Smart Materials and Structures

PAPER

A bio-inspired asynchronous skin system for crack detection applications

To cite this article: Nathan Sharp *et al* 2014 *Smart Mater. Struct.* **23** 055020

IOP Publishing

Smart Materials and Structures

Smart Mater. Struct. **23** (2014) 055020 (7pp)

doi:10.1088/0964-1726/23/5/055020

A bio-inspired asynchronous skin system for crack detection applications

Nathan Sharp[1], Alan Kuntz[2], Cole Brubaker[3], Stephanie Amos[4], Wei Gao[5], Gautum Gupta[5], Aditya Mohite[5], Charles Farrar[5] and David Mascareñas[5]

[1] Purdue University, West Lafayette, IN 47905, USA
[2] University of New Mexico, Albuquerque, NM 87131, USA
[3] Colorado State University, Fort Collins, CO 80523, USA
[4] Georgia Tech, Atlanta, GA 30332, USA
[5] Los Alamos National Laboratory, Los Alamos, NM 87545, USA

E-mail: dmascarenas@lanl.gov

Received 29 October 2013, revised 9 January 2014
Accepted for publication 6 February 2014
Published 1 April 2014

Abstract

In many applications of structural health monitoring (SHM) it is imperative or advantageous to have large sensor arrays in order to properly sense the state of health of the structure. Typically these sensor networks are implemented by placing a large number of sensors over a structure and running individual cables from each sensor back to a central measurement station. Data is then collected from each sensor on the network at a constant sampling rate regardless of the current timescales at which events are acting on the structure. These conventional SHM sensor networks have a number of shortfalls. They tend to have a large number of cables that can represent a single point of failure for each sensor as well as add significant weight and installation costs. The constant sampling rate associated with each sensor very quickly leads to large amounts of data that must be analyzed, stored, and possibly transmitted to a remote user. This leads to increased demands on power consumption, bandwidth, and size. It also taxes our current techniques for managing large amounts of data. For the last decade the goal of the SHM community has been to endow structures with the functionality of a biological nervous system. Despite this goal the community has predominantly ignored the biological nervous system as inspiration for building structural nervous systems, choosing instead to focus on experimental mechanics and simulation techniques. In this work we explore the use of a novel, bio-inspired, SHM skin. This skin makes use of distributed computing and asynchronous communication techniques to alleviate the scale of the data management challenge as well as reduce power. The system also periodically sends a ‘heat beat’ signal to provide state-of-health updates. This conductive skin was implemented using conductive ink resistors as well as with graphene-oxide capacitors.

Keywords: graphene oxide, asynchronous, bio-inspired, nervous system, low-power

(Some figures may appear in colour only in the online journal)

1. Introduction

Most current maintenance procedures call for periodic inspections to try to detect deteriorating conditions before failure occurs. Alternatively, the structural health monitoring (SHM) approach is to constantly monitor a structure so that the health state will be reported automatically without needing periodic inspections. For many structural health monitoring applications it is not possible to monitor the health state of an entire structure without having large sensor arrays to gather data all along the structure. However, employing large sensor arrays using traditional methods of acquiring and processing data will consume large amounts of power, require many channels of data which must be sampled and analyzed by a processor, and often consume large amounts of space or weight. Regardless, positive progress

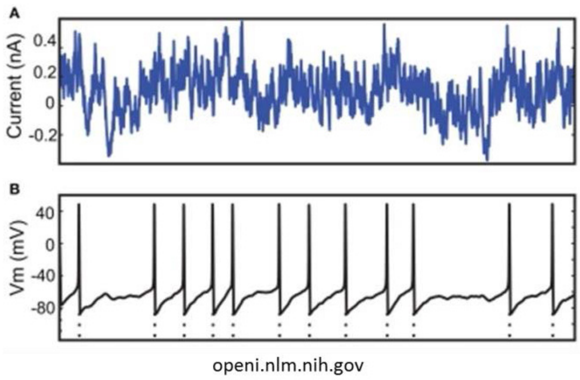

Figure 1. An example of neuron input (above) and the signal it sends to the brain (below) [8].

