Smart Sensor Network for Aircraft Corrosion Monitoring

2010 U.S. Army Corrosion Summit
February 9-11, Huntsville, AL

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This material is based upon work supported by the United States Navy under contract Nos. N68335-09-C-0099 & N68335-09-C-0107. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors(s) and do not necessarily reflect the views of the United States Navy.
**Smart Sensor Network for Aircraft Corrosion Monitoring**

1. REPORT DATE
   FEB 2010

2. REPORT TYPE

3. DATES COVERED
   00-00-2010 to 00-00-2010

4. TITLE AND SUBTITLE

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR’S ACRONYM(S)

11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
   Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
   U.S. Government or Federal Rights License

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:

   a. REPORT
      unclassified

   b. ABSTRACT
      unclassified

   c. THIS PAGE
      unclassified

17. LIMITATION OF ABSTRACT

   Same as Report (SAR)

18. NUMBER OF PAGES
   22

19a. NAME OF RESPONSIBLE PERSON

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Standard Form 298 (Rev. 8-98)
Proscribed by ANSI Std Z39-18
Outline

- Smart Sensor Network
  - *Needs and technology overview*

- Network Elements
  - *Hub, Network capable application processor (NCAP)*
  - *Node, Smart transducer interface module (STIM)*

- Corrosion Sensing and Measurements
  - *Corrosion rate*
  - *Cumulative corrosion*
  - *Environmental parameters*
Aircraft corrosion is a leading maintenance cost driver that impacts readiness and safety

- Costs increase as the fleet ages

A corrosion monitoring system for current and future weapon systems is need to:

- Identify, track and locate environmental conditions that cause corrosion damage
- Improve inspection efficiency by identifying only those aircraft and systems that require attention
- Reduce maintenance costs through early detection
- Maximize operational availability
Sensor Node and Hub

- **Sensor Hub**
  - Centralized wired or wireless data hub provides communications between user network and sensor network
  - Embedded processing for on-board data reduction
  - Ultra-low power, for use with energy harvesting technologies
  - Open architecture

- **Sensor Nodes**
  - Distributed sensor nodes for corrosion hotspot monitoring
  - Wired or wireless interface to sensor hub
  - Flexible modular design can support a wide variety of sensors
  - Integrated sensor elements for corrosivity and corrosion measurements
  - IEEE-1451 compliant for plug-and-play simplicity
Vehicle Health Management

Luna’s Corrosion Monitoring Sensor Network

Data Transfer

Sensor node

Sensor hub

Onboard Health Monitoring

Air Fleet Corrosion Hotspots

Corrosion Prevention and Control Manager

Off board Data Management Network

Maintenance

- O-level
- I-level
- D-level

Corrosion Monitoring & Control Condition Based Maintenance Information Systems • Logistics
IEEE-1451 standard defines sensor node and hub

- Both sensor node and hub are based off common hardware
- Sensor hub interfaces with user network and sensor nodes
  - Wired or wireless communications with other system elements
- Sensor node interfaces with transducer elements and hub
  - Communications between hub and node can be wired or wireless
  - Node contains transducer electronic data sheets (TEDS)
    - Plug-and-play capabilities between sensor nodes and hub elements
Modular Sensor Node and Hub

- Modular design allows for ease of development and application customization
- Design consists of three main hardware elements: base board, communications board, and analog board
  - *Base board is common to sensor node and hub*
    - microcontroller, power regulation, system memory, real time clock
  - *Communications board can vary as needed between sensor node and hub*
    - Wireless communications, USB or Ethernet controller, or UART pass-through
  - *Analog board is unique to the sensor node*
    - Analog board can be used to meet requirements for a wide range of transducer elements
    - Provides transducer excitation and signal conditioning
    - Direct access to all 8 microcontroller ADC channels,
    - Could incorporate multiplexers if additional transducers are required
Existing corrosion sensing technologies can be divided into three categories:

- *Instantaneous corrosion rate measurements*
- *Cumulative corrosion and material loss measurements*
- *Environmental measurements*

A suite of sensors offers the most robust measurements for building diagnostic algorithms and automating sensor validation routines

- *Corrosion damage can be measured using surrogate samples, or inferred with environmental data*
Sensor Development

- Miniature, light weight sensor suite can be used to measure corrosive severity of operational environments
- The sensor suite permits instrumentation of critical components, inaccessible areas, and “corrosion hotspots”
- Monitors multiple environmental parameters and corrosivity
  - $i_{\text{corr}}$, $E_{\text{ocp}}$, $ER$, Inductance, $RH$, $T_{\text{air}}$, $T_{\text{surf}}$, $TOW$, $[\text{Cl}^-]$
- Supports data fusion for improved state awareness and reduced uncertainty in estimating corrosion damage
### Instantaneous Measurements

**Instantaneous measurements are used to characterize corrosivity at any given time**

- *A measure of cumulative damage can be obtained by integrating periodic corrosion rate measurements*

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrosion rate</td>
<td>Low power and low frequency excitations. Provides a measurement of $R_p$ for calculating $i_{corr}$</td>
</tr>
<tr>
<td>Corrosion potential</td>
<td>Passive device. Requires high impedance input circuitry. Electrochemical measurement of $E_{ocp}$</td>
</tr>
</tbody>
</table>

