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Bio-inspired stretchable network-based intelligent composites

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Abstract
The human skin hosts an array of sensors that are capable of detecting and interpreting many traits important to how we function and survive. The goal of mimicking this capability in composites to create intelligent composite materials has led to the development of a bio-inspired stretchable network composed of numerous micro-fabricated sensors capable of detecting multiple stimuli. The components of the network are small scale and flexible making the network embeddable within complexly shaped composite layups and flexible structures with minimal impact on the host structure. This paper outlines recent progress in ongoing work to develop the bio-inspired network in order to create intelligent composite materials.

Keywords
Bio-inspired, embedded, intelligent, multi-functional, sensor

Introduction

The human sensory system consists of numerous types of sensors distributed over the body and capable of detecting and interpreting many stimuli important to how we function and survive. This is combined with a hierarchical nervous system, in the form of our central and peripheral nervous systems, providing local and global processing to manage the vast amount of data, depicted in Figure 1. There are many situations where it is desirable to have similar functionality in structures so that they can indicate their condition, capability and safety. This is particularly true of composite materials used in high-performance, low-design margin applications with numerous complex failure modes. An example of this is fly by feel aircraft, ideally capable of sensing their state and adjusting their operational envelope accordingly.

A team of researchers from the Structures and Composites Laboratory at Stanford University are currently conducting research in pursuit of this goal through the development of a bio-inspired, micro-fabricated, embeddable stretchable network capable of hosting multiple sensors and computational suites, illustrated in Figure 2. This system is based on the stretchable network substrate developed at Stanford University. The stretchable network system is fabricated using non-standard micro-fabrication techniques primarily utilized for micro-processors and designed around the simultaneous mass production of numerous similar parts, like millions of silicon transistors in a microchip, into an integrated system. This technology is leveraged to produce a full network consisting of sensor nodes and electrical interconnects potentially including wires, temperature sensors, strain sensors, ultrasonic actuators, ultrasonic sensors, addressing and processing capabilities. During fabrication, the substrate is etched into a form that can be stretched and expanded to cover an area orders of magnitude larger than the original processing area. The system can then be interfaced into local and global processors for data analysis.[1–5] Figure 3 contains before

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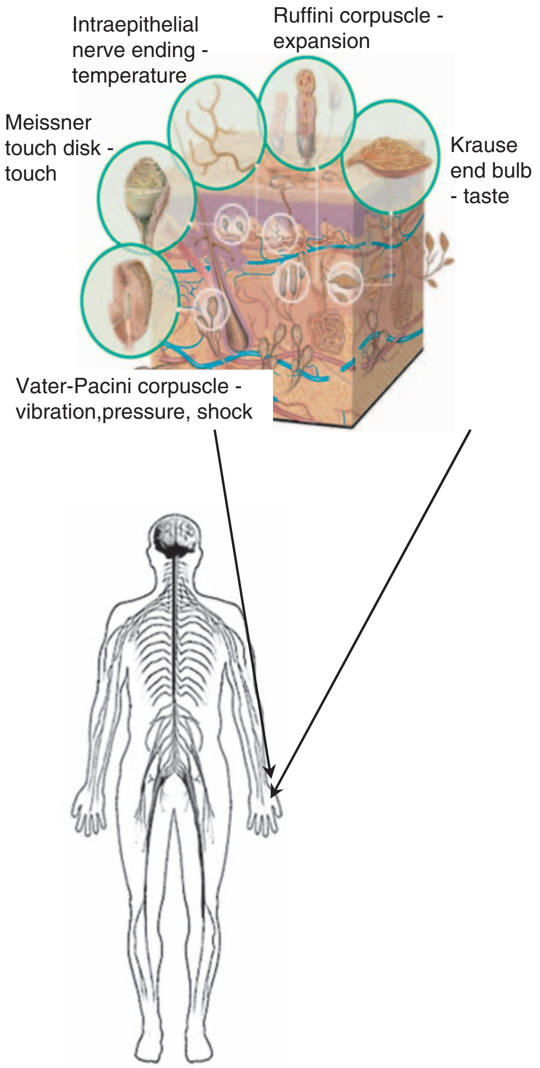

Figure 1. Sensors in the skin and the human nervous system.

