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Recent advancements and vision toward stretchable bio-inspired networks for intelligent structures

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Abstract

Significant progress has recently been achieved in structural health monitoring, maturing the technology through quantification, validation, and verification to promote implementation and fielding of SHM. In addition, there is ongoing work seeking to detect damage precursors and to deploy structural health monitoring systems over large areas, moving the technology beyond hot-spot monitoring to global state sensing for full structural coverage. A large number of small sensors of multiple types are necessary in order to accomplish the goals of structural health monitoring, enabling increased sensing capabilities while reducing parasitic effects on host structures. Conventional 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 capabilities. Traditionally, these sensors are 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 techniques of complementary metal-oxide semiconductor and microelectromechanical system fabrication, new methods are being developed to create integrated 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 enable 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 article reviews the current accomplishments and future vision for these systems in the pursuit of state sensing and intelligent materials for self-diagnostics and health monitoring.

Keywords

Intelligent materials, sensors, microfabrication, network, deployment

Introduction

Sensors are increasingly being utilized on a wide variety of products from transportation vehicles, civil infrastructure, to consumer products, and so on.[1–3] Structural health monitoring (SHM) technology provides a critical link between sensing data and determining the health condition of the products for real-time or condition-based assessment. Such information has the potential to provide tremendous advantages in operation management; improving performance, increasing efficiency, and reducing downtime.[4]

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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 and condition monitoring of a structure strongly rely on the location and density of the sensors onboard for a given SHM system.[5] In addition, more sensors are desirable to enhance the SHM capabilities for detecting damage initiation, detecting exposure to harsh environments, and generally increasing state awareness.

Many different types of sensors may need to be used for such applications. For instance, piezoceramic transducers are widely used for ultrasonic defect detection,[6,7] strain gauges for measuring strain state,[1] accelerometers for dynamic effects,[8] temperature sensors for monitoring environmental conditions,[9,10] and so on. Deploying a large number, for example, tens of thousands, of sensors of heterogeneous types, over a large structural area is practically prohibited by the current manufacturing techniques and implementation methods.

In order to overcome these issues, new approaches to design, fabrication, and implementation are necessary. This article presents and reviews recent accomplishments in developing a novel approach to create and deploy multifunctional sensor networks that can be embedded into materials monolithically and with minimal parasitic effects, mimicking biological sensory systems, for intelligent materials and SHM. The new approach would allow a structure to be designed with built-in distributed sensing and diagnostic capabilities and enable a structure to recognize its own health and integrity condition in real-time.

Problem statement

To achieve this, it is necessary to develop bio-inspired sensor networks consisting of large numbers of diverse types of small-scale sensors, switches, and processors with diagnostic software, which can be fabricated en masse at a low cost with high reliability and can be deployed over large areas of structures with various, complex configurations.

Approach

Microfabricated stretchable sensor networks have been developed to overcome many of the issues encountered in fabricating and installing traditional sensors into a structure. This technology leverages the mass, small-scale fabrication capabilities of complementary metal-oxide semiconductor (C-MOS) and microelectromechanical system (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.[11,12] 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 into a structure, simultaneously deploying numerous micrometer-scale devices over meter scale areas as depicted in Figure 1.[13–15]

The small size and weight of the resulting network minimize parasitic effects on a host structure while enabling mass simultaneous fabrication and installation of complete sensor networks to enable state awareness. However, there are many challenges to creating such complex, small-scale, expandable sensor networks.

Major tasks in developing stretchable sensor networks are depicted in Figure 2 involving the following:

- 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 microfabrication which will be illustrated briefly in the upcoming sections.

Network microfabrication

Many of the advantages achieved by the stretchable network are dependent on the substrate. Typical microfabrication substrates are brittle materials with low strain to failure such as silicon, germanium, and gallium arsenide.[16] In order to realize the large stretch ratios achieved, a non-standard polyimide substrate was employed. However, this required significant development and adaptation of existing microfabrication techniques due to the chemical, temperature, and processing capabilities of polymers.

Typical processing began with a silicon working substrate that would provide a rigid backing for processing and later be removed before network deployment. Protective layers and a release layer were deposited on the working substrate. Then a 10- to 30-μm-thick liquid polyimide layer was spin coated onto the silicon creating the network substrate.[17] Traditional microfabrication techniques allowed the creation of basic sensors, wires, electrodes, and dielectric layers on the polyimide substrate through photolithography and metallic deposition with little to no modification. Plasma etching was then used to shape the polyimide layers into a stretchable network pattern. Finally, the network was released from the silicon working substrate.[18] Specific processing was modified and tuned as necessary to create different types of sensing systems. For example, as discussed later, creating screen-printed

