Wireless Corrosion Monitoring for Evaluation of Aircraft Structural Health

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Abstract—The military spends billions of dollars annually on inspection, identification, and repair of damage resulting from aircraft corrosion. The currently available methods for identifying aircraft corrosion damage involve expensive, labor intensive scheduled inspections, resulting in longer periods in depot, and reduction in aircraft availability. In order to increase aircraft safety, availability, and operational efficiency, an on-platform monitoring system capable of fusing data streams from an array of environmental and corrosivity sensors is needed to provide inspection-free indicators of the existence of corrosion as well as the level of corrosive severity in difficult to access aircraft locations. This paper will discuss the design, test, and validation of such a system utilizing a wireless, ultra-low power network of sensors.  

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1. INTRODUCTION

Localized corrosion such as pitting, crevice corrosion, exfoliation, and environment assisted cracking is difficult to detect and can significantly degrade airframe structural integrity. The corrosion monitoring system discussed herein, using inputs from various environmental and corrosivity sensors, tracks component usage, environmental exposure, and specific material damage modes as a function of time. Corrosion diagnostic models embedded in the system are based on measurements of exposure conditions, corrosion rate, and cumulative environmental severity. By assuming usage scenarios, these models can be used as prognostic indicators to forecast appropriate inspection and maintenance intervals.

The literature provides methods for determining corrosion rate and damage state distribution densities, based on Weibull cumulative distribution functions. By measuring environmental severity and localized corrosion rate, correlating the corrosion rate distributions with pit depth distributions allows for levels of cumulative alloy damage to be determined. The corrosion prediction models for aircraft alloys provide a means for including the effects of corrosion in fatigue damage models, which in turn provide a means of identifying structural integrity issues within airframes. Using sensors for measurement of environmental parameters such as temperature, relative humidity, time of wetness, and solution conductivity with specific corrosion sensing technologies such as eddy current, bi-metallic galvanic, and polarization resistance can provide a path towards on-platform corrosion based structural health monitoring.

2. BACKGROUND

Maintenance for military and commercial aircraft continues to dominate lifetime costs of operations. Aircraft corrosion maintenance activities within the Air Force and Navy are estimated to exceed 30% of the total costs of maintenance, diminishing the capacity to acquire new systems, while the efforts associated with corrosion inspection and repair reduce aircraft availability and readiness [1]. Overall, it is estimated that up to 90% of the total cost of aircraft ownership is incurred after delivery, and the costs associated with corrosion only continue to grow as platforms age [2]. The effects of corrosion on aircraft structural integrity play a major role in the safety of airframes, as corrosion damage can significantly affect residual strength estimates and assumptions used in structural health management [3].

While significant advances have been made in recent years concerning diagnostics and prognostics for corrosion management, no system yet exists that provides a high resolution, direct measurement of corrosion over large areas of a structure [4-7]. As such, many health monitoring strategies rely on localized measurements of corrosion or environmental parameters that contribute to corrosion. These systems utilize corrosion models that are intended to support condition based maintenance activities, ultimately replacing
the current schedule based maintenance paradigm [6]. A move towards condition based maintenance can ultimately reduce costs of operation and increase aircraft readiness, while maintaining the high level of confidence in safety required for aircraft operations.

Historically, structural integrity in aircraft has been accomplished through safe-life and damage tolerant design methodologies. These philosophies require fatigue life determination based on expected load levels, and can be supported through the use of monitoring devices that determine actual usage, ultimately providing a means of determining when a part should be inspected, repaired, or replaced. Corrosion of airframes has been shown to accelerate the initiation and growth of fatigue cracks, and as aircraft age, the increases in corrosion damage may invalidate assumptions based solely on fatigue life [2, 8, 9]. The main focus of the current effort is to identify a method of monitoring environmental loading effects for the classification of corrosivity, determination of corrosion rates, and estimation of cumulative corrosion damage in aircraft structures that can be tied back into existing fatigue life models.

