Cover Page

Title: A vision on stretchable bio-inspired networks for intelligent structures

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ABSTRACT

Major progress has been made recently in structural health monitoring maturing the technology through quantification, validation and verification to promote implementation and fielding of SHM Systems, which are key activities in this workshop. In addition there is a lot of work seeking to detect damage precursors and to deploy SHM systems over large areas, moving the technology beyond hot-spot monitoring to global state sensing for full structural coverage.

A large amount of small sensors of multiple types are necessary in order to accomplish this, enabling increased sensing capabilities while reducing parasitic effects on host structures. Traditional sensors are large and heavy, adding to the weight of a structure and requiring physical accommodation without adding to, and potentially degrading the strength of the overall structure. Increased numbers of sensors must also be deployed to span large areas while maintaining or increasing sensing resolution and quantification capabilities. These sensors are typically assembled, wired, and installed individually, by hand, making mass deployment prohibitively time consuming and expensive.

In order to overcome these limitations the Structures and Composites Lab at Stanford University has worked to develop bio-inspired microfabricated stretchable sensor networks. Adopting the concept of C-MOS and MEMS fabrication techniques, new methods are being developed to completely integrate networks of large numbers of various micro-scale sensors, processors, switches and all wiring in a single fabrication process. Then the networks are stretched to span areas orders of magnitude larger than the original fabrication area and deployed onto host structures. The small scale components enables interlaminar installation in laminar composites or adhesive layers of built up structures while simultaneously minimizing parasitic effects on the host structure. Additionally, data processing and interpretation capabilities could be embedded into the network before material integration to make the material truly multifunctional and intelligent once fully deployed. This paper reviews the current accomplishment and future vision for these systems in the pursuit of state sensing and intelligent materials for self diagnostics and health monitoring.

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INTRODUCTION

Sensors are increasingly being utilized on a wide variety of products from transportation vehicles, to civil infrastructure, to consumer products, etc. Structural health monitoring technology provides a critical linkage between sensing data and determining the health condition of the products for real time or condition-based assessment. Such information could provide tremendous advantages in operation management; improving performance, increasing efficiency, and reducing downtime.

Recently, significant progress has been made toward maturing SHM technology for field applications over large areas, moving the technology beyond hot-spot monitoring to full structural coverage. The accuracy and reliability of health/condition monitoring of a structure strongly rely upon the density of the sensors onboard for a given SHM system. In addition, more sensors are desirable to enhance the SHM capabilities for detecting damage initiation, detecting potential exposure to harsh environments, and generally increasing state awareness.

Many different types of sensors may need to be used for such applications. For instance piezoelectric ceramic transducers are widely used for ultrasonic defect detection, strain gauges for measuring strains, accelerometers for dynamic effects, and temperature sensors for monitoring environmental conditions, etc. Deploying a large number of sensors, of varying types, over a large structural area is practically prohibited by current manufacturing techniques and implementation methods.

In order to overcome these issues new approaches to design, fabrication, and implementation are necessary. The Structures and Composites Laboratory at Stanford University is pursuing an approach, mimicking the nervous system, for creating and deploying sensor networks over various types of structures in different configurations, with built-in sensing and diagnostic capabilities. The new approach would allow a structure to be designed with built-in sensing and diagnostic capabilities in advance and enable the structure to recognize the health and integrity condition of itself in real time- leading to the design of intelligent structures.

Problem Statement

Develop a bio-inspired sensor network consisting of large numbers of various types of small scale sensors, switches, and processors with diagnostic software, which can be fabricated in mass at a low cost with high reliability and can be deployed over large areas of structures with various configurations.