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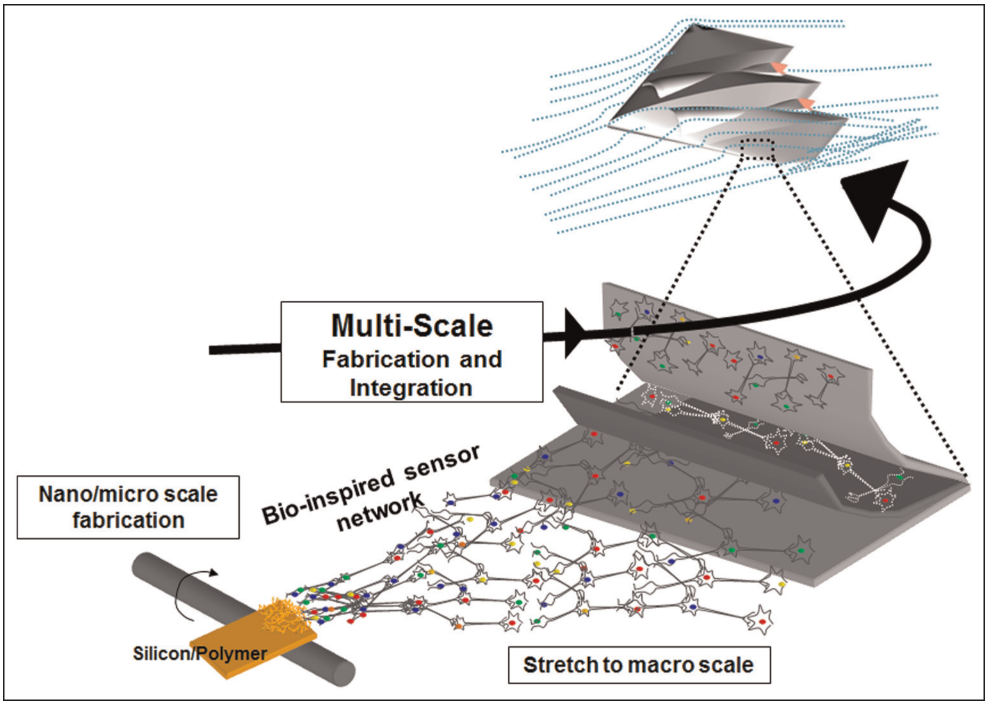

Figure 1. Microfabricated stretchable network concept: microfabricate complete integrated network (bottom left), stretch network (bottom center), and deploy network into structure (bottom right).

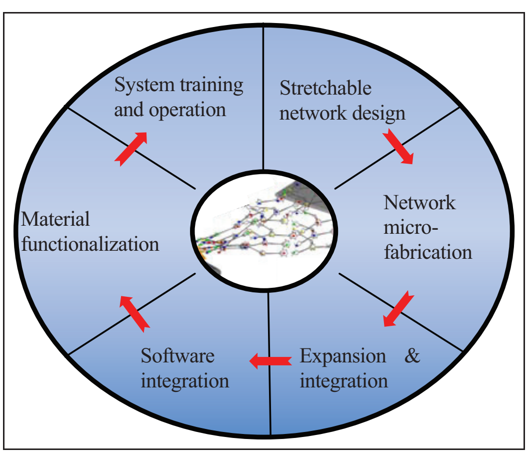

Figure 2. Major tasks for bio-inspired stretchable network development.

piezoelectric transducers on stretchable networks required significantly more complex processing than a network only carrying resistive temperature detectors (RTDs) due to temperature requirements to sinter piezoceramics, at greater than 1000°C, and chemical incompatibilities of the piezoceramic material.[19]

The flatness of the substrates was critical to processing and the ability to create small features. This was a challenge because the coefficient of thermal expansion of polyimide was 40 e^{-6}/°C, while the silicon wafer was 1.1 e^{-6}/°C.[17] This mismatch, of over an order of magnitude, caused wafers to bend after curing the polyimide at 350°C, especially if other high-temperature processing had previously been performed. Bending could exceed 300 μm from center to perimeter of a 100 mm diameter silicon wafer 500 μm thick, creating an effective radius of curvature of less than 41.8 cm, adversely affecting photolithography accuracy, and making samples unusable in many microfabrication tools. To reduce the bending to tolerable levels, multi-stage curing techniques were developed to reduce residual stresses. This involved partially curing the polyimide at 90°C and 150°C on hot plates for 5 min each before the final high-temperature curing at 350°C in an oven with a nitrogen environment. This process reduced the bending of wafers to tolerable levels and enabled high-resolution fabrication with features below 5 μm in width and less than 5 μm alignment error between layers. Feature resolution dictates the minimum size for sensors, systems, and substrate designs. High-resolution processing capabilities were used to create three conductive channels on each interconnect and new designs to reduce strain during expansion.

Stretchable network design

Substrate design, in addition to material selection, was critical to the creation of stretchable networks. Many

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stretchable network patterns have been developed consisting of nodes to carry sensors and other devices, and stretchable, spring-like interconnects that will straighten out during network expansion as depicted in Figure 3. A key advantage of the design and fabrication process was that systems were achieved through the removal of material. As a result, smaller features enable reduced parasitic effect through smaller components, larger stretch ratios by enabling more and longer interconnects, more sensor nodes in the same initial area, and greater final coverage areas. However, a consequence of reduced sizes is increased resistance in wiring, which is inversely proportional to cross-sectional area and is significant on the scales of this network. For example, gold wiring on an interconnect, measuring 10 cm long with a cross section of 40 μm by 200 nm, would have a nominal resistance of about 300 Ω at room temperature. Small geometries are also more prone to flaws and damage in processing. Therefore, new designs were developed in an attempt to leverage some of the benefits of high-resolution processing while maintaining other larger scale components.

