Decision Algorithms for Electrical Wiring Interconnect Systems (EWIS) Fault Detection

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Abstract—A number of methods exist for the characterization of wire in an EWIS, such as Time Domain Reflectometry, Frequency Domain Reflectometry or Standing Wave Reflectometry. These techniques can usually characterize the length of the wire, and if the wire is open or shorted. Using Time Domain Reflectometry, we attempt to characterize additional features of a wire under test, such as chafe or connectors.

The waveform from a Time Domain Reflectometry system is processed to remove multiple reflections and normalized to restore frequency content due to high frequency attenuation. This processed waveform is then characterized by a decision algorithm. We present a multiple hypothesis testing algorithm and other statistical techniques for wire event detection, with experimental results.

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1. INTRODUCTION

As the aircraft fleet ages, maintenance action concerning wiring becomes an increasing problem. Unfortunately, there are few tools available to the maintainer for trouble shooting EWIS issues. Traditionally, intermittent faults or device failures have been associated with the affected Line Replaceable Unit (LRU). This may result in unnecessary maintenance actions, including the replacement of the LRU. Furthermore, the maintenance action might not address the root cause of failure – bad wire.

Furthermore, there is no periodic maintenance procedure that directly addresses wire. The increasing age of the aircraft fleet, without periodic inspection of wire, will have more faults associated with faulty wiring. An inspection methodology is needed such that some measure of wire health can be tracked over time. This will allow scheduled maintenance to be performed when degradation in the wire is observed. This concept is not new and follows an "On Condition" maintenance paradigm. While detections of opens and shorts may be satisfactory for trouble shooting on the line, it would be desirable to detect chafes or other "soft faults". Logisticians could then plan for opportunistic maintenance, ordering parts, etc, resulting in more reliable fleet assets and reduced total maintenance cost. The added ability to detect soft faults will allow for a shift in maintenance philosophy from a reactive position to a proactive one. While a reliable troubleshooting tool is desirable, larger potential cost savings will be realized when and if a tool can reliably detect faults other than opens or shorts..

2. HARDWARE CONSIDERATIONS

In order to achieve a level of performance that would allow detection of EWIS events other than opens and shorts, a number of engineering issues require attention. Initially, there is the decision of which paradigm to use for wire characterization: Time Domain Reflectometry (TDR), Frequency Domain Reflectometry (FDR), Standing Wave Reflectometry (SWR) or some combination thereof (e.g. Time-Frequency Reflectometry?).

An initial choice was made to use TDR because the method is relatively simple to implement for a high bandwidth system. That is, it requires a fast rise time step function, and a high sample rate. A high sample rate allows for finer resolution time (length) of an event, while a fast rise time

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should allow for smaller changes in wire characteristic impedance. Change in characteristic impedance, ostensible, could be used for identification of different EWIS events.

The step function rise time governs the total bandwidth of the input signal, a perfect step function being infinite bandwidth. However, from an engineering perspective, this is unachievable. Given the availability of new RF devices, a low cost 148 pico-second rise time step generator was developed (figure 1). This is equivalent to a bandwidth of 2.3 GHz (ref 1).

The TDR was sampled with an effective sample rate of 5 GSPS. This was accomplished by using a TI ADS808 analog to digital converter (ADC). This ADC has 12 bit resolution, draws a modest 720 milliwatts (power consumption is a serious consideration for implementation in a PCMCIA card) and samples up to 70 MSPS with a 1 GHz analog input bandwidth. The hardware sequentially sampled the ADC at 12 MSPS, 400 times. Once the step generator was triggered, 14 samples where taken from the ADC and dumped to buffer, followed by 200 picoseconds delay prior to the next step function. In order to improve the bit resolution, this operation was performed eight times (e.g. an average of length eight, with a reduction in process noise of $1/\sqrt{8}$.

Additional Algorithmic Consideration: Scattering—TDR measures the voltage versus time from a fast rise time pulse. Changes in the wire inductance or capacitance per unit length cause changes in the characteristic impedance. A change in characteristic impedance reflects a small amount of the voltage in the transmitted waveform. The reflected voltage is a function of the incident voltage and the change in impedance:

$$V_{measured} = (Z_{i+1} - Z_i)/ (Z_{i+1} + Z_i) \cdot V_{incident} + V_{incident}$$

Any change in local wire capacitance or inductance will cause a change in the reflected voltage.