has been made in the area of sensing skins for structural health monitoring applications. Of particular note is the recent development of dense sensor arrays using 'large area electronics' technology [1, 2]. Biological nervous systems provide a function very similar to that desired by the SHM community. They take input from a large number of distributed sensors and provides the organism with actionable information on the organism's state-of-health. The human nervous system has neuron sensors estimated at around 85 billion [3] and the brain is able to process everything while consuming only 20 W [4]. The biological nervous system can be leveraged as a source of engineering inspiration as well as a form of benchmark for evaluating the quality of SHM systems. While some aspects of the biological nervous system cannot be directly copied, there are some strategies which it uses that could improve the performance of large sensor array SHM systems in their current state. The human nervous system conserves power and data processing in a couple of ways. First, the neuron sensors do much of the processing before sending signals to the brain. Instead of just taking measurements and reporting raw data, the neurons take a complex signal and report data in the form of very clean spike pulses which are very easy for the brain to analyze. Figure 1 shows a model of the input signal a neuron receives and the output signal it transmits. Because the neuron is executing processing locally it allows the neuron to send pre-processed information asynchronously only when an event of interest has occurred. This is important because it means the neuron is not required to pass along all the data it collects, only the important information. This processing also allows the neuron to transmit data with a robust encoding scheme that features a high signal-to-noise ratio. The SHM community has begun to utilize asynchronous concepts [5–7], but have focused on creating asynchronous individual sensors instead of putting traditional sensor arrays into a system which reports data asynchronously.

Another challenge involved with large sensors array systems is the necessity of providing the communication pathways for acquiring such a large number of signals. Increased numbers of communication pathways increase the space, cost, and power consumption of the system, while at the same time provide additional points of failure. This increases the required space, cost, and power consumption.

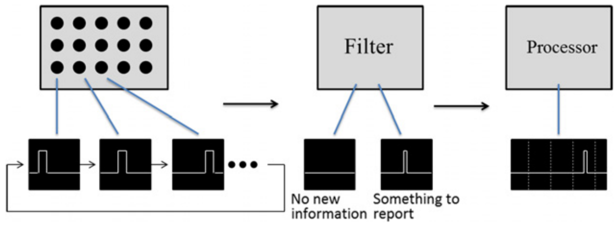

Figure 2. High-level circuit description.

The nervous system alleviates this problem by networking groups of neurons together [9].

In this paper, a system will be proposed which mimics the strategies used by the human nervous system to reduce power and data acquisition/analysis requirements for a sensor array. A potential application for this system will be displayed with a demonstration of a crack detection skin using conductive ink and graphene-oxide capacitors. This technology also has great potential to be used to make next-generation tamper-indicating seals that have inherent internal authentication and whose condition can be assessed remotely. Other potential applications will also be discussed.

2. Asynchronous sensor circuit

As discussed above, biological neurons reduce the processing power required by the central processor (the brain) by sending processed data instead of raw data and by grouping signals together onto a common input channel or bus. Our circuit incorporates both of these strategies. A graphic which explains the circuit concept at a generic and macroscopic view is shown in figure 2. The circuit operates by generating a series of signals which trigger each other in a loop. The output of each signal is sent through a filter which outputs a signal if there is something to report and outputs nothing otherwise. The output of the filter is sent to a common bus which is the input to a processor. When the processor receives a signal, it performs a time division de-multiplexing to identify the source of the signal, but should have to do little to no processing otherwise. The graphic for figure 2 was left very generic to convey the concept that this idea could be used in a variety of different ways and not just in the manner that it was done in this paper.