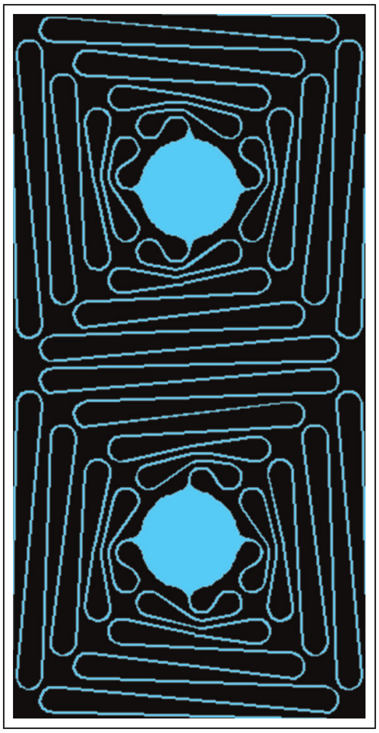

Figure 3. Nodes in a stretchable network with extendable interconnects.

New substrate designs, utilizing high-resolution processing capabilities, were developed to reduce the stresses that occur in the interconnects and prevent out-of-plane deformations during the stretching process. Finite element analysis with ABAQUS was performed to evaluate designs.[18] Segmented regions in the curved portions of the interconnects, as shown in Figure 4, reduced the width in the bending direction, reducing the maximum distance from a segment's neutral access to its edge and thus reduced the maximum strain.[20] This approach also allowed geometries that were narrower in the bending direction than through the thickness,

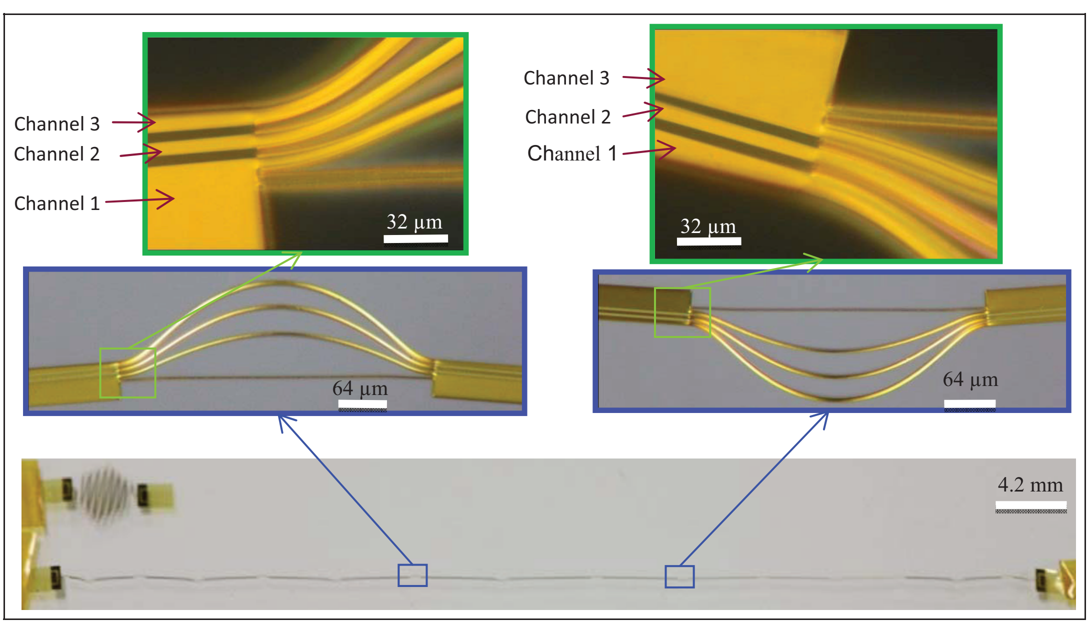

Figure 4. Segmented interconnect section to reduce strain during expansion. Three electrical channels are present for inter-nodal communication.[20]

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increasing the structural stability during expansion/bending and preventing out-of-plane deformations.

The pattern shown in Figure 4 achieved a stretch ratio of 1,051%, with distance between the centers of the nodes increasing from 7.4 to 77.81 mm, while only developing a maximum principal strain of 0.064%. Additionally, high-resolution processing enabled the creation of three electrical wires per interconnect which could be used for complex addressing for the large numbers of sensors carried on the stretchable networks.

Material functionalization

Various sensors have been integrated into the stretchable network. Basic sensing systems like RTDs and electrical wires were directly deposited onto the polyimide, with features as small as hundreds of angstroms in thickness and micron scale widths. These systems were created using relatively standard microfabrication techniques, like liftoff photolithography, but such systems have limited functionality. Other more complex sensing systems, like ultrasonic systems, have also been created but required significantly more complex fabrication process, complicated by the use of polymer materials that are more sensitive to temperature and chemicals than typical microfabrication substrates.

