SENSING SHEET FOR SHM BASED ON LARGE AREA ELECTRONICS

Branko Glisic
Princeton University, USA

Naveen Verma
Princeton University, USA

The need for reliable, robust, and low-cost Structural Health Monitoring (SHM) is rapidly increasing. In spite of its importance, however, SHM is rarely utilized on real structures. The main reason for this is the cost and limited reliability achievable by current monitoring technologies. The sensors currently available must be sparsely spaced and either provide severely insufficient spatial-resolution for early damage detection or rely on complex algorithms that degrade specificity against environmental and variable-load conditions.

The objectives of this research are two-fold: to investigate a sensing-system principle that provides low-cost monitoring through a dense and expansive array of sensors enabled by a technology called large-area electronics; and to experimentally study how the high-resolution sensing offered by such a system can overcome the robustness and reliability limitations affecting current SHM technologies. A novel sensing sheet containing dense arrays of sensors based on large-area electronics and integrated circuits is being developed and tested.

The primary concepts related to structural sensing are presented in this paper along with preliminary test results. These demonstrate that the proposed technology and direct sensing approach are beneficial for both reliable and low-cost damage detection, as well as the localization of damage over large areas of a structure.

Corresponding author's email: bglisic@princeton.edu

SENSING SHEET FOR SHM BASED ON LARGE AREA ELECTRONICS

Branko Glisic[1], and Naveen Verma[1]
[1] Princeton University, Princeton NJ, USA

ABSTRACT: The need for reliable, robust, and low-cost Structural Health Monitoring (SHM) is rapidly increasing. In spite of its importance, however, SHM is rarely utilized on real structures. The main reason for this is the cost and limited reliability achievable by current monitoring technologies. The sensors currently available must be sparsely spaced and either provide severely insufficient spatial-resolution for early damage detection or rely on complex algorithms that degrade specificity against environmental and variable-load conditions. The objectives of this research are two-fold: to investigate a sensing-system principle that provides low-cost monitoring through a dense and expansive array of sensors enabled by a technology called large-area electronics; and to experimentally study how the high-resolution sensing offered by such a system can overcome the robustness and reliability limitations affecting current SHM technologies. A novel sensing sheet containing dense arrays of sensors based on large-area electronics and integrated circuits is being developed and tested. The primary concepts related to structural sensing are presented in this paper along with preliminary test results. These demonstrate that the proposed technology and direct sensing approach are beneficial for both reliable and low-cost damage detection, as well as the localization of damage over large areas of a structure.

1 INTRODUCTION

Civil infrastructure in the U.S. is aging and has been identified as an area of critical need. Many bridges of great importance are approaching the end of their life span. It is necessary to determine and monitor their structural health in order to mitigate risks, prevent disasters, and plan maintenance activities in an optimized manner. The need for reliable, robust, and low-cost Structural Health Monitoring (SHM) is thus rapidly increasing. In spite of its great potential, SHM is not applied in a widespread or systematic manner. The main reason for this is the lack of generic monitoring solutions that are reliable and affordable. Today's technology gives bridge managers access to sparsely spaced sensors. These, unfortunately, do not allow reliable early detection of anomalies such as strain concentrations or cracks at locations of even modest distance from the sensors. This form of indirect damage detection thus requires complex algorithms whose accuracy is challenged by noise sources from the environment, such as temperature variations, precipitation, and variable loading.

The goals of the research presented in this paper are two-fold: (1) to research a sensing system principle that provides robust and intelligent monitoring through a low-cost but very dense two-dimensional array of sensors enabled by a technology called large-area electronics; and (2) to experimentally study how the high-resolution sensing offered by such a system can overcome the robustness and reliability limitations that affect current SHM technologies towards the detection of early signs of degradation. The overall concept and preliminary results are presented.

2 DIRECT DAMAGE DETECTION

The first signs of damage to a structure often have local character and occur in the form of strain-field anomalies. Typical examples are cracks and bowing in steel, and non-structural cracks in concrete. The primary underlying challenge in current strain monitoring technologies is that their spatial resolution is limited, which, as a consequence, leads to unreliable damage detection at points distant from sensors. As an illustration, recent measurements performed on the Streicker Bridge on the Princeton University campus are given in Figure 1, Glisic (2011). Long-gauge sensors (labeled P10h11U, P10h11D, and P10h11L) were embedded in concrete during the pouring. A crack occurred at the early age of the concrete at the location of P10h11U and P10h11D, and thus these sensors were directly activated. The crack created anomalies in the strain field that were reliably identified as a large change in the strain magnitude. The sensor P10h11L, however, which was installed less than one meter away, did not cross the crack. Although it reflected a small change in the strain (as shown in the figure), such minute perturbations are extremely difficult to diagnose, since the magnitude of the change is comparable with changes caused by temperature variations. Other sensors that were at a distant of two meters or more, did not register any change in the strain.

