Title of Innovation: Sensor Suite for Aircraft Corrosion Monitoring

Nominee(s)
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Category: Instrumentation

Dates of Innovation Development: From February 2009 to March 2014

Summary Description:

The Luna Sensor Suite for Aircraft Corrosion Monitoring (LS2A) is a wired or wireless sensor node capable of autonomously monitoring environmental and corrosivity parameters to determine the atmospheric severity of difficult to access regions within airframes. The technology uses both commercial-off-the-shelf and novel sensor elements to monitor a set of parameters and provide an ISO-9223 classification of the environment’s corrosivity. In addition to providing a high-level environmental severity classification, the nodes maintain all raw sensor data with internal storage for future access and engineering analysis. Data from the sensor nodes can be accessed via RS-485 wired or 802.15.4 wireless interfaces.

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. By tracking environmental severity and corrosion within targeted areas of airframes and identifying daily, seasonal, and operational patterns of exposure, maintainers may reduce total cost of ownership, increase aircraft efficiency, and improve overall fleet reliability.

Figure 1. The Luna Sensor Suite for Aircraft Corrosion Monitoring (LS2A).
Full Description:
(Please provide complete answers to the questions below. Graphs, charts, and photos can be inserted to support the answers.)

1. What is the innovation?

The LS2A system is a corrosion monitoring platform that measures both environmental and corrosion related parameters to make a determination of the severity of a given environment. By measuring a specific set of parameters including relative humidity, surface temperature, air temperature, condensate solution resistance, and aluminum corrosion rate, the LS2A platform is capable of determining the presence of conditions that can lead to corrosion damage. While the system is designed specifically for use in aerospace applications where corrosion can lead to significant reliability issues as well as high maintenance costs, the LS2A platform can be used to monitor environmental exposure of industrial machinery, pipelines, ground vehicles, and any other high value asset where exposure to corrosive atmospheres is a concern.

LS2A sensor nodes can be distributed throughout an airframe or at other critical locations such as corrosion “hotspots” to evaluate the extent of corrosion activity, determine whether maintenance activities are required, and cut down on unnecessary manual inspections. Corrosivity classification models are embedded within the system so that maintainers can assess environmental severity without the need for post processing or expert analysis. In addition to the on-board processing used to calculate an ISO standard environmental classification, a complete time-history of all measurements recorded by the LS2A system is maintained in memory. Engineers and scientists interested in evaluating the historical exposure of an area or component are able to access the entire time-history of the sensor nodes, providing information on daily and seasonal exposure trends. The small size and light weight of the systems provide an ideal platform for retrofit of existing assets. Billions of dollars each year are spent on maintenance due to corrosion; the LS2A system is an important part of any corrosion prevention and control program.

Figure 2 – The LS2A corrosion monitoring sensor node with annotated sensor elements.
2. How does the innovation work?

Damage caused by environmental exposure is a major contributor to the costs of corrosion and greatly reduces readiness of aircraft [1]. Corrosion damage caused by environmental exposure can degrade the airframe structure, electrical wiring and interconnection system, and avionics. A leading cost driver in aircraft corrosion is the inspection time required to evaluate an airframe for contaminant exposure and corrosion detection. Traditionally, corrosion inspections are only able to identify damage that has occurred in readily accessible areas, while damage or corrosion precursors in occluded or difficult to access locations can go undetected and untreated for years, ultimately compounding the structural damage and resulting in more extensive repairs or component replacement procedures. This affects system reliability due to unobserved structural damage and drives maintenance cost up due to more extensive repairs or component replacement procedures that could otherwise be avoided.

Improved health management of aircraft is needed to control the costs of corrosion. The cost of corrosion as a percentage of total maintenance is estimated to be more than 30% of total maintenance cost for Navy and Air Force aviation [1, 2]. It is estimated that 90% of the total life cycle costs can occur after aircraft delivery, and the costs due to corrosion continue to escalate as aircraft age [3]. Additionally, the effects of corrosion are a structural reliability issue, and corrosion can alter residual strength estimates and the assumptions used in managing aircraft structural integrity [4].

