DEVELOPMENT OF A BIO-INSPIRED STRETCHABLE NETWORK FOR INTELLIGENT COMPOSITES

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Abstract:
The human skin hosts an array of sensors capable of detecting numerous traits that are important to how we function and survive. This is combined with local and global processing in a hierarchical nervous system in order to manage the vast amount of data generated, in the form of our peripheral and central nervous systems, illustrated in Fig 1. With the goal of transferring similar functionality to composite structures the Structures and Composites Laboratory at Stanford University, in collaboration with researchers at UCLA, has developed a bio-inspired, micro-fabricated, embeddable stretchable network capable of hosting multiple sensors and computational suites, illustrated in Fig 2.

Utilizing non-standard micro-fabrication techniques, an entire networked array of elements is fabricated simultaneously, composed of sensor nodes and interconnects that can include wires, temperature sensors, strain sensors, ultrasonic actuators, ultrasonic sensors, and signal processing. The substrate is then etched into a form that can be stretched and expanded to cover an area orders of magnitude larger than the original processing area and interfaced into local and global processors for data analysis [1]. Fig 3 contains before 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, much like skin [2].

Due to the small physical size and dispersed nature of the network components, this network can be embedded into a composite laminate with minimal effect on the overall structural strength. However, due to the nature of the processing and use of a non-standard polyimide substrate, unique fabrication methods had to be developed to create this bio-inspired network.

This paper presents an overview of the ongoing research and systems that have been integrated into this 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, diodes, and microprocessors have been integrated into the network to serve these purposes. An un-stretched and expanded network consisting of piezoelectric elements and electrical interconnects can be seen in Fig 4 and Fig 5 respectively. Software interfaces, running on laptops, have served to process gathered information into a useful form mimicking the central nervous system.

Additionally, synaptic transistors based on carbon nanotube (CNT) based composite that can process the signals from the network have been developed at UCLA, shown in Fig 6. These synaptic transistors can be tuned and are capable of providing signal processing, memory, and learning functions through modification of ionic fluxes in neurons and synapses. This enables the circuit to collectively process the signals through 10^3-10^4 synapses to establish spatial and temporal correlated functions.

Introduction:
The human skin hosts an array of sensors capable of detecting numerous traits that are important to how we function and survive. A basic image of the various sensing mechanisms can be seen in Fig 1. Having similar capabilities in structures would enable them to self-monitor for damage or environmental conditions that may affect their functionality. This can have direct implications on the strength, stiffness, and safety of structures. Embedding electronic systems into composite layers has the potential to provide such monitoring capabilities, however traditional electronics are not suitable for this application.

Problem Statement
Embedding individual traditional sensor systems and associated network hardware has numerous drawbacks, namely; manual wiring is time consuming and costly, traditional sensors are large and can detrimentally affect the strength and life of a composite host structure, and with their size, traditional sensor systems can add significant weight to a composite material, reducing the strength to weight ratio that makes composites attractive in the first place.

Si-based electronic materials, devices, and circuits have been explored extensively to emulate biological neural networks, but to date they have not been able to match the synaptic functions in the neural network. The lack of a small, cheap device with the essential synaptic dynamic properties for signal processing, learning, and memory prohibits the Si-based circuits from approaching the scale and functions of the biological neural network.

Approach:
In order to overcome the size, weight, degradation and installation issues encountered with installing standard sensor networks in composite layups, The Structures and Composites Laboratory 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 multiple forms of sensors for detecting various aspects of touch and can potentially carry sensors for other biological senses, embedded within a material, conceptually illustrated in Fig 2.

In collaboration with this effort researchers at UCLA have designed and fabricated a synaptic transistor based on CNT/polymer composites by integrating a layer of ionic conductive polymer and CNTs, shown in Fig 6. The synaptic transistor can replace presently utilized complex and energy-consuming electronic circuits to emulate the neural network for signal processing, learning, and memory.

Designs:
This network is designed to host multiple types of sensors, network hardware, and even local processing capabilities, like the human skin and nervous system, in a form that is easily embeddable within a composite layup. The network is created using nonstandard micro-fabrication techniques, enabling the simultaneous creation of numerous small scale elements in an integrated system. Then the network is stretched to cover a large area and embedded into a composite layup, as depicted in Fig 2. Having micro-scale components sparsely distributed over a large area significantly reduces the weight of the network and structural impact on the host structure when compared to traditional sensors and network hardware. This fabrication method produces numerous sensors and components simultaneously and enables easier installation of an integrated system. Contrary to standard fabrication methods, this fabrication requires reduction in component sizes to increase coverage area and number of sensors. Therefore, increasing the coverage area and number of sensors actually reduces the impact on a host structure because components are smaller and lighter weight. The drawback to this is pursuing increasingly smaller components becomes more expensive and complex. Installation of the integrated network can be done all at once by simply laying the fully fabricated network, like a layer, into the layup during fabrication.

