DEVELOPING THE USE OF NEURAL-NETWORK TEST TECHNOLOGY FROM AVIONICS TO WIRING SYSTEMS

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Abstract

The Aerospace industry is committed to efficiency improvement, but in some areas it could be considered that progress has been more gradual. Many Maintenance, Repair and Overhaul (MRO) developments focus on structural integrity or on Lean process improvement, whereas technology has made less of an impact in key areas, notably 'No Fault Found' (NFF) and wiring integrity assurance. However the development of a neural-network test technology heralds major advances for the NFF phenomenon and invites the question "to what extent this technology could be exploited and applied to benefit other MRO activities".

In every facet of aerospace operations, activities are implemented and evolved to improve their efficiency to increase safety, enhance the customer experience, reduce the consumption of resources and energy and to maximise profits. The MRO sector is no exception, as every day a new technology or a new initiative is offered to the market to deliver MRO performance 'faster, better, cheaper'. Certain aspects of MRO have reached an improvement plateau in recent years or, at best, they continue to progress with incremental and gradual improvements only. NFF is still one such area where improvements are only being made gradually. Most initiatives focus on Line Replaceable Units (LRUs) because they tend to be the most visible symptom of the fault and are more readily accessible during maintenance, which exacerbates the problem. Whilst wiring is sometimes investigated during NFF maintenance this is the exception rather than the norm, and research has shown that successful diagnosis and rectification of avionics problems accounts for less than 40% of avionics maintenance tasks. Another area that would benefit immensely from a step-change in capability is the assessment of wiring integrity. Major improvements have been made to the *prioritisation* and *planning* of wiring integrity checks, such as the introduction of EASA regulations for managing the continuing airworthiness of the Electrical Wiring and Interconnection System (EWIS). However, the execution of EWIS integrity checking often relies on conventional methods still, such as visual inspection, continuity testing and insulation testing.

Whilst these areas have benefited from gradual improvements over time, there has been a particular case study in the USA where the application of a neural-network intermittent fault detection test system has had a significant impact. The neural-network tester in question has been applied to testing of LRUs that suffer high levels of NFF. It uses a wide range of testing modes to assess the System Integrity of the Unit-Under-Test (UUT), including Intermittency testing as the primary test feature, with the result that the Mean Time Between Repair (MTBR) of the LRU has more than doubled. This has major implications for the way in which NFF problems are tackled. Moreover, it invites the question of how else might this technology be applied to testing EWIS and electrical/electronic components and to what extent could it deliver wider benefit.

This Paper examines the aforementioned intermittent fault detection case study and evaluates the implications of how the neural-network test technology is being used and how that compares with conventional testing methods. It assesses the development progress being made to expand the applicability of the technology, identifies other MRO activities that might benefit from its use and examines the practical issues involved and the likely benefits that could be realised. The potential beneficiary MRO activities range from diagnostics to prognostics, and from product assurance of new design components at the start of their life cycle, to integrity testing of ageing EWIS.

1 Introduction

Managers of Aviation Maintenance, Repair and overhaul organisations use processes to guide qualified and experienced people toward making a profit. Having wrung out those tasks then the industry should be prolific with relaxed CEOs with feet up on the desk having a well-earned nap…………………………not quite the model you have experienced? Whilst wear, damage and hard faults can be fixed once and then disappear, the intermittent fault returns again and again; both types create system unavailability. Fault finding procedures and test equipment have been designed around hard faults but neither current test equipment nor procedures address the problem that comes, goes away for a while, then reappears. To continue making a profit, organisations must adapt to the changing failure landscape.

