Abstract — Health and Usage Monitoring Systems (HUMS) have been developed to improve the reliability as well as the functionality and the performance of high cost systems such as helicopters. As electronics is increasingly integrated into systems, the cost of electronic equipment failures is increasing similarly. Thus, HUMS are more and more valuable for diagnostics and prognosis. This trend is supported by aircraft manufacturers and the MoDs as well, which intend to extend the use of prognostics technologies on weapon platforms, vehicles and ammunitions.

To assess the feasibility of an onboard Prognostic Health Management (PHM) system, this paper discusses the demonstration of a real time PHM system for electronic interconnect fatigue prediction based on in-situ sensors, data fusion and relevant algorithms processing. The study focuses on thermo-mechanical degradation of electronic assemblies, because a significant percentage of field failures are related to the high temperature and temperature cycling operating environments of electronic equipment.

The prototype presented within this study is an autonomous embedded PHM system which integrates an onboard real time methodology for remaining life prediction based on a physics of failure approach. The results of accelerated failure testing applied on a Printed Wired Assembly (PWA) are compared to the modelling and predictions. They validate the identified prognostic features and show good agreement between the actual degradation status and the life expectancy forecasted for the PWA.

Index Terms — Data reduction, electronics, smart sensors, lifetime estimation, monitoring, prediction methods, reliability.

I. INTRODUCTION

The reliability of electronics heavily depends on the environmental constraints within which the system or equipment is operating. The field returns, privileged a few years ago to estimate the reliability of these systems, is no more sufficient today because of the fast evolution of electronics. This trend, which was accentuated this last decade, resulted in a greater focus on the failure mechanisms and in generalizing the use of the Physics of Failure (PoF).

The joint use of the PoF and the experience feedback makes it possible today to obtain convincing estimation of failures of electronic boards.

The new challenge is now to conceive systems able to compute the damage of electronic components, onboard and in real time, based on the analysis of the evolution of its environment and to give a prognosis for its end of life.

According to literature [1] for the failure mechanisms considered, the work is already quite advanced, particularly for the failures related to the thermo-mechanical constraints. However, the integration of prognosis calculations in an embedded platform, for a real time assessment, still requires some improvements to provide a low-cost onboard solution for Prognostics Health Management (PHM) [2] of systems.

In the first part of this paper, the monitoring system mock-up is presented. It has been developed to serve as a basis for the integration of smart capabilities enabling measurement, memorisation and processing. Then, the real time onboard prognostics (diagnostics plus prognosis) methodology is explained. Since on the fly processing generates high restrictions in terms of resources (memory and computation power mainly), an evaluation of the results is provided comparing theoretical, real and estimated results. Lastly, experimental results obtained by the monitoring system with in-situ sensors in a laboratory environment are presented.
II. THE MONITORING SYSTEM PRESENTATION

Basically, a datalogger embeds the necessary electronics to perform monitoring missions (sensors, memories and processing capabilities). Then, the denomination of the datalogger changes according to the level of smartness:

- The Time Stress Measurement Device (TSMD) [3] records the surrounding environment,
- The Health and Usage Monitoring System (HUMS) [4] is capable of making some primary diagnostics, using predefined thresholds, and triggering warnings,
- The new generation of these kinds of systems, able to make prognostics, have no common designation but can be called Lifetime Assessment Monitoring System (LAMS) [5] as they have to forecast the health status of devices for predictive maintenance.

The evolution between these monitoring systems is mainly the embedded software. As most of recent microcontrollers have a re-programmable memory, the same electronics can be used for the three previous systems, according to the firmware downloaded (Fig. 1). The small difference is linked to the mission the system has to carry out. Since the TSMD is used to know a real environment, it has to record as environmental parameters as possible and then needs a lot of non volatile memory. The LAMS, on the contrary, requires a local or remote display to present the results, very little non volatile memory but more Random Access Memory (RAM) and more processing power.

The system developed (Fig. 2) is working with 0.8 MIPS (Million of Instructions Per Second) but can evolve to 8 MIPS with the replacement of a quartz. It embeds a basis of 1Mb of Ferroelectric RAM which can be completed with a MultiMedia Card (MMC) integrating thousands of MB of FLASH memory for TSMD usage. The sensitive part includes a two-axis accelerometer and a temperature and humidity sensor. However only the temperature sensor has been used during the tests as the study is focused on the solder joints reliability, specifically linked to thermo-mechanical degradations.

