Bio-Inspired Intelligent Sensing Materials for Fly-by-Feel Autonomous Vehicle

MURI Team
Participating Institutions:
Stanford University, University of California at Los Angles, New York Institute of Technology, University of Colorado at Boulder, Johns Hopkins University, and University of British Columbia, Canada
**Report Documentation Page**

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19a. NAME OF RESPONSIBLE PERSON
Advantages of UAV

- Lower Cost in Manufacturing
- Reduced Cost in Maintenance and Operation
- Energy Saving for Smaller Size
- Minimal Human Risk
Aircraft Landing in stormy weather

F-15 safely landed with one wing
Fly-By-Feel Autonomous Flight

- Sensing
- Recognition
- State Awareness
- Decision

Autonomous Mode

Essential Steps
Fly-by-Feel Autonomous Flight

But the system must be:

• Minimal or no Weight Increase
• Low Cost in Manufacturing
• Robust in System Integration
• Easy for Installation
• Friendly in Implementation
Bio-inspired Smart Materials/Structures

Fly-by-Feel Autonomous Vehicle

Massively Parallel data processing, filtering, self-learning, diagnostics, and real-time decision

MILLIONS of nano/micro-sensors, electronics, processing units etc. over a large area

Bio-inspired Sensory Network

Information Processing

Sensory System

Meissner’s corpuscle
To measure vibration

Hair Follicle
To measure: flow, proximity and touch

Pacinian Corpuscle
To measure touch

Krause’s
To measure temperature

Merkel’s Disk
To measure touch

Ruffini Ending
To measure deformation

Nerve fiber
What is an Intelligent Material

**Signals**

Brain
Somatosensory cortex

Spinal Cord

**Materials**

Nerve receptors
Materials Development

Multifunctional Materials

Networks

Processors/Neuron circuits

Multi-functional Sensors
Sensor Processing Development

STAGE 3
Autonomous decision

STAGE 2
State Quantification

STAGE 1
State Classification

Prognosis, Decision Planning and Control

Structural Damage Diagnosis (Type, location, extent)

Flow Field Distribution (temperature, pressure, strain etc.)

Signal processing + machine learning algorithms

Load → Temp. → Damage → Pressure → Air-flow → Structural Damage Diagnosis

Flow Field Distribution

Multi-functional Sensors

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Bio-inspired Sensory Network
## Research Team

<table>
<thead>
<tr>
<th>Institution</th>
<th>Team Members</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stanford</td>
<td>Fu-Kuo Chang (PI) – Aero/Astro&lt;br&gt;Boris Murmann – EE&lt;br&gt;Shan Xiang Wang – EE&lt;br&gt;Andrew Ng – CS</td>
</tr>
<tr>
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</tr>
<tr>
<td>NYIT</td>
<td>Rahmat Shoureshi – ME</td>
</tr>
<tr>
<td>UC Boulder</td>
<td>Robert McLeod – ECEE</td>
</tr>
<tr>
<td>UBC</td>
<td>Frank Ko – ME&lt;br&gt;Peyman Servati – ECEE</td>
</tr>
<tr>
<td>JHU</td>
<td>Somnath Ghosh – ME</td>
</tr>
</tbody>
</table>
Major Tasks

• **Bio-inspired Sensor Network**
  – Stretchable sensor network to accommodate large arrays of sensors and electronics over a large area.

• **Micro/Nano Sensors for State Sensing**
  – Multi-physic multi-scale sensors with an ease of network integration.

• **Neuron Circuits and Interface Electronics**
  – Bio-inspired neuron circuits with appropriate electronics to interface with various sensors.

• **Modeling, Design, and Prognostics**
  – Multi-physic and multi-scale modeling of multifunctional materials with distributed sensing capabilities for design and validation.

• **Diagnostics and State Awareness**
  – Embedded intelligent software, Algorithms, tools, and processes to determine the state of the materials in real time.