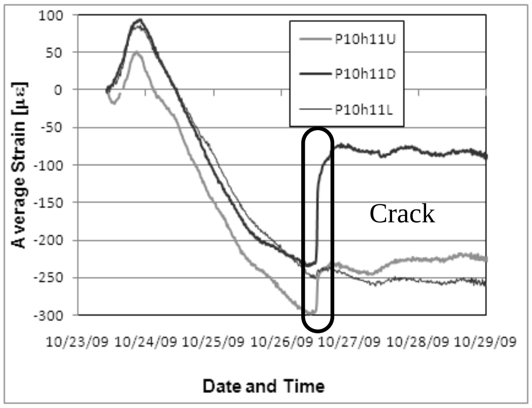

Figure 1. Direct crack detection vs. indirect crack detection in the Streicker Bridge.

It is important to highlight that the error limit of the monitoring system was 4 με, but the tiny crack (viz., 0.1 mm) would be detected thanks to the affected sensors (P10h11U and P10h11D) even if the accuracy was an order of magnitude lower. This example from a real application demonstrates the importance of direct damage detection not only for reliability and sensitivity, but also for the potential of very high robustness to on-site conditions.

Another example of the accuracy and robustness of direct damage detection is taken from our research on damage assessment of pipelines induced by permanent ground movement, Glisic&Oberste-Ufer (2011). A buried concrete pipe equipped with distributed fiber-optic sensors was exposed to relative shear movement between two parts of a testing basin, as shown in Figure 2. The movement caused crushing of the joints (seen in the figure). Although the crushing was successfully detected as a high strain change at the direct location of the damage, sensing points less than 50 cm away registered only bending, but no damage. Once again, the sensors in direct contact with the damage (i.e., direct damage detection) would have successfully detected and localized the damage, even if the error limit for the employed system (20 με) were worse by an order of magnitude.

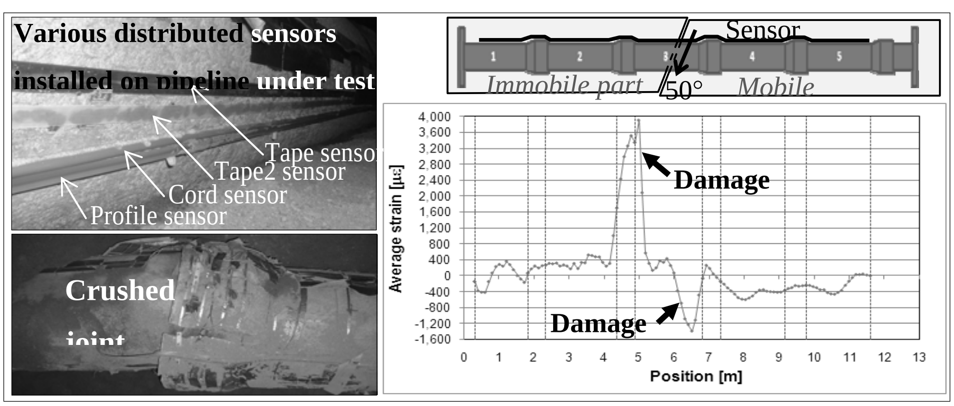

Figure 2. View of sensors after the installation (before burying), picture of the crushed pipe joint, and plot of the strain measurement showing damage detection and localization as extreme strain values.

Both of the case studies above motivate the need for a dense array of 2D-distributed sensors to overcome the reliability and robustness limitations of current damage detection methods. Unfortunately, currently available technologies for this purpose would be unviable from an economic perspective. For example, classical resistive strain gauges, which are among the cheapest strain sensors, cost about $20 each and have a gauge surface of 7.5 cm2. Assuming a 2D distribution with mutual distance of about 1 cm, the cost for monitoring a 1 m2 surface would be approximately $32,000, not including the cost of bonding, wiring, and interrogation of each sensor.