1.1 Intermittents

Flight control jams can result in fatalities. On two well separated occasions, the controls locked on a fighter type aircraft and no-one could fix them. Air crews were reluctant to fly the aircraft without an identifiable fault whilst maintainers always had just another very plausible but non-conclusive reason for the “transient control seizure”. The “ignition key” was secured in the safe, the aircraft placed on jacks and the many successive causes were scrutinised until the real one was found. The orphan was prominently sited in the centre of the hangar: everyone had to go around it. Through perseverance the cause was found: a loose screw floating in the box at the base of the control column. Under varying “g”, the screw would intermittently float inside the sealed control box and migrate to a critical crevice where it locked either the aileron or the elevator control rod! Three lessons emerged: no process, an inordinate amount of time following false leads before the fault was found and the loss of team confidence, built up over many years, that maintenance could be relied upon.

Aircraft have one main control system but millions of electrical and electronic circuits. Fault causes need to be mapped and some manner devised to trace, identify and repair intermittent faults.

2 Aim

The aim of this paper is to gather some of the many electric or electronic fault causes and examine how they can be detected, traced and repaired cost effectively.

3 The Cause of Intermittent Faults

3.1 What is an Intermittent

"A failure in a product occurs when it no longer performs its intended function. An intermittent failure is the loss of some function or performance characteristic in a product for a limited period of time and subsequent recovery of the function" [1]. Predicting the type of failure, the location of the failure and the time of failure are the difficult questions. Whilst having no faults keeps the books "clean", the operator sees any equipment failure as a maintenance problem and nothing destroys the team relationship between user and repairer more than a repeating No Fault Found entry into the aircraft log. A comparable and common frustration level is a frozen computer screen in the middle of an important task where only a reboot, along with a complete data loss, fixes the problem.

3.2 The Costs

The cost of No Fault Found can be exponential and most likely hidden until that cost triggers a visibility level: Line replaceable units [LRU] returned to the Original Equipment Manufacturer as faulty but are fully serviceable or excessive platform downtimes. Physically replacing the "box" temporarily corrects the cable/connector fault, the system works then a short time later the cable or connector fault reappears. The box overhaul, the transportation and the time to remove and replace all have a cost element: meanwhile the LRU was not the problem. The pressures of time along with limited staff are in conflict with finding a real cause and in desperation, any solution will do.

The rate of intermittent fault recording has been estimated to be as high as 50% in military aircraft [2], however ranges of between 20% and 70% have been identified [3]. As the automotive industry has transitioned to electronic engine control systems, more intermittent faults have emerged. In 2001, Ford settled the largest class action reimbursing owners whose Thick Film Ignition module randomly caused the car to stall; the problem was widespread. This and other automotive experiences revealed that module and full system testing was inadequate at detecting intermittent faults: a complete fault-finding rethink is required. If intermittent faults are so widespread, cause significant loss of capability and are expensive then the causes deserve investigation.

3.3 The Causes

Human Factors pervade all aspects of the repair process. Technicians are qualified and experienced but if the process demands super human qualifications, skill developed like a sixth sense over decades of experience and extensive time to find the fault, then replacement and not repair may be more cost effective. The training must be pitched at the average technician level and the test equipment made appropriate to the task. Test equipment users will range from apprentices to experienced persons who may have been trained in different techniques. Fertile minds will adapt to new technologies whilst the more experienced will seek to revert to older, ingrained actions that have worked in the past. Test equipment must make the most of emerging technologies whilst concomitantly be user friendly. Communications is often overlooked: fault reporting, fault diagnosis, rectification and the reinvestment of all that knowledge to improve the process.

Avionic Printed Circuit Boards [PCB], connectors, components and their interconnections are all sources of failures. A Fish Bone diagram links the breakdown of these primes into failure cause classifications [Figure One