• **Integration**
  – An effort to develop a prototype of “intelligent sensing material.”
**Robust and Low Cost Materials Development**

**Multifunctional Materials**

**Networks**

**Processors/Neuron circuits**

**Multi-functional Sensors**
Micro Fabrication for Macro Application

Multi-Scale Fabrication and Integration

Nano/micro scale

Bio-inspired sensor network

Silicon/Polymer

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Stretch to macro

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Fly-by-Feel Autonomous Vehicle

Intelligent sensing materials

Power on

Step 1: Stretchable Network Design

CMOS Process

Step 2: Nano/Microsensors and Electronics

CMOS/MEMS Process

Step 3: Network Stretch and Expansion

Making network

Adding sensors/electronics

Step 4: Integration and Functionalization

Step 5: Training and Learning

NANO-MICROSCALE DESIGN AND FABRICATION (CMOS PROCESSES)
**OTFD Sensors for Stretchable Network**

- **Integration of Organic Thin Film Diodes (OTFDS)**
  - Packaged OTFDs in the network
    - Improved diode performance
    - Protect OTFDs in harsh environment:
      - High temperature (350°C),
      - Solvents, acids
    - To measure temperature

- **Organic thin film diode I–V curves**
  - Improved diode performance

- **Network node**
  - Degraded I–V (2011)
  - Improved I–V (2012)

- **Temperature measurement (I–T) of an OTFD**

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**Bio-inspired Sensory Network**
Video: 169 nodes network after release
Coating 3D bodies

G. Lanzara, J. Feng and F.K. Chang, Smart Materials and Structures, 19, 045013, 2010

G. Lanzara et al, Advanced Materials, 2010
Fully Stretched Sensory Network

Area increased by 10,000%
Single wire resistance unchanged during/after full stretch (400 Ω)

Network before stretch

Network after full stretch

Sensor network warped on curved surface
Multi-physic and Multi-scale Sensors

Chang, Wang – Stanford
McLeod – UC Boulder
Carman – UCLA
Servati, Ko – UBC
Network Functionalization

OTFD sensor
Airflow sensors
PZT sensor
Carbon nanotube sensors
Magnetoelectric sensors
PZT Actuators/Sensors for Stretchable Network

Create piezoelectric sensing systems on the stretchable network

Method: Integrate thick film ceramics into C-MOS processing

Challenges: Temperature & chemical compatibility issues

Release Piezos onto polyimide

Printed Piezoelectric Nodes

Embed Within Composite

Stretch Network

Cure Structure

Monitor Structural State
Recent Accomplishments

- Screen printed piezo-ceramics integrated into C-Mos type processing & released onto a polyimide film with electrodes.

Thick film piezos on a silicon backing

Piezos released onto a polyimide film

- Innovations
  - New method to transfer piezos from a fabrication substrate to an organic substrate
Ongoing Work

• Create a stretchable network from the screen printed piezos released onto an organic backing
• Characterization of materials
• New transducer designs

Piezos on a polyimide film

Stretchable wire pattern

New Transducer designs
Air Flow Sensor Configuration

(Yue Guo, Prof. Shan X. Wang)

- **Aim:** Obtain the real-time air flow profile (velocity + direction) surrounding the entire airplane

1. **Air Flow hits the pillar**
2. **Deflection in the beam**
3. **Strain in the sensing elements**
4. **Inverse Magnetostrictive Effect**
   Stress $\rightarrow$ Magnetization rotation $\rightarrow$ Resistivity change, $\Delta R/R$
   Or **Piezoresistive Effect**
5. **Voltage change from $\Delta R/R$**

<table>
<thead>
<tr>
<th>Pillar</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>50 um</td>
</tr>
<tr>
<td>Width</td>
<td>50 um</td>
</tr>
<tr>
<td>Height</td>
<td>250 um</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Beam</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>350 um</td>
</tr>
<tr>
<td>Width</td>
<td>52 um</td>
</tr>
<tr>
<td>Thickness</td>
<td>1 um</td>
</tr>
</tbody>
</table>