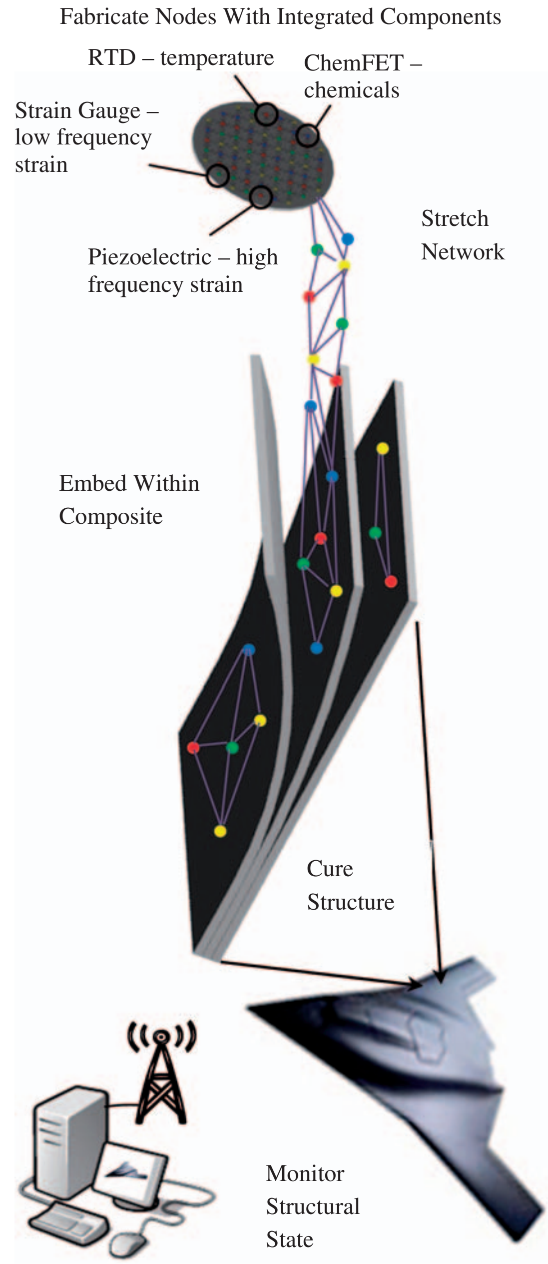

Figure 2. Bio-inspired stretchable sensor network, fabricated with multiple sensors at the micro-scale, stretched and embedded in to composite layups.

and after photos of an interconnect undergoing 1-dimensional extension. When embedded in a composite, this form of sensor network has the potential to provide localized sensor information about multiple aspects of the composite's condition, including temperature, deformation and damage, like skin. At the same time, the distributed nature of the sensors enables full coverage of a structure too large to completely micro-fabricate.

The stretchable substrate has several key traits that make it particularly appealing for embedding within a composite layup. The first is that, in making components smaller, the potential coverage of the stretched network is actually increased. This occurs because smaller features in the pattern enable the creation of more, longer micro-wires and more nodes in the same physical space or from the same piece of material. This is achieved through the adaptation of micro and nano-fabrication techniques initially developed to make microprocessors and MEMS. Once stretched, the small physical size and dispersed nature of the network components make them minimally intrusive when embedded within a composite laminate, adding minimal weight and having the least possible effect on structural strength. Additionally, the network is extremely flexible and compliant, allowing it to conform to complex shapes like double-curved surfaces or be employed in flexible structures. Unique fabrication methods had to be developed to create this bio-inspired

