A STRUCTURAL NEURAL SYSTEM FOR INTEGRATED SYSTEMS HEALTH MANAGEMENT

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UC Institute for Nanoscale Science and Technology – Where nanotechnology takes shape
Unprecedented Opportunities for SHM

787 Composite Aircraft

747 Metal Aircraft

Figure from NASA
Figure from Boeing
Figure from Boeing
Figure from Boeing
THE BIOMIMETIC STRUCTURAL NEURAL SYSTEM

Advantages
• Highly Distributed Nerves for Sensing
• Massively Parallel Signal Processing
• Active and Passive Systems

Sensor Types
• Acoustic Emission (piezoelectric neuron)
• Dynamic Strain (nanotube neuron)
• Corrosion (nanotube neuron)

Other Applications
• Sensing temperature, light, sound, radiation, chemicals, biological agents, pressure

Data acquisition system and signal processing
On board Computer for damage detection and warning

Artificial Nervous System
Advanced Aircraft

Human Nervous System
Brain

Human Body
• Integrated Systems Health Management ideally would continuously check the health of the structure in near real time

• Simplifying the sensor system and the data acquisition equipment plays a very important role in achieving this goal

• The SNS uses long continuous sensors and biomimetic signal processing to simplify health monitoring

• The main element of the system is a neuron which is formed by connecting long sensor elements to an analog processor

• The SNS is formed by connecting multiple neurons to mimic the signal processing architecture of the neural system of the human body

• This approach reduces the required number of data acquisition channels and predicts the location of damage within a grid of miniature neurons
Different types of sensors can also be used:

- A piezoelectric ribbon sensor can passively sense damage due to impact or crack growth because these damages generate lamb waves that are detected by the neural system. The neuron can also receive diagnostic waves generated to actively check the structure on demand. The firing order of the neurons is used to indicate damage.

- In addition, new continuous carbon nanotube sensors are being used as strain and crack detection neurons that operate during both static and dynamic loading.

In general, the SNS may provide an advantage for the continuous monitoring of most large sensor systems in which anomalous events must be detected, and where it is impractical to have a separate channel of data acquisition or wiring for a large number of sensors.

Moreover, the data reduction technique and damage detection algorithms are easy to understand, simple to implement, reliable, and many sensor types can be used.
• Sensors connected in series to form continuous sensors
• Each red dot indicates two sensors that are placed in the same location.

• Structural Neural System Analog Processor (SNSAP) consists of discrete analog components that aid in the reduction of data acquisition channels.

• 100 channels of data acquisition is reduced to 4 channels of data acquisition.

• SNS predicts the location of damage within a grid of sensors.

• SNS works simultaneously for both active and passive health monitoring.
A DUAL MODE ACTIVE/PASSIVE SNS IS BEING TESTED

Advantages

- Inexpensive health monitoring system.
- Combines active and passive methods for health monitoring.
  - Maintenance on demand
  - Continuous Health Monitoring
- Reduce the required number of data acquisition channels using Structural Neural System
- No individual data storage is required.

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Wave Propagation Simulation is used to Design the SNS and Signal Processor

<table>
<thead>
<tr>
<th>Description</th>
<th>Step Excitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of the plate (meters)</td>
<td>1.22</td>
</tr>
<tr>
<td>Width of the plate (meters)</td>
<td>1.22</td>
</tr>
<tr>
<td>Number of modes used</td>
<td>250</td>
</tr>
<tr>
<td>Number of time steps used</td>
<td>2000</td>
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<tr>
<td>Time step (Sec)</td>
<td>5e-7</td>
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<tr>
<td>Type of Input</td>
<td>Step Input (AE)</td>
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<tr>
<td></td>
<td>Amplitude = 0.75 N</td>
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<tr>
<td>Impact Location (x, y, meters)</td>
<td>(0.254, 0.254)</td>
</tr>
<tr>
<td>Max frequency of 250th mode (kHz)</td>
<td>885.3</td>
</tr>
</tbody>
</table>
Simulated Response of a Plate Due to an Acoustic Emission

Time: 4.95e-5 sec

Time: 2.515e-4 sec

Time: 6.555e-4 sec

Time: 9.585e-4 sec
Raw Time Signals from the Neurons before Processing
Simulation Result of the Firing Response of the Neurons and the Composite Time Response of the Neurons

Figure (a)

- Firing Response of (C1) Column Neurons.
- Indicates excitation in between sensor 2 and Sensor 3.
- Response of Row Neurons (Not Shown) because of symmetry will indicate that the crack is located in between Neurons 12 and 13.
- The Intersection of all these neurons will indicate the location of crack within a grid of sensors.