III. THE PROGNOSTICS METHODOLOGY

In aeronautics, more and more valuable electronic parts will be monitored to improve the maintenance process and reduce the life cycle costs. This trend requires the implementation of embedded smart monitoring systems with specific software tuned according to the part under monitoring. To be able to perform an onboard lifetime assessment of electronics in real time, a piece of software has been developed following a particular methodology (Fig. 3).

The first stage consists in analysing and identifying the major failure mechanisms of the monitored part. The knowledge of the electronic part and its environment is essential here.

Some simulations with PoF tools and real tests have then to be conducted to assess and verify the life cycle of the monitored part and identify the most critical components according to the environment in which it is placed.

High performance algorithms, with low processing power needs for real time life consumption monitoring, are then applied. These algorithms are based on the identified failure mechanisms and use PoF simulation results or field returns to enable prognostics of electronic parts:

![Figure 1: Generic overview of a monitoring system](image)

![Figure 2: Generic electronics monitoring system for TSMD, HUMS and LAMS missions.](image)
- From the failure mechanisms and the knowledge of the environment, the sensor requirements have to be established to select the best sensors to measure the relevant environmental parameters (i.e. temperature, humidity, pressure, vibrations...).

- To decrease the quantity of data to be used to compute in real time the remaining life and limit the processing needs, different simplification algorithms have to be implemented to reduce the amount of data from all the measurements (i.e. data reduction applying quantifications and identification of ramps, dwells, patterns, cycles...). The raw data profile is then simplified into a new profile containing only useful information.

- These simplified profiles (one for each environmental parameter) are processed using algorithms based on a PoF approach, which takes into account the environment and the material properties of the electronics to deduce, on the fly, unitary damages according to each failure mechanism.

- According to all the identified failure mechanisms and the associated loads, the unitary damages are analysed and combined to assess the health status of the electronic part monitored. At this stage, a diagnostic of the monitored part can be provided.

- The evolution of the health status (given by the diagnostics evaluation) is processed to assess the trend of the degradation of the monitored part according to the monitoring duration. This last calculation provides a prognosis which consists in a time-to-failure result directly usable for maintenance purpose.

In this study, since the thermo-mechanical degradation was considered as a priority, the in-situ temperature sensor of the LAMS was used to measure the environment evolution and process the prognostics of an electronic test board (Fig. 4) [6].

The algorithms used for data reduction are based on iterative models [7] inspired by the Ordered Overall Range [8] and Rainflow [9] methods. The unitary damages are computed directly from the temperature cycle reconstructions and their associated degradation provided by the PoF simulation results or field returns. These damages are summed up to constitute the diagnostics assessment of the electronic test board. A degradation ratio can then be displayed to have the immediate health status of the board.

By the follow-up of the diagnostics, a trend can be calculated to assess the duration after which the monitored test board will reach a defined threshold of degradation. In this study, the prognosis functionality is based on an adaptative linear regression method applied on the degradation evolution. This technology can also be envisaged for a LAMS supporting the same stresses as the monitored electronics, only if the LAMS has a better reliability [10].

IV. EXPERIMENTAL RESULTS

In a first approach, the test board was modelled and simulated with Calce PWA software [11]. In parallel, a test board was installed in a thermal chamber to stress it with a specific thermal cycle (Fig. 5) repeated until all the components fail.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{max}}$</td>
<td>128°C</td>
</tr>
<tr>
<td>$T_{\text{min}}$</td>
<td>-40°C</td>
</tr>
<tr>
<td>Dwell at $T_{\text{max}}$</td>
<td>15 minutes</td>
</tr>
<tr>
<td>Dwell at $T_{\text{min}}$</td>
<td>10 minutes</td>
</tr>
<tr>
<td>Ramp up rate</td>
<td>5.5°C/minute</td>
</tr>
<tr>
<td>Ramp down rate</td>
<td>8.5°C/minute</td>
</tr>
</tbody>
</table>

Figure 3: Embedded Real time Prognostics methodology

Figure 4: Test board with 12 daisy chained components

Figure 5: Specific thermal cycle used
This study highlights the coherence of the results (Fig. 6) processed by simulation according to those obtained with real measurements. The number of cycles to failure for the solder joint interconnects in each component on the board in testing are quite close in order of magnitude between simulation and experimentation.