Proposed Approach

The Structures and Composites Laboratory at Stanford University has developed microfabricated stretchable sensor networks, which overcome many of the issues encountered in installing traditional sensors into a structure. This technology leverages the mass, small scale fabrication capabilities of C-MOS and MEMS processing, capable of creating billions of transistors on a microchip, to create numerous sensors of various types, including all wiring, in complete integrated systems [1] [2]. After fabrication the systems can be stretched to span an area more than two orders of magnitude larger than the original fabrication area and embedded

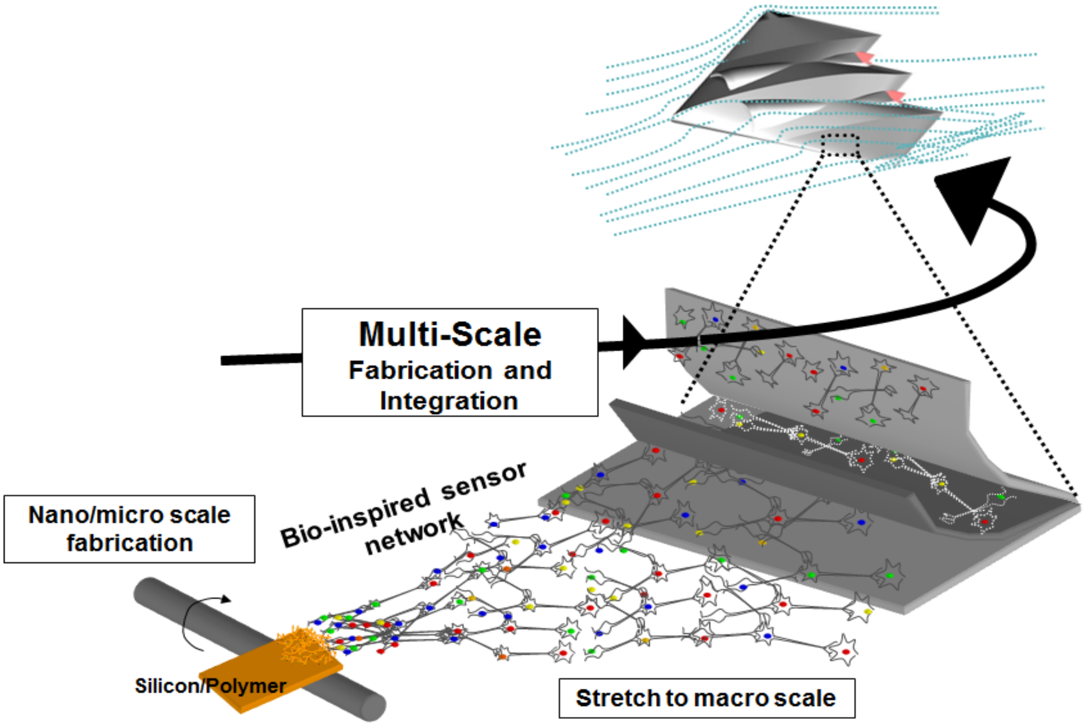

Figure 1 – Bio-inspired stretchable network concept for fabrication and deployment

into a structure, simultaneously deploying numerous micrometer scale devices over meter scale areas as depicted in Figure 1 [3] [4] [5].

This approach minimizes parasitic effects on a host structure and enables mass simultaneous fabrication and installation of complete sensor networks to enable state awareness. However, there are many challenges to creating such complex, small scale and expandable sensor networks. The stretchable networks are fabricated on polyimide substrates in order to tolerate the large strains experienced in the expansion process. New processes to microfabricate sensors and electronics on polyimde substrates had to be developed in addition to switching and addressing systems in order to enable selection of specific sensors.

Therefore, as depicted in Figure 2, the major tasks involve:

- Stretchable network design
- Network microfabrication
- Expansion and integration
- Software integration
- Material functionalization
- System training and operation.

These tasks are particularly challenging because of the complexity and capabilities of micro-fabrication which will be illustrated briefly below.