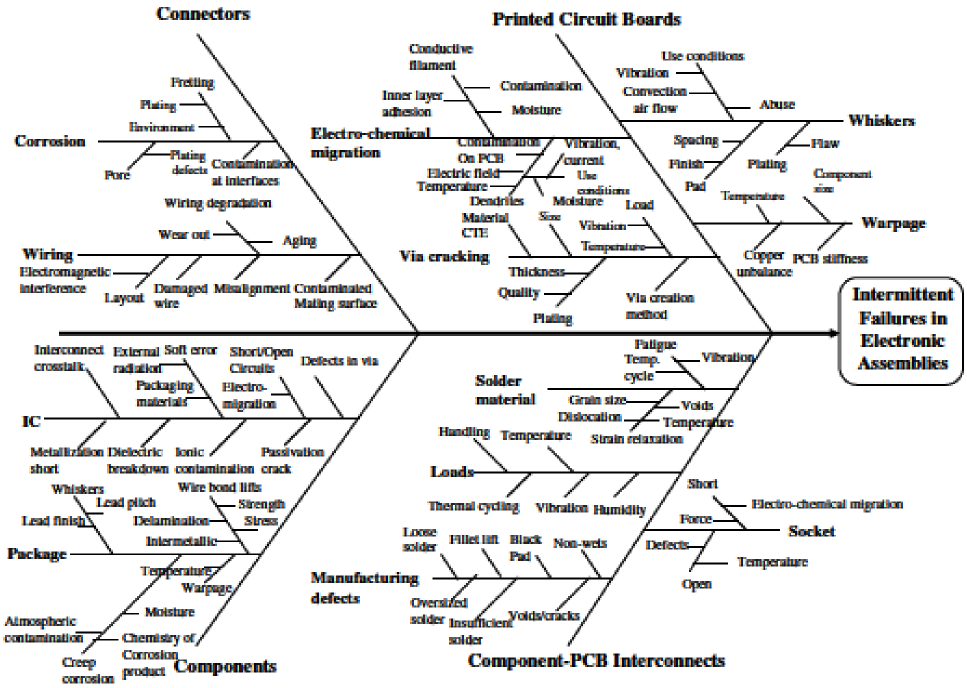

Fig 1: Intermittent Faults Cause and Effect Diagram

3.4 Failure mechanisms

Root causes of PCB failure can be temperature, moisture, contamination, mechanical manufacture or the secondary consequences of the particular construction process. During multi-layered board manufacture, "Via"s are created to link boards. Multiple construction methods are available but all are subject to plating separation or cracking. The Via cracking can close under assembly or use and then open when exposed to varying operational environments. This can be a most frustrating source of Intermittent Faults and may never be found. Sophisticated manufacturing methods to make PCBs lighter and more densely populated lead to an even greater range of fault types. Dendrites caused by electrochemical migration in the presence of moisture, contaminants and applied voltages can short circuit adjacent PCB tracks. These filaments can grow and then evaporate during operation making fault diagnosis more complex. PCB copper tracks have "electroless" nickel/gold finish to reduce in-service corrosion and facilitate surface mounted component soldering, but this process has its drawbacks. Black Plate Phenomena is a phosphorous layer created during the soldering process but leads to a brittle fracture of the solder. These are a few examples of the numerous PCB design, manufacture and assembly techniques that can lead to obscure intermittent faults. These fault types can be identified and engineered out of the LRU manufacturing process but the system also includes cables and connectors.

With sliding connections at sockets and plugs, the environment is rife for intermittent faults. The sliding action of contacts due to in-service flexing along with "removal and connection" cause oxidation, contact surface changes and spring force degradation. The effect is increased contact resistance in an erratic manner. Figure Two shows the results of contact resistance following contactor vibration.