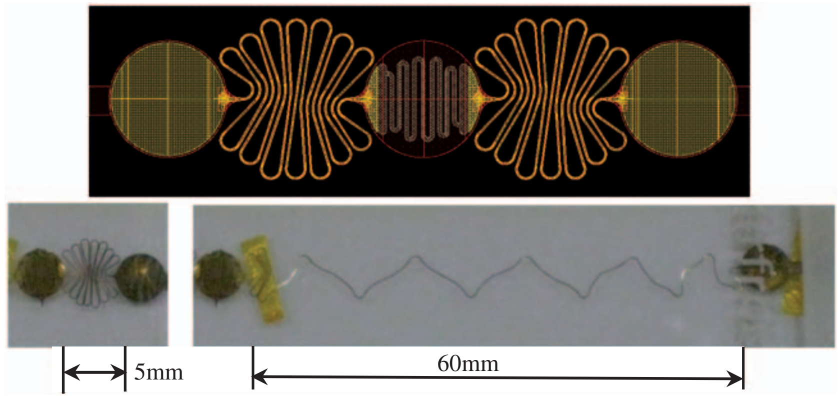

Figure 3. Two-node system of resistive temperature detectors (RTDs) undergoing one-directional expansion.

network due to the nature of the processing and use of a non-standard, polyimide substrate.

This paper presents an overview of the ongoing research and development of systems that have been integrated into the stretchable network in pursuit of a bio-inspired material capable of detecting temperature, damage, deformation and other traits. To date, resistive temperature detectors (RTDs), resistive strain gauges, piezoelectric elements and diodes have been integrated into the network to serve these purposes. Onboard microprocessors have served to pre-process data which was then passed to laptops with software interfaces that interpreted it and presented it in a useful form, mimicking the peripheral and central nervous system.

Problem statement

Traditional sensor network systems and their associated network hardware have numerous drawbacks that make them unsuitable for embedding within composite layups. Specifically, traditional sensors and networking components are large and, when embedded within a composite layup, can detrimentally affect the strength and life of a composite host structure. Along with physical size, added weight reduces the strength-to-weight ratio that makes composites attractive. Finally, manual assembly and installation of traditional sensor systems is labor-intensive and costly.

Approach

In order to overcome the parasitic effects of incorporating standard sensor networks into composite layups, including size, weight, degradation and installation issues, The Structures and Composites Laboratory (SACL) at Stanford University has developed a bio-inspired, micro-fabricated, embeddable stretchable network capable of hosting multiple types of sensors and computational hardware. Like the skin, this network is capable of hosting large numbers of multiple forms of sensors for detecting various stimuli embedded within a structural material, conceptually illustrated in Figure 2. Additionally, this system could be used to host senses not typically found in the skin, like chemical presence and penetration, or electromagnetic variations, similar to the biological senses of smell, taste and sight.

Designs

The stretchable network design is intended to host multiple types of sensors, network hardware and even computational hardware, like the human skin and nervous system, in a form that is easily embeddable within a composite layup with minimal invasive and parasitic effects on the layup. Non-standard micro-fabrication techniques are used to simultaneously create numerous small-scale components in an integrated system on the stretchable network substrate. The network is then expanded to cover a large area, orders of magnitude larger than the original working area. This stretched spider-web-like network can then be embedded within a composite layup as depicted in Figure 2. Having micro-scale components sparsely distributed over a large area significantly reduces the weight of the network and the impact on the properties of the host structure when compared to traditional sensors and network hardware. For example, commercially available flex circuit-based sensor networks are typically greater than 1 cm wide and 100 μm thick and can be several times that thickness at the sensors. Stretchable networks have been fabricated in the SACL with stretchable interconnects 4 μm in width, as a point of reference a single filament in Toray T800H carbon fiber is 5 μm in diameter.[6] Additionally, this fabrication technique has an inverse relation between the amount of material or size and weight of components used and the area covered, i.e. In traditional fabrication, adding sensors or covering a larger area requires the addition of material in the form of more/longer wires and more sensors.