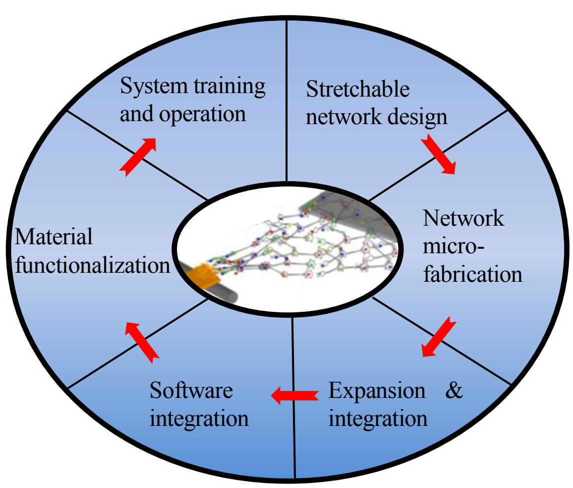

Figure 2 – Major tasks for bio inspired stretchable network development

STRETCHABLE NETWORK DESIGN

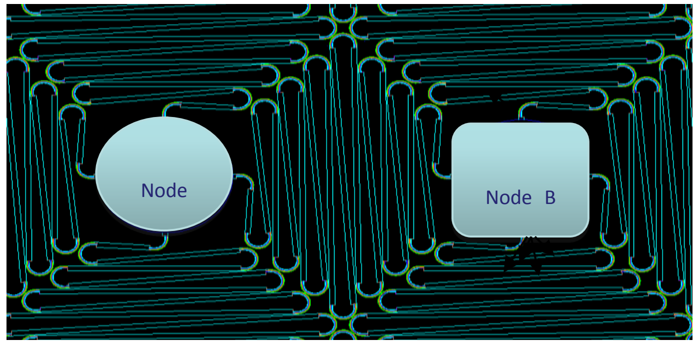

Figure 3 – Nodes in a stretchable network with extendable interconnects.

The key innovation of this research is to apply advanced nano and micro fabrication techniques, which have been extensively developed in electronic and thin-film fields, to create organic 3-dimensional sensor network infrastructure substrates on which sensors, electronics, and switches could be built. The innovation is to create the flexible infrastructure by removing material, allowing the substrate to be stretched and expanded through rigid body rotation and linear translation while minimizing local strain accumulation at the joints and corners of the network communication wires as shown in Figure 3. Advanced finite element analysis with Abaqus was performed to evaluate the stretchability for a given number of sensors as shown. The PI and his associates have developed a design for low stress, highly stretchable interconnects between adjacent nodes shown in Figure 4 [6]. When 'stretched', the spring-like wire extended, increasing the spacing between the nodes up to 1,057% while developing a maximum principal strain of no more than 0.064%.

NETWORK MICROFABRICATION

Many of the advantages achieved by the stretchable network are dependent on the substrate. In order to enable the simultaneous fabrication and deployment of micro-scale sensors over macro areas a highly stretchable network substrate was developed based on spin-coated polyimide materials.

This process starts with a silicon supporting wafer, a sacrificial layer is deposited (germanium or silicon dioxide) on the silicon wafer surface and then a liquid