Figure 3 shows a schematic of the actual components used for the crack detection circuit that will be discussed subsequently. In this schematic, monostable 555 timers generate pulses which trigger each other in a loop. Each 555 output is sent into a passive low pass filter and the output of the filter is sent to the gate of an N-channel MOSFET. If enough of the 555 timer signal passes through the low pass filter, the MOSFET is activated and a signal is sent to the bus. The MOSFETs allow signals from each sensor to travel on the same line without influencing each other. The bus signal is sent into a comparator which turns the signal into a high–low signal which can be read into a processor without the need for analog-to-digital conversion. Not only does this eliminate the need to convert analog signals to digital signals, but it allows a whole array of sensors to pass information on a single line. A key advantage to this setup

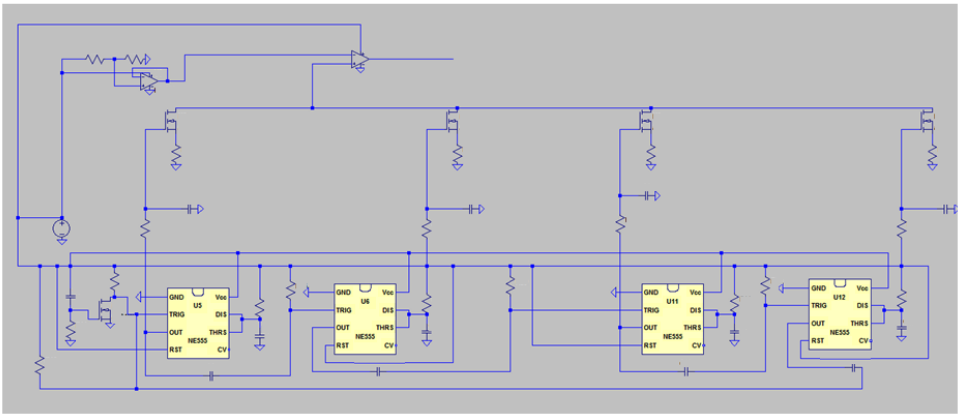

Figure 3. Circuit schematic for the crack detection system.

is that the processor can be moved off-board and the signal can easily be sent wirelessly since the amount of information being passed is sparse. These advantages can greatly reduce space, cost, and power requirements. This could especially be useful in applications like unmanned aviation systems (UASs) where weight and power are both major constraints or in other situations where data must be transferred wirelessly since it greatly reduces the amount of data that needs to be transferred.

The sensor could be placed in the circuit in the place of either the resistor or capacitor on either the 555 timer or low pass filter depending on the application. If the sensor is placed in the monostable 555 timer circuit then the length of the timer pulse will change based on the sensor reading. If the sensor is placed in the low pass filter then the sensor reading will affect how much of the timer pulse is attenuated.

2.1. Circuit health monitoring

One issue with an asynchronous monitoring system is the inability to distinguish between a healthy, well-functioning system with a system that is not reporting because it is completely broken. To remedy this, the asynchronous system needs to be capable of sending a signal to signify that everything is functioning properly. In this paper we will refer to this as a 'heartbeat' signal. The heartbeat signal is achieved by feeding the output of one timer in the timer loop to the input of a ripple counter. When the timer loop has reached a set number of cycles, the ripple counter causes the circuit to output a pulse for each functioning sensor and then the counter is reset. Figure 4 shows a block diagram outlining this strategy. A specific example of how to accomplish this strategy is described in section 3.1.

2.2. Power consumption

Because the system triggers itself in a loop, adding sensors to the system does not change the amount of data being sent at a given time. Therefore, the only additional power consumption resulting from adding a sensor is the power that a 555 timer consumes while not active. Figure 4 shows the prototype system that was built and tested. The CSS555C micropower

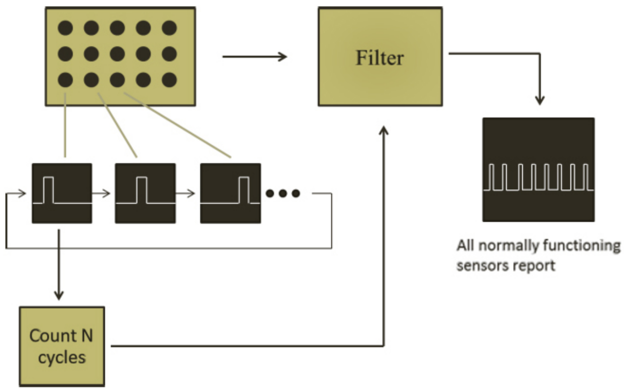

Figure 4. Block diagram of the heartbeat signal.

