* B **87,** 226–232.
18. Hong H P, Jung K H, Min N K, Rhee Y H and Park C W. (2012). A highly fast capacitive-type humidity sensor using percolating carbon nanotube films as a porous electrode material. *Proc. IEEE Sensors (Taipei, Taiwan, October 2012)* .1–4.

19. Laflamme, S., Saleem, H. S., Elkashef, M., Wang, K., & Cochran, E. (2015, April). Conductive paint-filled cement paste sensor for accelerated percolation. In *SPIE Smart Structures and Materials+ Nondestructive Evaluation and Health Monitoring.* **943722-943722**. International Society for Optics and Photonics.
20. Laflamme, S., Saleem, H. S., Vasan, B. K., Geiger, R. L., Chen, D., Kessler, M. R., & Rajan, K. (2013). Soft elastomeric capacitor network for strain sensing over large surfaces. *Mechatronics, IEEE/ASME Transactions.* **18:6,** 1647-1654.
21. Yoda, R.(1998). Elastomers for biomedical applications. *Journal of Biomaterials Science, Polymer Edition.* **9:6,** 561–626.
22. Stoyanov, H., Kollosche, M., McCarthy, D. N., and Kofod, G.(2010). Molecular composites with enhanced energy density for electroactive polymers. *Journal of Material Chemistry 20.* 7558–7564**.**
23. J.-C. Huang.(2002). Carbon black filled conducting polymers and polymer blends. *Advances in Polymer Technology.* **21:4,** 299–313.
24. Laflamme, S., Kollosche, M., Connor, J. J., & Kofod, G. (2012). Robust flexible capacitive surface sensor for structural health monitoring applications. *Journal of Engineering Mechanics*. **139:7,** 879-885**.**
25. Saleem, H., Thunga, M., Kollosche, M., Kessler, M. R., & Laflamme, S. (2014). Interfacial treatment effects on behavior of soft nano-composites for highly stretchable dielectrics. *Polymer*, *55*(17), 4531-4537.
26. J. Wu, C. Song, H. Saleem, A. Downey, & S. Laflamme (2015). *Network of flexible capacitive strain gauges for reconstruction of surface strain*. Meas. Sci. Technol. **26:055103**
27. Kharroub, S., Laflamme, S., Song, C., Qiao, D., Phares, B., & Li, J. (2015). Smart sensing skin for detection and localization of fatigue cracks. *Smart Materials and Structures*. ***24*:6**, 065004.