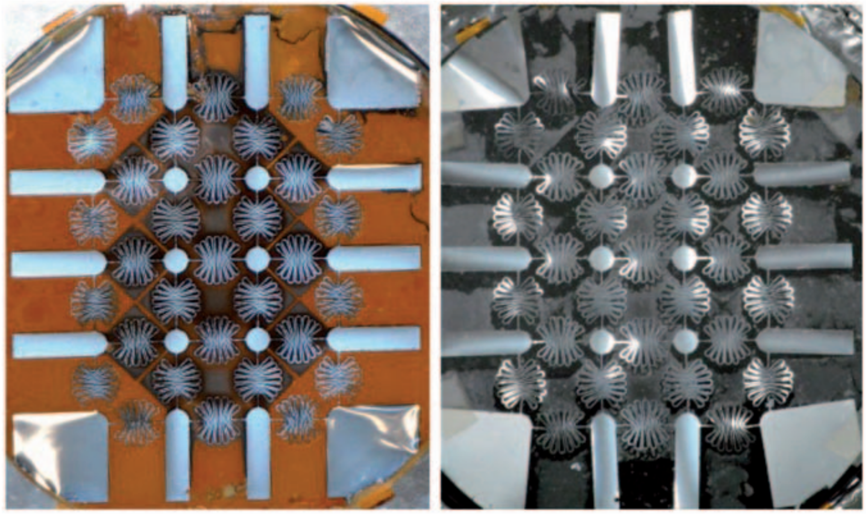

Figure 4. High-voltage stretchable network with Pt wires before plasma etching (left) and after plasma etching (right).

Conversely, in the stretchable network, making the components smaller, removing more material, enables the fabrication of more components and longer interconnecting wires, reducing weight and covering greater areas. However, smaller features require more complex and more expensive fabrication methods.

The integrated nature of the network additionally eases installation of the network into a composite because a whole network with all the numerous components can be installed at once, as opposed to the traditional method of manually installing individual sensors a few at a time.

In order to achieve this, there is ongoing work to develop and integrate many different systems onto the stretchable network including interconnecting wires, temperature sensors, strain gauges, high-frequency strain sensors, damage detection capability, addressing hardware and onboard microprocessors.

The stretchable substrate

The stretchable network substrate is critical to deploying an integrated, micro-fabricated system over a large area. This network consists of spring-like interconnects capable of hosting conductive micro-wires and nodes capable of hosting sensors, actuators, microprocessors and other hardware.[1–3] This substrate is fabricated out of polyimide materials, typically supported on a standard silicon clean room wafer, and then released and stretched to cover an area orders of magnitude larger than the original working area. The use of a polymer substrate is necessary to accommodate the relatively large strains involved in the expansion process.

The stretchable network was fabricated using non-standard micro-fabrication process specifically adapted for the system. In the cases shown here, a 25-μm-thick Kapton® film was mounted on a silicon backing wafer. Then, using photolithography and liftoff techniques, the conductive micro-wires were formed on the Kapton®. Similarly, a metallic plasma etch mask was patterned with wet etch techniques. An example network at this point is shown in Figure 4 (left). The Kapton® was then etched in an MRC plasma etcher, this step can also be used to shape the conductive micro-wires. Finally, the residual mask was wet-etched off. The etched network substrate is shown in Figure 4 (right). Functional wires of various dimensions and composed of gold, platinum, aluminum and other metals have all been produced in the course of this research with some exposed to and surviving direct current electrical potentials in excess of 800 V.

Due to the non-standard substrate material, new processes and designs had to be implemented in order to functionalize the network through the addition of sensor, actuator, networking and processing hardware. The fact that the substrate is polyimide significantly complicates fabrication because most micro-fabrication is done on silicon, therefore new or modified processing and testing of the systems had to be developed. Sensors, actuators and systems can be created on the substrate either before or after etching.

Temperature detection

Intraepithelial nerve endings provide the human skin with a sense of temperature, to mimic this, RTDs were developed on the stretchable network substrate.

As an initial demonstration of a functional network, platinum RTDs with gold interconnecting wires were designed and fabricated on the nodes using liftoff micro-fabrication. This system was selected as an initial demonstration due to its simplicity and robustness in

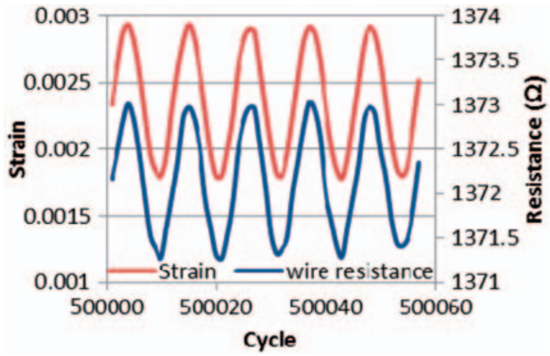

Figure 5. Micro-wire, functional as a strain gauge, mounted on Toray – 800 unidirectional specimen.