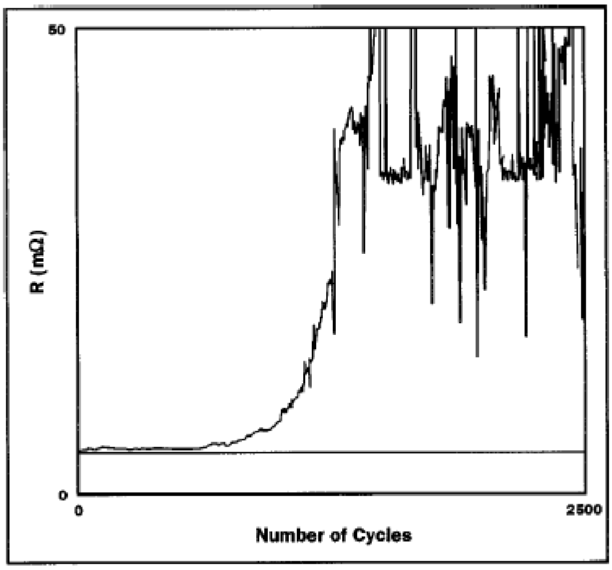

Fig 2: Change in Contact Resistance versus Cycles

Soldered joints can suffer mechanical failure, oxide film contamination, solder fracture, low temperature formation and many others.

Of all the component related causes, “Tin Whisker” growth in lead free soldered joints has been identified as a major electronic system fault cause [4]. There is no widely accepted test for the propensity of this phenomena but residual stresses and intermetallic compounds are thought to be the prime causes. The result is multiple transient faults most of which are intermittent in particular:

a. Debris from fractured and loose whiskers.
b. In space operation leads to plasma arcing fed by the surrounding tin.
c. Transient shorts from whiskers which bridge then fuse under applied currents.
d. Stable short circuits in low current bridging whiskers [5].

External lead de-bonding within the semi-conductor and single event upset caused by semiconductor ionisation are prime but obscure intermittent fault precipitants and are difficult to duplicate and trace. The thrust toward lighter and smaller avionics equipment has innovated reductions in component size and mounting: Surface Mounted Devices [SMD].

With the reductions in PCB thickness and board stacking reaching their limits of practicability and reliability, the industry turned toward the size of components [6]. Surface Mounted technology grew out of the hybrid assemblies developed in the 1950s. Manufacturing techniques progressively improved and through-hole mounting reached its limit; SMDs were the replacement. Automated flow soldering, underside component attachment and the technique to use the soldered contact as both an electrical and mechanical bond saw the rapid development of smaller and smaller SMDs [7]. With differing component manufacturing techniques, changes to mechanical bonding and more densely populated PCBs came the propensity for a greater number and more obscure faults. Whatever the cause – and this paper has canvassed but a few – intermittent faults are the product of modern construction techniques and need just as advanced technology to detect, locate and correct them. There are many fault-finding techniques with the more effective requiring purpose-to-type test equipment and differing levels of skill and experience.

3 Fault Finding Techniques

3.1 Different Faults, Different Techniques

At one extreme, wise heads and simple test equipment can persevere with an intermittent fault and through a complex and very time consuming process of elimination, find it. Technicians with this experience demand a high salary, lock themselves in quiet rooms and to a manager, are targeted as the cause of equipment unavailability. Unloved, they chose a different occupation but the faults remain "you can't dig a new hole by digging the same hole deeper." [8]. Test equipment that is purpose built but requires only average technical ability can be used to find the fault in a fraction of the time transforming what may only be useful as a ship’s anchor into a fully serviceable avionic item. These technicians are prized as they fix the problem in what is classified as a “reasonable” time. The focus is on developing items of intelligent fault finding test equipment and repeatable procedures.

4.2 The Old Way

Analogue multi-meters show absolute values and rate changes. Through capturing parameter states over time on a wire by wire basis, intermittents can be found. In a workshop environment, ruggedized liquid crystal display oscilloscopes can partially meet this need but demand a lot of time, a lot of experience and a “sixth sense” interpretation to examine each wire in turn. Old heads return to the equipment with which they are familiar and despite the exponential growth of electronic control in cars, some auto technicians insist on a wire by wire test to find a fault. A video clip [9] examines the role of an auto technician over a period of three days finding one severed wire which, up until the end, had displayed only an intermittent fault. I am sure the satisfaction after three days would have been exhilarating but the cost and customer inconvenience would have left the latter stunned.

4.2 Switching between Wires

Switching techniques, where signal samples are gated into a comparator, can locate intermittent faults provided the fault coincides with the gating period. As intermittent faults are frustratingly random, there is no stand-alone gating system that can be synchronised with a fault occurrence.