COMSOL Simulation

Cross-section View (MEMS)

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Bio-inspired Sensory Network
Magnetoresistance (MR) Air Flow Sensor

Bottom View of Beams

Ni$_{86}$Fe$_{14}$ Sensing Elements

- 4 x10 array in series for larger output signal
- Square shape for avoiding demagnetizing field

MR signal is related to beam stress and thus air flow velocity.

$$H_k \sin(\theta - \frac{\pi}{4}) \cos(\theta - \frac{\pi}{4}) + \frac{3M_s \sigma}{\mu_0 M_s} \sin \theta \cos \theta = 0$$
### Design Comparison

<table>
<thead>
<tr>
<th>Sensing Elements</th>
<th>$L_{\text{sensor}}$</th>
<th>$W_{\text{sensor}}$</th>
<th>$t_{\text{sensor}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magneto-resistance</td>
<td>4µm x10</td>
<td>4µm x4</td>
<td>25nm</td>
</tr>
<tr>
<td>Piezo-resistance</td>
<td>50µm</td>
<td>25µm</td>
<td>40nm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Strain 1e-5</th>
<th>Magneto-resistance</th>
<th>Piezo-resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>1 mW</td>
<td>1 mW</td>
</tr>
<tr>
<td>Resistivity</td>
<td>15e-8 ohm·m (Ni$<em>{84}$Fe$</em>{16}$)</td>
<td>2e-5 ohm·m (PolySi)</td>
</tr>
<tr>
<td>Resistance</td>
<td>240 ohm</td>
<td>1000 hm</td>
</tr>
<tr>
<td>Voltage &amp; Current</td>
<td>0.5 V, 2 mA</td>
<td>1 V, 1 mA</td>
</tr>
<tr>
<td>Current Density</td>
<td>2e10 A/m²</td>
<td>1e9 A/m²</td>
</tr>
<tr>
<td>Resistance Change</td>
<td>0.11 % (AMR), 0.44 % (GMR)</td>
<td>0.029 %</td>
</tr>
<tr>
<td>Voltage Change</td>
<td>0.55 mV (AMR), 2.2 mV (GMR)</td>
<td>0.29 mV</td>
</tr>
<tr>
<td>Johnson Noise</td>
<td>2 nV/√Hz</td>
<td>4 nV/√Hz</td>
</tr>
</tbody>
</table>

Anisotropic magneto resistive (AMR) and giant magneto resistive (GMR) air flow sensors with 1 mW power consumption are feasible and outperform similar piezoresistive air flow sensors.
Magnetoelastic Sensors for Detecting Magnetic Field (Carman’s Group)

Detecting incoming threats using magnetic perturbation

Beak and/or visual cortex contains superparamagnetic particles to track/see magnetic flux lines

Develop sensitive magnetometer using biological inspiration & phenomena present only at nanoscale

Coercivity

Piezoelectricity
Curie, 1880

Energy Transduction

Spaldin, Fiebig, Science 15 July 2005

Joule, 1842

Magnetostriction
Method of Approach

Nanoscale Magnetolectric Materials for Detecting Magnetic Fields

- 2001 – Giant magnetolectric in bulk composite (Ryu) > 1000 papers
- 2004 – Magnetolectric in thin film > 50
- 2007 – Magnetolectric in SD (UCB and UCLA) > 5
- 2011 – Magnetolectric in SP (UCLA) ~ 0

Thin film

- PMN-PT

Single domain

Superparamagnetic

Normalized Magnetization

Magnetic Field (Oe)

Normalized Magnetization

Magnetic Field (Oe)
**Method of Approach**

**Magnetoelectric Control of Superparamagnetism**

- Magnetoelectric composite induces strain in Ni nanoparticles
- $E=0$ produces superparamagnetic behavior
- $E=0.4$ MV/m produces single domain structure

**Diagram:**
- TEM image showing Ni nanoparticles with an average size of 16 nm.
- Magnetoelectric composite labeled as (011) PMN-PT.
- Graphs showing normalized magnetization vs. magnetic field for $E=0$ and $E=0.4$ MV/m, indicating superparamagnetic and single domain behaviors respectively.
Nano-Strain Sensors (Servati & Ko’s Group)

- Strain sensors based on electrospun nanofibers.
- Core-shell nanofibers for ultra-sensitive strain monitoring.