Significant efforts have been made to establish relationships between atmospheric conditions and corrosion rates of specific alloys, in general finding that temperature, humidity, precipitation, and atmospheric chemicals such as chlorides are the primary drivers in metallic corrosion [10-13]. Corrosion prediction models have been shown to predict mass loss of numerous aluminum alloys, steel, and copper by evaluating 1) time period, 2) percentage of time that relative humidity is in excess of 70%, 80%, and 90%, 3) cumulative precipitation, and 4) chloride deposition [13]. Furthermore, ISO standards 9223 and 9224 provide guidance for predicting corrosive severity under specific atmospheric conditions. These standards can be used to estimate corrosion rates of a number of metals such as carbon steel, weathering steel, zinc, copper, and aluminum [10, 14]. The ISO method of corrosivity classification, in contrast to the methods described in [13] use 1) time of wetness (TOW) based on the period of time spent above 80% relative humidity while the temperature is above 0 °C, 2) SO₂ deposition rate, and 3) airborne salinity. The ISO standard provides look-up tables that can be used to determine the corrosivity classification based on these parameters, as well as the resultant expected corrosion rates. The correlation between environmental parameters and corrosion is well established; however, as microclimates within an airframe can vary significantly depending on location, local monitoring of these microclimate conditions is needed, particularly in corrosion prone locations.

While environmental factors have been well correlated to corrosion, damage state predictions due to corrosion can be improved through the uses of corrosion sensors evaluating specific alloys of interest [15]. Numerous corrosion detection sensors have been developed, based mainly on electrical, electrochemical, or ultrasonic evaluation techniques. These sensors are capable of either directly evaluating a structure, or monitoring a surrogate sample material to determine corrosion rate or cumulative damage within an alloy. Both cumulative damage measurements and corrosion rate measurements provide additional benefits to systems measuring environmental parameters. First, corrosion rate measurements can be used to correct or supplement models based solely on environmental inputs. Corrosion rate sensors can also be used to loosely determine cumulative corrosion damage by integrating the measurements over a given exposure period; however, this requires that a history of sensor data be maintained such that integration over extended periods can be performed. Cumulative corrosion damage sensors, however, require no historical data to determine damage state, and can be used to validate and correct models based on corrosion rate data. In general, cumulative corrosion sensors do not have the high level of sensitivity required for corrosion rate determination over short periods of time, so the use of both cumulative and corrosion rate sensors to supplement environmental parameter measurements provides the most robust corrosion and corrosivity monitoring system.

The goal of implementing a corrosion monitoring system is to ultimately tie in corrosion effects with existing fatigue damage models. To perform this tie in, the health management models require a means of estimating corrosion rates and applying the rates to obtain estimates of corrosion damage, such as pit depth. In the present efforts, corrosion rates are determined using environmental factors and electrochemical sensors while cumulative damage is determined through the integration of corrosion rate data. These measurements are used as inputs to the ISO corrosion model to determine environmental corrosivity per ISO standard 9223.

3. SENSOR TECHNOLOGY AND EXPERIMENTATION

Both commercially available and novel, custom sensors have been selected for use in the corrosion monitoring system development (Table 1). The performance of the individual sensors selected for this effort has been detailed in previously published studies [16, 17].

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Measurand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interdigitated gold electrode</td>
<td>Time of wetness ($T_{w}$)</td>
</tr>
<tr>
<td>Interdigitated AA7075-T6 electrode</td>
<td>Solution resistance ($R_s$)</td>
</tr>
<tr>
<td>Inductive corrosion sensor</td>
<td>Polarization resistance ($R_p$)</td>
</tr>
<tr>
<td>Humidity and temperature probe</td>
<td>Cumulative corrosion (Ind)</td>
</tr>
<tr>
<td>RTD probe</td>
<td>Percent relative humidity (RH)</td>
</tr>
<tr>
<td></td>
<td>and air temperature ($T_a$)</td>
</tr>
</tbody>
</table>
For this effort, responses of the temperature and relative humidity sensors were evaluated using a controlled set of exposures in a Thermotron SM-4 test chamber. The sensor responses were validated over a range of cyclic tests with varying temperatures in the range of 20 °C to 40 °C. Relative humidity was varied between 40% and 100%.