4.3 Digital Averaging

Digital instrumentation has been associated with higher accuracy as more digits to the right of the decimal place appear at reducing costs however, more digits may not give increased measurement quality. Following the crash of American Airlines Flight 587, the NTSB identified missing Flight Data Recorder information attributed to “digital averaging”. Random intermittent faults or glitches are averaged out in digitally logged data and therefore never cross the detectable threshold: they never show up. High speed is at one end of the measurement bandwidth whilst accuracy is at the other: they have opposing penalties.

Digital measurement can deliver very accurate readings, but only when the signal being measured is itself constant. If the signal of interest is intermittent, the outcome cannot be guaranteed to be correct [10]. Only luck determines whether you catch the glitch, part of it or progress blindly with no indication at all. Digitally based equipment is suitable for hard failures with blinding accuracy but only analogue testing can locate the intermittent faults. Some method of sensing all of the individual wires all of the time is required.

4.4 All of the wires all of the time

Most civil air transport aircraft can operate with redundant avionic systems unserviceable under a Minimum Equipment Listing. In a military aircraft, all of the systems must work all of the time if the weapon system is to be flexible and effective. Military avionics therefore, can show significant availability gains from intermittent fault diagnosis and repair. Multiple and different theatres, recapitalisation of older weapon systems due to delayed introductions to service and constraining budgets require defence services world-wide to improve maintenance capabilities whilst driving down the costs. In the US military, age related faults which result in repair shops classifying items as No Fault Found or Cannot Duplicate consume a large identifiable part of the US$20 billion allocated to avionic repair. Automatic Test Equipment and sampling type wire testers have been condemned as ineffective in diagnosing intermittent faults: a tester that monitors all of the wires all of the time is the only assured solution. One such tester is in use at Ogden Air logistics Centre, USA.

5 Testimonials

5.1 AN/APG-68 Radar

The F-16 AN/APG-68 Radar System Modular Low Power Radio Frequency [MLPRF] Unit experienced significant in-service failures and No Fault Found classifications. Prior to the use of an all-of-the-wires-all-of-the-time, tester, the average shop repair time was 24 months and of the units repaired, 15% had NFF at Level Two Maintenance whilst 21% had NFF at Level Three Maintenance. Shop maintenance costs exceeded US$2m. One Hundred and ninety five MLPRF units were tested using an Intermittent Fault Detection and Isolation System [IFDIS] of which 130 had intermittent faults; these faults were identified and fixed. Of the 33 units which had been in the shop for more than one year and the nine units that had been in the shop for three years, all were recovered. The savings were greater than US$36m and the Mean Time Between Failure extended from 289 hours to 729 hours. Future savings are expected to exceed US$ 1.5m per year. How much does this type of capability cost to achieve the aforementioned savings?

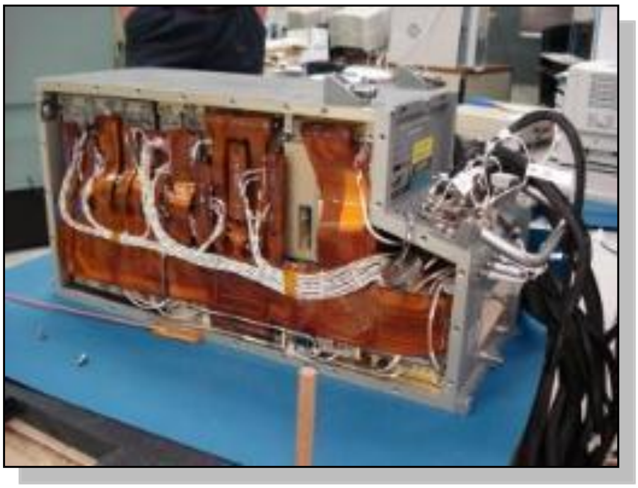

Fig 3. AN/APG-68 Radar Under Test

5.2 Capability not a Box of Tricks

Firstly, it is a capability rather than a magic box and an “Abracadabra” wand. The capability comprises a scripted process, type training and the application of smart technologies. On the question of how much, the MLPRF solution yielded an 18 times benefit on total investment whilst the system can be readily configured for other cables, connectors and chassis.