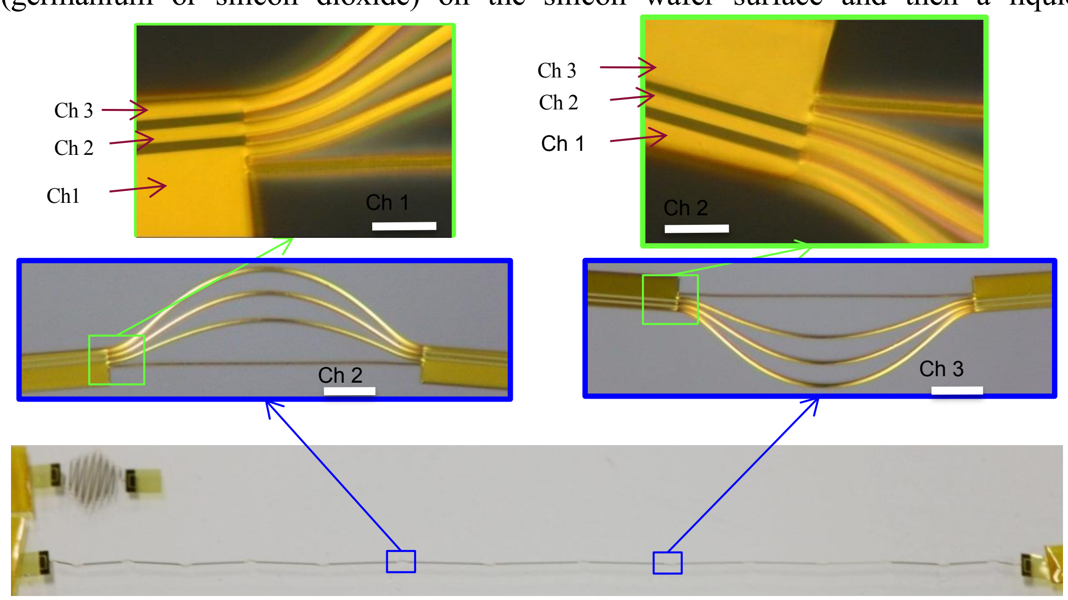

Figure 4 – Segmented interconnect section to reduce strain during expansion. 3 electrical channels are present for inter-nodal communication.

polyimide layer 10 to 30 μm thick was spin coated on to serve as the network substrate on the supporting wafer. Traditional processing allowed the creation of basic sensors, wires, electrodes, and dielectric layers on the polyimide substrate through direct deposition. Plasma etching was then used to shape the polyimide layers into a stretchable network pattern. Finally, the network was released by wet etching the sacrificial layer (germanium or silicon dioxide) between the polyimide substrate and the supporting silicon wafer.

Figure 4 shows a 3 channel stretchable interconnect fabricated based on the spin coated polyimide substrate. This particular design serves to reduce strain in the curved portions of the interconnects. There were 3 electrical wires on each of the stretchable interconnects enabling communication with the sensors in the network. The ability to create multiple wires per interconnect enables complex addressing for the large numbers of sensors that will be carried on the stretchable networks.

Various sensors could be integrated into the proposed stretchable network. Basic sensing systems like resistive temperature detectors (RTDs) could be directly deposited on to the polyimide, with features as small as hundreds of angstroms thick and sub-micron widths, but such systems have limited functionality. Other more complex sensing systems can require significantly more complex fabrication process. Ultrasonic sensing systems are capable of detecting multiple stimuli and including damage and impacts using SHM techniques. Additionally, the distributed nature of these systems is especially compatible with stretchable networks. The cores to ultrasonic sensing systems are piezoelectric transducers, typically Lead Zirconate Titanate (PZT), which can actuate and sense ultrasonic signals. Unfortunately PZT type ultrasonic transducers are very size dependent and require processing that prevents fabrication directly on polyimide substrates.

Microfabricating piezoelectric transducers on a stretchable substrate posed a unique challenge. While small transducers are desirable to minimize parasitic effects on a host structure, as transducer size is decreased so is its capability to produce significant strain waves that can propagate and be sensed at a distance. In addition, PZT type materials require high temperature processing, exceeding the limitations of polyimide and most organic materials.

Screen printed piezoceramics are capable of being microfabricated in sizes from 4 μm to 100 μm thick and as little as about 75 μm in width. This is thicker than currently possible with thin-film, sol gel, piezoceramics which are limited to a maximum of about 10 μm thick due to internal stresses that build up during processing [7]. This is also thinner than commercially available bulk ceramics, which are a minimum of about 125 μm thick due to processing limitations. This range enables embedding piezos completely within typical adhesive layers without affecting the thickness enabling embedding screen-printed piezoceramics into bonded and laminated structures. However, screen printed PZT type materials must be sintered at temperatures of about 1000 ºC which prevents direct deposition on polyimide substrates which only survive about 400 ºC.