3 LARGE AREA ELECTRONICS

Large-area electronics is an emerging technology that allows a broad range of electronic devices to be integrated on low-cost plastic sheets, Arias et al. (2010) and Someya et al. (2008). Through the use of micro-fabrication techniques, thin-film transducers (including pressure sensors, vapor sensors, particle sensors, etc.) have been demonstrated, and these can be formed into dense arrays spanning large areas (i.e., tens of square meters).

This in itself has important implications for SHM. For instance, thin-film resistive strain gauges on polyimide are commercially available, and they are presently one of the most widespread modalities for monitoring civil structures. Such devices are compatible with the substrates and processing used for large-area electronics, and thus millions of strain gauges can be fabricated onto a single sheet that is both low in cost and highly conformal.

Another important benefit of large-area electronics is that it enables the integration of functional thin-film transistors (TFTs). This means that basic circuit functionality is available to facilitate readout from the large number of sensor channels. While these TFTs can provide basic functionality, the device-level characteristics that make them compatible with flexible, large-area substrates also severely limit their energy efficiency. Thus, large-scale processing over the sensor channels is not viable. Standard electronics technologies (e.g., based on integrated circuits) have achieved very high efficiency for instrumentation and processing thanks to nearly five decades of Moore's-law scaling. The objective is thus to exploit the basic functionality possible through the TFTs to create specialized interfaces between the large-area sensors and a potentially large number of readout and processing devices.

The concept of wireless sensor networks is extremely valuable for large-scale SHM, since it allows monitoring and interrogation over distributed point sensors. Wireless sensor nodes combine sensing, processing, communication, and possibly energy harvesting functionality into a miniature form factor. This permits the possibility of a large number of nodes for high-spatial-resolution sensing and large coverage area. Recent efforts have focused on minimizing the power consumption for compatibility with self-powered operation (through energy harvesting) and physical miniaturization to mitigate the obtrusiveness of the nodes. An example state-of-the-art node is shown in Figure 3a, Chen et al. (2010).

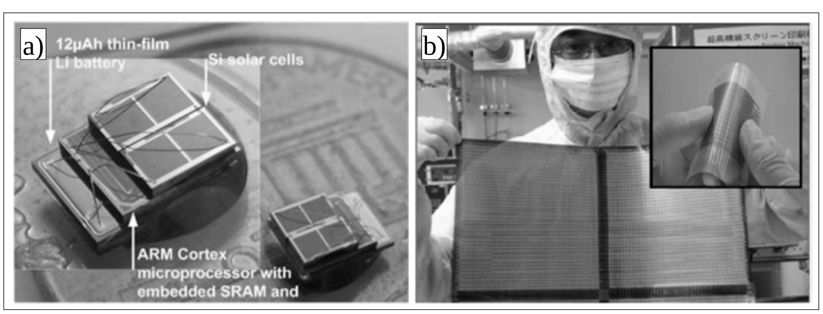

Figure 3. a) Example of wireless sensor node, Chen et al. (2010), and b) large area electronic with pressure sensing sheet, Someya et al. (2004).

This in itself has important implications for SHM. For instance, thin-film resistive strain gauges on polyimide are commercially available, and they are presently one of the most widespread modalities for monitoring civil structures. Such devices are compatible with the substrates and processing used for large-area electronics, and thus millions of strain gauges can be fabricated onto a single sheet that is both low in cost and highly conformal.

Another important benefit of large-area electronics is that it enables the integration of functional thin-film transistors (TFTs). This means that basic circuit functionality is available to facilitate readout from the large number of sensor channels. While these TFTs can provide basic functionality, the device-level characteristics that make them compatible with flexible, large-area substrates also severely limit their energy efficiency. Thus, large-scale processing over the sensor channels is not viable. Standard electronics technologies (e.g., based on integrated circuits) have achieved very high efficiency for instrumentation and processing thanks to nearly five decades of Moore's-law scaling. The objective is thus to exploit the basic functionality possible through the TFTs to create specialized interfaces between the large-area sensors and a potentially large number of readout and processing devices.

The concept of wireless sensor networks is extremely valuable for large-scale SHM, since it allows monitoring and interrogation over distributed point sensors. Wireless sensor nodes combine sensing, processing, communication, and possibly energy harvesting functionality into a miniature form factor. This permits the possibility of a large number of nodes for high-spatial-resolution sensing and large coverage area. Recent efforts have focused on minimizing the power consumption for compatibility with self-powered operation (through energy harvesting) and physical miniaturization to mitigate the obtrusiveness of the nodes. An example state-of-the-art node is shown in Figure 3a, Chen et al. (2010).