both design and fabrication along with the well-documented thermal characteristics of the materials involved. Testing evolved from single nodes to multiple nodes with 1:1 electrical contact to sensor mapping, to systems with basic addressing involving semi-conductors, which will be discussed in further detail below. A single RTD node built on a stretchable substrate, both before and after stretch, can be seen in Figure 3. The RTD demonstrated excellent functionality with 150Ω resistance, as designed, and excellent signal linearity, with an R^2 greater than .999. This first test established that sensor systems can be integrated into the expandable network substrate and the overall capability for the network to host more complex sensing systems, like human skin. Networking hardware, onboard processing and addressing systems continue to be developed on this system due to the simplicity of the sensors.[3,7]

Strain detection

In the skin, Ruffini corpuscles and Meissner touch disks detect low-rate strain. In order to mimic this, strain sensing capabilities were developed for the network.

Gold-coated interconnects provided a ready system potentially capable of detecting strain. In order to demonstrate this ability, the resistance of an extended micro-wire, mounted on a host structure, was monitored while the structure was loaded. The setup involved two nodes with an extended interconnecting gold wire adhered to the surface of a specimen of cured unidirectional Toray T-800 CFRP, aligned in the 0° direction, as shown in Figure 5. This setup was connected to standard data acquisition hardware for strain gauges to produce data. This specimen was then cycled over 500,000 times with maximum strain of 0.0625% and an R = .15. The interconnecting wire not only survived but recorded resistances that correlate to the strain of the specimen.[2]

Figure 6. Plot of strain and wire resistance after over 500,000 cycles.

Figure 6 shows the result of the micro-wire functioning as a strain gauge, compared to the mechanical extension of the specimen after nearly 500,000 cycles. While the center point of the detection shifted slightly over the course of the test, the peak to peak span remained consistent.

This demonstrates the ability to use the interconnecting wires as strain gauges in the bio-inspired expandable network. Current addressing capabilities do not allow implementation of this system on a full network. However, future development can make this into a functional sensor for the network.

Vibration detection

Piezoelectric transducers have the capability to reproduce multiple biological sensing functions, providing multi-functional capability. Piezoelectric elements can directly sense high-frequency deformations, much like Vater-Pacini corpuscles in the human skin. In the proper configurations, piezoelectric elements can be used to sense temperature changes and even chemical presence. Additionally, with the application of appropriate data processing algorithms, piezoelectric elements can be used for the detection and location of impacts and damage as demonstrated in acoustic ultrasound-based structural health monitoring (SHM). The capability of this form of SHM has been demonstrated in the detection of multiple forms of damage, including fiber breakage, matrix cracking, disbonds and corrosion in many materials including polymer matrix composites, advanced metal hybrid composites and metals.[8–15] Additionally, these impact and damage detection systems are designed around a dispersed network and therefore are ideal for adaptation to this design.

Among the systems integrated into the stretchable substrate to date, piezoelectric systems are the only ones that are voltage-based, and the potential voltages involved can be orders of magnitude larger than those used in any other system to date. Additionally, the physical size and weight of the piezoelectric transducers are much greater than anything else previously mounted on the stretchable substrate. Therefore, creation of a stretchable network with mounted piezoelectric transducers simultaneously verifies fabricatabilty of the piezoelectric system and the network's functionality and capability to host it.