Custom built cyclic atmospheric test chambers were used to perform longer term corrosion exposures. These test chambers are capable of controlling temperature and humidity by actively heating and humidifying the chamber, while cooling and dehumidification is performed passively. Daily test cycles, as specified in Table 2, were repeated for three days and sensor measurements were taken at two minute intervals throughout each test run. During each step of the eight hour day time cycle, electrochemical impedance spectroscopy (EIS) measurements using 10 mV peak to peak excitation from 0.01 Hz to 10 kHz were made on a parallel plate electrode fabricated from 0.032 inch thick AA7075-T6 sheet material. Each electrode plate was 0.75 inches wide, and the plates had a 100 µm separation distance. A laboratory quality Series G 300 Gamry potentiostat running Echem Analyst software was used to take the EIS measurements. These measurements served as a ground truth for validating the monitoring system’s sensor response during testing. The configuration of the sensors under test as they were installed in the environmental chamber is shown in Figure 1.

### Table 2 - Exposure regiment for cyclic atmospheric corrosion testing

<table>
<thead>
<tr>
<th>Daily Cycle Reps</th>
<th>Time [hr]</th>
<th>RH</th>
<th>Temp</th>
<th>Measurement</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1.5</td>
<td>High</td>
<td>Low</td>
<td>EIS</td>
<td>Condensation event</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>High</td>
<td>High</td>
<td>EIS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>Med</td>
<td>High</td>
<td>EIS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>Low</td>
<td>High</td>
<td>EIS</td>
<td>Dry off event</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Low</td>
<td>Low</td>
<td>EIS</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>2</td>
<td>Med</td>
<td>Low</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>High</td>
<td>Low</td>
<td>-</td>
<td>Condensation event</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>High</td>
<td>High</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Med</td>
<td>High</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Low</td>
<td>High</td>
<td>-</td>
<td>Dry off event</td>
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<td></td>
<td>3</td>
<td>Low</td>
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<tr>
<td></td>
<td>2</td>
<td>Med</td>
<td>Low</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

At the beginning of each three day test cycle, a different concentration of salt was sprayed onto the EIS, Rs, and Rp sensors. The solution was applied until a continuous meniscus was formed over the sensor surface. Solutions with NaCl concentrations of: no NaCl, 1 mM, 5 mM, 10 mM, 50 mM, 100 mM, and 1000 mM were used. The solutions were completely dried off before initiating each three day test cycle. The sensors shown in Figure 1 were electrically connected to an analog interface board that provided sensor excitation and signal conditioning of sensor output signals. The conditioned signals were then fed into a National Instruments USB-6251 data acquisition unit. Data collection was handled by a custom designed LabView graphical user interface.

![Figure 1](image1.png)

**Figure 1 - Mounted sensor suite for cyclic exposure testing**

### 4. Experimentation Results

The two primary sets of experiments performed were used to evaluate 1) the response of environmental sensors to varying atmospheric conditions, and 2) the response of the corrosion monitoring sensors to varying levels of atmospheric corrosivity.

#### Environmental Sensor Testing

Responses of the surface and air temperature sensors were compared to the chamber control sensor. Both the air and surface temperature responses lagged the chamber control temperature by about 14 minutes, with the surface temperature having the largest lag time during chamber cooling. The air temperature and surface temperature measurements had a one to one correlation to the chamber control sensor. There was an approximate 0.5 °C offset between surface and air temperatures, within the tolerances of the sensors selected for use. Measurement of both air and surface temperatures is critical for atmospheric conditions that may lead to condensation on structure surfaces.