Therefore a new process was developed to release networks of screen printed piezoceramics from a high temperature fabrication substrate onto a polyimide stretchable substrate, as shown in Figure 5 [8]. While the process involved many harsh chemicals, known to damage or destroy PZT type materials, no significant degradation was detected when signals from these samples were compared to those of baseline samples that had not undergone processing. Many signal waveforms typical to SHM have been actuated and sensed between screen printed piezoceramics released onto polyimide films, and environmental effects on signals, such as temperature shifts, have been found to be similar to those of systems using bulk piezoceramics commonly used in ultrasonic SHM.

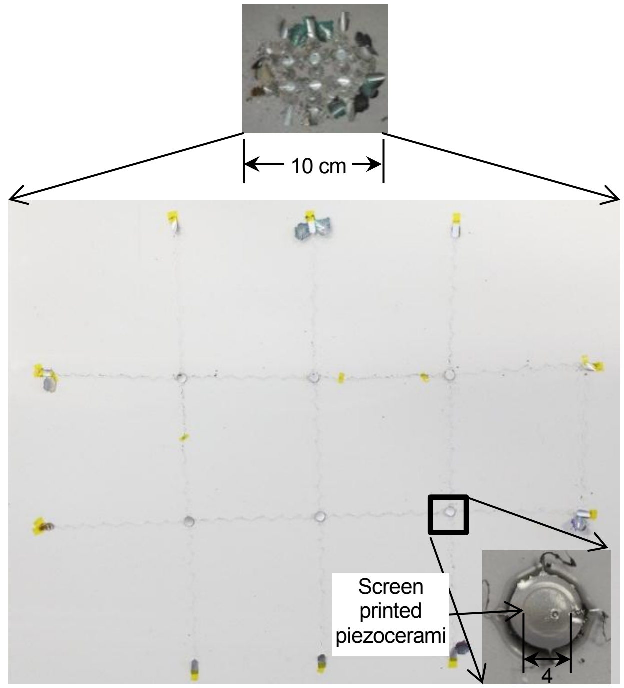

Figure 5 – Screen printed piezoceramics released onto polyimide and deployed on an expandable network. Before expansion (top) and after expansion (bottom). With a close up of a piezoceramic node (bottom right).

STRETCHING AND INTEGRATION

After fabrication, the network was stretched along two directions on a flat plane as shown in Figure 6. First the network is stretched in the x direction by 1,000% of the originally length, then it is stretched by 1,000% along the y direction. After stretch, the total area covered by the network is increased by 100 times compared to its initial area. The stretched network is then laminated with carbon fiber composite layers. As shown in Figure 7, the composite layup with integrated stretchable sensor network is cured in autoclave with elevated temperature and pressures (176 °C, 30 psi) resulting in a composite panel with an embedded functional sensor network.