timer was used to generate the pulses. The timer measured 20 μA of current in its passive state at 1.5 V (the lowest voltage at which the circuit operated successfully). This means that the circuit will consume an additional 30 μW of power for each additional sensor in the circuit. The power consumption was tested for a circuit with 3, 4, 5 and 6 sensors and the results are shown in figure 5. The data points are indeed linear with a 30 μW increase with each additional sensor and 180 μW consumption for everything else. In this circuit all of the power increase per sensors is due to the power consumption of the 555 timer in its passive state. In future work, alternatives to the 555 timer will be explored in an attempt to reduce power consumption further. This design can be scaled up to include a large number of sensors without affecting the performance. The only constraint to scaling up the number of sensors is the sensing rate. In an array of n sensors, each sensor only has the ability to report $1/n$th of the time. Therefore, this design would not work well for something like impact identification where sensors need to be constantly monitoring, but would work well in many applications where periodic measurements will suffice.

3. Crack detection skin

The circuit described above was built and tested as a crack detection skin sensor array. The crack detection system was

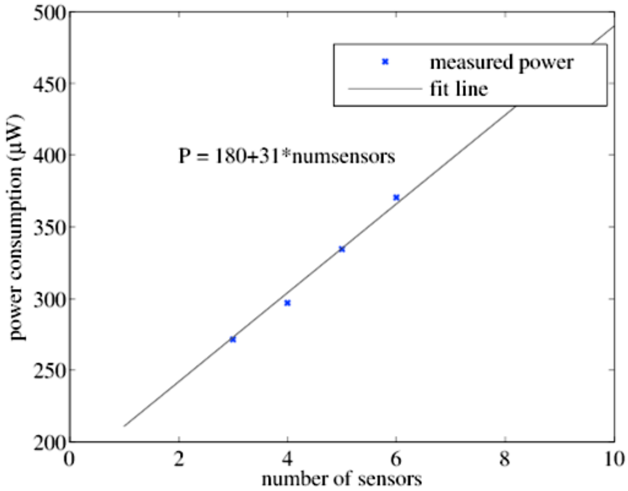

Figure 5. Measured and extrapolated power consumption.

tested using two different kinds of sensors: conductive ink resistive sensors and graphene-oxide capacitive sensors. There have been groups who have developed systems which have similar functionality [10, 11]. The functionality of the crack detection array described here is similar to the other systems. The primary advantage of this system is that its nature allows it to scale up more easily and reduces the amount of data to analyze.

3.1. Resistive sensors

Conductive ink resistors were chosen to test as crack detection sensors because they are inexpensive and easy to produce. For the initial proof-of-concept testing, a conductive pen was drawn onto a sheet of paper using a stencil. Wires were passed through the paper on each end and crimped into place. Conductive ink was then drawn over the wires, forming an electrical connection once the ink dried. An array was created with 5 conductive ink sensors and placed in the circuit shown in figure 3 in place of the 555 timer resistor. The pulse width of a monostable 555 timer is equal to:

$$pw = 1.1 * R * C.$$

Therefore, higher resistance means a longer pulse width. When the resistor is cut, the resistance increases, lengthening the pulse width and creating introducing a lower frequency component into the pulse. Therefore, a low pass filter that does not output a high enough voltage to activate the MOSFET and send a signal to the bus when the resistor is in its normal state can generate an output signal when the resistor is damaged. Figure 6 shows the prototyped conductive ink sensor array circuit. Figure 7 shows an image of a breadboard prototype of the physical circuit. The wires on the top center of the circuit are attached to the sensor electrodes shown in figure 7. The left side of the breadboard is the timer loop and the low pass filters. The center bottom has the MOSFETSs and bus line. The right bottom is the counter and an 'and' gate used to reset the counter. The right center components are capacitors which are attached in parallel to the timer capacitors. When the counter reaches the preset number of cycles all of the capacitors on the right center are connected to ground, which increases the pulse width of each timer and the output pulses for each functioning timer. This is the heartbeat signal discussed earlier. The top right of the circuit is a comparator and the output of the comparator is the output of the circuit.