Maintenance activities based on the nature and intensity of ambient corrosion conditions are supported by a number of studies conducted that have established relationships between environmental parameters and corrosion of specific alloys [11-15]. In general, corrosiveness depends on meteorological conditions of temperature, humidity, and precipitation, along with atmospheric chemicals such as chlorides. Corrosion prediction models based on collected data have been developed that can be used to predict mass loss of aluminum alloys AA6061-T6, AA7075-T6, and AA2024-T3, steel, and copper using: 1) time period, 2) percent of time relative humidity (RH) is above 70%, 80%, and 90%, 3) cumulative precipitation, and 4) chloride deposition [15]. ISO 9223 and 9224 are standards developed to aid in predicting the corrosion severity of specific conditions and estimate corrosion rates of carbon steel, weathering steel, zinc, copper, and aluminum [11, 12]. The ISO corrosivity classification uses: 1) time of wetness (TOW), based on the annual number of hours RH is above 80% and temperature is greater than 0 °C, 2) SO2 deposition rate, and 3) airborne salinity. Look-up tables are used to determine the corrosivity category and resultant corrosion rate estimates. The significance of environmental parameters is well established, but since microclimate conditions vary throughout a structure, local monitoring is required to obtain the relevant environmental data at corrosion prone areas.

A range of commercially available or custom fabricated sensors have been utilized in the development of the LS2A monitoring system (Table 1 and Figure 2). The sensors include measurements of air temperature (T<sub>a</sub>), surface temperature (T<sub>s</sub>), relative humidity (RH), polarization resistance (R<sub>p</sub>), and solution conductivity (R<sub>s</sub>). Responses of the environmental sensors for humidity and temperature have been tested and verified in controlled exposure tests [21, 22].
Table 1 - Sensor technologies being used in the LS2A system.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Measurand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold interdigitated electrode (IDE)</td>
<td>Time of wetness ($TOW_{Au}$)</td>
</tr>
<tr>
<td></td>
<td>Solution resistance ($R_s$)</td>
</tr>
<tr>
<td>AA7075-T6 interdigitated electrode (IDE)</td>
<td>Polarization resistance ($R_p$)</td>
</tr>
<tr>
<td>Humidity and temperature probe</td>
<td>Percent relative humidity (RH) and air temperature ($T_a$)</td>
</tr>
<tr>
<td>RTD probe</td>
<td>Surface temperature ($T_s$)</td>
</tr>
</tbody>
</table>

With the sensor elements included in the LS2A corrosion monitoring sensor node, it is possible to use the ISO 9223 standard for classification of environmental severity based either on time of wetness and chloride deposition or on aluminum corrosion rate. Relative humidity data is used to calculate the ISO time of wetness by dividing the total time for which RH>80% by the total exposure time (Table 2).

Table 2 - 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>

According to ISO 9223, air-borne salinity is expressed as a mass of chloride ions accumulated over an area per day (mg/(m²*day)). The solution resistance sensor is used to estimate chloride mass accumulation rate by assuming a conductivity of the moisture present on the gold interdigitated electrode (IDE), and only using solution resistance values obtained under specific environmental conditions. When the humidity reaches the deliquescence relative humidity for NaCl (75.7%) a saturated NaCl solution (6.16 M NaCl) is formed on the electrode surface. The volume of salt solution and total mass of chloride can be estimated using the dimensions of the gold IDE and the conductivity of saturated NaCl (225 mS/cm). Based on the deposition rates of chloride, an ISO category can be obtained (Table 3).

Table 3 - 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>$60 &lt; S \leq 300$</td>
</tr>
<tr>
<td>$S_3$</td>
<td>$300 &lt; S \leq 1500$</td>
</tr>
</tbody>
</table>

Corrosion rate measurements using the AA7075-T6 IDE provide another means to classify atmospheric corrosivity and obtain estimates for cumulative corrosion. Following conversion of corrosion rate data to annual mass loss rates (g/(m²-a)), ISO classifications can be determined (Table 4).
Table 4 - ISO 9223 atmospheric corrosivity classifications based on aluminum corrosion rates.

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

All parameters measured by the LS2A system, along with corrosion classifications calculated using the node’s embedded processing are available via either wired or wireless downloads. The units utilize a robust, aerospace tested RS-485 serial interface for wired downloads and an ultra-low power 802.15.4 based wireless interface. The sensor nodes connect to Luna’s custom graphical user interface for data collection and display. Data is collected in the industry standard .csv format, allowing for further analysis of the collected data following data downloads.

**Initial Deployment and Testing**

Initial testing of the sensor node was performed on the Naval Aviation Center for Rotorcraft Advancement (NACRA) UH-1N test bed aircraft during the period from July 10, 2012 to December 17, 2012. Results from the NACRA testing performed on a UH-1N rotorcraft show a strong seasonal trending in the data collected. Additionally, it is clear that the relative humidity measurements within the airframe are generally significantly lower than the ambient conditions (Figure 3). The primary reason for this is due to the fact that as the seasons change from the summer through the fall and into winter, the measured temperature within the rotorcraft is higher than the external ambient temperature (Figure 4). The divergence in temperature between the reported NOAA weather station data and the measured rotorcraft interior temperature begins in the late October/early November timeframe, which coincides with the reduction in aircraft internal RH, again, showing the significant seasonal dependence of environmental activity within an airframe.