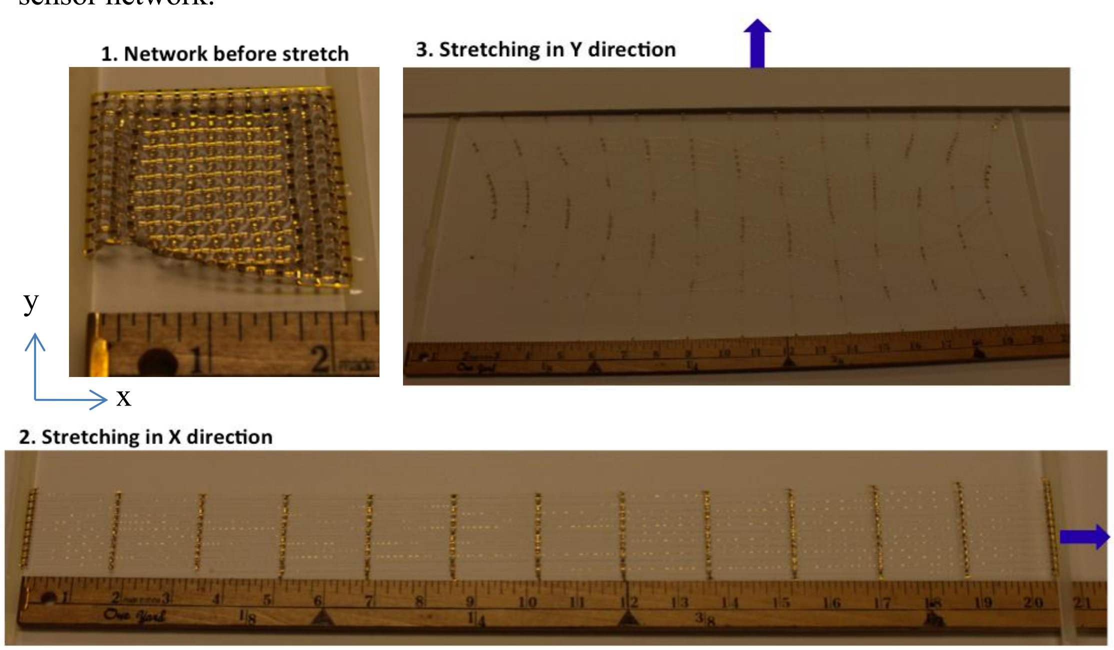

Figure 6 – Stretching of a 169 node sensor network

SOFTWARE INTEGRATION

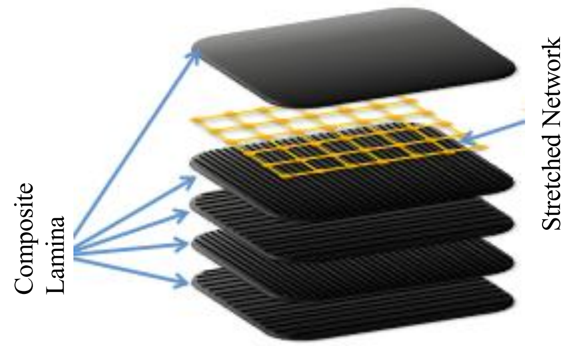

Figure 7 – Integration of a stretched sensor network into carbon fiber composite materials

Figure 8 shows the schematic for interpreting structural health state using distributed multi-functional sensor data, collected from the structure in real-time. Apart from being sensitive to structural changes, sensor signals are also vulnerable to changes due to variations in environment and operational conditions. In the absence of environmental compensation, accurate interpretation of in-situ sensor data becomes difficult which leads to false structural state diagnosis. The proposed methodology intends to combine physics-based environment compensation models with machine-learning based data driven algorithms to identify the true state of structure [9] [10] [11]. The advantage of using physics-based models, to assist in data-driven techniques, is that one need not collect a large set of baseline training data for every possible combination of structural state and ambient conditions which is practically a challenging task to implement. Instead, one can take advantage of underlying physics to generate a large set of baseline training data with limited set of in-situ sensor measurements as described in [11]. Environmental compensated sensor signals combined with unsupervised feature-learning based novelty detection algorithm provides accurate structural state awareness which can be used for taking necessary control actions by the autonomous controller as shown in Figure 8.