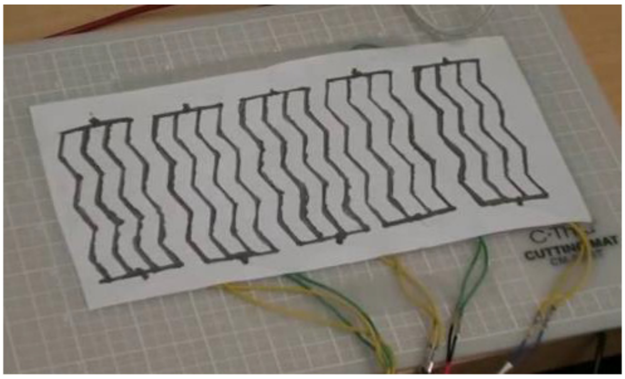

Figure 6. Conductive ink sensor array.

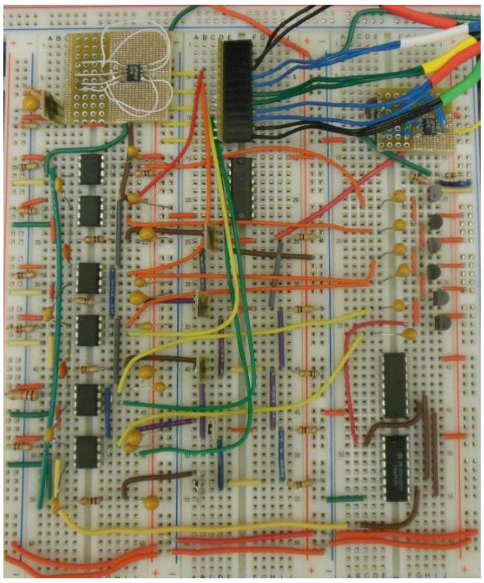

Figure 7. Circuit prototype.

The sensors were created with 4 parallel resistive paths to explore the possibility of sending information on crack length from the sensor. Figure 8 shows the circuit output as 1, 2, and 3 paths are cut and shows that the output pulse gets longer for increased damage. Figure 9 displays the heartbeat signal of a healthy system.

3.2. Graphene-oxide capacitive sensors

There has been much interest lately in using graphene-oxide supercapacitors as energy storage devices [12–14] or as particle sensors [15, 16]. We were interested in exploring their potential as crack detection sensors, perhaps with the potential to eventually be used as dual energy storage members/crack detection sensors. Graphene oxide (GO) was prepared as

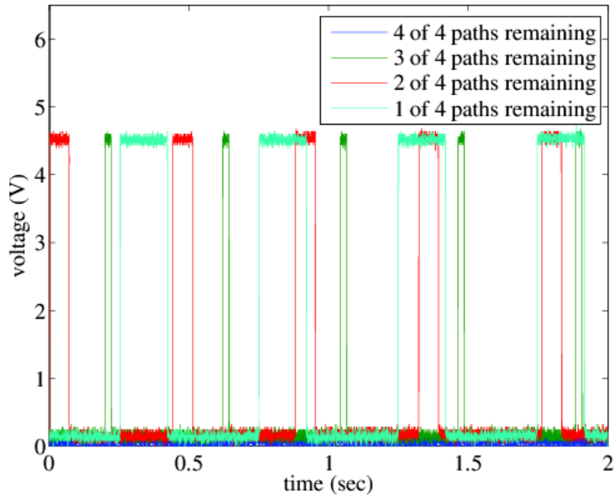

Figure 8. Output pulse width increases with increased sensor resistance.