Despite these advances, however, wireless sensor nodes face important limitations in SHM applications: the spatial resolution achievable is limited by the density of the node arrangement; the technologies required for sensing, energy harvesting, and the electronics are disparate, i.e. no standard methodology for combining these exists, and thus device optimizations to address energy and manufacturability are difficult to pursue; the need to minimize the node size limits the dimensions of the energy harvester; wireless communication between nodes over distances of centimeters to meters dominates power consumption.

Large-area electronics offers unprecedented possibilities for overcoming these challenges. Figure 3b shows an example of a large-area electronics pressure sensing sheet, Someya et al. (2004), that illustrates several important characteristics: (1) a large number of sensors can be integrated with high density (e.g., the pressure sensors in Figure 5 have a pitch of 2.54 mm); (2) the cost per sensor can be very low, thanks to inexpensive substrates and fabrication methods, Arias et al. (2010); (3) a wide range of materials can be used to form diverse transducers (e.g., the sheet in Figure 5 incorporates pressure-sensitive rubber and organic semiconductors); and (4) flexible and large substrates can be used, also making very low-loss interconnect over long range possible. In addition to sensing devices, the possible transducers include energy harvesting and storage devices. For instance, thin-film photovoltaics have been demonstrated on plastic, and piezoelectric and thermoelectric harvesters have been demonstrated along with thin-film batteries and energy-storage super capacitors. Thus, large-area electronics makes self-powered operation possible.

4 SENSING SHEET WITH VERY DENSE ARRAY OF SENSORS

The insights pursued in this research are focused on two areas: (1) the use of large-area electronics as a sensing technology and its functional TFTs to facilitate readout permits high-resolution monitoring and assessment over a physically large structure; and (2) the resulting resolution can greatly facilitate early detection and, as a result, improve detection reliability and robustness to provide actionable outcomes.

Beyond sensing, large-area electronics can introduce long-range interconnects. Due to the size of civil bridges, communication between sensor nodes over distances of several centimeters and up to several meters is necessary, and the power needed for transmission is an important concern. Wired interconnects, on the other hand, incur much lower power consumption. Thus, the long-range interconnects provided by large area electronics allows for the low-energy communication required over the large number of distributed sensors.

The sensing technology that can result from this will consist of a dense array of 2D-distributed resistive strain sensors (at less than 1 cm spacing) on a thin plastic (polyimide) substrate. This can be bonded onto critical areas of a structure and provide early detection and localization of specific relevant types of damage. Based on the experiences cited in the previous section, the indicators are expected to provide direct correspondence with the 2D strain field, where damaged regions are typically expressed by several orders of magnitude in increased strain. As an example, a 0.1 mm crack detected by a sensor with a gauge length of 100 mm will induce an average strain change of 0.1/100 = 0.001 = 1000 $\mu\varepsilon$, which is too high to be masked by environmental influences or by monitoring-system noise. In addition, measurements from surrounding undamaged material will permit analysis of relative differences, improving the prospects of overcoming false positives (i.e., increasing specificity) as well as false negatives (i.e., increasing sensitivity).

Figure 4 shows 2D strain measurements, illustrating how these provide a reliable modality (i.e., offering high sensitivity and specificity) for detection and localization of structural anomalies.

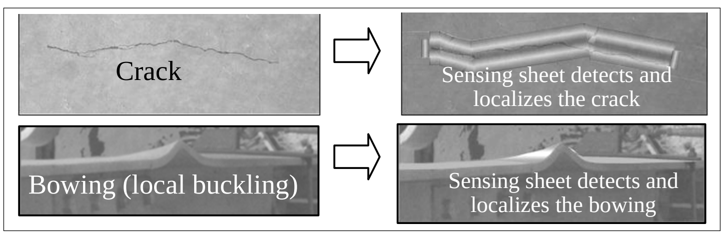

Figure 4. Illustration of the potential for direct damage detection using high-resolution 2D strain-field measurements. Left-side images show the damage, and right-side show the expected measurement.

Figure 5 shows a flexible sensing sheet which consists of (1) dense 2D-distributed arrays of resistive strain gauges on a polyimide substrate combined with functional large-area electronics and (2) interface devices for automatic readout, data processing, and communication. The preliminary specifications are: (i) range of strain measurements = -2000 to +2000 $\mu\varepsilon$ (typical failure strain levels in concrete and steel), (ii) initial spacing between the sensors of 1 cm, (iii) initial strain resolution of 10 $\mu\varepsilon$ (sufficient for detection of strain changes of 100 $\mu\varepsilon$). The technology envisioned can enable a realization of such a sensing system with an estimated cost of less than $100 per square meter of monitoring area (based on large-area electronics processing and fabrication methods). The polyimide substrate will allow conformability to the surface of the monitored structure as well as resilience to extreme outdoor temperature conditions (-40°C to +80°C). Low cost, besides economical affordability, also allows for “tailoring” (cutting out) the sensing sheet in order to adapt it to complex geometries of structural elements frequently found on site.