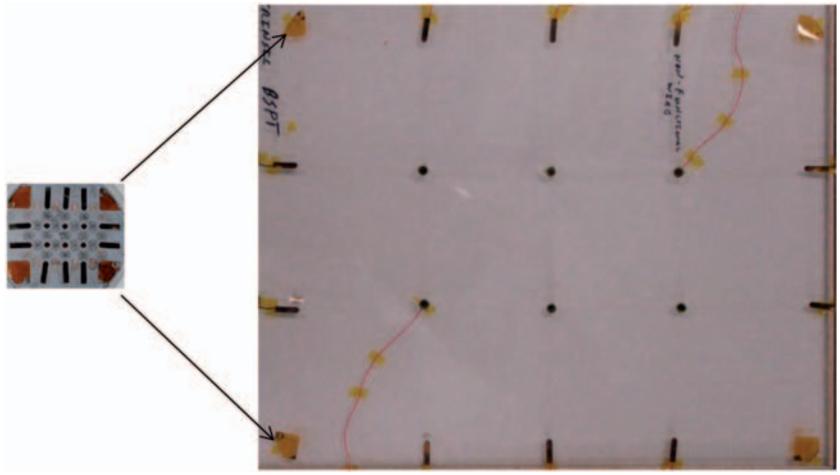

Figure 7. Stretchable bismuth scandium lead titanate (BSPT) network before expansion (left) and mounted on 1.9-mm-thick glass after expansion (right). Pictures are the same scale.

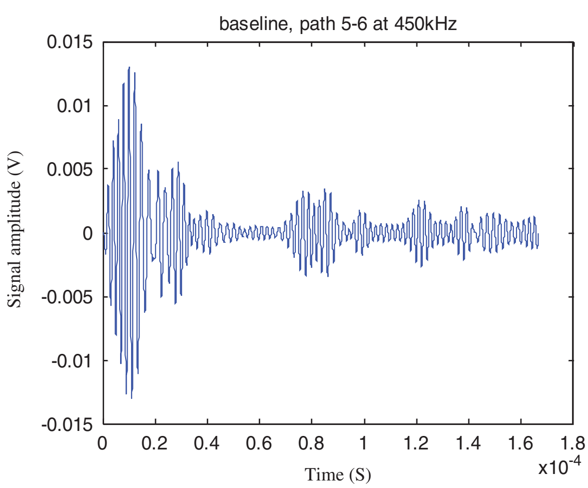

Figure 8. Signal actuated and sensed by bismuth scandium lead titanate (BSPT) over a distance of 9 cm. Actuation was a Gaussian windowed 5-peak tone burst at 450 kHz with a peak amplitude of 50 volts. The signal propagated through 2-mm-thick glass.

The hosting polyimide stretchable network was designed with platinum wires of relatively large dimensions, 100 µm wide by .1 µm thick. Platinum was selected because of its lack of reactivity to the assortment of etchants and chemicals the network is exposed to during processing. However, the use of platinum, as opposed to the typical gold or aluminum conductors demonstrated in the past, also complicated the fabrication process, specifically the plasma etch recipe had to be modified to accommodate the platinum. The relatively large dimensions of the interconnecting microwires was selected to reduce their electrical resistance, though still significantly larger than that of a typical SHM network. Addressing was accomplished through 1:1 mapping from node to peripheral contact pad. Fully functional, and polarized, bismuth scandium lead titanate (BSPT) piezo-ceramics were manually mounted on all of the internal nodes of the un-stretched substrate using conductive epoxy. Great care had to be taken to prevent shorting of the circuits or adhering the network to underlying media before expansion.[16]

After the conductive epoxy cured, the electrical interconnects were tested with an ohm meter to ensure functionality and absence of shorts in the system. One microwire was clearly broken in processing, and one other showed unsatisfactory electrical functionality, however all of the rest showed excellent functionality with approximately 450 Ω resistance. Additionally, a 10 kHz sinusoidal actuation at 10 V was performed on each piezo, each produced an audible tone confirming functionality.

At this point, the entire system was laid on a piece of glass, which would be its final backing, and the entire network stretched in one direction, then in the perpendicular direction with the interior nodes sliding to their desired locations. This was achieved by temporarily adhering the external nodes along opposite sides to small beams, then manually separating them, once expanded in one direction one edge of nodes was adhered to the backing, and the process was repeated in the perpendicular direction, similar to the process described in the work by Lanzara et al.[1,2] That work addresses the repeatability of expansion and node location. This expansion took the network from a functional area of 20 cm^2 to 1000 cm^2, an expansion of 5000%. Small dabs of Hysol 9396 epoxy were used to adhere the sensor nodes to the glass substrate and conductive epoxy was used to adhere wire leads to the contact pads to enable connection to a data acquisition computer. Before and after pictures are presented in Figure 7.