![Figure 2](image2.png)

**Figure 2 - Response of air and surface temperature measurements compared to chamber control sensor**
The relative humidity sensor response was also compared to the chamber humidity control signal under environmental testing (Figure 3). Note that the humidity in the chamber was uncontrolled during periods of time when the humidity set point was at zero. During these times the chamber returned to ambient laboratory conditions. Figure 4 shows a strongly correlated linear dependence between the sensor output and the chamber measurements. The results of the temperature and humidity testing provide strong confidence in the use of these sensors for evaluation of environmental conditions that will lead to corrosion of structural alloys.

Figure 3 - Response of chamber and sensor RH measurements

Figure 4 - Relationship between sensor and chamber RH measurements

Cyclic Corrosion Testing
As described in Section 3, the mounted sensor suite was exposed to series of NaCl salt solutions and environmental cycles. For each NaCl salt exposure, the samples were subjected to three days of repeated cyclic exposures, as outlined in Table 2. The response of the environmental sensors recorded during these tests is shown in Figure 5.

Solution resistance measurements were taken during the cyclic tests to identify changes in surface conductivity with changes in salt depositions. Measurements using high frequency excitation signals were made to determine the solution resistance of moisture on a gold interdigitated electrode exposed to various concentrations of NaCl solution. The solution resistance sensor response was shown to be dependent on both salt concentrations and humidity. The sensor response showed that larger solution resistances occur during periods of low humidity and low salt concentrations (Figure 6). It was observed that condensed moisture can bead on the gold interdigitated electrode, and shedding of moisture from the surface can remove salt deposits. Such a decrease in solution resistance was noted for the 50 mM NaCl exposure after 2,500 minutes. Also, at the highest salt concentration 1000 mM the measurement system response was saturated and erroneous readings were obtained. Adjustments to the circuit were made and the performance is currently being investigated.

Figure 5 - Environmental sensor responses in a typical 72 hour exposure cycle

Figure 6 – Response of the solution resistance sensor under cyclic environmental testing for varying salt depositions.

In order to obtain rate of corrosion measurements, low frequency excitation impedance measurements were made to the interdigitated aluminum-aluminum electrodes during the cyclic corrosion tests. As with the solution resistance sensors, varying salt concentrations were applied to the sensors throughout the cyclic testing (Figure 7).

Figure 7 - Corrosion rate of AA7075-T6 as measured by the corrosion rate sensor under varying NaCl concentrations
As expected, corrosion rates, expressed in current density in Figure 7 (higher current density indicated higher corrosion rate), increase with increased humidity and higher salt concentrations. The results of the corrosion rate sensor were compared with the results of the electrochemical impedance spectroscopy “ground truth” results, and a good correlation between the datasets was observed (Figure 8).

From the data taken during cyclic environmental testing, the average time of wetness for all seven 72 hour exposure cycles is ~24%, giving a $\tau_3$ time of wetness categorization. This is an expected result, as each three day cycle was nominally identical. Figure 9 shows the conversion of relative humidity measurements to percent time of wetness per the ISO standard for each of the seven test runs. Variances between the three day test cycle results for each NaCl concentration are most likely due to changes in RH and temperature of the ambient laboratory environment.

![Figure 8 - Comparison of AA7075-T6 corrosion rate sensor measurements and electrochemical impedance spectroscopy measurements](image)

**5. DATA ANALYSIS**

The responsiveness of the sensor elements to varying environmental conditions and varying levels of corrosivity was fully demonstrated using environmental and cyclic test chambers. The parameters measured by these sensors can be used to classify atmospheric corrosivity based on ISO 9223, which is suitable for classification of corrosion severity for outdoor and sheltered environments. Enclosed areas within aircraft can be considered “sheltered environments”, and as such, the used of ISO 9223 is appropriate for classifying corrosivity within airframes.

