Smart Sensing Technology for Infrastructure Monitoring

Supported by FHWA and USDOT

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Two Technologies

- Long-term Tagging Technology
- Events Detection and Condition Monitoring Technology
Damage

Measured Strain Distributions
Relative shift
Strain level * time
Further from damaged area = less effect = smaller shift

Data compression Protocol

Material
Sensors
Damage area
Potential Location of Sensors
Neutral Axis
Beam center

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Damage area
Potential Location of Sensors
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8th RILEM International Conference on Mechanisms of Cracking and Debonding in Pavements (MCD2016)
Data Recording Protocol on the sensor

Challenges:

• Size
• Attachment to the host structure
• Location
• Meaning of data
• Data interpretation and prognosis methods
Pavement Monitoring System

• At Turner-Fairbanks Highway Research Facility.
Manufacturing

Data Interpretation - Damage
Data Interpretation - Damage

Cumulative Distributions Variation

Normalized Density Distributions

Probability distribution of the damage index versus the number of cyclic loading events.

Data Interpretation - Damage

Example - Variation over time of the mean damage index (from sensor) versus the damage index evaluated using data from a COD gage.

Example - Variation over time of the standard deviation of the damage index distribution.

<table>
<thead>
<tr>
<th>Actual remaining life</th>
<th>Predicted remaining life using the sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>391</td>
<td>325</td>
</tr>
<tr>
<td>420</td>
<td>425</td>
</tr>
<tr>
<td>9350</td>
<td>7125</td>
</tr>
<tr>
<td>7022</td>
<td>11048</td>
</tr>
<tr>
<td>10980</td>
<td>23011</td>
</tr>
</tbody>
</table>
Asphalt concrete sample:  
- Length: 18" (457.2 mm)  
- Span length: 15" (381 mm)  
- Thickness: 6.5" (165.1 mm)  
- Width: 6" (152.4 mm)

- Damage states:  
  - Intact: a = 0 mm  
  - Damage 1: a = 7/8" (22.2 mm)  
  - Damage 2: a = 1 1/4" (31.75 mm)  
  - Damage 3 (crack propagation): a = 1 3/4" (44.45 mm)

Single Edge Notched Beam Test

The crack propagation phase during the test

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Damage Detection Based on the FE Results

Damage Detection Based on the Experimental Results (0.2 mm, 5 Hz)
Smart Sensing Technology for Infrastructure Monitoring
**Moore’s Law and Structural Health Monitoring**

*Chakrabarty, Feng, Aono, SPIE 2013.*

- Economically viable to embed a million transistor IC in every concrete brick, on a pound of titanium alloy, a pound of steel

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**Sensing Issues in Civil Structural Health Monitoring**

- Cost
- Size
- Power Source
- Maintenance – Maintenance free sensors
- Data meaning and interpretation
- Ease of installation and use
- Data type and format – Integration with existing management systems
- Extreme events monitoring
Pavement Tagging Technology

PCC Mixture Design Inputs
Cement Content (lbs)
  Type of cement
Supplementary Cementitious Materials (lbs)
  Type of SCM
Coarse Aggregate (lbs)
  Aggregate Geology
  Coefficient of thermal expansion
Fine Aggregate (lbs)
  Aggregate Geology
Water (lbs)
Admixture(s) (fl.oz)
  Type of admixture(s)

Fresh Concrete Properties
Slump (inches)
Unit Weight (lb/ft³)
Concrete Temperature (°F)
Entrained Air (%)

Hardened Concrete Properties
Compressive Strength (psi)
Flexural Strength (psi)
Elastic Modulus (psi)
Measure CTE

Construction
Ambient Temperature at the time of concrete placement (°F)
Relative Humidity at the time of concrete placement (%)
Wind Speed (mph)
Curing material
## Pavement Tagging Technology

### Pavement Design
- Slab thickness (inches)
- Base thickness (inches)
  - Base type
- Subbase thickness (inches)
  - Subbase type
- Resilient Modulus of base (psi)
- Resilient modulus of subbase (psi)
- Modulus of subgrade reaction (psi/in)
  - Type of subgrade
- Joint spacing
- Joint sealant type
- Dowel diameter
- Dowel spacing
- Dowel bar material

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### Pavement Tagging Technology

![Pavement Tagging Technology](image)

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### Pavement Tagging Technology

![Pavement Tagging Technology](image)
Two Technologies

- Long-term Tagging Technology
- Events Detection and Condition Monitoring Technology

MSU PFG Technology

- Sensors embedded inside “smart structures” that can self-prognosticate damage and mechanical failure.
- Zero Maintenance Sensors: Operational life of sensors comparable to the useful life of the structure – Powering is one of the key challenges.

Sensor Size and Powering
Self-powered Sensors

- Sensors that operate by scavenging energy from the ambient environment.

Passive Sensors
- Sensor is active only when the interrogation signal is present – radio-frequency, optical or acoustic sensing. (NOT Zero-downtime – cannot sense rare events)

Trickle-charge Sensors
- Energy stored by trickle-charging and active only when powering conditions met. (NOT Zero-downtime – cannot sense rare events)

Direct-powered Sensors
- Harvest energy for operation from the signal being sensed – e.g. piezoelectric signal used for powering and sensing mechanical strain.

Can we use existing commercial solutions?

- Harvestable power too little to be mapped onto existing solutions.

Transfer energy from the transducer to the energy storage:
1. Power Efficiency (Output Power/Input Power)
2. Leakage (important in sleep mode)
3. Source Impedance Matching (maximum power transfer)
4. Start up power

Convert buffered energy into regulated power required for multi-voltage, multi-function biasing:
1. Conversion Efficiency
2. Dynamic Range
3. Start up power
Piezo-floating-gate technology
(US Patents: 7,757,565 and 8,056,420)

Eliminate power regulators, energy storage, data converters, RAMs and digital signal processors. Use the physics of the device and the structure to perform computation and storage (Use analog computation instead of digital).

- Piezoelectric ceramics and polymers can generate high-voltages for low strain-levels but at ultra-low-driving currents.

Recorded data on the sensor
Comparison with other technologies

<table>
<thead>
<tr>
<th>Process</th>
<th>0.5-µm standard CMOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>1900µm x 1500µm</td>
</tr>
<tr>
<td>Maximum Current consumption</td>
<td>110nA (7-channel level crossing monitoring)</td>
</tr>
<tr>
<td></td>
<td>90nA (3-channel impact monitoring)</td>
</tr>
</tbody>
</table>

Interfacing PFG with Gen-2 RFID

- Mechanical usage data in the EPC is continuously updated on the non-volatile memory and is powered by strain-variations.
- COTS platform (MSP430 based) to implement the Gen-2 protocol stack (derived from WISP).
Damage was introduced by making a notch at the middle of the steel plate. The damage states were defined by increasing the notch size (2a) as follows:

- Intact: 2a = 0 mm (Intact plate)
- D10: 2a = 10 mm
- D20: 2a = 20 mm
- D30: 2a = 30 mm
- D40: 2a = 40 mm
Looking into the Future

- Internet-of-Things and Big Data Integration.
- Vehicle-to-Infrastructure Communication

- Self-powered Sensor Array
- 3G/4G mobile
- BIG DATA Cloud
- LAN
- Highway Management and Planning Software
- Analysis Center
- Internet-of-Things and Big Data Integration.
- Vehicle-to-Infrastructure Communication