5.3 Ribbon Cable

Success breeds success and the F-16 Radar Azimuth and Elevation Ribbon Cable had a 61% failure rate during an upgrade programme. The items had a long supply lead time delaying the weapon system return to service after modification.

Fig 4. Ribbon Cable Under Test

The contractor was blamed for an in-service problem but was forced to look for a solution. Twenty one of the 95 Ribbon Cables tested were recovered following intermittency testing using knowledge and equipment adapted from the MLPRF programme. At US$1600 each, the replacement saving was US$33,000 along with eliminating the production lead time bottle neck.

5.4 Vibration is an Enemy

Helicopters and vibration have a strange synergy so an helicopter example was inevitable. Communication LRUs returned to the OEM for repair were tested and returned to the owner serviceable as NFF. When LRU intermittency testing was introduced, 57% of the LRUs tested failed but 75% of the total batch had passed the ATE requirements. ATE does not test for intermittencies until the intermittency becomes a hard fault. The OEM recalled the LRUs found intermittent, repaired them and is still in business today.

5.5 Uncontrollable “Wheels Up”

An aircraft undercarriage wiring harness was providing intermittent, false down indications. The safety critical nature of this fault required immediate item replacement with the offending cable subsequently investigated: if the cable proved fully serviceable then some other part of the system required attention. The intermittent fault began appearing on other aircraft and the cable type was allocated a replacement life. The standard continuity tester passed all tested items as serviceable even those cables which had given false indications when installed. The IFD equipment and process was used to test the undercarriage cable and the intermittency test trapped all of the faults and their location. Pre-installation testing confirmed new items as fault free. As an outcome, cable failures in service were reduced to a very small number and the useable life of the cable type was doubled then subsequently extended on the basis of “safe-life”. The savings included “first time” mission accomplishment, crew confidence in their equipment along with a concomitant reduction in both maintenance down time and support costs. The OEM reversed the broadly held feeling that “all of his products were sub-standard and that his company name was associated with unsatisfactory performance”.

5.6 Ageing Aircraft

Britain’s front line fighter aircraft is the Tornado GR4: “…..a variable geometry, two-seat, day or night, all-weather attack aircraft, capable of delivering a wide variety of weapons.” [11]. The two RR RB199 Mk103 turbofans have a Cross-Drive Clutch for accessories which item has suffered intermittent faults since 2006.

An individual Tornado aircraft had suffered from an intermittent symptom of un-commanded CDC engagements whilst the fault had been recurring for over 5 years. Repair efforts had cost over 500 maintenance man-hours, and over 30 components and LRU replacements.

Fig 5. IFD Testing of Tornado CDC

IFD testing detected intermittent faults, continuity faults and excessive noise in 12% of the cables. These faults were repaired and repeat IFD testing confirmed the wiring’s integrity. Subsequent engine ground running revealed that the CDC fault had evolved to a hard fault, and its un-commanded operation was being triggered by an external input. Expanding the scope of the diagnosis revealed a circuit breaker (CB) on another system that was linked to the CDC. The CB was tested and found to be highly intermittent under vibration. When reset to the ‘closed’ position the CB would function normally for a period of time but would then create extensive intermittent contacts (Figure 6). The thick line illustrates the real-time resistance measurement and the ‘noisy’ thin line below represents the deviation from the starting value. Figure Seven is the trace for a serviceable item.

An IFD analyzer can successfully test on-aircraft systems for wiring and other EWIS intermittencies. Otherwise serviceable systems can use IFD to find associated, yet unsuspected, components that were the primary fault.