In the ISO 9223 standard, classification based on environmental parameters is performed using time of wetness, calculated as the percentage of time RH is above 80% and temperature is greater than 0 °C, and airborne salinity. ISO 9223 also includes exposure to sulfur dioxide, but in the present study sulfur dioxide exposure has not been tested. Using the data collected in the cyclic corrosion testing, relative humidity data, shown in Figure 5, is used to calculate the ISO defined time of wetness. This is done by summing the amount of time that the relative humidity is greater than 80%, and dividing by the total exposure time. Table 3 provides the ISO environmental classification for percent time of wetness.

![Figure 9 - Time of wetness determined from the relative humidity sensor response based on ISO 9223. The raw RH response for a single exposure cycle is given for reference.](image)

**Table 3 - Environmental classification for percent time of wetness according to ISO 9223**

<table>
<thead>
<tr>
<th>Category</th>
<th>Time of Wetness (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_1$</td>
<td>$\tau \leq 0.1$</td>
</tr>
<tr>
<td>$\tau_2$</td>
<td>$0.1 &lt; \tau \leq 3$</td>
</tr>
<tr>
<td>$\tau_3$</td>
<td>$3 &lt; \tau \leq 30$</td>
</tr>
<tr>
<td>$\tau_4$</td>
<td>$30 &lt; \tau \leq 60$</td>
</tr>
<tr>
<td>$\tau_5$</td>
<td>$60 &lt; \tau$</td>
</tr>
</tbody>
</table>
measurements when relative humidity was greater than 75% and the surface temperature was greater than the air temperature. Cumulative chloride is determined by summing any increases in chloride mass with time. When RH is greater than 75%, any decreases in solution resistance with time are treated as chloride accumulation.

Figure 10 - Chloride accumulation data obtained calculated from solution resistance measurements for cyclic corrosion tests with 5 mM NaCl solution applied

Chloride deposition rate, according to ISO 9223, is given in terms of mass per unit area per day (mg/(m²·day)). The chloride deposition rate for each cyclic corrosion test with 1 mM to 100 mM NaCl solutions were calculated by dividing the accumulated mass of chloride at a given time by the current exposure time. The results are shown in Figure 11.

Figure 11 - Chloride deposition rate as a function of exposure time

Since each chloride (NaCl) application was a discrete event prior to exposure, the accumulation rate starts off high and decays with time of exposure. Increases in chloride accumulation, during any given three day exposure cycle, were potentially due to redistribution of chloride by wetting and drying cycles, and may also indicate that refinements need to be made to the rules used to filter the chloride mass accumulation data. Finally, if the 72 hour exposure cycle duration is arbitrarily chosen as the appropriate time basis for establishing the chloride accumulation rate, ISO 9223 salinity categories are found to be $S_0$ and $S_1$ (Figure 12 and Table 4).

Table 4 - ISO 9223 chloride deposition rate categories

<table>
<thead>
<tr>
<th>Category</th>
<th>Deposition rate of chloride mg/(m²·day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_0$</td>
<td>$S \leq 3$</td>
</tr>
<tr>
<td>$S_1$</td>
<td>$3 &lt; S \leq 60$</td>
</tr>
<tr>
<td>$S_2$</td>
<td>$60 &lt; \tau \leq 300$</td>
</tr>
<tr>
<td>$S_3$</td>
<td>$300 &lt; \tau \leq 1500$</td>
</tr>
</tbody>
</table>

The combination of time of wetness and salinity categories give a C3 or “medium” classification of atmospheric corrosivity for aluminum according ISO 9223.

As mentioned, ISO defines corrosivity classification based on environmental parameters, as described above, or through the use of corrosion rate measurements. In the system described herein, corrosion rate measurements are performed using the interdigitated AA7075-T6 electrodes. Cumulative corrosion of the electrodes is then obtained using Faraday’s Law to convert current densities to rate of mass loss, and then integrating the result over exposure time for each of the salt deposition tests performed. The results of these conversions are shown in Figure 13.