To this end the network is composed of multiple integrated components, including the stretchable substrate, interconnecting wires, temperature sensors, strain gauges, damage detection capability, addressing hardware, and onboard microprocessors.

The Stretchable Substrate

In order to deploy sensors over a larger area, a stretchable network substrate was developed consisting of nodes, capable of hosting sensors, actuators, microprocessors and other hardware, and spring like interconnects capable of hosting conductive wires [1] [3] [4]. This substrate can be fabricated and then stretched to re-distribute the nodes over an area many orders of magnitude greater than the initial area while maintaining electrical functionality. In order to withstand the large strains associated with the expansion process; this substrate is made of polyimide. Fabrication was performed via plasma etching of Kapton masked with metal to define the pattern.

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

Temperature Detection:

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

As an initial demonstration of a functional network, platinum Resistive Temperature Detectors were designed and fabricated on the nodes, with gold interconnecting wires, using liftoff micro-fabrication. This developed temperature monitoring capabilities as well as employed a very basic sensor for initial demonstrations of the network. Testing developed from single nodes to multiple nodes with 1:1 electrical contact to sensor mapping, to systems with basic addressing, 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 Fig 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.

Strain Detection:

Strain gauges provide a material with a capability to determine low frequency deformations, like Ruffini corpuscles and Meissner touch disks in the skin. Therefore static/low rate strain gauges were developed for the network.

In order to demonstrate this capability the resistance of a gold coated interconnecting wire was monitored during loading. The setup involved two nodes with an interconnecting gold wire adhered to a specimen of cured unidirectional Toray T-800 CFRP, aligned in the 0˚ direction. 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 directly correlate to the strain of the specimen [2].

Vibration Detection:

Piezoelectric elements have been integrated into the stretchable substrate providing an ability to sense high frequency deformations, much like Vater-Pacini corpuscles in the human skin. Additionally Piezoelectric elements can be used for damage detection, as demonstrated in Acoustic ultrasound based Structural Health Monitoring. Acoustic Ultrasound based Structural Health Monitoring techniques have been employed to detect fiber breakage, matrix cracking, delamination and other damage forms in many different composite materials and applications [5] [6]. Additionally these systems are designed around a dispersed network and therefore would be ideal for application to this problem.

In order to demonstrate this functionality, six Bismuth Scandium Lead Titanate (BSPT) transducers, fabricated in house, were applied to an un-stretched network substrate with platinum wires in a 1:1 pin to node addressing setup as shown in Fig 4. The network was then stretched and adhered to a glass host structure shown in Fig 5. To demonstrate functionality these elements were actuated with a waveform generator at 10V p-p at 10kHz and an audible tone was produced. This demonstrated both that the micro-wires survived extension and that the

piezoelectric elements were functional through the extended micro-wires. Additionally, actuating one node at various frequencies in the hundreds of kHz range and attaching an oscilloscope to other transducers indicated that the system was propagating ultrasonic waves through the glass at frequencies appropriate for Structural Health Monitoring. 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 to for damage detection if Structural Health Monitoring techniques are employed.

Network Hardware

In any large sensor network, addressing capability and local processing will be necessary in order to select nodes and sensors, and locally preprocess the vast amount of data that may be produced. Following the bio-inspired nature of this system, a multi-tier structure is being pursued. A peripheral nervous system, 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, central nervous system.

An initial demonstration of this was performed by employing chip diodes and a commercially available microprocessor on a stretchable network with 16 RTDs. This microprocessor functioned as an analog to digital converter and switch, 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 synaptic transistors are being developed to fill this role.

Synaptic transistors based on CNT/polymer composites

The structure of the synaptic transistor is shown schematically in Fig 6. A 10 μm wide strip of single-walled self-assembled CNT network was fabricated as the transistor channel. A 90 nm thick poly(ethylene glycol) monomethyl ether (PEG) layer was then deposited and contacted the central section of the CNT network through the Al_2O_3 window. An Al/Ti top gate electrode was fabricated on the top of the PEG layer. An electrochemical cell is integrated in the transistor with the PEG polymer layer as an electrolyte, and the Al/Ti and CNTs as electrodes. Protons can be generated and drifted in the PEG polymer with a high mobility under the influence of external electrical fields. When a positive gate voltage is applied on the gate electrode with respect to CNTs, protons drifts from PEG polymer toward CNTs; PEG polymer is dehydrogenated, and CNTs are hydrogenated CNTs are hydrogenated. When a negative gate voltage is applied, PEG polymer is hydrogenated, and CNTs are dehydrogenated. After the CNT channel was electrochemically configured to a desired state, the back gate electrode switched the device as a conventional transistor.