Ultrasonic sensing systems are capable of detecting multiple stimuli including damage and impacts using SHM techniques. Additionally, the distributed nature of ultrasonic SHM systems is especially compatible with stretchable networks. Ultrasonic SHM often utilizes bulk piezoceramic transducers as actuators and sensors.[21,22] However, these systems are typically manually assembled and their size has parasitic effects on a host structure. Microfabrication of piezoceramic transducers in complete networks would enable mass fabrication with reduced parasitic effects.

Microfabricating piezoelectric transducers on polymer films and stretchable substrates posed a unique challenge. While small transducers are desirable to reduce parasitic effects on a host structure, as transducer size is decreased so is its capability to produce significant displacements and strain waves that can propagate and be sensed at a distance. In addition, lead zirconate titanate (PZT)-type ceramic materials require high-temperature processing, exceeding the thermal limitations of polyimide and most polymeric materials.

Screen-printed piezoceramics were selected because they can be microfabricated in sizes from 4- to 100 μm thick and as little as about 75 μm in width. This is thicker than the 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.[23] This is also thinner than commercially available bulk ceramics, which are a minimum of about 125 μm thick due to processing limitations. This size range allows the potential to embed piezoceramic transducers 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°C which prevents direct deposition on polyimide substrates that can only survive about 400°C.[24,25]

Therefore, a new process was developed to deploy networks of screen-printed piezoceramics on a polyimide stretchable substrate.[19] The new process involved creating the entire electrical network on a temporary silicon working substrate, including screen printing the piezoceramics and all high-temperature processing without the polymeric substrate. Then in a reversal of typical fabrication techniques, the polyimide substrate was spin coated onto the complete network. At this point, RTDs and additional devices could be fabricated on the opposite side of the polyimide from the piezos, and the network could be etched into the stretchable patterns using the normal network fabrication techniques. The 30 μm thickness of the piezoceramics created many challenges that had to be overcome, because they were up to three orders of magnitude thicker than other components, like wires, and limited the minimum feature size achievable. Finally, the complete network with the polyimide substrate was released from the working substrate intact and stretched. An example of the resulting network is shown in Figure 5.

The resulting process involved many harsh chemicals, known to damage or destroy PZT-type materials, including hydrofluoric acid and potassium hydroxide,[24] requiring the use of many protective barrier layers that were integrated into the process and network. Testing was performed to ensure that the screen-printed piezoceramics maintained functionality and were not significantly degraded as a result of the process.

Baseline and test samples were created for testing, using the same processing. The baseline samples were created by ending processing after deposition of the electrodes and wiring, leaving screen-printed piezos adhered to a silicon working wafer. The test samples went through the complete release process, creating screen-printed piezos on a polyimide backing, which was then adhered back onto a silicon wafer using Hysol 9396 epoxy in order to provide somewhat similar media for signals to propagate through.

Hamming windowed tone bursts, typical of SHM, with a peak voltage of 30 V were actuated and sensed with multiple sets of screen-printed piezoceramics at multiple frequencies in both samples. The signal strength, measured by both the peak voltage and the

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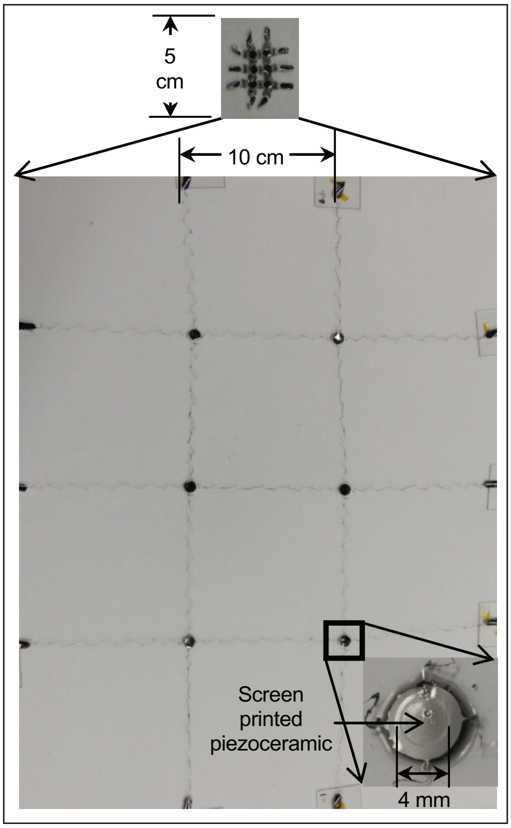

Figure 5. Screen-printed piezoceramics released onto polyimide and deployed on an expandable network. Before expansion (top) and after expansion (bottom) at the same scale. With a close up of a piezoceramic node (bottom right).