Figure 13 - Cumulative mass loss from AA7075-T6 sample in cyclic corrosion tests after being exposed to various concentrations of NaCl solution

The data from Figure 13 can also be represented as an annual mass loss rate in g/(m²·a) for ISO classifications, as defined in Table 5. When represented in this fashion, data from each...
of the cyclic corrosion test runs can be graphed over time to show the associated ISO corrosivity category. As the corrosion rate for the data varies dramatically over each wet and dry cycle of the test, a 400 minute time averaging window is used to obtain an estimate of the average corrosion category for a complete wet/dry cycle of the exposure. Results of this process are shown in Figure 14. In terms of the discrete ISO categories, the averaged corrosion cycle test data ranged from C2-C4, or “low” to “high”.

There is reasonable agreement between the sensor data for environmental and corrosion rate classifications using the ISO 9223 methods. The environmental data did not yield the same span of responses, but this may be due to the significance of time of wetness in establishing corrosivity, and the use of only a single test cycle for performing this series of exposure tests.

Table 5 - ISO 9223 atmospheric corrosivity classifications based on aluminum corrosion rates

<table>
<thead>
<tr>
<th>Category</th>
<th>Corrosivity</th>
<th>Al Corrosion (g/(m²-a))</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Very Low</td>
<td>Negligible</td>
</tr>
<tr>
<td>C2</td>
<td>Low</td>
<td>r_{corr} ≤ 0.6</td>
</tr>
<tr>
<td>C3</td>
<td>Medium</td>
<td>0.6 &lt; r_{corr} ≤ 2</td>
</tr>
<tr>
<td>C4</td>
<td>High</td>
<td>2 &lt; r_{corr} ≤ 5</td>
</tr>
<tr>
<td>C5</td>
<td>Very High</td>
<td>5 &lt; r_{corr} ≤ 10</td>
</tr>
</tbody>
</table>

Figure 14 - Average ISO atmospheric corrosivity based on mass loss rates for AA7075-T6 interdigitated electrodes

Once a means is available to obtain usage data that includes estimates for corrosion rate and cumulative damage, it is necessary to estimate damage in the structure that can be utilized in determining residual strength and fatigue life. Harlow and Wei formulated a mechanistically based approach to develop a damage function that incorporates internal (alloy chemistry and microstructure) and external (mechanical load and environment) parameters and time [18]. In this model, crack nucleation is a competitive process between pitting and fatigue crack growth, such that damage nucleation is corrosion dominated when the pit growth rate is greater than the fatigue crack growth rate. Using Faraday’s Law, the growth rate for a hemispherical pit is:

\[ \frac{da}{dt} = \frac{MI_p}{2\pi D F a^2} \]  

\text{Equation 1}

where \( a \) is pit radius, \( t \) is time, \( M \) is the molecular weight of the metal, \( I_p \) is the pitting current, \( n \) is the valence, \( \rho \) is density, and \( F \) is Faraday’s constant [18]. For aluminum alloys such as AA2024-T3 and AA7075-T6, pit growth is due to the galvanic corrosion between the anodically polarized alloy matrix and exposed constituent particles [18, 19]. Therefore, the number of pits and size distribution is dependent, in part, on the size and distribution of constituent particles and the progressive nature of the process, where pits nucleate, grow, and stifle [5, 18-20]. These environmental and alloy properties influence pit growth, and pit depth is generally observed to have a power law dependency with respect to time:

\[ a(t) = k t^m \]  

\text{Equation 2}

where \( k \) and \( m \) are parameters that are relatively constant over long time periods [20].