SEM photomicrograph of core-shell (Au-PAN) conductive nanofiber mesh.

Cross section of core-shell (Au-PAN) nanofiber mesh in PDMS.

Several parallel nanofiber strain sensors embedded in PDMS.

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Accomplishments: Stable, High-Sensitivity Response for Planar Strain and Vibrational Monitoring

Change in resistance and gauge factor $K$ under uniaxial tensile strain.

Measured changes in resistance due to vibrations of a rigid metallic blade, showing both tensile and compressive strain sensing response.

Stable change in resistance over 1000 repeated stretching and unloading of the sensor.

Vibrations
Laminated nanofiber mesh sensor
Data flow and CU program overview

Wing with sensors and actuators

Amplifiers

Living neural network

Multi-channel sensor interrogation

Precision signal processing
Precision interrogation results

Multiple (100’s) sensor precision ranging supported by single network.

Higher bit-depth DAQ
- New noise floor = 3.0 attoseconds
- Range uncertainty $= \pm 1.29$ Angstroms in silicon
Neuron Circuits and Interface Electronics

Chen – UCLA
Murmann – Stanford
Material Development for Reasoning

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In this project, we plan to develop electronic neuron circuits based on carbon nanotube/polymer composites, and integrate the neuron circuits with sensing networks that can (1) promptly process a large amount of signals in parallel to recognize exogenous threats accurately and effectively, (2) implement real-time learning autonomously, and (3) provide dynamic prognosis for appropriate response for UAV.
A synaptic transistor has been developed by integrating CNT and polymer materials to emulate biological synapse with spike signal processing, learning, and memory functions.

An image of a large scale neuron circuit by integrating 8192 synaptic transistors with Si MOS circuits with the functions of signal parallel processing, real-time pattern recognition, adaptive learning.
Neurologically inspired theoretical models and architectures has been directly integrated and applied to establish the circuit architecture. The circuits have been integrated with the temperature sensing network developed at Prof. Chang’s group at Stanford University. We will demonstrate (1) promptly process a large amount of signals in parallel to recognize exogenous threats accurately and effectively, (2) implement real-time learning autonomously, and (3) provide dynamic prognosis for appropriate response for UAV.
Interface Circuits for PZT Actuators (Murmann’s Group)

Densely Integrated Interface Circuits for State Sensing Network

- Using Pulse-Width-Modulation (PWM) to generate the excitation waveform
- Render the waveform by a series of precisely timed binary pulses
- High power efficiency: (a) is bounded by 78%; (b) is bounded by 100%

(a) Structure of (a) a conventional piezo drive, and (b) a PWM piezo drive
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Chip layout (to be taped out on 8/19)

- Multiphase clock generator
- SRAM (PWM time table)
- Gm-C integrator, Latch, & OS calibration DAC
- Power transistors
- Gate driver
- ~40,000 logic gates
- Digital control
Potential Way

**Baseline Generation**

*Generate large database of sensor responses for different structural states during training*

- Record sensor responses at state ‘$S_1$’
- Record sensor responses at state ‘$S_2$’
- Record sensor responses at state ‘$S_N$’

- **Enormous amount of effort & time consumption**
- **Next to impossible to span entire range of environmental conditions and structural states**
The Proposed Approach

Distributed Actuator/Sensors

Autonomous Guidance units

Decision Management

Supervised Learning

State Estimation
- Structural changes
- Damage types
- Others ...