This phenomenon has been well documented and is currently being used in many TDR devices for the detection of opens and shorts. For example, if Z_{i+1} is large compared to Z_i, a condition indicative of an open, the measured voltage will approach two times the incident voltage. Conversely, if Z_{i+1} is small compared to Z_i, which is a short, the measured voltage approaches zero. The distance to the open and short is function of the wire velocity of propagation (VOP – which is a percentage of the speed of light) and the time between transmission and reception of the change in voltage.

It is apparent that any change in wire capacitance or inductance (due to damage or change in the distance between the wire under test and the return path) will result in changes to the local characteristic impedance. This can be identified by a change in measured voltage. The measured voltage is the superposition of incident voltage and reflected voltage. The ratio of the reflected voltage to the incident voltage is the reflection coefficient.

$$rho = V_{reflected}/V_{incident}$$

Because of energy conservation, the energy that is not reflected is transmitted down the wire. The transmission coefficient is then:

$$\tau = \sqrt{1 - rho^2}$$

When two events occur on the wire, the reflected energy of the second event is transmitted through the first event (which is measured at a time associated with the second event) and reflected back towards the second event. Some small portion of the energy is reflected and transmitted between the two events, resulting in measured events delayed in time. The situation becomes more complex with multiple events on the wire.

This scattering effect adversely distorts any calculation of impedance and must be controlled for. By making a simplifying assumption that the transmission line can be modeled as a Goupillaud medium (i.e. a medium in which the response at any discontinuity point $\varsigma = id$ at any time t depends only on the input at the times t, $t\text{-}d$, $t\text{-}2d$, etc.) the inverse scattering problem can be solved. This solution is found by representing the current and voltage as a coupled first-order partial differential equations (ref 2). The inverse scattering problem gives a better representation of the true EWIS impedance (figure 2). Figure 2 depicts an artificial test harness using a 50 Ohm coaxial cable interspersed with two lengths of 75 Ohm coaxial cable and is not atypical of an aircraft harness. However, it is a good test of the inverse scattering algorithm.

Additional Algorithmic Consideration: Frequency Attenuation—The TDR signal is a step-pulse with a short rise-time. As noted, this equates to a high frequency component within the TDR signal, which due to the properties of the transmission line, is attenuated and dispersed in time. In order to correct for this behavior, an inverse filter is required that is matched to the transmission line transfer function for a given frequency and length.

Attenuation for shorter transmission lines (3 meters or less) is governed by skin effect. Maxwell's equation shows that very high frequency attenuation is an exponential function of wire core diameter, frequency, characteristic impedances, and length (see [3]):

$$A(f, Z_o, L) = e^{-\left(\text{LengthK} / \text{dZ}_o f^{.5} \right)},$$

where: *Length* is distance, K is the conductivity, Z is the characteristic impedance, and f is the frequency. For longer transmission lines, the attenuation is predominately a function of transmission line resistance and capacitance. This allows the loss to be modeled as a RC circuit, a function of the capacitance and resistance of the wire itself.