A framework for corrosion prediction of aircraft was also developed by Kelly et al. that utilized damage depth distributions and databases of corrosion rate distributions [4, 5, 21]. The corrosion model predicts damage by applying the corrosion rate distribution for a given aircraft utilization (basing) to a current known condition to obtain the future state. Both the corrosion rate and damage state distributions are approximated using the Weibull cumulative distribution function:

\[ f(x) = 1 - \exp \left[ -\left( \frac{x}{\eta} \right)^\beta \right] \]  

\text{Equation 3}

where \( \beta \) is the shape parameter, and \( \eta \) is the scale or life parameter. This corrosion prediction model assumes that the corrosion protection system has failed and that some level of corrosion is present, characterized by nondestructive inspection.

The corrosion prediction models for aircraft alloys provide a means for incorporating the effects of corrosion in fatigue damage models [5, 18, 22-24]. These health management models all require a means for estimating corrosion rates, and applying the rates over a material surface for a given time period to obtain estimates of corrosion damage such as pit depth. The sensors and sensor analysis described within this paper provides the necessary inputs for such a health management model, through the use of electrochemical interdigitated electrode measurements.
6. System Configuration

The system described in this paper, designed to take sensor measurements, execute data fusion, and perform algorithmic evaluation of the various sensor elements, is based on the open architecture IEEE 1451 standard for smart transducer interfaces. The system consists of a set of smart transducer interface modules (STIM), and at least one centralized network capable application processor (NCAP), as defined by the IEEE 1451 standard [25]. By incorporating low power electronics with advanced embedded processing, diagnostic and prognostic functionality can be integrated at the transducer or application processor level, providing actionable notifications at the aircraft with no off-system processing required.

In the described system, the two IEEE 1451 components, the STIM and the NCAP, are referred to as the sensor nodes and sensor hubs respectively. The sensor hub provides a gateway between the distributed sensor network installed on an airframe and any arbitrary external user network. This gateway is provided via an ultra-low power wireless 802.15.4 communications link. On aircraft, data can be sent and received between sensor nodes and the sensor hub via either the same low-power 802.15.4 interface, or a wired RS-485 communications protocol.

The sensor nodes provide an analog interface to the sensor elements described in this paper (Figure 15). As part of the IEEE 1451 standard compliance, Luna’s smart transducer interface modules contain transducer electronic datasheets (TEDS) that store all critical sensor information at the sensor elements. By storing information such as calibration coefficients, scaling factors, output parameters, and general sensor identification information, the sensor nodes can identify and provide the necessary information for interpreting each sensing element output automatically without the need for other external user inputs. Characterization of the sensors, as described above, allows development of the TEDS that will ultimately reside in each of the sensor nodes. The use of these TEDS allows the sensor nodes developed in the effort to be inserted seamlessly into any IEEE 1451 compliant network.

Both the sensor nodes and the sensor hub devices are built around a common electronics platform. The common electronics utilize a Texas Instruments MSP430 microcontroller to perform all processing tasks within the system. The MSP430 is an ultra-low power device capable of operating with extremely low current consumption. By developing firmware that utilizes the power saving modes of this microcontroller, and designing the surrounding peripheral electronics to be extremely energy efficient, the devices within the system are capable of operations off of energy harvesting technologies that gather ambient energy from sources such as vibration, heat, and RF signals. The use of energy harvesting technologies to provide power to the system is particularly advantageous for retrofitting aging aircraft, where access to aircraft power may be limited.

The sensor node was designed to be small size and lightweight, both critical features for aircraft installation. The device shown in Figure 15 measures approximately 2.375” wide by 1.25” high by 4.0” wide (with mounting flanges; 3” wide without mounting flanges) and weighs approximately 5.25 ounces. The device packaging has been designed to allow the system to undergo all necessary safety of flight qualification tests, including environmental test conditions per MIL-STD-810, and electromagnetic compliance tests per MIL-STD-461. Installation of the devices can be performed by either bracket mount, using the integral mounting flange, or the devices can be mounted adhesively, as the weight of each node is low.