Physics based compensation models

Unsupervised learning (Neural-net Architecture)

Stage 1

Stage 2

Stage 3
Modeling and Prognostics for Design and Validation

Ghosh – Johns Hopkins University
Chang – Stanford
To develop an coupled multi-scale, multi-physics computational model and code for analysis of electromagnetic devices, e.g. sensors, antenna leading to design

### Methods of Approach

<table>
<thead>
<tr>
<th>Coupled Simulation</th>
<th>Multi-time Scaling</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Large Deformation Dynamic Response</strong></td>
<td><strong>Transient Electromagnetic Field</strong></td>
</tr>
</tbody>
</table>

**Nonlinear hyper-elastic material**

\[
S = \lambda \cdot tr\left(\frac{E}{E}\right) + 2\mu \cdot \frac{E}{E}
\]

**Finite deformation problem**

\[
\int_{\Omega_o} \left( \delta u^T \rho_o \ddot{u} \right) dV + \int_{\Omega_o} \left( \delta F^T \cdot P \right) dV - \int_{\Omega_o} \left( \delta u^T \rho_o b \right) dV
\]

\[
= \int_{\partial \Omega_o} \delta u^T t_o dS
\]

Solve for \( \dot{u} \) & \( u \)

\( S: 2^{nd} \) Piola-Kirchhoff Stress Tensor

\( E: \) Lagrangian Green Strain Tensor

\( u: \) Displacement

\( \lambda, \mu: \) Lame Constants

**Maxwell equations in total Lagrangian**

\[
\nabla \times (H(X,t)) = \frac{\partial D(X,t)}{\partial t} + J(X,t)
\]

**Scalar and vector potential in reference configuration**

\[
B = \nabla \times A \quad E = -\nabla \phi - \dot{A}
\]

\[
H(X,t) = \begin{bmatrix}
\varepsilon_0 J \left\{ -\nabla \Phi - \dot{A} - (E^{-1} \cdot \ddot{u}) \times (\nabla \times A) \right\} \cdot C^{-1} \times (E^{-1} \cdot \ddot{u}) \\
+ \frac{1}{\mu_0 J} \left\{ (\nabla \times A) \cdot C \right\}
\end{bmatrix}
\]
Coupling of Mechanical and Electromagnetic Field

**Coupled static electromagnetic field and dynamic mechanical field**

1. Electromagnetic field is affected by the mechanical field
2. The magnetic potential is evolving by the velocity field other than the displacement field

**Coupled transient electromagnetic field and dynamic field**

1. Electromagnetic field is evolving with the mechanical field
2. Frequency difference brings in significant computational expense

\[
\frac{f_{em}}{f_{me}} = 4
\]

\[
\frac{f_{em}}{f_{me}} = 40
\]
Multi-physics Spectral Element Method (Chang’s Group)

Efficient multi-physics computation tool for modeling ultrasonic waves

Equations of Motion
\[ \sigma_{ij, j} + f_i = \rho \ddot{u}_i \]

Gauss’s Law for Electricity
\[ D_{i,i} = 0 \]

Induced Ultrasonic Stress Waves and wave-crack interaction

Voltage Input to Piezo Actuator

Induced Ultrasonic Stress Waves and wave-crack interaction

Voltage Output at Piezo Sensor

Aluminum plate with 20 mm cracks
Design of Piezoelectric Sensor Network

- PESEA: accurate simulations for a complex structure
- Genetic algorithm: 100% damage detectability with minimum number of Piezo actuators and sensors

Integration of PESEA and GA-based Optimization

Given Structure → PESEA ↔ GA-based Optimization → Optimal Sensor Layout

Detection and Localization

100% Detection
Diagnostics and State Awareness

Chang, Ng – Stanford
Shoureshi – NYIT
Sensor Data Processing

STAGE 1
State Classification

STAGE 2
State Quantification

STAGE 3
Autonomous decision

Prognosis, Decision Planning and Control

Structural Damage Diagnosis
(Type, location, extent)

Flow Field Distribution
(temperature, pressure, strain etc.)