MATERIAL FUNCTIONALIZATION

For addressing, diodes and transistors are also necessary. The PI and his associates have successfully integrated organic thin film diodes into the highly stretchable sensor network and demonstrated the proper functionalities of the network after it was

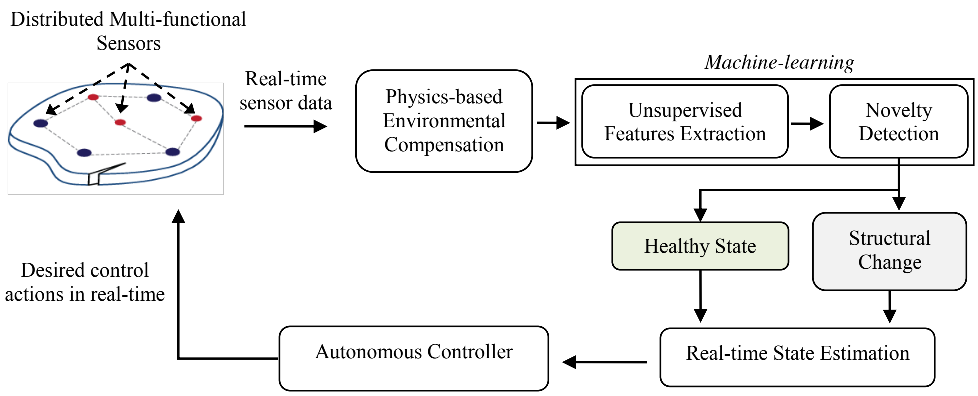

Figure 8 - Schematic for structural state identification and autonomous control actions in real-time using physics-based environmental compensation models and machine learning algorithms.

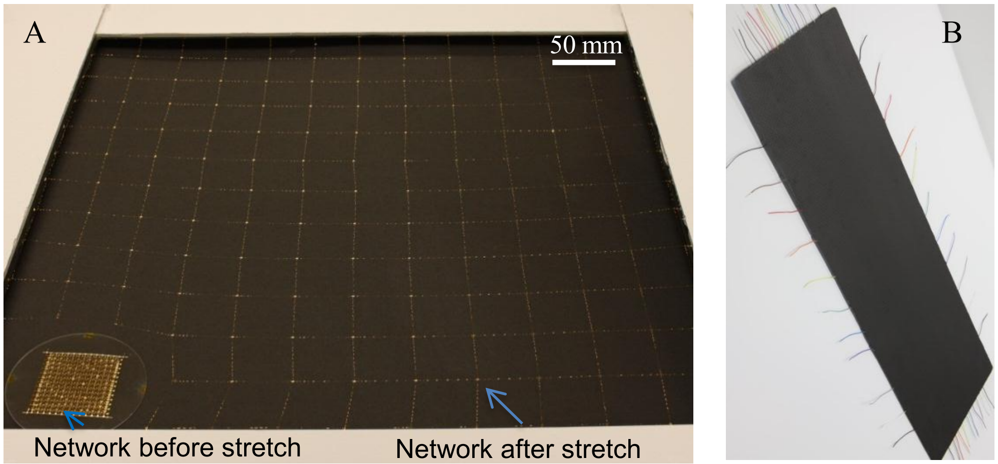

Figure 9 - A stretchable sensor network is embedded into carbon fiber composite materials.

embedded into carbon fiber composite materials. Organic thin film diodes were selected because they could be deposited directly onto polyimide substrates, unlike silicon diodes which must be transferred. A sandwich structure for the network was designed to encapsulate all the devices between layers of dielectric polyimide, electrically insulating the network from the host structure.

Figure 9A shows a stretchable sensor network of resistive temperature detectors with organic diodes for switching before and after stretch. The area of the network is increased by 100 times and embedded into carbon fiber composite materials (Figure 9B). The organic thin film diodes that went through the embedding and curing process maintained consistent I~V.