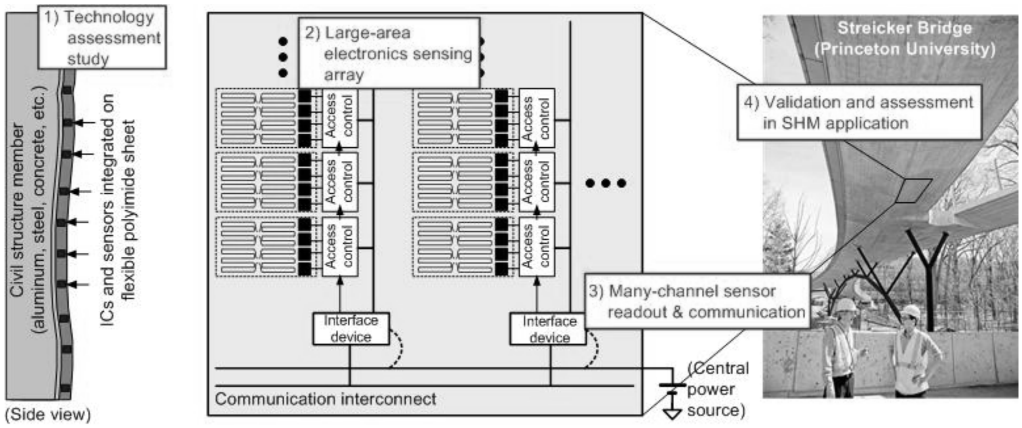

Figure 5. Schematic representation of sensing sheet, its components, and its application. For initial investigation, the ICs directly receive power from a central source.

For our initial study, the interface devices are powered by a central energy source (battery) that distributes power over patterned interconnect on the large-area electronics substrate; as noted earlier, self-powered operation remains a promising possibility for the future.

5 PRELIMINARY RESULTS

Resistive strain gauges are used as the unit sensors to be integrated into the sensing array. Their sensing principle has been proven over many years of long-term use, and they provide easy readout for the interface devices. The first step is to investigate how to create an array of sensors on a polyimide sheet that can be read out by devices using a minimum number of signaling channels from the large-area electronics.

The number of channels required poses a key limitation to the cost of such a system. To detect slowly evolving structural anomalies, the rate of acquisition required from the individual sensors can be quite low. The interface devices, on the other hand, can offer high performance processing. Taking advantage this, potentially hundreds of sensors can be handled by each device, allowing the signaling channels to be heavily time-shared (the precise number of sensors to interface to each device will ultimately depend on the computations to be performed). To accomplish the time sharing, enable switches formed using TFTs can be controlled that multiplex the sensor signals. Figure 6 shows a preliminary sample demonstrating the large-area electronics processing that can be used to create a many-channel integrated sheet. This involves metal patterning to provide connectivity to individual strain gauges.

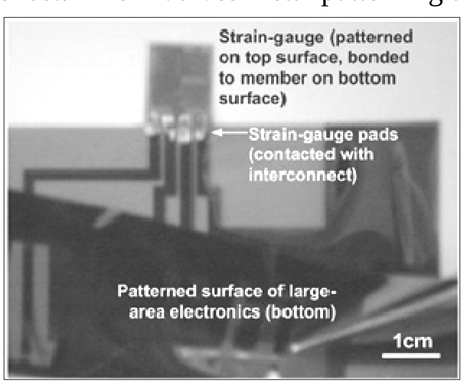

Figure 6. Thin-film resistive-bridge strain-gauge contacted with large-area electronics having patterned interconnect.

For readout from the strain gauges, we explore the use of AC signaling to bias and measure the resistive bridge output. Although this is an unconventional method of using such sensors, the benefit of AC signaling is that non-contact electrical-coupling techniques may then be used in the future. We have preliminarily verified the readout method as follows. Commercially available strain gauges (Omega SGT-4/1000-FB13) are bonded to an aluminum plate, as shown in Figure 7a. The aluminum plate is fixed at one end and it is free at the other end, thus behaving as a cantilever. The sensors are then installed close to the fixed end, i.e., in the area of highest stress and strain. Calibrated loads are then applied to the plate, and the sensors are read out by an AC-signaling bench-top instrumentation setup, as shown in Figure 7b.