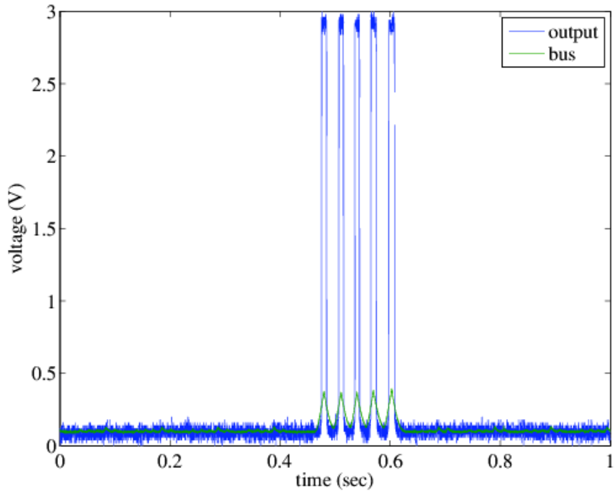

Figure 9. Heartbeat signal of a healthy system.

reported in the literature [17]. Free-standing GO films were vacuum filtrated, producing a 22 μm thick GO sheet. Parts of the sheet were then reduced with a CO_2 laser printer. Reduced graphene oxide (rGO) can be used as the electrodes of an electrochemical capacitor, with unreduced hydrated GO acting as the electrolyte [17]. The capacitors can be made into any shape, but in this case only concentric circle capacitors were made, as shown in figure 10. Wires were attached to each end of the capacitors using the same method used for the conductive ink resistors. Figure 11 shows the capacitors after the leads were attached.

Originally we had planned to replace the capacitors making up the low pass filter in the circuit described above with the graphene-oxide sensors, which would allow the signal to propagate through when a cut develops and the capacitors decreased in capacitance. However, this did not work because all electrochemical capacitors are frequency dependent, with the capacitance dropping at higher frequencies [18]. Because of this phenomenon, GO capacitors cannot act as low pass filters since the capacitance is itself a function of frequency.

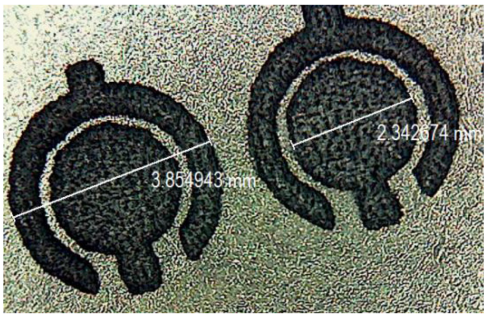

Figure 10. Laser-reduced GO capacitors.

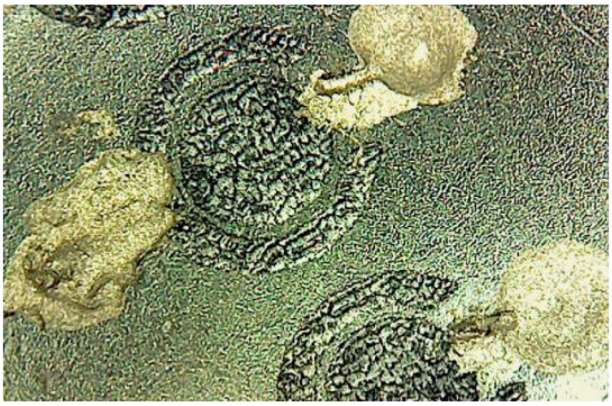

Figure 11. GO capacitors with wires attached using conductive ink.

Therefore, the original design was slightly changed so that the GO sensors would be used as the capacitor associated with the monostable 555 timers. When a sensor is cut the capacitance drops, decreasing the pulse width. In order to make a pulse width drop trigger the output instead of a pulse width increase, the inputs to the comparator were simply switched so that the circuit triggers on low bus voltage instead of high bus voltage and the filter parameters were chosen such that the voltage remained above the threshold unless the pulse width dropped. The GO capacitors were input into the circuit and damage was simulated by cutting the capacitors with a razor blade. Figure 12 shows the bus and output signals before damage and after two sensors were cut.