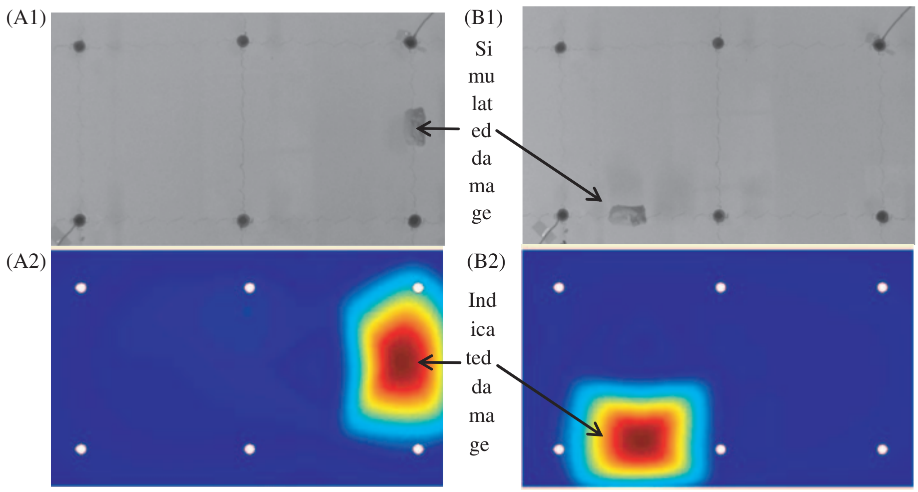

Figure 9. Bismuth scandium lead titanate (BSPT) stretchable network mounted on glass with simulated damage mounted on the back side (A1 & B1) and damage location via direct path imaging diagnostic algorithms (A2 & B2). Both images were produced using Gaussian windowed 5-peak tone bursts at 300 kHz to 600 kHz in 50 kHz steps. A2 was produced using the entire signal and B2 was produced with a signal windowed to only include the first few wave packet arrivals.

This represents the fully fabricated network. Individual elements were tested again for tones and conductivity. The interconnecting microwires were found to have maintained nearly the same resistance of approximately 450Ω through the stretching process. No new failures occurred due to the expansion process.

Several tests were performed on the fabricated stretchable network with BSPTs mounted on it. These include fundamental impact detection capabilities, pitch catch type signal propagation for acoustic ultrasound-based SHM and damage detection. Finally, the SHM capabilities of the system were tested using simulated damage techniques and a commercially available data acquisition computer designed for SHM using lead zirconate titanate transducers.

Impact detection capabilities were tested by connecting the network to an oscilloscope and lightly impacting the glass. Even impacts occurring far from the BSPTs produced significant voltages verifying the potential for BSPT to be used in impact detection systems. Strain wave actuation and detection were tested by actuating one BSPT at a time, while all of the others functioned as sensors. The system was actuated with a typical signal used in SHM, a 5-peak Gaussian windowed tone burst at a range of frequencies between 200 kHz and 600 kHz with peak actuation amplitudes of 10 to 50 volts. An example of the signal, actuated with 50 V at 450 kHz and propagated over a distance of 9 cm through 1.9-mm thick glass can be seen in Figure 8. The amplitude of this signal, about .005 V, is on par with that of lead zirconate titanate (PZT). This shows that the BSPT piezo-transducer has the potential to function in ultrasonic situations as well as the PZTs typically used

As a final test, the full network was used, with the same data acquisition computer, designed for PZT-based networks, and diagnostic algorithms were run on the resulting signals to produce images of 'damage' location. A sticky patch was used to simulate damage at various locations on the back side of the glass panel and additional data was taken. Figure 9 shows the results of this testing, verifying the functionality of BSPT in SHM systems.

These experiments indicate that BSPT has functionality on par with PZT-5A and can simply replace the PZT in existing SHM systems without other system alterations. Similarly, this indicates that the stretchable network is capable of functioning in SHM systems, at the high voltages and frequencies required. The results also indicate that the resistance of the wires in the stretchable network does not inhibit the functionality of the SHM system, though resistances are significantly higher than the wires in typical SHM systems.