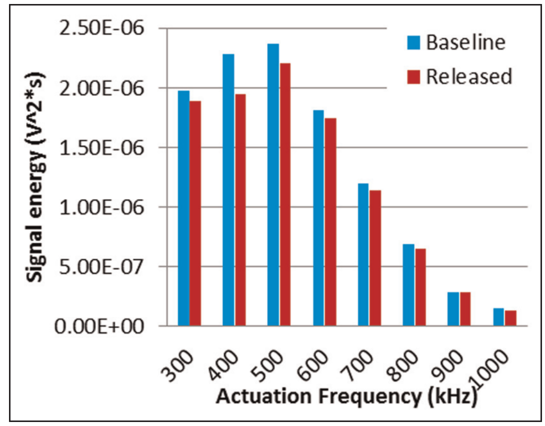

Figure 6. Propagated signal energy between pairs of Baseline and Released screen-printed piezoceramics 2 mm in radius, 34 μm thick, and 14 mm apart on center adhered to 0.5-mm-thick silicon wafers.[19,26]

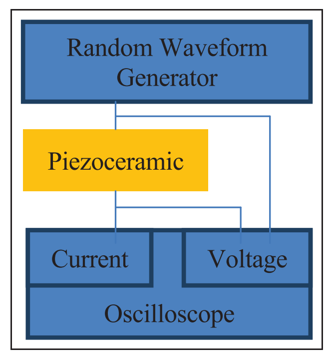

Figure 7. Testing setup schematic for impedance transfer function.

signal energy, was compared and found to be similar in both samples. Across all frequencies tested, the peak voltage of the first wave packet in the released sample was on average 23% stronger than the baseline sample, and the output signal energy was on average 9% less in the released sample as shown in Figure 6.[26] Additionally, the waveforms were similar, though not identical, in comparable cases. Differences were expected because of differences in the structure the strain waves propagated through.[27] This indicated that no significant degradation of the piezoceramic material had occurred due to processing. Testing was performed at various temperatures to inspect for variations in signals and the shifts in the waveforms were found to be similar to systems using bulk piezoceramics.[10,19,28]

Additional testing was performed to characterize properties of the screen-printed piezoceramics which was challenging because of their small size. To inspect sensor properties, released piezoceramics on the polyimide backing with electrodes were tested without being adhered to any other structure. Testing was performed by actuating the piezoceramic with a broadband white noise signal with constant power across the bandwidth up to 16 MHz. The voltage across and current through the piezoceramic were simultaneously measured using an oscilloscope as shown in the schematic in Figure 7. Estimating the transfer function across the spectrum using MATLAB's tfestimate function with the voltage as the input and the current as the output provided a measure of impedance at different frequencies. A typical transfer function is shown in Figure 8. Very few distinct resonances are apparent, with the first one appearing at 7.76 MHz. Additionally, the transfer function is monotonic up until this point, indicating that the screen-printed transducers have good properties, easily approximated below this frequency.[29]

In addition, released samples were created with RTDs opposite the piezoceramics as previously described and shown in Figure 9.[19,26] These RTDs were created by spin coating a photoresist layer onto the sample which was patterned using optical photolithography. Then a 50 Å thick Cr bonding layer and 500 Å thick gold layer were deposited using an e-beam evaporator. Acetone was used to dissolve the remaining resist and

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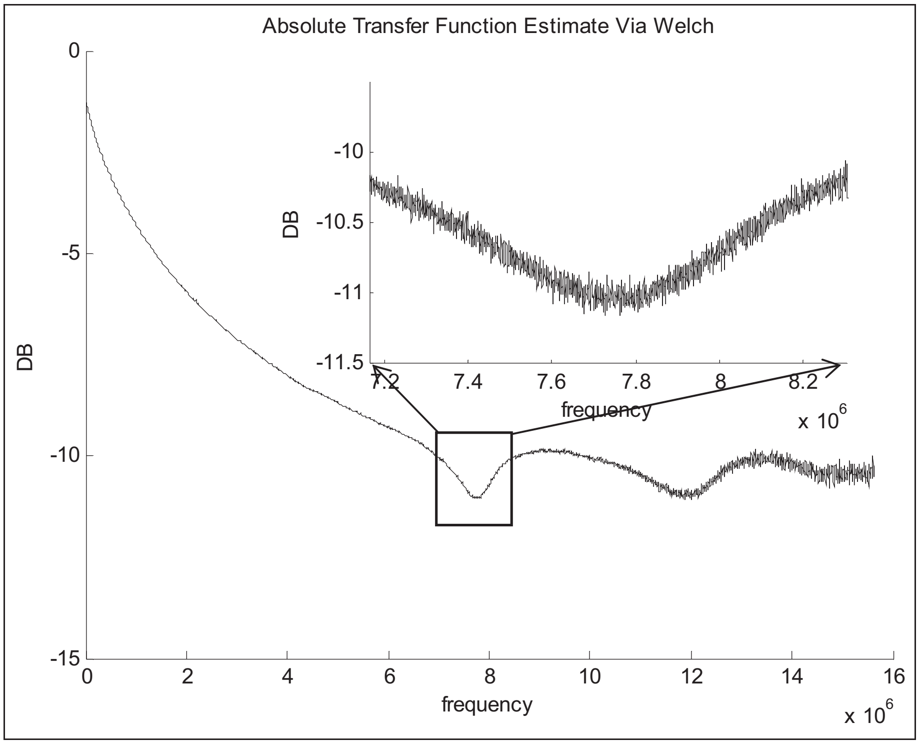

Figure 8. Transfer function between voltage and current of a released screen-printed piezoceramic across a wide range of frequencies.