<table>
<thead>
<tr>
<th>Component type</th>
<th>Cycles to failure</th>
<th>Discrepancy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BGA169-1</td>
<td>358</td>
<td>298</td>
</tr>
<tr>
<td>BGA169-2</td>
<td>993</td>
<td>1095</td>
</tr>
<tr>
<td>OFF256-1</td>
<td>993</td>
<td>1162</td>
</tr>
<tr>
<td>OFF256-2</td>
<td>1201</td>
<td>1354</td>
</tr>
<tr>
<td>OFF208-1</td>
<td>1201</td>
<td>1421</td>
</tr>
<tr>
<td>OFF208-2</td>
<td>1190</td>
<td>576</td>
</tr>
<tr>
<td>BGA352-1</td>
<td>1190</td>
<td>830</td>
</tr>
<tr>
<td>BGA352-2</td>
<td>1559</td>
<td>1115</td>
</tr>
<tr>
<td>BGA225-1</td>
<td>1559</td>
<td>1027</td>
</tr>
</tbody>
</table>

Figure 6: Comparison table between experimental and simulation results

In a second approach, a LAMS integrating simulation results with various types of thermal cycles (amplitude and mean) was positioned with another test board in a thermal chamber to validate the onboard in-situ lifetime assessment concept (Fig. 7).

The stresses generated by the thermal chamber have been defined deliberately from two different environments to feed the degradation models of the LAMS with more than one repeated dummy cycle. That is why the embedded failure estimation curve shows two kind of thermal loads (Fig. 8).

The study has been focused on the two BGA169 components, which are the most critical components of the test board. For these components, two damage accumulation results were computed, one pessimistic and the other optimistic [7]. These two values come from one of the data reduction algorithms (cycle extraction), which sometimes generates orphan half cycles [9]. Looking at both components, the gap between the end of life assessment and the actual failures is quite small (up to 100% more) and seems to reveal an over pessimistic estimation.

The diagnostic results can be improved by 2.5% integrating interpolation between the closest PoF simulation results for the unitary damage affectation smoothing the intrinsic quantification.

From this diagnostics evolution, which behaviour is quite close for the other components, the lifetime assessment has been calculated for the BGA169 (Fig. 9), considering a threshold of 100% of degradation for maintenance actions.
Since the diagnostic model seems over pessimistic, the lifetime prognosis can only be the same. However, except for the artefact generated by the change of the thermal cycling stresses, which lead to a discordance between the optimistic and pessimistic prognosis over a short period, the prognosis approach seems very promising. And it is evident that the greater the accuracy of the damage accumulation model, the better the appropriateness of the prognostics.

However, the second example of prognosis with the two BGA352 (Fig. 10) brings more questions: the actual failure of both components occurred very early according to previous laboratory simulations and experimentations given in Fig. 6. Hence a complementary failure analysis will be conducted on these components to study their failure modes.

![Figure 10: Lifetime prognosis for BGA352 versus actual failure](image)

This onboard real time prognostics approach require at least one matrix of simulation results or field return by failure mode and by component. Moreover, if the environmental stresses are very different from one component to another, it will also need various sensors and data reduction functions in parallel.

V. CONCLUSION

Prognostics (diagnostics and prognosis) is the process of predicting the life expectancy of a system. The aim of using such technologies is to be able to assess the impact of environmental loads on a particular system of interest for its health status. The development of onboard PHM functions to forecast the health status of electronics is a real challenge for predictive maintenance.

The paper presents an approach to compute life expectancy of electronic boards on the fly. This work demonstrates that real time onboard calculation can be achieved at low power and cost. The methodology also eliminates large and frequent regular data-downloads and data-transfers needed for ground-based analyses. Hence the time elapsed between the stress-level monitored and the warning generated by the LAMS solution is considerable short. This objective has been achieved by integrating smart sensors, PoF approach, and customized data fusion algorithms. The methodology and prototypes developed have been successfully demonstrated to determine life expectancy of PWAs exposed to thermal cycling loads.

REFERENCES