This demonstrated that the piezoelectric elements on the stretchable network could actuate and sense high-frequency deformation like Pacini corpuscles and also have the functionality necessary for damage detection if SHM techniques are employed.

Network hardware

Like the human skin, the stretchable networks presented here are composed of numerous sensors that produce vast amounts of data. Again, mimicking the human skin, methods to locally process signals must be developed in order to manage and condense the large amount of data the sensors will produce. In order to achieve this, a local processor must be integrated into

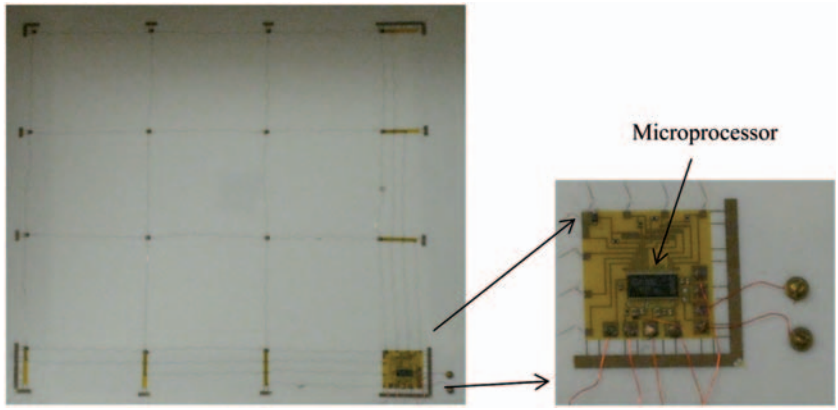

Figure 10. Sixteen-node resistive temperature detectors (RTDs)-based temperature-sensing network with diode addressing and mounted micro-processor.

the network to select nodes and sensors, and locally preprocess data. Following the bio-inspired nature of this system, a multi-tier structure is being pursued. This system consists of local processors, mimicking the peripheral nervous system, and a global processor, mimicking the central nervous system. The peripheral nervous system is formed by the local network components interfacing through a local processing unit that will only handle data from a small set of nodes and will only pass critical data to the global processor. Then, the global processor can function like the central nervous system to make decisions.

An initial demonstration of this was performed by employing chip diodes and a commercially available microprocessor on a stretchable network with 16 RTDs, shown in Figure 10. Being a resistance-based DC system, the diodes were sufficient to provide addressing functionality to the network. The microprocessor, shown in Figure 10 (right), functioned as an analog to digital converter and switch, selecting individual nodes and pre-processing raw sensor information before sending it to a laptop for interpretation and display. However, these discrete devices are not suitable for the long-term goals of the bio-inspired network. Therefore, thin film diodes and transistors are under investigation for integration into the network.

Aside from chip components listed above, this network was micro-fabricated and expanded onto a non-conductive backing in a process similar to the one for the piezoelectric network. The network demonstrated excellent real time temperature monitoring functionality.

Conclusions

The networks and components developed and demonstrated have the potential to be combined into a single functional bio-inspired network that can contain multiple forms of sensors at varying densities and be embedded into a composite layup. Replacing components with micro-fabricated thin and thick film systems, thin film diodes, transistors and microprocessors will truly minimize the effect on host structures. This forms the basis for developing intelligent composite materials with many of the same sensing capabilities as the human skin with the potential to revolutionize the medical and transportation industries.

Future work

Research is ongoing on methods to integrate more components at varying densities using layer-wise micro fabrication compatible processes including integration of synaptic transistors, screen-printed elements and thin-film semiconductors. Additional sensing systems are also under development to add more capabilities to the network. This is challenging because the typical process used to fabricate one component may destroy another. Therefore, compatible fabrication processes and transfer methods must be developed. Electrical insulation and protective layers are also under development to enable embedding within conductive composites and to ensure reliability. Additionally there is ongoing work on methods to automatically expand the network and embed it within composite layups.

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Conflict of interest

None declared

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