Next, a prototype graphene-oxide sensing skin was built to illustrate how the capacitive crack sensors could be deployed in actual applications. For this demonstration graphene oxide was spray-coated on a sheet of cellulose paper. Reduction of the graphene oxide to form capacitive sensors was achieved using a laser patterning technique. The resulting sensing skin can be seen in figure 13. In this image the graphene-oxide-coated cellulose paper is cut through using a utility knife. A red LED is connected to the associated electronics to indicate both the presence and location of damage in the skin. A graphene-oxide sensing skin placed on cellulose paper has potential to be used to create the next generation of intelligent tamper-indicating seals whose state of health can be monitored remotely, and features authentication capabilities. This is an important application for nuclear safeguards applications

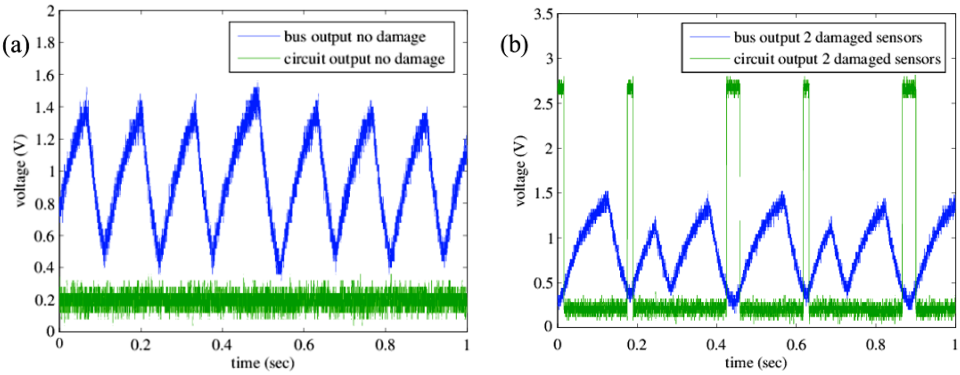

Figure 12. Oscilloscope signals of (a) healthy and (b) damaged skin.

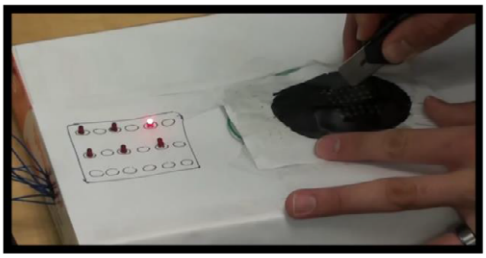

Figure 13. The graphene-oxide–cellulose composite skin being damaged by a through-cut with a knife. The red LED indicates the presence and location of the damage.

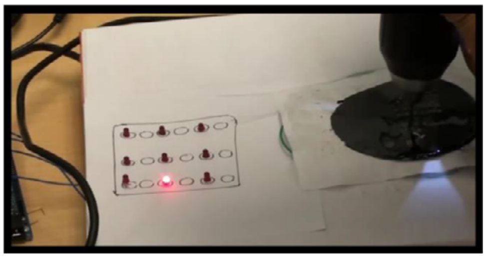

Figure 14. Epoxy-coated graphene-oxide–cellulose skin being damaged by being drilled through. The red LED indicates the damage location.

where continuity of knowledge concerning whether or not nuclear materials containers have been accessed.

Next, a portion of the graphene-oxide–cellulose skin was coated in epoxy to help illustrate how this material might be employed in a structure made from fiber-reinforced-plastic. Figure 14 shows the epoxy-coated skin being drilled through to induce damage. Once again the red LEDs are used to indicate the presence and location of damage. This initial demonstration of the concept suggests we can embed graphene-oxide sensing skin layers in fiber-reinforced plastic layups. The sensing skin could then indicate when a crack has developed in the resulting composite structure.

4. Conclusions

We have looked at the strategies used in the human nervous system and employed them in a circuit using inexpensive off-the-shelf components to create a circuit that conveys sensor information in an asynchronous manner, performs most of the signal analysis in the circuit itself to reduce data analysis requirements, and groups sensors together onto a common bus to lower wiring and data acquisition requirements.