Signal processing + machine learning algorithms

Low-level preceptor

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Motivation

Sensor Data Interpretation in Real-time

Distributed Actuator/Sensors

Sensor Response: \( S_i = f(\Delta \text{load}, \Delta \text{temp.}, \text{localized damage}, \Delta \text{BCs}, \Delta \text{sensor state} \ldots) \)

State field distribution
- Temperature
- Pressure
- Air-flow
- Strain
- Structural damage

Environmental Effects
Ambient temperature, humidity, moisture.....

Corrupted Sensor Data

How to accurately assess the structural state information from a network of multi-functional sensors?
State Classification: Designed features

Table: Sensor signal measurements under simulated environmental conditions

<table>
<thead>
<tr>
<th>Number of Samples</th>
<th>Temperature Range</th>
<th>Load Range</th>
<th>Simulated Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 coupons</td>
<td>30°C - 95°C</td>
<td>0kips – 5kips</td>
<td>0.25” - 1.5” Notch at the edge</td>
</tr>
</tbody>
</table>

4 sensing paths per actuator; Paths per measurement = 16; # of measurements = 1136

Difficult to identify true state under combined action of load and damage; State Classification Accuracy (logistic regression) < 30%
State Classification: Self-Learned Features

Unsupervised Features Learning: Neural-net based ‘Sparse Auto-Encoders’

Self-learned features outperform the self-designed features for state classification
Current system scales better; but still some distance to go for a full-scale application.

- Prior art: 10^4 neurons, 1M parameters, 50,000 examples
- Our previous system: 10^6 neurons, >2M parameters, 50,000 examples
- Fly-by-feel aircraft: Goal: 10^7 to 10^8 neurons, 100M parameters, >10M examples

Local receptive fields, weight-tying
• Fold prior MURI work into extremely large-scale system:
  – Scalable K-means learning
  – Online training
  – Locally connected neurons.
  – New invariant-feature learning approach.
• Applied to unlabeled image data.  
  66M parameters, 57M data points.  
  (1000x more data than standard benchmarks.)

1.4 million images.  57 million patches.  

Single neuron selects complex patterns like
From Sensing to Decision Making (Shoureshi’s Group)

Sensing → Diagnostics

Intelligent Sensing Materials/Structures

Decision → State Awareness

Recognition

NYIT Research Focus
Goals

- To develop an analytical technique for observability and controllability of large-scale, dynamic systems
- To develop a bio-inspired data/information architecture for feature-based global diagnostics of a large-scale system
- To develop a bio-inspired, feature-based re-configurable control system to maintain vehicle functionality in the presence of system failures
- Design a testbed to assess MURI team research results
Controller and Diagnostics Testbed
COMPOSITE PANEL
integrated with: multifunctional sensor network

State Sensing:
Stresses, Strains, Temp, Pressure,
Loads, Damage/Failure, Remote Threats, etc.

Prototype I
Prototype II: Learning without Training

Data transfer

Sensors output

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Fly-By-Feel UAV

• Lower Cost in Manufacturing
• Reduced Cost in Maintenance and Operation
• Energy Saving for Smaller Size
• Minimal Human Risk

Learning from others
Learning from itself
Traditional design of structures is divided into a few disciplines

Resulting in
- overdesigned structures
- heavy airplanes
- time consuming inspections
- inappropriate maintenance schedules
- catastrophes
Technologies developed during MURI

Requires \textit{re-thinking} the traditional design strategies
Intelligent design constitutes the interplay of many... but will result in
Concept: “Build confidence on design”

Minimize uncertainties → weight Saving

Confidence on design and performance
Life cycle management

- Manufacturing
- Transportation
- Assembly
- Service
- Maintenance & Repair

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