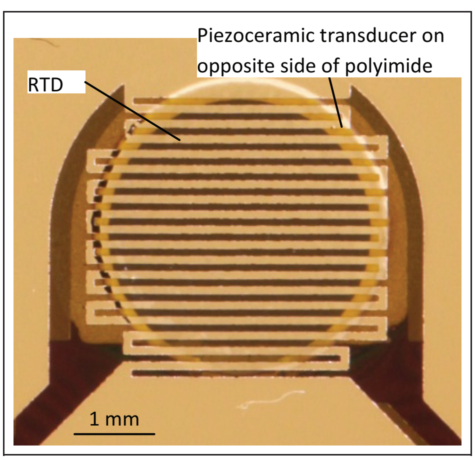

Figure 9. RTD and piezoelectric transducer on opposite sides of a polyimide layer.[19,26]
RTD: resistive temperature detector.

liftoff the unwanted metal resulting in RTDs with a nominal resistance of 410 Ω, indicating the metal had a combined resistivity of 3.28×10^{-8} Ωm.

Testing across different temperatures showed the RTDs produced highly linear signals, with R^2 values greater than 0.998 and slope of 0.7418 Ω/°C. This highlights the capability to microfabricate multiple heterogeneous sensors on a single network substrate. Additionally, studies of the effects of temperature on ultrasonic signals have shown that the majority of the change occurs due to changes in the piezoceramic and adhesive properties.[10] Here, co-location with the most effected components could support improved compensation for environmental effects, discussed in the software integration section.

Semiconductor devices like diodes and transistors can be used for addressing in the large networks. Pursuing this need, organic thin film diodes were integrated into the highly stretchable sensor network and tested. Organic thin film diodes were selected because they could be deposited directly onto polyimide substrates, unlike silicon diodes which must be transferred. A second polyimide layer was deposited over the network, after deposition of the diodes, to insulate the system. After integration into a carbon fiber composite layup, the diodes maintained proper functionality, keeping a consistent I–V curve through the cure cycle. This technology has the potential to allow complex addressing and even digital logic to be embedded into stretchable networks moving beyond the direct wired addressing employed in most stretchable networks to date.

Stretching and integration

Multiple expandable networks have been produced with differing arrays of sensors and overall geometries.

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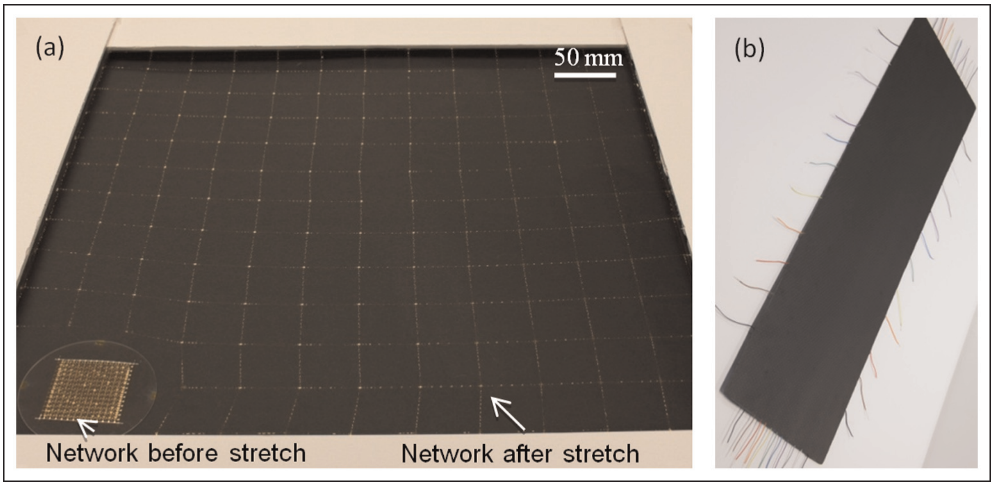

Figure 10. a) Stretchable network before and after stretching. b) Network embedded into carbon fiber composite.

After fabrication, the networks were deployed by stretching them in one linear direction, over a distance of up to 10 times the original span, and then in a perpendicular direction reaching 10 times the original span for a final area that could span over 100 times the original fabrication area. At this point, the networks were mounted onto a temporary frame and integrated into final structures for testing.