The circuit was successfully tested on a prototype crack detection skin where both conductive ink resistors and GO capacitors were tested as crack detection sensors. Both types of sensors could be coated directly onto the structural member that needs to be monitored, thus minimizing the addition of weight or size from the presence of a large sensor array. This skin has applications in the area of intelligent tamper-indicating seals, and shows promise to be embedded in fiber-reinforced plastic layups. Current work is now focused on design techniques to layout the sensing skin sensor elements and the associated wiring in such a way that the overall system is highly scalable as well as robust to damage.

This work is a preliminary effort towards enabling the next generation of ‘networked materials’ that inherently have means to provide information on their state-of-health. Ongoing work is currently focused on how communication channels can be setup inside these materials in a robust manner. We are also developing new concepts for material property measurements that can be used to characterize these materials. Examples of important new material properties that will need to be defined include measures of the density of data available from the material and the associated latency, their mechanical/communication channel robustness, and their coupled channel noise characteristics with respect to vibro-acoustic/electromagnetic interference.

Acknowledgments

The authors would like to acknowledge the support of the Los Alamos National Laboratory—Laboratory Directed Research and Development Program, grant number 20130527ER. We would also like to acknowledge Karen Miller of Los Alamos National Laboratories for encouraging us to explore the use of smart materials for novel, tamper-indicating seal technology.

References

[1] Glisic B and Verma N 2011 *Proc. 8th Int. Workshop on Structural Health Monitoring* vol 2 pp 1409–16

[2] Yao Y, Tung S-T E, Verma N and Glisic B 2013 *Proc. 9th Int. Workshop on Structural Health Monitoring* vol 2 pp 2787–94

[3] Herculano-Houzel S 2009 *Front. Hum. Neurosci.* **3** 31

[4] Drubach D 2000 *The Brain Explained* (Upper Saddle River, NJ: Prentice-Hall)

[5] Huang C and Chakrabartty S 2012 *IEEE J. Solid-State Circuits* **47** 476–89

[6] Chintalapudi K, Paek J, Gnawali O, Fu T S, Dantu K, Caffrey J, Govindan R, Johnson E and Masri S 2006 *Proc. 5th Int. Conf. on Information Processing in Sensor Networks* pp 475–82

[7] Chakrabartty S 2013 *Advances in Energy Harvesting Methods* ed N Elvin and A Erturk (Berlin: Springer) pp 345–67

[8] Rossant C, Goodman M, Platkiewicz J and Brette R 2010 *Front. Neuroinform.* doi:10.3389/neuro.11.002.2010

[9] White J, Southgate E, Thomson J and Brenner S 1986 *Phil. Trans. R. Soc.* **314** 1–340

[10] Zhang B, Zhou Z, Zhang K, Yan G and Xu Z 2006 *J. Intell. Mater. Syst. Struct.* **17** 907–17

[11] Pyo S, Loh K, Hou T, Jarva E and Lynch J 2011 *Smart Struct. Syst.* **8** 139–55

[12] Xu J, Wang K, Zu S, Han B and Wei Z 2010 *ACS Nano* **4** 5019–26

[13] Liu C, Yu Z, Neff D, Zhamu A and Jang B 2010 *Nano Lett.* **10** 4863–8

[14] Brownson D, Kampouris D and Banks C 2011 *J. Power Sources* **196** 4873–85

[15] Lu G, Ocola L and Chen J 2009 *Nanotechnology* **20** 445502

[16] Robinson J, Perkins F, Snow E, Wei Z and Sheehan P 2008 *Nano Lett.* **8** 3137–40

[17] Gao W, Singh N, Song L, Liu Z, Reddy A, Ci L, Vajtai R, Zhang Q, Wei B and Ajayan P 2011 *Nature Nanotechnol.* **6** 496–500

[18] Sarangapani S, Tilak B and Chen C 1996 *J. Electrochem. Soc.* **143** 3791–9