7. Conclusions & Future Work

Corrosion prevention and control plays a major role in maintaining existing military and commercial air fleets. Rising ownership costs of aging aircraft due to corrosion inspection, maintenance, and repair, necessitates an efficient means of tracking the severity and cumulative corrosivity that an aircraft experiences. Incorporating a system consisting of accurate, reliable sensors along with an intelligent network providing embedded diagnostic capabilities will be useful in supporting a condition based maintenance strategy to improve readiness, reduce costs and minimize labor required for corrosion inspection, maintenance, and repair.

The present investigation has demonstrated in cyclic corrosion tests, the capacity to use environmental and corrosion sensor data to classify atmospheric corrosivity using methods similar to those embodied in ISO 9223. Further testing using a wider range of conditions that better simulate atmospheric environments is needed to refine the classification algorithms, and validate the sensor system performance. These algorithms will be embedded into the system to allow for a fully stand-alone corrosion monitoring network capable of identifying corrosion damage trends, and providing maintainers with the tools to reduce operational costs, increase aircraft efficiency, and improve overall fleet readiness, reduce costs and minimize labor required for corrosion inspection, maintenance, and repair.
safety. Furthermore, the algorithms developed under future efforts will be embedded into device firmware, allowing for at-node determination of level of corrosivity. The system will provide clear indicators of structural health based on corrosion measurements, and will reduce the overall cost of maintenance by allowing for a transition to condition based maintenance. As the device is compatible with energy harvesting technologies and utilizes sensors with significant lifetimes, maintenance requirements for battery and sensor replacement will be minimal, imparting no additional burden on aircraft maintenance crews. The devices developed under this effort will be fully qualified for environmental and electromagnetic compliance, evaluated on test bed platforms, and ultimately, the system responses will be validated against real-world corrosion effects on military and commercial airframes.

REFERENCES


**Biographies**

**Jeff Demo** is the Electrical Systems Lead in the Intelligent Systems Group at Luna Innovations. He has led multiple SBIR and non-SBIR programs related to both fixed- and rotary-winged aircraft corrosion. He has focused on sensor development, instrumentation, and data collection, specifically associated with Luna’s ultra-low power wireless sensing platform. Prior to working with Luna, Jeff developed aerospace electronics subsystems, including work on the F-35 Joint Strike Fighter’s air data system. Jeff is a member of IEEE and the IEEE Aerospace and Electronics Systems Society.

**Fritz Friedersdorf, Ph.D.** is the Director of the Intelligent Systems group at Luna Innovations. He has conducted research on materials, sensors, and health monitoring techniques while at Luna. He was Luna’s Principal Investigator for the Air Force Aging Aircraft program to develop predictive damage models of aluminum alloys. Fritz has authored numerous publications on sensors, health monitoring, materials testing, stress corrosion cracking, corrosion-wear and coatings performance and has eight USPTO patent filings. He is a member of NACE International, ASM International, and ASTM International.

Conrad Andrews is an Electrical Engineer within Luna Innovations’ Intelligent Systems Group. Since joining Luna, he has designed and built a series of low cost temperature and humidity controlled environmental chambers for the testing of Luna’s corrosion and corrosivity sensors. He has contributed to multiple ultrasonic, electrical, mechanical, and electrochemical projects throughout Luna. Recently, Conrad has been involved in the testing and characterization of Luna’s environmental sensors, and in the development of the analog excitation interface board for the sensor suite program. Prior to Luna, Conrad has worked as an IT assistant manager and an audio/visual technician. Conrad is also an IEEE member.

Mateja Putic is a Research Engineer within the Intelligent Systems Group at Luna Innovations. During his graduate studies, Mateja developed a hardware/software co-design methodology for ultra-low power embedded systems, achieving energy reduction as high as 37% over traditional designs. This work facilitated the establishment of research that has produced proposals to the National Science Foundation (NSF) and other funding agencies to procure over $300,000 in research grant, and lead to an invited journal publication in the Proceedings of the IEEE. In his current position, Mateja is working to develop innovative embedded wireless structural monitoring platforms. Mateja is a member of IEEE and Eta Kappa Nu.