In addition to the reduced relative humidity measurements internal to the aircraft observed during winter months, corrosion rates and condensate conductivities are also reduced during this time period (Figure 5). A reduction in condensate conductivity is indicative of a reduction in the aggressiveness of the environment, a leading factor in the initiation and propagation of corrosive damage. The measured corrosion rates can be converted to ISO 9223 classifications, indicating the level of environmental severity to which the sensors are exposed (Figure 6). In general, the ISO classification indicates that the UH-1N aircraft was operated in relatively benign environments with the classification falling between the “Very Low” and “Low” categories per ISO 9223 (Table 4). Note that while the instantaneous integer value of the corrosion classification varies between levels C1 and C3, the data shown in Figure 6 is a weighted average over the history of the sensor node’s exposure, more indicative of the general ISO classification over time. Furthermore, as per the observed seasonal dependence of corrosive activity,
the classification value tends to decrease into the winter months. This contrasts with the initial spike in corrosion that occurred immediately following deployment and throughout the summer months.

Figure 3 – Relative humidity for the UH-1N LS2A sensor compared with NOAA weather station data for the period from July 10, 2012 to December 17, 2012.

Figure 4 – Air and surface temperature for the UH-1N LS2A sensor compared with NOAA weather station data for the period from July 10, 2012 to December 17, 2012.
Figure 5 – Condensate conductivity and corrosion rate measurements for the UH-1N aircraft sensor for the period from July 10, 2012 to December 17, 2012.

Figure 6 – Average ISO 9223 Classification for the UH-1N aircraft sensors over the period of July 10, 2012 to December 17, 2012.

The close correlation between seasons and corrosive activity may provide additional information to aircraft maintainers, leading to reduced costs associated with corrosion maintenance during winter months through a reduction in frequency of inspections. Further data associated with seasonal
trending of corrosion activities and environmental severity may assist in performing more efficient scheduled maintenance and support the transition towards a condition based maintenance paradigm.

To support improved visualization of data collected with the LS2A sensor nodes, data processing techniques to convert measured corrosion rates into clear graphical representations of corrosion severity over time have been evaluated. Corrosion data recorded on the UH-1N NACRA aircraft was analyzed on an hourly and monthly basis, and plotted to assess corrosion severity for each hour of the day averaged over each month of deployment (Figure 7). By presenting the data in a more visually intuitive format, the diurnal and seasonal trends related to corrosion severity are much clearer than in the standard time based plots of corrosion. The graphical representation provides improved understanding and assessment of when corrosion is most severe, in terms of both time of day and time of year.

The grid display used to represent hourly corrosivity averaged for each month can be used to quickly identify when corrosion is greatest and least. By selecting a subset of the data in the grid display, the percentage of the corrosion activity during the selected timeframe can be compared with the corrosion activity over the entire time period. For example, the corrosion that occurred between 4 AM and 11 AM from July to September constituted 29% of all corrosion over the time period from July to December of 2012, but is only 15% of the total time (Figure 7, inset A). By contrast, only 4.5% of the total corrosion occurs at all times of day during November and December (Figure 7, inset B). Identification of high corrosivity during specific times of day or specific months of the year will enable aircraft maintainers to take appropriate actions (dehumidification, washes, etc.) during these periods to minimize aircraft corrosion. Additionally, this will allow maintenance and control activities that anticipate known variations in corrosion severity based on long-term usage data for a given airframe and geographic location. This will ultimately enable more focused, tailored, and proactive maintenance processes.

Figure 7 - Data visualization of LS2A data collected during the UH-1N NACRA rotorcraft deployment.

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 aircraft experience. Incorporating a system consisting of accurate, reliable sensors along with intelligent embedded diagnostic capabilities will support a condition based maintenance strategy to improve readiness, reduce costs, and minimize labor required for corrosion inspection, maintenance, and repair.

References

3. Describe the corrosion problem or technological gap that sparked the development of the innovation? How does the innovation improve upon existing methods/technologies to address this corrosion problem or provide a new solution to bridge the technology gap?

Exposure to harsh, corrosive environments during operations and on the ground can degrade aircraft structures and systems. The U.S. DoD spends $4.7 billion annually on preventative corrosion maintenance, driving the high total lifecycle costs of aircraft. Additionally, a finite pool of maintenance man-hours (MMH) exists that, without accurate assessments of corrosion, may not be scheduled effectively. Currently, there is no way to track, assess, or project corrosion within an airframe to
prioritize individual aircraft inspection and fleet maintenance for more efficient allocation of maintenance man-hours (MMH), for assessing the impact of deferred actions, or for early detection of corrosive conditions requiring attention.