AA7075-T6 interdigitated electrode

Ag/AgCl electrode
Cumulative Corrosion Sensors

- Cumulative corrosion sensors measure the total damage to a sensing element
  - *The total amount of damage can be determined at any time*
  - *Corrosion rate from the change in state for a given time interval*

<table>
<thead>
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<th>Sensor</th>
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</thead>
<tbody>
<tr>
<td>Inductive/Eddy Current Sensor</td>
<td>Requires low power AC excitation. Inductive coupling between sensor and surrogate sample provides measure of material loss. Sensor can be used for localized corrosion of an alloy.</td>
</tr>
<tr>
<td>Electrical Resistance Probe</td>
<td>Low power Wheatstone bridge measurement technique. Resistive changes dependent on material loss. Typically a copper sensor for generalized corrosion.</td>
</tr>
</tbody>
</table>
Environmental Sensors

- Environmental sensors are used to measure corrosivity
  - *Atmospheric conditions or microclimates within a structure*

<table>
<thead>
<tr>
<th>Sensor Technology</th>
<th>Specifications &amp; Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of Wetness (TOW) / Surface conductivity</td>
<td>Gold-gold interdigitated electrode design. Requires low power, low voltage AC excitation source.</td>
</tr>
<tr>
<td>Chloride Sensor</td>
<td>Passive device. Requires high impedance input circuitry.</td>
</tr>
<tr>
<td>Relative Humidity / Air Temperature</td>
<td>Miniature, digital module +/-2.0% RH accuracy, +/-0.3% Temp accuracy. Average power consumption of 150μW.</td>
</tr>
<tr>
<td>Surface Temperature</td>
<td>Platinum RTD with accuracies to +/-0.15°C @ 0° (Class A RTD). Sensors can be driven with low power constant current circuitry.</td>
</tr>
</tbody>
</table>

![RH Air temp](image1)

![Sensirion, SHT15](image2)

![Au/Au interdigitated](image3)

![Ag/AgCl reference](image4)

![Al alloy reference](image5)

![Surface temp RH, Air temp](image6)

![Inductance](image7)

![Conductivity / TOW](image8)

![Icorr](image9)
Reference Electrode

- Reference electrodes are used to measure the corrosion potential ($E_{ocp}$) for a given alloy and environment
  - For a given alloy, $E_{ocp}$ can be used to predict pitting or uniform corrosion
  - AA2024-T3 or AA7075-T6 working electrode
- Reference electrode can also be used to measure chloride concentration (Nernst Equation)
  - Pure silver working electrode for measuring $[Cl^-]$

$$E = E^o - \frac{RT}{F} \ln a_{Cl^-}$$
Reference Electrode

- Reference electrode testing for stability of potential measurements
  - 0.01, 0.1, 0.5, and 1. M NaCl solutions in 90% RH
  - Immersions tests at 1.0 and 0.1 M NaCl
  - long term potential is unaffected by chloride concentration
Interdigitated Electrodes

- Interdigitated electrodes can be used to measure polarization resistance \( (R_p) \) and solution resistance \( (R_s) \)
  - Corrosion rate \( (i_{corr}) \) can be determined from \( R_p \)
  - \( R_s \) is dependent on salt concentration
  - \( R_s \) can be used to measure time of wetness

Interdigitated electrode
(AA7075 & AA2024)

Luna interdigitated electrode
(gold)
Interdigitated Electrodes

- **Polarization resistance**
  - Impedance analysis used to determine $R_p$
  - Two electrode measurement
  - Low frequency excitation to measure $2R_p + R_s$
  - High frequency measurement for $R_s$

\[
R_p = \frac{\Delta E}{\Delta I} = \frac{b_a b_c}{2.3(b_a + b_c)i_{corr}}, \text{ or } i_{corr} = \frac{B}{R_p}
\]

\[
Z_{\omega \rightarrow 0} = 2R_p + R_s, \text{ and } Z_{\omega \rightarrow \infty} = R_s
\]

\[
R_p = \frac{Z_{\omega \rightarrow 0} - R_s}{2}
\]
Interdigitated Electrodes - TOW

- Impedance magnitude for Au/Au sensor excited at 1 kHz indicates TOW and deliquescence point of surface
- Relationship of RH to corrosivity is dependent on deliquescence of salt deposits and corrosion products
Copper corrosion rates were measured by a number of techniques over a range of salt concentrations.

Flat copper plate electrodes were evaluated using LPR, EIS and DC step methods.

Interdigitated electrodes were tested using low frequency (0.01 Hz) 5 mV excitation.

There is reasonable agreement between EIS with the interdigitated electrode and other measurement methods.
Inductive Corrosivity Sensor

- Inductive corrosivity sensor measures cumulative corrosion damage
  - *Sensitive to localized corrosion*
  - *Coating system breakdown*

- Sensor is composed of an induction coil and sensing element (AA2024-T3 or AA7075-T6)
  - *Sensing element is fabricated so gage section has exposed end grains*
Inductive Sensor

- Inductive sensor can detect changes in gage section geometry due to corrosion
  - AC current excitation
  - As corrosion occurs, induced EMF into sample decreases
  - Need to relate output to corrosion damage

Gage cross-section
The system is designed to support data processing at the sensor node and hub
- Embedded diagnostic and prognostic routines including automated sensor validation
- Data reduction decreases the overall data volume, thus requiring fewer data transmissions
- Reduction in communications lowers system power consumption

Designed experiments and accelerated corrosion tests will be performed to establish diagnostic algorithms
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