SYSTEM TRAINING AND OPERATION

As an initial demonstration of state sensing capabilities an autonomous robotic arm was developed and outfitted with a stretchable sensor network containing temperature, pressure, and piezoelectric sensor systems, shown in Figure 10. In this

Figure 10 – Robotic arm with a stretchable network for state sensing

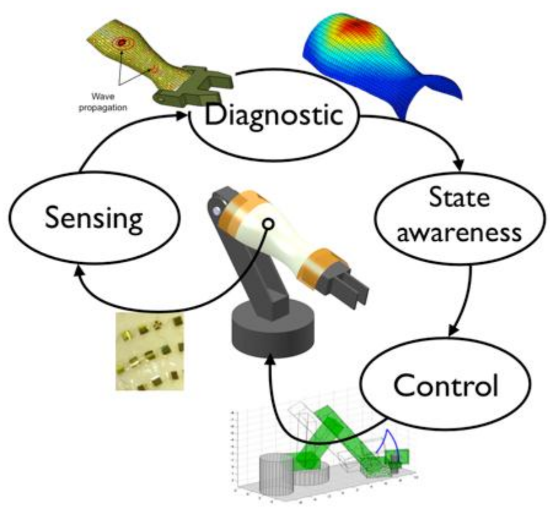

Figure 11 – Flowchart of feedback control of a robotic arm

process the network was stretched to conform to a complex, double curved surface and interfaced with a laptop running control algorithms. Programs were developed to calculate the path to pick up and move an object from one place to another. While doing this the sensor network detected thermal threats, impacts, and the presence of the object, a flowchart of the feedback control is shown in Figure 11. If the object to be moved was absent and not detected the arm returned to a ready position. If a thermal threat or impact was detected the control algorithm calculated a new path and moved the arm to achieve its goal while avoiding the threat.

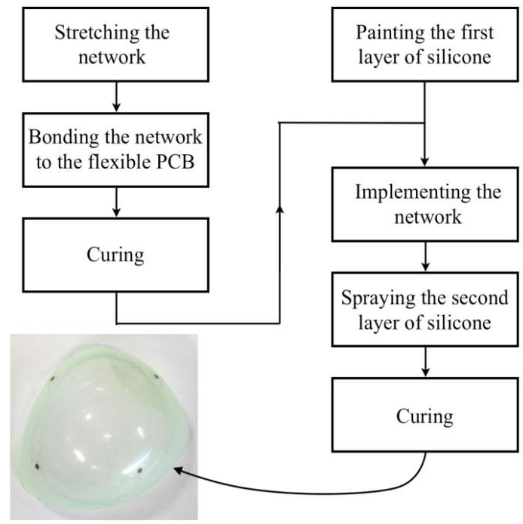

Figure 12 – Process for integrating stretchable networks into silicone membranes.

The small scale of the network components (wires and sensors) made them fragile; therefore a system to protect them was designed in the form of 'e-skin'. The objective was to protect the network during transfer and use. The 3D shape of the arms posed a challenge. Expandable sensor networks were integrated into flexible and extensible silicone membranes, allowing the skin to adapt to any surface using the process outlined in Figure 12. While this skin made the system more robust to physical damage, it complicated connection issues. Additionally, the capabilities of the sensors were reduced when embedded into the silicone skin, which insulated the sensors from external stimuli.

Embedding the stretchable network into a silicone membrane opens other options for device designs increasing capabilities. For example, texturing the face of the silicone e-Skin, similar to like human fingers, in conjunction with the PZT sensors, which are sensitive to dynamic strain, could enable detection of surface roughness.

FUTURE VISION

Mass fabrication and deployment of micro scale sensors on expandable networks overcomes many of the issues that currently inhibit the implementation of SHM systems. The creation of sensors and electronics on stretchable substrates remains a challenge and further research is necessary to enable the creation of more types of sensors to detect different stimuli with high accuracy, high precision, and low noise. Continual efforts to reduce the size of the systems are also necessary.

Addressing, communication, and computational systems must also be further developed to handle the large amount of data from numerous sensors. A bio-inspired approach could use onboard peripheral processors to interpret and simplify local data, and make local decisions, passing critical high level information to a central processor to make global decisions mimicking the Central and Peripheral nervous systems.

With further development, testing, and characterization these systems have the potential to revolutionize the capabilities and fielding of SHM.

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