Integration to date has included surface mounting, embedding between composite lamina, and embedding within a flexible silicone membrane.[12,15,18,19] For example, Figure 10 shows a stretchable network that was embedded into a carbon fiber composite layup which survived curing in an autoclave at 176°C and 210 kPa over pressure for several hours. In addition to surviving harsh manufacturing environments, the networks can survive large deformations after deployment. For example, networks have been deployed into flexible silicone membranes, as shown in Figure 11, and on flexible polymer films after which they survived large deformations.[11,20,30]

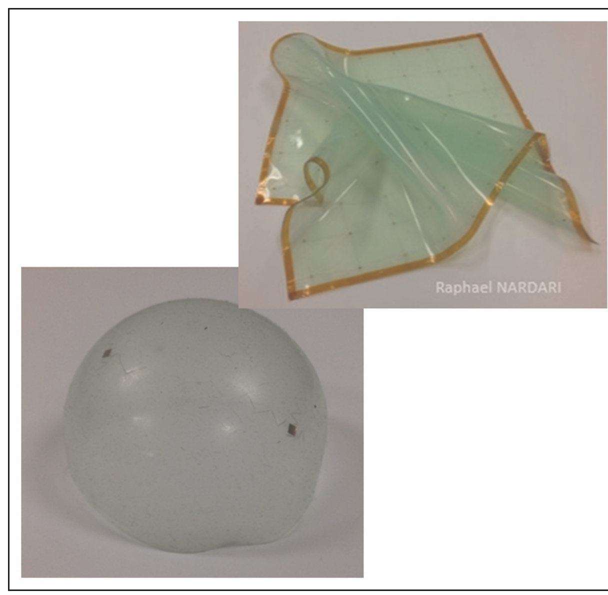

Figure 11. Stretchable networks embedded into flexible silicone membranes.[20]

Software integration

Ultrasonic sensor systems are sensitive to many different stimuli which makes them very useful as sensors, but also results in signal changes from environmental effects. Multifunctional sensor networks, capable of hosting multiple types of sensors for detecting multiple stimuli, also support signal compensation for environmental effects but algorithms to compensate for the different stimuli are necessary. These algorithms must be accurate and precise in order for SHM systems to estimate the initiation, extent, and severity of damage. Similarly, feedback control based on intelligent structures will require high-precision data in order for proper control. Complex signals, like those used in ultrasonic SHM, are particularly challenging and require complex algorithms to compensate. Many strategies proposed for compensating these signals by the SHM community are based on taking a large number of baseline measurements across the operational range of global conditions.[31] In many cases, this is not practical. Therefore, physics-based methods have been developed to enable signal compensation with a reduced set of baseline data points. Figure 12 shows the schematic for interpreting structural health state using distributed sensor data from multiple types of sensors, collected from the structure in real-time.

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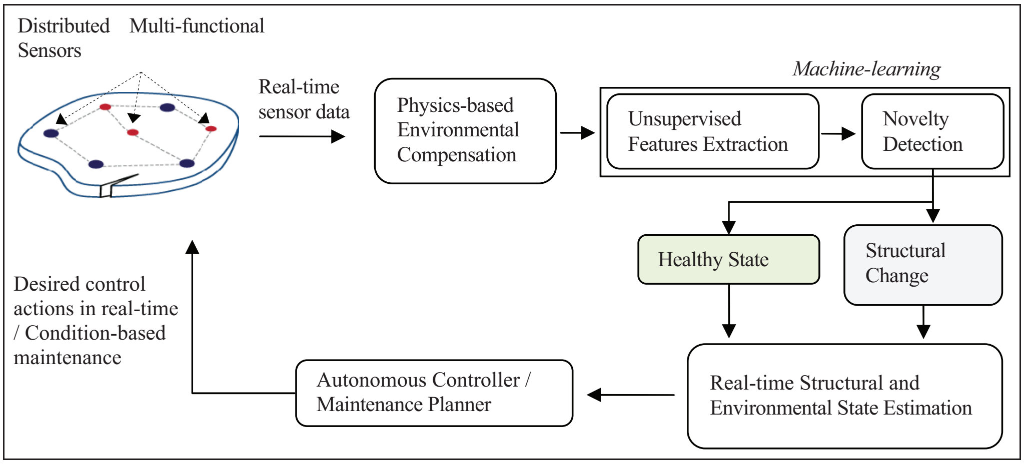

Figure 12. Schematic for structural and environmental state identification to enable, autonomous controller to take real-time control actions, and/or maintenance planner to perform condition-based maintenance of the structure.

The proposed methodology intends to combine physics-based environmental compensation models with machine learning–based data-driven algorithms to identify the true state of a structure.[32,33] 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. Underlying physics can be used to enable compensation across a large range of conditions with a limited set of training data as described in Roy et al.[10] Sensor signals undergo compensation based on environmental effects and are combined with unsupervised feature learning–based novelty detection algorithm to provide accurate structural state awareness which can be used for taking necessary control actions by the autonomous controller, as shown in Figure 12.

It is widely reported that changes in signals, $V_{out}(t)$, are a function of temperature and mechanical load in ultrasonic guided-wave–based SHM using piezoelectric transducers.[9,34–36] As mentioned in Roy et al.,[32] sensor output voltage can be expressed as

$$V_{out}(T, \epsilon, t) = D(T, \epsilon) V_{in}(t) \quad (1)$$

$$V_{out}(T + \Delta T, \epsilon + \Delta\epsilon, t) = D(T + \Delta T, \epsilon + \Delta\epsilon) V_{in}(t) \quad (2)$$

where T represents the ambient temperature, ε represents the mechanical strain, and t denotes time. $V_{in}(t)$ is the applied input voltage to the piezoelectric actuator and D is a composite function of physical properties of piezoelectric transducers and other structural components as explained in Roy et al.[32] Equation (2) provides a physical framework to relate the changes in material properties under combined influence of varying ambient temperature and applied mechanical loads to the changes in the sensor signal output voltage. The effects of varying ambient temperature on piezoelectric sensor signal using the physical framework shown in equation (2) have been studied in Roy et al.;[32] however, influence of varying operating conditions such applied loads on the piezo-sensor signals is still under investigation.