CNTs in the composites were functionalized by electrochemical hydrogenation driven by gate voltages, which tunes CNT bandgaps continuously and reversibly to nonvolatile analog values between 0 and 3.2 eV. The characteristics of the transistor are influenced by the ionic mobility in the polymer, and can be adjusted to desired values by integrating appropriate ions and polymers in the transistor gate.

Conclusions:

The networks and components developed and demonstrated have the potential to be combined into a single functional bio-inspired network which can contain multiple forms of sensors at varying densities and be embedded into a composite layup. The incorporation of synaptic transistors based on CNT/polymer composites with the flexibly tunable bandgaps enable the memory and learning functions of the network. 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.

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Figures:

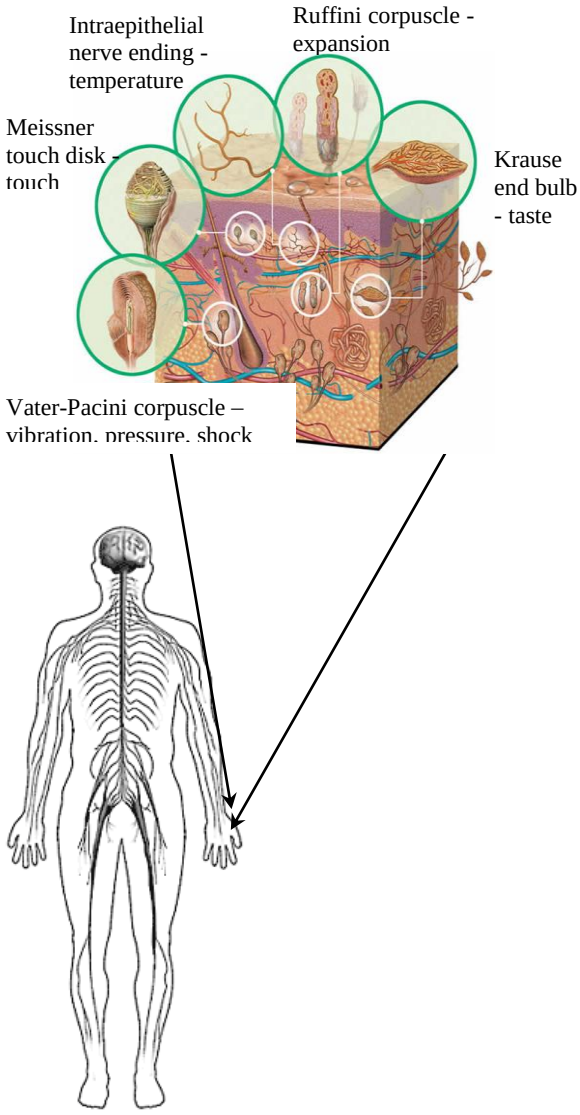

Fig 1 – Sensors in the skin and the human nervous system

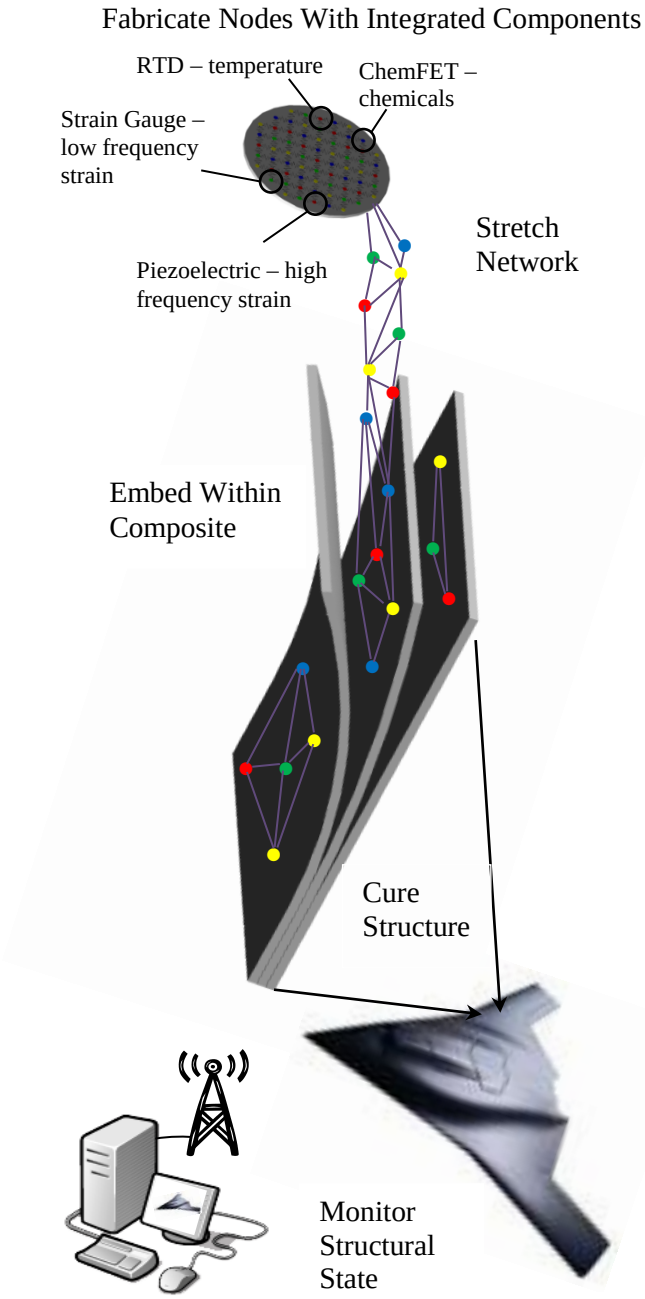

Fig 2 – Bio-inspired stretchable sensor network, fabricated with multiple sensors at the micro-scale, stretched, and embedded in to composite layups

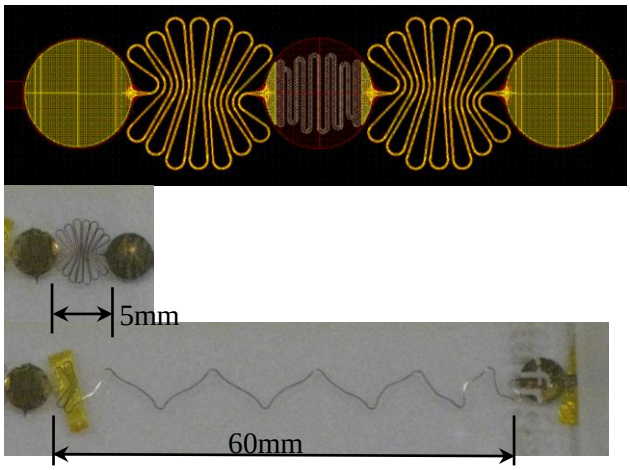

Fig 3 Photos of an individual functional RTD node and electrical interconnect undergoing extension to many times its original spacing illustrating the expansion process.

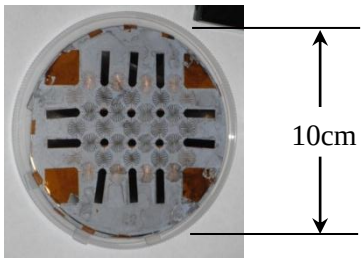

Fig 4 Un-stretched network as fabricated

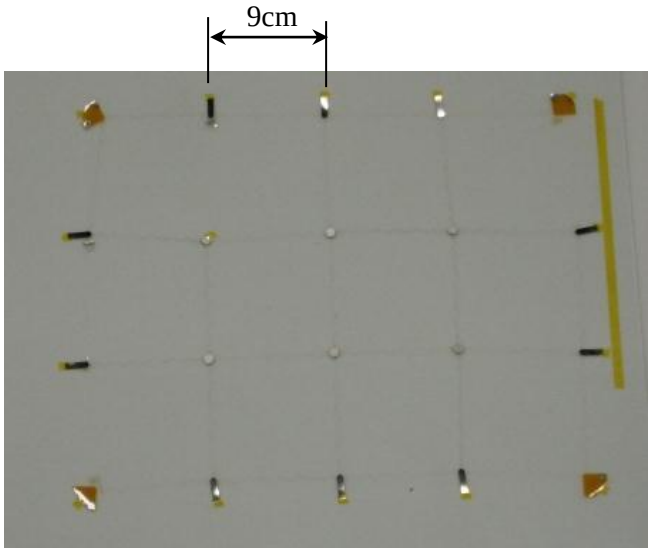

Fig 5 Stretched network with onboard BSPT piezoelectric transducers, expanded to cover 36 times the original area

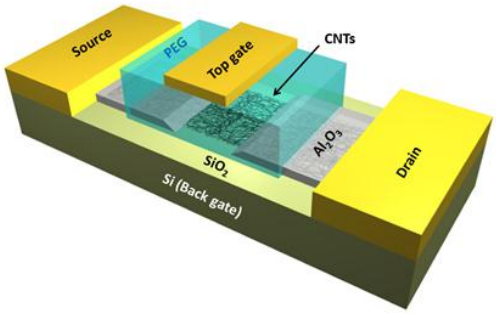

Fig 6 – The structure of a synaptic transistor based on carbon nanotube (CNT) composites.

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