The LS2A sensor suite for aircraft corrosion monitoring has been developed to assist with managing costs and labor associated with aircraft corrosion maintenance. To provide in situ measurements of environmental severity, the LS2A corrosion monitoring system can be used as a wired or wireless sensor network that continuously measures, records, and analyzes environmental and corrosivity parameters. To support use by the maintenance community, Luna has developed data analysis techniques to track and visualize environmental severity within airframes for clear, intuitive, and informative presentation of long-term environmental exposure. LS2A sensor nodes can be distributed throughout an airframe or at other critical locations such as corrosion “hotspots” to evaluate the extent of corrosion activity, determine whether maintenance activities are required, and cut down on unnecessary manual inspections. Corrosivity classification models are embedded within the system so that maintainers can assess environmental severity without the need for post processing or expert analysis. In addition to the on-board processing that calculates an ISO standard environmental classification, a complete time-history of all measurements recorded by the LS2A system is maintained in memory. Engineers and scientists interested in evaluating the historical exposure of an area or component are able to access the entire time-history of the sensor nodes, providing information on daily and seasonal exposure trends.

4. Has the innovation been tested in the laboratory or in the field? If so, please describe any tests or field demonstrations and the results that support the capability and feasibility of the innovation.

The LS2A sensor nodes have been evaluated both in the laboratory and the field. Initial testing focused on evaluations in environmental test chambers. These tests were followed up with a series of additional field and laboratory deployments to determine functionality in service, and under extremely harsh conditions. A sampling of the deployment scenarios includes:

- Installation on a NAVAIR UH-1N rotorcraft for flight testing
- Installation on Air Force HH-60 rotorcraft for flight testing
- Installation in a B-52 for evaluation of lightening hole covers throughout a deployment to Guam
- Installation on the USS WASP for sea-based environmental and corrosion evaluations
- Accelerated test chamber evaluation, including 500 hours in SO₂ exposure
- Outdoor exposure in Brest, France as part of the EU Clean Sky program
- Installation on NH-90 rotorcraft for corrosive condition evaluations within airframes and on board ships deployed in the Gulf of Aden
- Outdoor exposure testing at the Navy Research Laboratory facility in Key West, Florida
- Installation in the CH-53K Ground Test Vehicle in West Palm Beach, Florida
- Installation on the Dwight D. Eisenhower for sea-based corrosivity evaluations

Results from field testing to date as well as additional on-going activities have shown value as outlined in the system description above. The LS2A system supports the vision of a distributed corrosion monitoring sensor network for improved environmental severity monitoring through enhanced instrumentation.
5. How can the innovation be incorporated into existing corrosion prevention and control activities and how does it benefit the industry/industries it serves (i.e., does it provide a cost and/or time savings; improve an inspection, testing, or data collection process; help to extend the service life of assets or corrosion-control systems, etc.)?

The LS2A system has been designed as a means to improve the testing and inspection for aircraft corrosion. With significant maintenance requirements for both military and civil aircraft, corrosion is a leading driver of total aircraft lifecycle costs. Additionally, a limited amount of maintenance personnel and man-hours exists that, without accurate assessments of corrosion, may not be scheduled effectively. Without a method to track, assess, and project corrosion within an airframe to optimize inspections and fleet-wide maintenance practices, maintainers are not limited in their potential to reduce corrosion maintenance costs and increase aircraft reliability. By using the LS2A to track corrosion severity within an airframe, more effective use of finite labor resources can be accomplished. Unnecessary corrosion inspection and testing can be avoided and identification of aircraft at high corrosion risk can be achieved. The LS2A system is being used to establish corrosion management models in Army and Navy programs, including Army Capability-Based Operations and Sustainment Aviation (COST-A), Navy Integrated Hybrid Structural Management System (IHSMS), and Navy Sea-Based Aviation. The system has also been successfully deployed to detect corrosive conditions in HH-60 search and rescue rotorcraft, NH90 rotorcraft performing antipiracy missions in the Gulf of Aden, and to characterize performance of aircraft covers and dehumidification systems. The small-size, lightweight packaging provides is ideal for retrofit of existing assets, and can provide benefits from both a cost and MMH standpoint.

6. Is the innovation commercially available? If yes, how long has it been utilized? If not, what is the next step in making the innovation commercially available? What are the challenges, if any, that may affect further development or use of this innovation and how could they be overcome?

Yes, the system is commercially available, and has been since early 2014. The system is available online at the following location:

http://devstore.lunainc.com/collections/luna-sensor-suite

7. Are there any patents related to this work? If yes, please provide the patent title, number, and inventor.

Yes, we have a patent application submitted related to classification of atmospheric corrosivity with the system: