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Intermittent fault finding strategies

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Abstract

Intermittent faults are regarded as the most difficult class of faults to diagnose and are cited as one of the main root causes of No Fault Found. There are a variety of technical issues relating to the nature of the fault which make identifying intermittent. This paper discusses some of these issues by introducing the concept of intermittent fault dynamics, modelling approaches and a selection of the state-of-the-art testing and diagnostic techniques and technologies.

Keywords: *Intermittent Faults; No Fault Found; Testability; Fault Diagnosis; Test Equipment*

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1. **Introduction**

Systems faults are usually classified as permanent, transient or intermittent fault [1]. A system experiencing a permanent fault, also referred to as a ‘hard fault’ will exhibit a continuous deviation from its specified performance specifications. Intermittent faults can be defined as a temporary malfunction of a device. These malfunctions last for a finite period of time, where the device will then recover its normal functionality. Intermittent faults are repetitive and occur at periodic and often irregular intervals, separated by a fault ‘reset’ event where normal behavior resumes. Transient faults, at first glance often appear to be in the same class as intermittent faults, that is their symptoms also only last for a finite time. We can however define some fundamental differences. We define the root cause of an intermittent fault as the measurable symptom of the degradation of some physical aspect of the system. As this degradation increases, the rate and severity of the intermittent symptoms will also increase in severity until eventually the degradation has resulted in the intermittent fault becoming a permanent system fault. Transient faults however, do not necessarily repeat themselves as we define them as the symptom of a one-off, single event interaction. The fundamental difference is that transient faults therefore are not necessarily considered as symptoms of degradation.

Understanding the fundamental nature of intermittent faults would allow for the design of reliable and robust diagnostic techniques and technologies, for both in-situ and maintenance test-bench applications. The deployment of intermittent fault diagnostics is also of paramount importance in solving the phenomena known as No Fault Found (NFF). Traditionally, any product removal that exhibits no fault (during subsequent acceptance testing) can be categorised as NFF However, for a number of these events, further investigation could conclude that the reason for the product removal was caused by an external influence not present during testing of the removed system, these may include environmental effects, integration with other systems, damaged wiring or loose/damaged connections. However, it may be that the removed system is inherently faulty but the test equipment is inadequate to identify the nature of the fault, this is usually because the fault was not perceived during the systems design, or the fault has not been experienced before so that the symptoms are not recognised; or the fault is

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intermittent and does not manifest within the test window.

A 2012 survey of 80 aerospace organizations [2] ranked intermittent faults as the highest perceived cause of NFF, with technician experience of diagnostics and intermittent faults ranking 2nd and 3rd. The results of this survey provide a strong motivation to reduce NFF through the development of new intermittent diagnostic capabilities, encompassing both fault detection and fault isolation.

2. **No Fault Found**

It is commonly accepted that NFF phenomena arise from a minimum of two test levels. At any test level, a fault may be recognised and localised as belonging to an individual piece of equipment which, when re-tested, at a subsequent level, the recognition/localisation of the reported fault may be unsuccessful. NFF events pose problems to almost everyone that is involved with the product/vehicle/machine, from customers to manufacturers and their suppliers. The impact of NFF will range from mere nuisances, to increased financial costs through to risking safety. These are considered as the two most significant impacts of NFF which need to be addressed and are therefore explored in more detail.

Information regarding financial costs of NFF within many industries in particular the aerospace industry, is difficult to obtain with very little information in the public domain. However we can consider a theoretical scenario of avionic equipment fitted to a fleet of aircraft and fails every 300 hours. The NFF rate is 50%. The fleet flies 30,000 hours per year and cost of returns and replacements is £10,000. Fault rate is 30000/300=100 returns per year. As the NFF is 50% so the occurrence of NFF is 50 per year. So NFF per year is £500,000. This does not include the cost of aircraft troubleshooting and recovery. The included cost per fleet will become millions pounds per year [3].

3. The Nature of Intermittent Faults

3.1. Intermittent faults

Often in the literature the words transient fault and intermittent fault are used interchangeably as they are often regarded as having the same attributes. This is however argued by the author as not the true case and they should be treated as unique fault cases.

What is key is that a transient fault is the result of some unobserved behavioral mode resulting from an interaction with an environment. For example, a temporary spike in a proximity sensor due to a magnetic coupling between the sensor and a structure; a reset event in an avionics system due to solar neutrino radiation or a sudden temporary change in resistance in a circuit due to temperature fluctuations. All of these events are recoverable and do not represent a physical degradation of the system. Intermittent faults however do represent symptoms of physical degradation and will reoccur after some time with a similar fault signature. A transient fault may reoccur but the exact circumstances will not be reproduced and will have an identifiably different signature. This leads onto a set of specified rules which are proposed in resistance in a circuit due to temperature fluctuations. All of these events are recoverable and do not represent a physical degradation of the system. Intermittent faults however do represent symptoms of physical degradation and will reoccur after some time t with a similar fault signature. A transient fault may reoccur but the exact circumstances will not be reproduced and will have an identifiably different signature. This leads onto a set of specified rules which are proposed in this current research to separate the two fault types.

- Rule 1: Intermittent fault behavior is the switching of a constituents physical behavior between (at least) two conditions that correspond to elementary behavior modes
- Rule 2: The fault event f_i must have occurred at least twice with separated by a fault reset eventr_i.
- Rule 3: If the last event to occur is r_i the system is operating within the 'normal' behavioural mode, else if the last event to occur was $f_i$the system is operating within the 'faulty' mode (intermittent and present)

The importance of being able to distinguish between these two classes of faults is that they often require two different maintenance activities. Transient faults will not necessary require a system removal/replacement/repair whereas intermittent faults being the symptom of degradation will require a physical replacement/repair.

3.2. Intermittent fault dynamics

What is assumed in this paper about intermittent faults is that they are a symptom or manifestation of the degradation of some physical property of a system component. As it is a well-established fact that degradation will increase over time until a point where that component completely fails 'hard-fault' it stands to reason that the nature of the intermittent fault signal will also change with this degradation. For example, consider Figure (2), which represents a theoretical curve of degradation. Within a region below the threshold of Point A there will be no symptoms of faults and the system will continue operating uninterrupted. Above the threshold Point B the system will have degraded to such an extent that a permanent "hard" fault is continuously observed. Between Points A and there is a region where we would expect intermit tents to occur. At the early stages of degradation the intermittency is likely to have a small amplitude, short duration and low frequency; whilst in the later stages of degradation the signal will have large amplitude, long duration, high frequency as shown in figure 1. This concept does allude to the idea that if intermittent faults start out as a mere 'nuisance' and eventually result in 'hard-faults' then we can introduce a concept that intermittent faults have dynamics

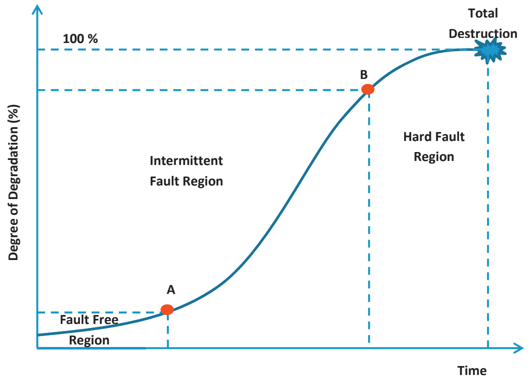

Figure 1: Relationship between intermittent faults and degradation

There are a number of approaches to estimating the level of intermittency, the simplest approach being a counting of the number of times intermittency occurs within the time frame. In this model the concept of Intermittent Fault Density is used as the measure [4]. The density captures the faulty dynamics within the specified time and is defined as the average time the fault is active within a time window and is described by:

$$\rho(T) = \frac{\sum_{i=1}^{CNT}((TR_i - TF_i) - T_A)}{W} \tag{1}$$

Where CNT is the number of faults within the window of length W; $(TR_i - TF_i)$ represents the fault duration time of fault i. The density is calculated from $ti - W$ to ti and takes into account the duration of a fault that occurred before $ti - W$ and continued active inside of the window thus:

$$T_A = FT_{(k-1)} + T_{(k-1)} - (ti - W) \tag{2}$$

Through direct monitoring of the density of faults over time a pre-set threshold level can be set, to signify the maximum acceptable level.

3.3. Modeling intermittent faults

One of the most popular techniques for modelling intermittent faults is through the use of Markov chains/models. The concept is that if the system is intermittent then at any given time it must be in either a faulty or a non-faulty state. Many published works make use of a 2-state Markov model as shown in figure 2. In this model the transition probabilities between two states are given as $P_{1,0}(t)$ and $P_{0,1}(t)$ and the probability that the system remains in its current state is $P_{1,1}(t) = 1 - P_{1,0}(t)andP_{0,0}(t) = 1 - P_{0,1}(t)$. In this modeling process there is a basis upon the probabilities of transitions between the FA (fault present and active) and FN (fault is present but inactive). It is possible to identify four types of data which are of significant importance when considering intermittent faults. These are (1) the set of windows where the fault is considered to be active $(FA = [FA_1, FA_2, \cdots FA_n])$; (2) the set of the windows where the fault is present but not active$(FN = [FN_1, FN_2 \cdots, FN_n])$;(3) the indices for when a transition occurs between state FN and FA $(\mathrm{TF} = [\mathrm{TF}_1, \mathrm{TF}_2, \cdots, \mathrm{TF}_n])$; and (4) the set of times when the system recovers from being in the FA state $(TR = [TR_1, TR_2, \cdots TR_n])$.

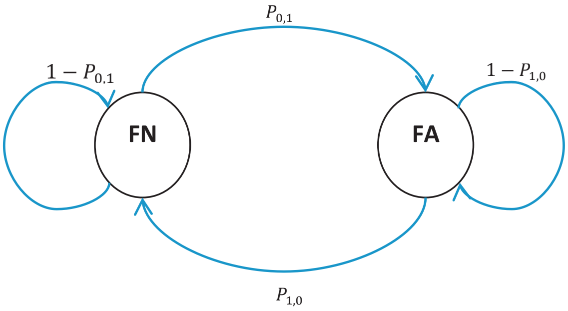

Figure 2: 2 state Markov model

In previous applications of Markov models applied to intermittent faults the purpose has been to evaluated intermittent testing regimes, more specifically to determine the time required to spend testing each connection to ensure maximum probability of the system entering a faulty state during that test.

In previous applications of Markov models to the intermittent fault case the assumption has been made that the occurrence of intermittent faults follows a stationary process [5]. However, this does not capture the implicit natural behavior of intermittent as laid out in section 3.2. The notion of intermittent fault dynamics ensure that there is an on-going variation in the intermittent occurrence process – that is the changing between faulty and healthy states can be considered as not stationary. The probability of transition between a healthy and faulty state in the case of intermittent failures will not be consistent and new modeling techniques are required to capture this dynamic transition of probability.

4. Intermittent Fault Detection

4.1. The difficulties with testing

It could be argued that as more complex electronic systems enter the market, the ability to maintain them is becoming ever more challenging and expensive. It has also been reported that conventional test equipment, which is required to carry out the fault investigation, are not always successful. This can be due to the fact that the necessary levels of confidence and efficiency are inappropriate in the many industries which are suffering NFF failures. If testability as a design characteristic was successful, perhaps NFF would not be so problematic. This is particularly evident in the case of attempting to detect and isolate intermittent faults at a test station – the ability to test for short duration intermittency at the very moment that it re-occurs using conventional methods is so remote that it will almost certainly result in a NFF. The one major issue with designing component testability is that the focus is on functionality and integrity of the system at the ATE is not tested [6].

There are many test equipment that are used to detected anomalies in electrical parameters and temperature profiles. The more common ones include multi-meters that detect steady or slowly varying electrical signals. On the other hand, digital oscilloscopes are used for rapid changes based on the sampling function. Problem with an electric intermittent fault is that it occurs for only a short duration, making it difficult to detect unless a very high sample rate it used. This goes beyond the capabilities of typical test equipment. The current state-of the-art in intermittent fault detection during maintenance testing includes latching continuity testing, analogue neural network technology and time domain reflectrometry.

4.2. Latching Continuity Testing

The latching continuity testers are typically designed to detect continuous electrical parameters (such continuity) for open and closed circuits and power interruptions. It is essentially based on the working principle of a threshold comparator where a Schmitt trigger is used to detect the change in the voltage. The latching function uses the bi-threshold configuration. When an input voltage exceeds the first threshold, it triggers the output to a high level and 'latches' to that high state unless the input signal drops to a second threshold level. This is been used in capacitively coupled neural network to capture very short duration, up to nano second , intermittent fault **[7].** Continuity testing is the general principle employed in standard industry Automatic Testing Equipment (ATE).

4.3. Reflectrometry

Time Domain Reflectrometry (TDR) [8] is an electronic instrument to diagnose faults in electrical conductors. It is regularly used to test wiring in aircraft and can also be used in Printed Circuit Board. TDRs transmit a short duration pulse into the circuit which is reflected if there is any damage within the connection or wiring [9]. The reflected signal is generated due to an impedance mismatch; if no change in impedance is encountered then the injected signal will be absorbed in far end.

There are a variety of different reflectometry techniques. Spread Spectrum Time Domain Reflectrometry (SSTDR), for example, is a technique used to identify the continuity faults in the electronic circuits [10]. SSTDR has advantage on other time domain reflectrometry because it offers the ability to be used in high noise and live environments. It is also good at locating faults with a higher precision due to higher operating resolution. The working principle of SSTDR is to modulate the signal with Pseudo Random code and cross correlate the received signal with the reflected signal to check the continuity faults in the circuits.

It is recognised that when a Radio Frequency (RF) signal is applied to an electrical or electronic circuit and it encounters a discontinuity due to an impedance mismatch, the small portion of signal reflected back will depend upon the difference of impedance. It is very hard to determine the fault location with single frequency but the use of broad band frequencies are used to improve the resolution and determine the exact distance the fault is along the wiring/connection.. The basic working principle is the same as TDR but the measurement methods are different. In frequency domain reflectrometry there is frequency, magnitude and phase that can be used for the continuity test [11] measurements. There are three methods that are used in the FDR. The Frequency Modulated Carried Waves (FMCW), Phase Detection Frequency Domain Reflectrometry (PD-FDR) and Standing Wave Reflectrometry (SWR). In FMCW a very quickly varying modulated carrier applied to the system and frequency shift is calculated to localize the fault. This calculated by using the shift in frequency correspond to time delay in the time domain property. In PD-FDR it is similar to FMCW but the phase in frequency domain to derivatives in time domain property is used to calculate delay time for the localization of the open or short circuit. In SWR the magnitude of standing waves or location of null in frequency domain is used to calculate the location of the malfunction.

4.4. Analogue neural network technology

Some early discussions with academics have suggested to the fact that intermittent connections which are caused by wear and stress could perhaps progressively get worse over time. Traditional testing methods (that measure one point at a time using scanning methods) may not always be effective in detecting these intermittent connection problems during incipient stages. A sensitive analyser was introduced by Universal Synaptic to simultaneously monitor test lines for voltage variation, and seems to have become an attractive tool for detection of the intermittency. Conducting the intermittency test simultaneously using an analogue neural-network process provides an increase in probability of this substantial increase in the probability of detection, combined with the reduction in the time taken to complete the test (because the testing is performed for multiple points simultaneously, rather than testing one line at a time) mean that exploiting analogue neural-network equipment to detect and eradicate intermittent faults in electrical and electronic aerospace components, are potentially of the most effective test methodology as the overall test coverage is of several orders of magnitude higher than other methods as illustrated in figure 3.

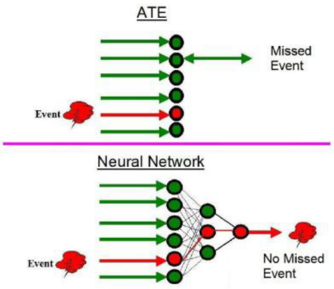

Figure 3: Automatic Test Equipment vs Analogue Neural Network [6]

5. Intelligent Fault Diagnostic Approaches

5.1. Health monitoring of electrical systems

If it is possible to assess in-situ the extent of degradation of electronic systems then this data would be invaluable in meeting the objective of providing efficient fault detection and identification which would include evidence of "failed" equipment found to function correctly when re-tested (no-fault found) and hence improve maintenance processes, extend life, reduce whole life costs and improve future design. There are essentially the following four current approaches to heath monitoring and management of electronic products

- Built-In-Test (BIT)
- The use of fuses and canaries
- Monitoring and reasoning of failure precursors
- Monitoring accumulative damage based on measured life-cycle loads

Within the aerospace industry there is often a perceived restriction on integrating new in-situ health monitoring which require additional sensors. One trend therefore is to move more towards techniques that rely on knowledge of the systems physics and models rather than significant levels of measured data.

5.2. Model based diagnostics

Several common approaches include the use of parameter estimation, observers and parity equations. All of these methods operate by generating a set of residuals which can be compared to the systems nominal behaviour and hence used to indicate any faults which are present or developing. These residuals can be analysed and machine faults can be detected, isolated and identified. The typical example of Model-Based diagnosis has been illustrated in the figure 4.

Model base diagnosis for the intermittent faults includes physical equations, state equation, state observers, transfer-function, neural and fuzzy models [13].

The use of robust nonlinear observers is of particular interest as a model-based diagnostic approach for diagnostics. The observer is basically a model of the plant; it has the same input and follows a similar differential equation Not all of the systems states $x(t)$ can be directly measured (as is commonly the case). We can therefore design an observer to estimate them, while measuring only the output $y(t) = Cx(t)$.. An extra term compares the actual measured output y(t) to the estimated output of the observer$\hat{y}(t)$; minimising this error will cause the estimated states $\hat{x}(t)$ to tend towards the values of the actual real-system states x(t). It is conventional to write the combined equations for the system plus observer using the original state $x(t)$ plus the error state [1].

$$e(t) = x(t) - \hat{x}(t) \tag{3}$$

It is possible to design the observer so that the existing error dynamics between the estimated and actual states are stable even in the presence of uncertainties and unknown inputs. The main advantage of nonlinear observers is that it is possible to diagnose the intermittent faults by generating a residual and an adaptive threshold which is highly sensitive to faults and insensitive to any bounded uncertainties. The residual can also be designed alongside the use of adaptive thresholds so that the fault detection is only sensitive to faults of a specific magnitude.

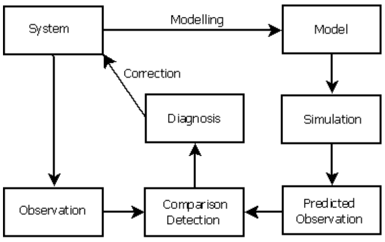

Figure 4: Model-based diagnostics

6. System Level Analysis

6.1. Component level symptom vs. platform level fault

The avoidance of NFF requires the successful identification of the root cause of the unscheduled removal. However, there is evidence that often, testing may result in the identification of faults which are taken as being the root cause but in truth they are not. These are referred to as 'secondary faults' and are of particular importance in intermittent fault related NFF cases. Intermittent grow over time, and in the context of a connector intermittent, they begin by being seen as small, short duration fluctuations, voltage drops or electrical noise that generally do not necessarily cause problems. With the increasing sensitivity of test equipment, which usually tests for intermittent on the intermittent level, smaller and smaller intermittent can be detected. What is required is a mechanism that allows these component level symptoms to be traced back through the component/subsystem/system level to determine if they are the real cause of the initial fault warning at the vehicle level. This requires knowledge on the dynamics of coupled systems and is actively being researched through the use of Phase Space Reconstruction methods by the authors.

6.2. Diagnostic fault trees & case based reasoning

Fault-tree analysis can be a useful analytic tool for verifying the reliability and safety of a complex system. They are traditional manual fault diagnostic approaches that use 'diagnostic decision tree maps' to troubleshoot a system by reducing the number of test points. To be able to diagnose, a system designer seeks to answer some questions, like what kind of components has been used and what is their impact on the system. Singh et al has used the fault tree method for intermittent faults diagnosis for electronic control unit (ECUs) and sensors for vehicles and built a data-base of signals to describe the possibilities for intermittent failure. It provides a series of cascaded decision trees containing different and independent features, when features are being used it reduces the decision tree. They develop computer software to automate this. Case-Based Reasoning (CBR) is a way of using past solutions to a similar new problem [15]. It is the process to retrieve a prior case from the database, and attempts to determine its relevance to decide what and how the solution should be done, [16]. CRB has been applied to aircraft malfunction handling and rail fault detection [17]. CBR is effective when combined with decision trees and has been applied for intermittent fault diagnosis in vehicles.

6.3. Phase space reconstruction

There are interesting observations that hint that intermittent faults in different system elements have distinct ‘footprints’ and that they will affect the dynamics of coupled systems differently. A new area of NFF research is focused on the use of ‘Reconstruction of Phase Space’ (RPS) for systems [18]. A dynamical system is defined as a mathematical description for time evolution of a system in a state space. State space is the set of all possible states of a dynamical system, and each state corresponds to a unique trajectory in the space. State space represents the motion of the dynamical system in geometric form. However, for an experiment, the available information is usually not a phase space but only time series data from some of the states. Therefore the problem of converting time series data into an induced state space is well known, and commonly referred to as phase space reconstruction.

The use of state space is useful when there are coupled systems with dependent variables. For example, the most famous is described by the Lorenz contractor described by the following differential equations, an example of the 3-dimensional phase space for this is illustrated in Figure 5.

The topology structure and geometry characteristic are analyzed from the reconstruction phase or three-dimensional phase orbit. After reviewing the orbit embranchment and the geometry aberrance of the orbit, the variation of the system’s dynamic parameters or outside environment may cause a change of balance. The two most popular techniques for analysis of phase-space for the application of fault diagnostics are the use of the largest Lyupanov exponents or the use of principle component analysis to identify parameters that can be used as the characteristic parameters of fault diagnosis [19].

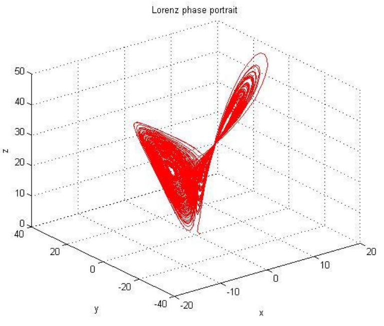

Figure 5: 3-d phase space for the Lorenz contractor

7. Conclusions

The research presented in this paper is ongoing as part of the EPSRC Centre in Through-life Engineering Services No Fault Found research, which include the prediction of NFF related faults through the use of nonlinear observers, the analysis of system stability and coupling using phase-space reconstruction. Further work is focused on the development of hardware implemented health monitoring algorithms aimed specifically for the intermittent fault case. This future work will include enhancing the simple hard decision threshold methods in latching continuity to soft decisions using fuzzy logic and cross correlation function or impulse response can be used to monitor the intermittent faults in the electronics circuits.

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