Why Prognostics for Avionics?

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Abstract—Prognostics, by providing early information on potential equipment failures, permit maintenance to be transformed from a purely responsive (and hence largely uncontrollable) activity into one that can be planned and controlled. The ability to plan and control maintenance activities is becoming increasingly important because of the shortage of skilled personnel and the complexity of current avionics products. The benefits of prognostics are well established for mechanical and electromechanical equipment, and this motivates the extension of the technique to the electronics field. But there are very large differences between mechanical and electronic components in failure mechanisms, in the design process, and in the physical dimensions of the parts subject to failure that preclude direct migration of the prognostic techniques. These differences are examined in detail and a procedure for developing prognostics specifically targeted at solid state electronics is suggested.[1][2]

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1. INTRODUCTION

Prognostics for avionics are urgently needed because of the increasing number of electronic components in current and future aircraft and a possible shortage of technicians capable of servicing them. Additional factors motivating efforts for health management of avionics are the increasing sophistication and multimode functionality of many units that limit the usefulness of functional trouble shooting; provisions for output regulation that prevent observation of decreasing performance; and hardware/software interactions.

But the following factors make it more difficult to develop useful prognostics for electronic components than for mechanical or electromechanical ones:

- Electronic components have many parts with individually low failure rates (less than 10^{-6} per hour) and multiple failure mechanisms compared to mechanical equipment with relatively few parts and at least some with recognized high failure rates
- Although some wear-out mechanisms have been identified[1] (electro-migration, dielectric breakdown, etc.) they are not the drivers for reliability analysis which depends mostly on "random" failure assumptions (constant hazard).
- Detection of deterioration for many failure mechanisms is technically possible, but the sensors may be more complex (and probably less reliable) and larger than the parts being monitored. The increase in size, weight and cost precludes practical use of these techniques.

Thus it must be recognized that the benefits of prognostics for electronic components will be more limited and that direct migration of the techniques found useful in the mechanical domain will not be possible. To help guide us to areas where prognostics for avionics will be practically feasible it will be useful to consider applicable economic factors. Not only must the benefits in reduced maintenance cost and increased availability be greater than the expenditures for the prognostic provisions and their operation, but they must also be greater than the benefits that could be obtained by equal expenditures for reliability improvements. Proposed prognostic measures must be evaluated against both criteria.

In spite of the technical and economic constraints we will identify some techniques by which prognostics may be practically useful for avionic equipment and systems. Thus, the need that we have identified at the outset can be met if we approach the problem with realistic expectations, careful evaluations, and a good deal of patience.

2. THE NEED FOR PROGNOSTICS

Modern aircraft are increasingly dependent on avionic systems for communications, navigation, flight control (including stability augmentation), engine control and fuel management, environmental control and collision avoidance. Military aircraft have been referred to as "computers with wings". Because most of the avionic systems are essential for safety of flight they are redundant,

[2] IEEEAC paper #1378, Version 4, Updated Jan, 10 2006

frequently multiply redundant. The redundancy overcomes the serious consequences of equipment failure but it imposes an increased maintenance burden because the equipment added for redundancy will fail just like the original one.

Compounding the maintenance problem posed by the quantity of equipment is its increased complexity. Digital components are able to operate in multiple modes, and designers are making full, sometimes exaggerated, use of this capability. This makes it much more difficult to reason from an observation of unusual aircraft or system behavior to the likely source of the anomaly. Built-in test and on-board diagnostic software are intended to identify and localize component failures but very few would claim that they are perfect. Electronic parts can fail in a number of modes, not all of them permanent or easily detectable. Can the software be expected to cope with all failure modes? And can it be expected to be tested for all failure modes?

Thus much of the responsibility for the localization of a failure and for corrective action lies with the electronic technician. But experienced electronics technicians have received significantly higher salary increases in recent years than other aircraft maintenance personnel as seen in Table 1. This indicates that there are not hordes of them waiting to be hired.

Table 1. 2004 – 2005 Salary Increases[2]

Labor Category	% Incr.
Avionics Tech	27
A&P Corporate	14
A&P Airline	0.5

These data pertain to commercial aircraft maintenance. It would be surprising if technician availability was any higher in the military. Thus any measures to reduce the maintenance workload or increase the efficiency of servicing failed equipment should be investigated. Let us look how prognostics can help.

When an aircraft lands with a "squawk", a failure indication originated by the crew or by the on-board maintenance computer, the organizational maintenance technician must verify the failure and after doing so locate and install a properly operating replacement item. He then retests the affected system and clears the aircraft for further missions. For none of these activities can a successful outcome be taken for granted, and thus the control of technician time is impossible. If prognostics can provide warning of the degradation of a device even with as little as 10 flight hours of time to failure, the steps up to the installation and re-test can be pre-planned, resulting in saving of technician time and considerable reduction in its variability. Moreover, if the replacement item is not available from organizational stores, the affected aircraft will not be mission available until the item can be located.

Creditable data on the allocation of present maintenance time to the individual tasks of restoring service after a failure are hard to come by. From unpublished information on the FAA's BRITE radar (Faciltiy Code 461C4) we were able to obtain some mean-time-to-restore (MTTR) service data that permit estimation of the benefit of prognostics. Maintenance on this radar is performed either pre-arranged or unscheduled after a failure. Pre-arranged maintenance is a condition where observations from monitoring equipment or the traffic controllers indicate degradation in equipment operation (equivalent to prognostics).

Table 2. MTTR for BRITE Radar

Maintenance Type	No. Events	Total Hrs.	MTTR Hrs.
Pre-arranged	3937	4439.5	1.13
Unscheduled	382	6932.1	18.15

The difference in MTTR is approximately 17 hours. The duration of unscheduled activity was fifteen times that of the pre-arranged one. We do not know whether the failures covered by the two types of maintenance were the same, nor can it be claimed that these activities on ground equipment are comparable to those on aircraft equipment. But with all these reservations, the data provide a strong motivation to investigate prognostics for avionic systems.

3. OBSTACLES TO PROGNOSTICS

Prognostics have been successfully applied to automotive equipment[3], aircraft controls[4] and shipboard power plants[5]. In each of these applications there were a few dominant failure mechanisms affecting a few high failure rate parts with recognized signatures (noise, vibration, temperature rise, or degraded output). By contrast, we find in avionics

- A multitude of failure modes and mechanisms
- A very large number of parts, each with a very small failure probability
- Only a few failure mechanisms that have a recognized signature.

A Multitude of Failure Modes and Mechanisms

The term *failure mode* usually refers to the externally observable manifestation of a failure (high leakage current, no output etc.) while *failure mechanisms* designates the semiconductor characteristic that may cause the failure (oxide film breakdown, hot carrier injection, etc.). Failure mode data can be obtained from field failures; a sample distribution for a microprocessor is shown in Figure 1[6].

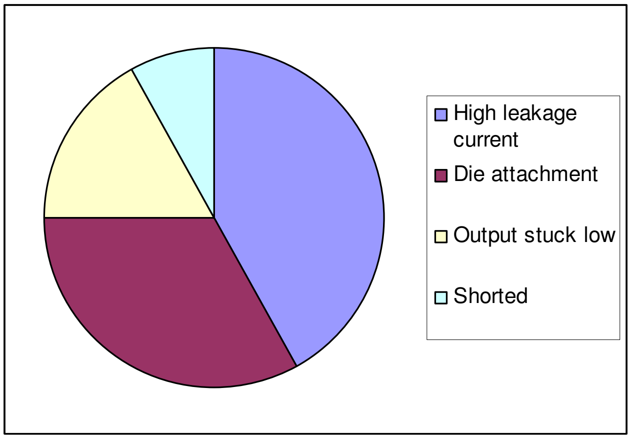

Figure 1 Failure Mode Distribution

Identification of the failure mechanism usually requires a detailed and expensive failure analysis and it is therefore carried out predominantly on failures found during the manufacturing process. Because they may reveal processing problems data on their distribution are usually considered proprietary. Also, the distributions found by the manufacturer may not be representative of the failure mechanisms responsible for field failures. Yet the most effective prognostics for semiconductors will probably be those based on failure mechanisms. A further obstacle for the identification of failure mechanisms is that practically all failure modes can be caused by multiple failure mechanisms, and practically all failure mechanisms may manifest themselves in multiple failure modes[7]

Very Large Number of Parts, Each with Very Small Failure Probability

The relatively low cost and size of electronic components mean low barriers to their use wherever their capabilities enhance functions or performance. As an example, one of six LRUs in an avionic system contained five microprocessors, 30 other types of integrated circuits (ICs) and over 1000 discrete electronic parts. The predicted failure rate for the ICs is 10^{-6} per flight hour and for most of the discrete parts it is less than 10^{-7} per flight hour. Providing individual prognostics for parts of such low failure probability is not economically viable as will be seen in Section 4.

Only a Few Failure Mechanisms have a Recognized Signature

Figure 2 shows the progression of time dependent dielectric breakdown (TDDB) as a function of temperature and applied voltage. The accumulated defects (left scale) cause leakage current that can serve as a useful prognostic.

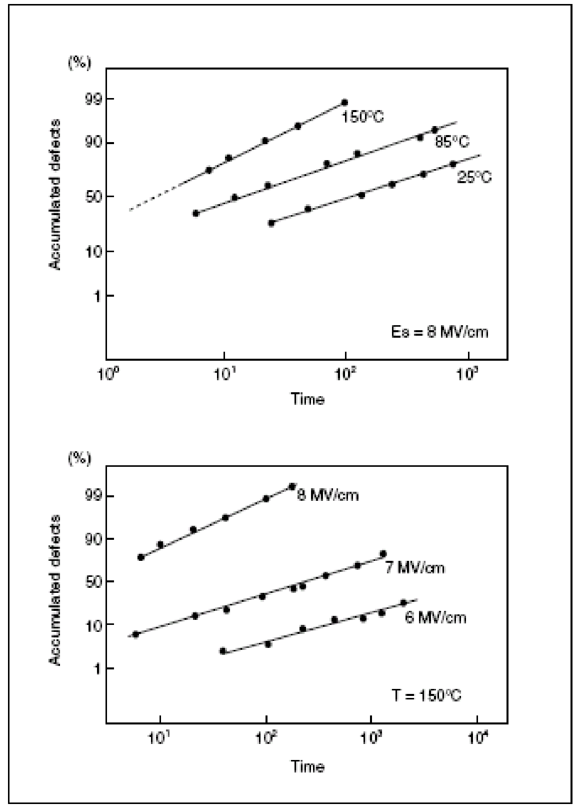

Figure 2 Time Dependent Dielectric Breakdown

Similar time characteristics have been published for hot carrier injection and for the increase in thresh a
old voltage in MOS circuits. But no time dependence data are available on bonding failures, cracks in substrate, passivation, or aluminum features or for failures due to external events such as electrostatic discharge, latchup and package failures. That prognostics may not cover all types of electronic failures is not necessarily a deterrent as long as the ones that are correctly diagnosed provide significant savings in maintenance and an increase in aircraft availability.

Another difficulty is posed by the small size of the electronic parts. In mechanical components the parts subject to failure are usually large compared to the sensors that are used for prognostics, e. g., a gear box compared to a microphone, or a motor compared to a thermocouple. By contrast, the typical electronic part subject to failure has the same physical size or is even smaller than a typical detector, e. g. a diode compared to a current sensor or a transistor (as a discrete component) compared to a thermocouple. Regarding integrated circuits (ICs) and programmable logic arrays (PLAs}the comparisons can become ridiculous if sensing of failures of individual circuit elements is attempted. The comparatively larger physical dimensions of the detectors will be objectionable in aircraft because of the weight and volume constraints.

All of this suggests that at the present time successful prognostics will require sensing of parameters that include multiple failure modes and that encompass multiple circuit elements with detectors that are small, light and inexpensive. The latter aspect is more fully explored in the next heading.

4. ECONOMIC GUIDELINES

In a recent SBIR study[8] we developed an expression for the economic benefit of prognostics, B, that in its most general form is

$$B = (M_U - M_P) \times N - C \qquad (1)$$

Where M_P and M_U represent the repair and unavailability expense for unscheduled maintenance and for pre-planned maintenance, respectively, N is the number of correct prognostic events within the time horizon, and C is the cost (including cost equivalent of weight and volume) of installing a prognostic sensor. .The entire expression is per component and all terms except N are in units of currency. The time horizon used for counting the failures (N) is explained in an earlier paper[9]; it typically ranges from three to five years.

While recognizing the difficulty of obtaining creditable values for M_U and M_P we can still use this equation to scope the direction that prognostics for electronic equipment has to take in order to be economically viable. For this purpose we expand N as shown in eq. 2.

$$N = E \times F \qquad (2)$$

where E represents the effectiveness of the prognostic (the fraction of failures usable warning time is provided) and F represents the total number of failures expected over the time horizon. The values for these quantities that are shown in Table 3 are hypothetical but they were selected to be on the high side for typical avionic components..
The cost of the prognostic equipment, C, is assumed to be the same in all cases.

Table 3. Effect of Scope of Prognostic

Scope of Prognostic	*F*	*E*	*N*
LRU	1	0.1	0.1
Assembly	0.2	0.4	0.08
Part	0.04	0.9	0.04

An LRU typically consists of more than five major assemblies and the typical assembly consists of more than five parts. Thus the breakdown shown in the table allows for selection of the highest failure rate components at each level. A perfect prognostic (E = 1) is unlikely for avionic components because of the number of potential failure modes and because some of these cannot be detected with enough warning time by existing technology (e. g., lead breakage or die detachment). Thus the effectiveness of 0.9 for the part level represents a very optimistic assumption.

Verification of the prognostic parameters at the lower levels of the equipment hierarchy is much more difficult than at the LRU level. On one hand a smaller number of failures are encountered, and on the other hand a greater number of correct prognostic events are required. Other things being equal, the investigation for prognostic measures for avionics should therefore focus on the higher levels.

Next we address the question of how far to press for improvement of the prognostic effectiveness. The effectiveness of 0.1 postulated for the LRU level in Table 3 can serve as a starting point; certainly this value should be easier to improve than the higher values for the assembly and part level. A thermocouple may have been employed to achieve the effectiveness of 0.1 and we will assign a cost of $10.- for this implementation. Also, let us assume that this is the marginal improvement so that B = 0. We can then solve eq. 1 for $(M_U - M_P)$

$$(M_U - M_P) = C/N = \$10/0.1 = \$100 \qquad (3)$$

If we can double E at an additional cost of $10 the $(M_U - M_P)$ for the marginal improvement will remain constant, but in the very likely case that increasing the prognostic effectiveness will cost more than $10.- the $(M_U - M_P)$ for the marginal improvement will increase. If we aim at an effectiveness of more than 0.2 the cost is likely to increase at an even greater ratio to the improvement. These considerations suggest that it may be more beneficial to employ prognostics at a modest level of effectiveness for several components rather than increasing the effectiveness at a single one.

If the prognostics are implemented such that B is positive, the same considerations apply. The statement that $(M_U - M_P)$ for the marginal prognostic will increase then translates into a decrease in the benefit B..

5. PROMISING PROGNOSTIC TECHNIQUES

Four examples are presented in which prognostics can provide significant maintenance savings. In accordance with the economic guidelines described in the previous section the techniques described are aimed at the LRU or assembly level, operate at a modest prognostic efficiency (at least initially), and emphasize detection of broad spectrum anomalies rather than those that indicate a very specific failure process.

- power dissipation
- output degradation
- external events indicating aging of semiconductors
- internal measures of aging of semiconductors

Power Dissipation

Many failure mechanisms cause an increase in power dissipation of the affected components. Measuring the temperature by means of a resistance thermometer or thermocouple is one approach to capturing this failure mechanism. Because the case or board temperature can be affected by many external factors, and thus this measurement may not furnish a good prognostic. But a direct measurement of dissipation by subtracting output power from input power avoids the external factors and may be a more economical approach where voltage and current are already monitored by the maintenance computer. In power converters input and output power are in most cases already monitored, and thus only the calculation of dissipation needs to be added to the computer workload. The most effective prognostic, in this as well as in all other metrics, is based on analysis of trends, and thus storage of prior values will be required. For components other than power converters the monitoring of power dissipation may be practical where (a) the output power is negligible or essentially constant or (b) the output power can be monitored.

Output Degradation

Impending failure of semiconductors in communication and radar systems frequently results in degradation of the output power of these systems that can be monitored and used as a prognostic. Again, trends will be much more effective than instantaneous measurements. Where the output level is held steady by negative feedback, the feedback signal can be monitored rather than of the output.

External Events Indicating Aging of Semiconductors

As semiconductors age the incidence of temporary data errors (soft errors or SEs) tends to increase[10]. Detection of soft errors by means of error detecting or error detecting and correcting (EDAC) codes is a common practice. The immediate cause of soft errors is usually a radiation event (due to space radiation or due to thorium that is a contaminant in the packaging material) and the rate of occurrence of these events follows a Poisson distribution. Deviations from this distribution that show a consistent time trend (e. g., due to aging) can be detected at a high confidence level as shown in Table 4 that has been constructed for a average occurrence rate of 10 SEs per interval. The entries in the body of the table indicate the probability that the event can occur if the parameter of the Poisson distribution remains unchanged at 10. The complement of the entry is the confidence that a change in parameter has occurred. Thus, for four consecutive counts of 11 or more SEs per interval there is 99.15% confidence that the parameter has increased.

For many microprocessor operations soft errors can also be detected by software codes although these will decrease the processor throughput.

Table 4. Significance Level for Consecutive Events

No. of SEs	Consecutive Events = or > 1	2	3	4
10	0.4170	0.1739	0.0725	0.0302
11	0.3032	0.0919	0.0279	0.0085
12	0.2084	0.0434	0.0091	0.0019
13	0.1355	0.0184	0.0025	0.0003
14	0.0835	0.0070	0.0006	0.0000
15	0.0487	0.0024	0.0001	0.0000

Internal Measures of Aging of Semiconductors

In Section 3 we have identified several semiconductor parameters that are useful for identifying aging. These parameters can not be accessed in normal operation of the parts but it is possible to attach special test areas (similar to coupons used at the wafer level) that permit measurement of the parameters for the purpose of detecting deterioration of device performance. A specific design technique for providing special test areas has been proposed[11].

In this technique, as well as in the preceding one, it is assumed that once degradation has been detected on a semiconductor device timely replacement of the affected LRU (and subsequent further diagnostics at a higher level maintenance activity) will sufficiently reduce the incidence of unscheduled maintenance requirements to warrant the early removal (and hence loss of service time) for the LRU. Much work will still be needed to define the degree of degradation and the associated service interval that will lead to real maintenance savings.

6. CONCLUSIONS

There can be little doubt that the maintenance workload for avionics is going to increase and no evidence that a corresponding increase in the required skill levels can be accomplished. Thus all facilities that can reduce maintenance requirements need to be explored. Prognostics can convert the need for unscheduled maintenance into a predictable and controllable activity and is therefore a promising candidate. Prognostics have been shown to be beneficial for mechanical and electromechanical components but the approach followed there has limited legacy into the electronics field where failure mechanisms are more diverse and difficult to track and where random failures have predominated in the past and still are the paradigm for the logistics format.

We have been able to identify four techniques that hold promise for yielding useable prognostics for avionic components and we have identified economic criteria for selecting favorable implementation opportunities.

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BIOGRAPHY

Herbert Hecht is Chief Engineer of SoHaR Incorporated, an R&D and consulting company for high dependability systems. The name of the company is a contraction of Software and Hardware Reliability. In addition to his managerial duties he supervises technical work in hardware and software reliability analysis, sneak circuit analysis and safety analysis.

He received a Bachelor of Electrical Engineering degree from City College, New York, and a Master's degree in the same subject from Polytechnic Institute of Brooklyn (now part of Polytechnic University of New York). In 1967 he received a Ph. D. in Engineering from the University of California at Los Angeles, with a dissertation on Economics of Reliability for Space Launch Vehicles.

Hecht's professional activities include a term on the Board of Governors of the IEEE Computer Society, service as Visitor in Computer Engineering for ABET, and membership in standards working groups of the IEEE, the AIAA, and the ISA. He is the author of *System Reliability and Failure Prevention* published by Artech House, 2003. He has over 100 papers in refereed journals or conference proceedings and holds 12 patents in the field of highly reliable control systems. He is licensed as a Professional Engineer in Control Systems Engineering by the State of California.