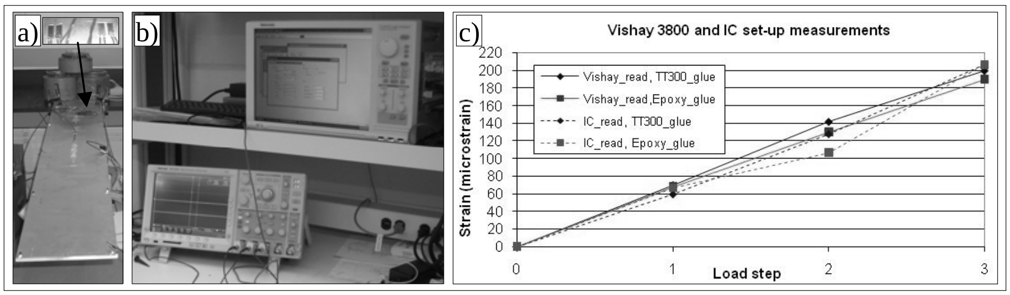

Figure 7. a) Aluminum plate with strain gauges; b) AC readout set-up; c) results of test.

For validation, a commercially available non-AC reading unit (Vishay 3800) is also used. The results of the preliminary tests are shown in Figure 7c, validating good agreement of the readout approach. The strain gauges used in the test are patterned on the same substrate material that is used for the sensing array sheet, i.e., polyimide, and are thus compatible with the processing methods for an integrated sheet.

Using the setup of Figure 7, the adhesive for the installation was also preliminarily tested. Two strain gauges were glued side-by-side using different adhesives: TT300 glue (recommended by the manufacturer) and epoxy glue (Araldite 2012). Epoxy glue is preferable for on-site applications, because it is easier to apply on large structures, and it adheres very well to both steel and concrete. The results suggest good performance of the epoxy glue in laboratory conditions.

6 CONCLUSIONS

A novel sensing technology for direct damage detection over large areas is presented. The sensing sheets are based on large-area electronics. The research is motivated by the insights that (1) high-resolution strain-field measurements can provide much better monitoring of SHM in bridges (as opposed to current methods where strain is monitored only through sparsely-spaced discrete-point measurements), and (2) large-area electronics can enable the requisite sensing technology. Preliminary results have supported the feasibility of such a sensing sheet. Further research will focus on the development and laboratory testing of sensing sheet prototypes. The authors believe that the distinct reliability, robustness, and low cost that this technology can offer has the potential to transform SHM, vastly improving safety and reduce maintenance and life-cycle costs for civil infrastructure.

7 ACKNOWLEDGEMENTS

This research has been supported by The Princeton Institute for the Science and Technology of Materials (PRISM).

8 REFERENCES

Arias, AC, MacKenzie, JD, McCulloch, I, Rivnay, J, and Salleo, A. 2010. Materials and applications for large area electronics: Solution-based approaches, Chem. Rev., 110(1): 3–24.

Chen, G, Fojtik, M, Kim, D, Fick, D, Park, J, Seok, M, Chen, M-T, Foo, Z, Sylvester, D, and Blaauw, D, 2010. A millimeter-scale nearly-perpetual sensor system with stacked battery and solar cells, in Proc. Int. Solid-State Circuits Conference, Feb. 2010, pp. 288–289.

Glisic, B. 2011. Streicker Bridge: an on-site SHM laboratory at Princeton University campus, SMAR, Paper No. 306, Dubai, UAE.

Glisic, B, and Oberste-Ufer, K. 2011. Validation Testing of Fiber Optic Method for Buried Pipelines Health Assessment after Earthquake-Induced Ground Movement, Proceedings of 2011 NSF Engineering Research and Innovation Conference, Atlanta, GA, USA.

Someya, T, Sekitani, T, Iba, S, Kato, Y, Kawaguchi, H, and Sakurai, T. 2004. A large-area, flexible pressure sensor matrix with organic field-effect transistors for artificial skin applications, Proc. National Academy of Science, 101(27): 9966–9970, July 2004.

Someya, T, Pal, B, Huang, J, and Katz, HE. 2008. Organic semiconductor devices with enhanced field and environmental responses for novel applications, MRS Bulletin, 33:690–696.