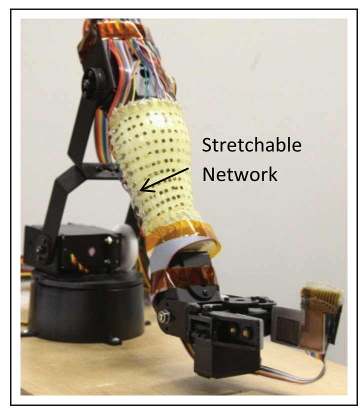

Figure 13. Robotic arm with a stretchable network for state sensing.

Distributed heterogeneous sensors in a stretchable network provide necessary knowledge of environmental and structural operating conditions in the absence of which structural health diagnostic algorithms are more vulnerable to erroneous diagnostics.

System training and operation

As an initial demonstration of state sensing capabilities, an autonomous robotic arm was developed and outfitted with a multifunctional stretchable sensor network containing temperature, pressure, and piezoelectric sensor systems, as shown in Figure 13. The arm was

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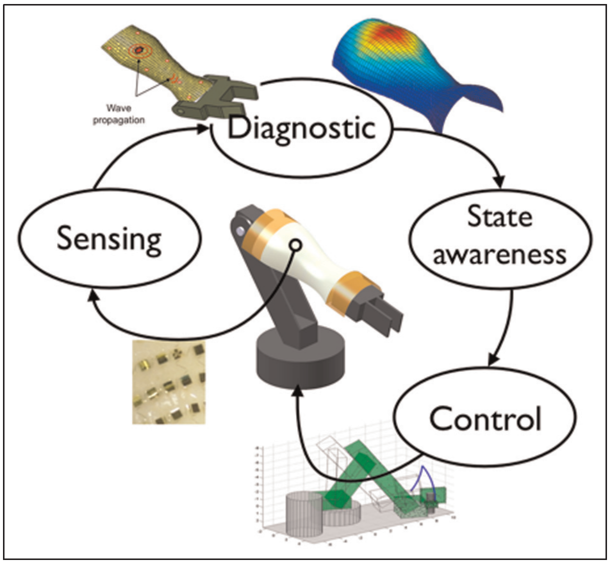

Figure 14. Flowchart of feedback control of a robotic arm.

programmed to complete a task using feedback control based on the network of sensors.

In this process, the network was stretched to conform to a complex, double-curved surface and interfaced with a computer running custom control algorithms. Programs were developed to calculate a path of movement to pick up and transport an object from one place to another. While doing this, the sensor network detected thermal threats, impacts, and the presence of the object. If an obstruction or threat was detected, an alternate path was calculated and pursued. A flowchart of the feedback control is shown in Figure 14. If the object to be moved was absent and not detected, the arm returned to a ready position.

The small scale of the network components (wires and sensors) made them fragile; therefore, a system to protect them and ease handing was designed in the form of a polymeric sensory material. A major objective of this material was to simplify application of the network onto the robotic arm and protect the network. The three-dimensional (3D) shape of the arm posed a challenge. Expandable sensor networks were integrated into flexible polymer membranes, allowing the material to adapt to complex shapes as shown in Figure 13. While the polymer made the system more robust to physical damage, it complicated interfacing issues and reduced the sensitivity and reaction time of the sensors by insulating them from outside influences.

Despite the adverse effects, embedding the stretchable network into a silicone membrane opens other options for device designs increasing capabilities. For example, texturing the face of the polymer sensory material, similar to human fingers, in conjunction with piezoelectric sensors for high frequency strain could enable detection of surface roughness.

Conclusion and future vision

Mass fabrication and deployment of micro-scale sensors on expandable networks overcome many of the issues that currently inhibit the implementation of SHM systems and serve as a foundation for creating intelligent materials. While progress has been made in the creation of an initial set of sensors and electronics on stretchable substrates, it remains a challenge and further research is necessary to create, improve, and deploy more types of sensors on stretchable networks to detect different stimuli with high accuracy, high precision, and low noise. Research to understand and utilize the unique properties and capabilities of new sensor designs must also be continued, for example, understanding the properties and capabilities of unique piezoceramics. Continual efforts to reduce the size of the system components will also serve to reduce parasitic effects on host structures and enable the deployment of networks that span larger areas and contain more sensors.

Addressing, communication, computational systems, and algorithms must also be further developed to handle and interpret the large amount of diverse data from numerous sensors. A bio-inspired approach could use onboard peripheral processors to interpret and simplify local data and make local decisions, only passing critical high-level information to a central processor that would then make global decisions similar to the central and peripheral nervous systems. Initial development of algorithms and systems is under way, but there remains significant work to enable implementation and fielding of intelligent structures. With further development, testing, and characterization, these systems have the potential to revolutionize the capabilities and fielding of SHM and intelligent materials.

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