Figure (b)

- Cumulative Voltage Values of all neurons (T1).
- “Might indicate the severity of damage”.
EXPERIMENTAL SETUP

LABVIEW and MATLAB

Oscilloscopes for Diagnostics

Power Supplies

Test Beam (MTS system not shown)

SNS Processor

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Results of passive SNS

(a) Geometry of the composite specimen.
(b) Output from SNS analog processor indicating the time domain output of the neurons (T1) for an acoustic emission near neuron 1.
Results of passive SNS testing: (a) Output of SNS analog processor – Crack location channel information (C1) (b) Output of passive SNS software correctly indicating the location of damage near neuron 1
Active Structural Neural System Testing

- **a)** Geometry of the test specimen
- **b)** Excitation signal
- **c)** Output of SNS analog processor

Results of testing the active SNS
- a) Geometry of the test specimen
- b) Excitation signal
- c) Output of SNS analog processor

Testing is performed by removal of an aluminum reinforced beam to represent damage.
Results of active SNS (a) Output of SNS analog processor – Damage location information (b) Output of SNS active software correctly indicating that the damage (removal of aluminum beam) exists near neuron 3
Design of a Carbon Nanotube (CNT) SNS

Neural System and crack propagation

Spray-on neuron under development
Simple Architecture of the CNT-SNS

Spray-On Carbon Nanotube Neurons of Arbitrary Density

Five wire bus control of the entire SNS
MODELING OF THE ELECTROCHEMICAL CNT STRAIN AND CORROSION SENSOR

Experimental Electrochemical Impedance Spectra (0.5Hz to 10KHz) and electrical model

- The CNT is a strain sensor (piezoresistive effect) and a highly sensitive corrosion sensor (electrical impedance effect)
TESTING A CNT NEURON

Response of a carbon nanotube neuron:
(a) change in resistance due to crack propagation;
(b) change in capacitance and resistance due to electrolyte on the neuron

- Resistance: $9.27\, \Omega \rightarrow \infty$
- Capacitance: $44\, \text{pF} \rightarrow 0$

- Resistance: $117\, \Omega \rightarrow 123\, \Omega$, 5%↑
- Capacitance: $19.1\, \text{pF} \rightarrow 1109\, \text{pF}$, 6000%↑
THE CNT NEURON IS ALSO A CONTINUOUS CORROSION SENSOR

Corrosion Mechanism Model: (a) EIS Interface model of corrosion on an aluminum structure; (b) Electrical model of corrosion sensor; and (c) EIS model of the interface layer.

- The corrosion occurring on a metallic structure produces a diffusion layer at the interface between the structure and the CNT corrosion sensor.
- The corrosion ions penetrate into the CNT polymer sensor and form a double layer charge injection at the diffusion layer on the nanotube surface.
Dynamic Response of a CNT Neuron on a Cantilever Beam

The CNT neuron has a bandwidth of about 15 Hz

Results of Dynamic Testing

• Damage (50%) has a small effect on the amplitude and frequency of the dynamic response of the neuron on the cantilever beam

• Electrochemical Impedance Spectroscopy (EIS) is more sensitive than vibration for SHM using carbon nanotube neurons
SUMMARY AND CONCLUSIONS

• Successfully performed wave propagation modeling of Lamb waves

• The SNS reduces the number of data acquisition channels. A SHM module to monitor a large component uses four channels of data.

• Analog circuitry of the SNS analog processor involves commercially available op-amps

• An active damage detection technique is being developed that can reduce the required number of data acquisition channels and add redundancy when used with the passive technique

• The SNS can use other type of sensors including carbon nanotube sensors, and chemical, pressure, and temperature sensors

• The Carbon Nanotube SNS uses digital switches and is simple, reliable, and improves prognostics because the crack length is accurately estimated
The Ultimate Finesse in Structural Health Monitoring: Diagnostics and Prognostics Based on a Digitally Controlled Carbon Nanotube Structural Neural System

A Carbon Nanotube Artificial Neural System will have applications in other areas including Biosensing and Homeland Security
SHM Systems and Carbon Nanotube Sensors Licensing and Co-Development Opportunities with the UC and NCA&TSU

For Licensing Information Contact:
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• Invention Disclosure, Univ. of Cincinnati, 8-26-03, “An Artificial Neural System,” Goutham Kirikeria, Saurabh Datta, Bo Westheider, Mark J. Schulz, Mannur J. Sundaresan, William N. Martin, Jr., Anindya Ghoshal, UC 103-046.