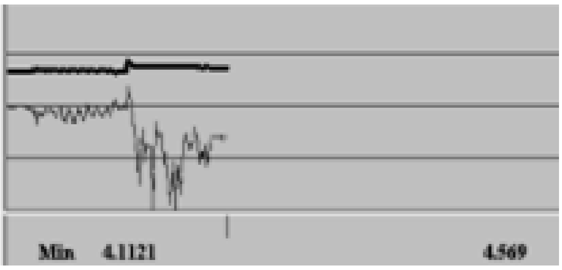

Fig 6. Faulty Tornado CB

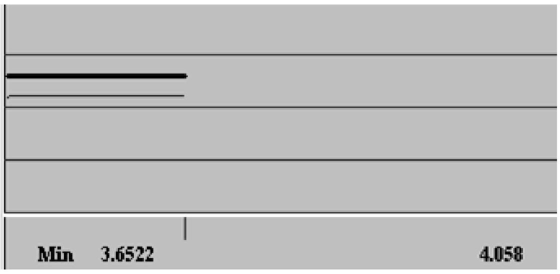

Fig 7. Serviceable Tornado CB

The Cross-Drive Clutch has ceased to be a system demanding particular engineering management.

5.7 EWIS Testing: Connectors

A mission system cabling on a surveillance aircraft is being assured by IFD. The IFDIS approach has led to specific maintenance practices for a connector type (Fig. 8)

Fig 8. Mission System Cable Connector; Partially Locked.

Fig 9. Mission System Cable Connector; Fully Locked

During the project, connectors [Figs 8 and 9] could be placed in a securely fitted configuration, but not tightened to a fully locked position. The cable connector was tested in both positions and whilst all test points passed a conventional continuity test, one specific test point failed Intermittency Testing during ‘un-lock’ connector tests. As part of the modification assurance and continuing airworthiness, the “Fully-locked” witness mark is included as a separate action.

5.8 White Coffee with One Please

Whilst mission accomplishment is critical to military operations, passenger and crew coffee can be just as important to airline choice by the travelling public. On a VIP aircraft, the Espresso machine experienced intermittent fault symptoms which manifested as a memory “loss” for coffee type selected. While not an airworthiness issue, this machine provided a service that clients expected. A test regime was devised to isolate the root cause of the intermittent fault.

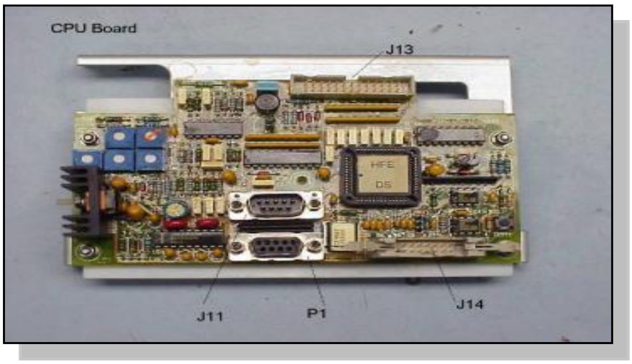

Fig 10. Coffee Maker Motherboard

An Intermittent Fault Detection test set was umbilicaled to test points on the coffee maker circuit board. Circuit interconnectivity, and then intermittent fault testing was carried out; each time that the processor was gently tapped, the interconnects between the processor and the holder on the circuit board produced an intermittent circuit. The Espresso machine OEM introduced a modification to correct the problem for this application and the equipment now makes coffee of the selected type reliably and without a fuss!

6. Potential IFD applications

The case study examples in this paper illustrate that the analogue neural-network of the IFD analyser has a test coverage advantage when dealing with certain fault types compared with conventional or digital ATE. In particular, the ability to detect nanosecond intermittent ohmic changes in multiple test points, simultaneously and continuously, coupled with a range of other test functions including Continuity and Log Scope, means that the IFD analyzer is uniquely positioned to fulfil testing roles in the following MRO scenarios.

6.1 Fault Detection & Troubleshooting

Shortfalls in records about the extent to which LRUs contain the root cause of NFF occurrences result in an extreme tendency to fix intermittent faults by LRU replacement. LRUs can be eliminated from the diagnosis by using simple 'ship or shelf' procedures, before assessing which on-aircraft components are the likely cause. Studies have shown [13] that investigating wiring aspects in NFF situations can take 10-15 times longer than other repair activities, so it is no surprise that 'LRU swapping' is the foremost response taken. However, analysis of maintenance history data reveals where the true NFF unserviceabilities are located and where IFD testing is to be applied.

6.2 Wiring Integrity

In aerospace applications, through-life airworthiness and integrity of EWIS is now mandated in much the same manner as it is for airframes. The combined test functionality of an IFD analyser can be used to test new wiring harnesses and installed, ageing harnesses. Test results are automatically recorded and hence they can be trend-analysed against the 'gold' standard for the Unit Under Test, or trended against itself to assess degradation and usage effects. The low impact of IFD testing, with a maximum output measured in milliamps, causes no detrimental effect to the Unit Under Test and so it can be tested repeatedly without detriment. High-potential wiring testers to assess arc-over susceptibility create carbon tracks and have a low repeatability threshold. Therefore, IFD wiring integrity testing can be carried out as part of aircraft Checks or component scheduled overhauls.

6.3 Product Assurance

Product assurance testing can take many forms and an IFD analyser can be readily applied to integrity assurance testing of components including:

- Integrity testing of new-build wiring harnesses;
- Confirmation of correct wiring installation and integrity, for Final Assembly Checks;
- Integrity testing and trending of new-design PCBs, with test 'posts' built-in as described earlier in this paper.

6.4 Prognostic Fingerprint Technology (PFT)

As on-board Prognostics and Health Management (PHM) grows, the test output data collected by an IFD analyser can be exploited to inform PHM evidence-driven decision-making. Knowing the degradation in and life remaining of avionics and wiring components, keeps them 'on-wing' for longer periods. Development of PHM use of the IFD analyser, entitled PFT, is at an embryonic stage and a feasibility study has substantiated further R&D to make PFT a reality.

7 Conclusion

Electronic circuits and their umbilical cables and connectors in aircraft have increased exponentially in the past 25 years: the proliferation of digital technology has introduced compounding effects of intermittent and noisy signals. Avionic modules [LRUs] have become smaller, lighter and with increased capability extracting these attributes from smarter Printed Circuit Boards, surface mounted components and higher density circuitry all of which bring their own failure modes and their intermittent cousins.

High speed is at one end of the measurement bandwidth whilst accuracy is at the other. They each have opposing penalties. Digital averaging can miss signal pulses and give false confidence that equipment is fully serviceable. Whilst specialized training for qualified and experienced technicians along with processes to find intermittent faults is crucial, testing all-of-the-wires-all-of-the-time is the only way of capturing short transients. Addressing the technical issues are only part of the problem. Communications between the user and the maintainer, classifying the fault as intermittent so that appropriate techniques can be used and cataloging the savings so they can be properly attributed are as critical to extracting maintenance savings as are the faults themselves.

Avionic LRUs have expanded in capability, reduced in size, weight and power consumption but still require cables and connectors to form a complete system. System available is crucial to equipment service in a low cost, high profit outcome. IFDIS has been proven to reduce cost and increase availability: for the F16 MLPRF, an MTBF extension from 289 hours to 729 hours and savings of US$36; for the F16 Radar, US$33,000 savings and elimination of the need for a long new item supply chain; for the GR4 Tornado, savings on expensive accident damage and for a VIP coffee machine, happy customers.

IFD equipment can go further, penetrating the system assurance function on new items and “finger-printing” installed systems to keep items in those systems installed for longer periods in a fully serviceable condition.

Intermittent faults are a prime cost driver. There is specialist training and test equipment to reduce this cost driver and owners of fixed infrastructure and transportation assets can benefit from its use.

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