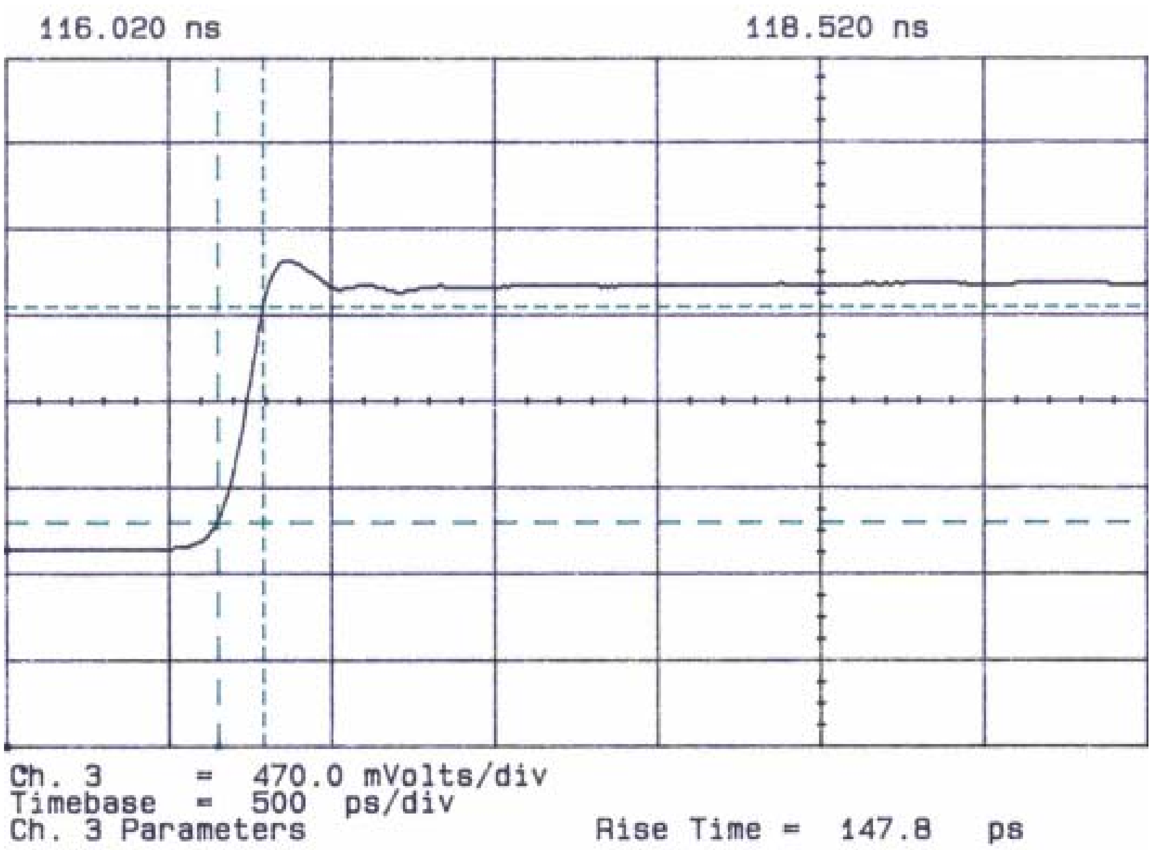

Figure 1 148 PS Step Generator

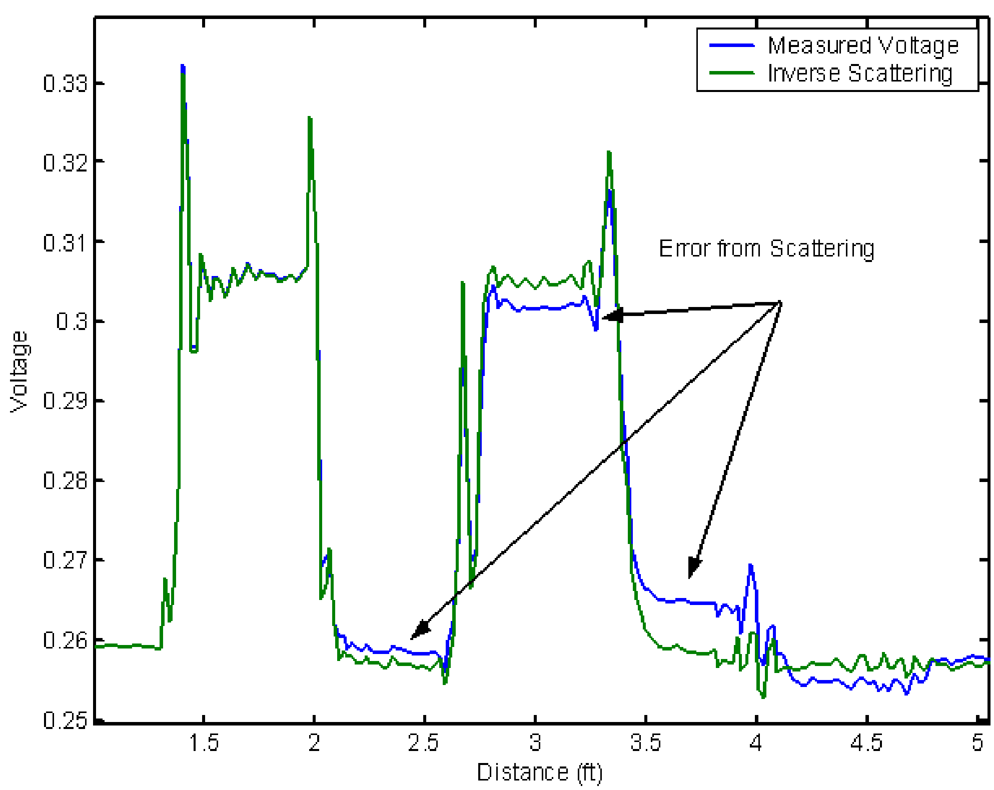

Figure 2 Example of Scattering in EWIS

The resistance of the wire is a function of wire segment,

$$R = dLength2/(2r^2K),$$

where *r* is wire radius. The capacitance is a function of the measured characteristic impedance z:

$$C= 1./(c*vop*z),$$

c is the speed of light and *vop* is the velocity of propagation, taken as $1/\sqrt{dielectric}$. The transfer function is the: $H_i = F(1/RC * e^{-t/RC})$, where F is the Fourier transform.

What remains is to model the frequency response for each transmission line segment. The frequency loss is a function of cumulative resistance and capacitance. Thus, attenuation at the end of the transmission line is significantly greater effect than the beginning of the transmission line due to the linear relationship between resistance, capacitance and wire length. The frequency response for transmission line segment *i*, H_i, can then be described by the Fourier transform of RC impulse response of the wire under test for a given distance and wire gauge (see [2]). An appropriate filter to compensate for the attenuation can be built by use of a convolution matrix.

3. STATISTICAL EVENT DETECTION

Once a good representation of the true characteristic impedance has been calculated, a decision algorithm needs to perform two operations: detection and classification. Detection is the process of identifying some anomalous event on the EWIS, where classification is concerned with naming an event to a specific type. While a number of decision methodologies have been developed, such as artificial neural networks, fuzzy logic, Baysian Belief networks, a purely statistical approach was used: hypothesis testing.

Hypothesis testing is a formal procedure that uses the scientific method: one observes the impedance of the EWIS, formulates a theory, and then tests this theory against the observation. In this context one poses the theory that the current impedance is not different from the previous impedance on the EWIS. The model for impedance is that of a function of inductance and capacitance:

$$Z = \sqrt{L_i / C_i}$$

An event of the wire, due to a chafe or connector will change the local EWIS inductance or capacitance. This will necessarily change the local impedance: a change in impedance is an indicator of either a change in inductance or capacitance. Formally, the test is:

$$H_0 : Z = Z_0$$

$$H_a : Z \neq Z_0$$

The test statistic is then

$$\theta = \hat{Z} - Z_0 / \sigma_{\hat{Z}}$$

where one rejects the null hypothesis when $|\theta| > \theta_{\alpha/2}$, where θ is the normal Gaussian statistic for the two tailed rejection region and the probability of type I error is α. A type I error is made if H_0 is rejected when H_0 is true (see [4]).

Of importance is the selection of the sample size for mean and variance in Z. There are a number of environmental factors that will cause the variance of the impedance to change across the EWIS. Errors in the wire normalization result in the variance at the beginning of the wire to be different from the end of the wire, and the events themselves will skew the calculation of the variance. Because of this, a small sample test was used to calculate the local impedance mean value and variance, which where used for the hypothesis test. These local statistics where calculated from the 31 sample just prior to the impedance value being tested. As an example, figure 3 shows the raw measured voltage and inverse scatter/compensated voltage waveform. This is an example of a 22 gauge twisted shielded pair. The wire has a total length of 40 feet with two connectors and a chafe.

A type I error of 10^{-5} was used, such that we reject the null hypothesis when |θ| is greater than 4.42. The detection algorithm then identifies an event as the first point in a run of 3 θ greater than the 4.42. Figure 4 depicts calculated θ values, the detected events, and the measured voltage waveform.

A number of other detection methodologies where tried, such as event detection on the 1st derivative of the normalized voltage or χ^2 goodness of fit of the waveform for templates of defects. These other methods resulted in either lower probability of event detection or unacceptably high false alarm rates.

4. EVENT CLASSIFICATION

Classification of an event is akin to testing the hypothesis that the event is a chafe, connector, or some other feature. After sampling the impedance waveform and events, *n* possible hypotheses (decision outcomes) are defined: H_0, H_1, ... H_{n-1} (a multiple hypothesis test). By convention, H_0 is called the null hypothesis, corresponding to a unknown event type or the nominal wire environment.

The observation is a parameterized measurement of a system, which is a function of some probabilistic law. This reduces the hypothesis-testing problem to one of deciding which hypothesis most represents truth, based on the measurement impedances (a vector of impedance values). The range of θ is the observation space, Φ.

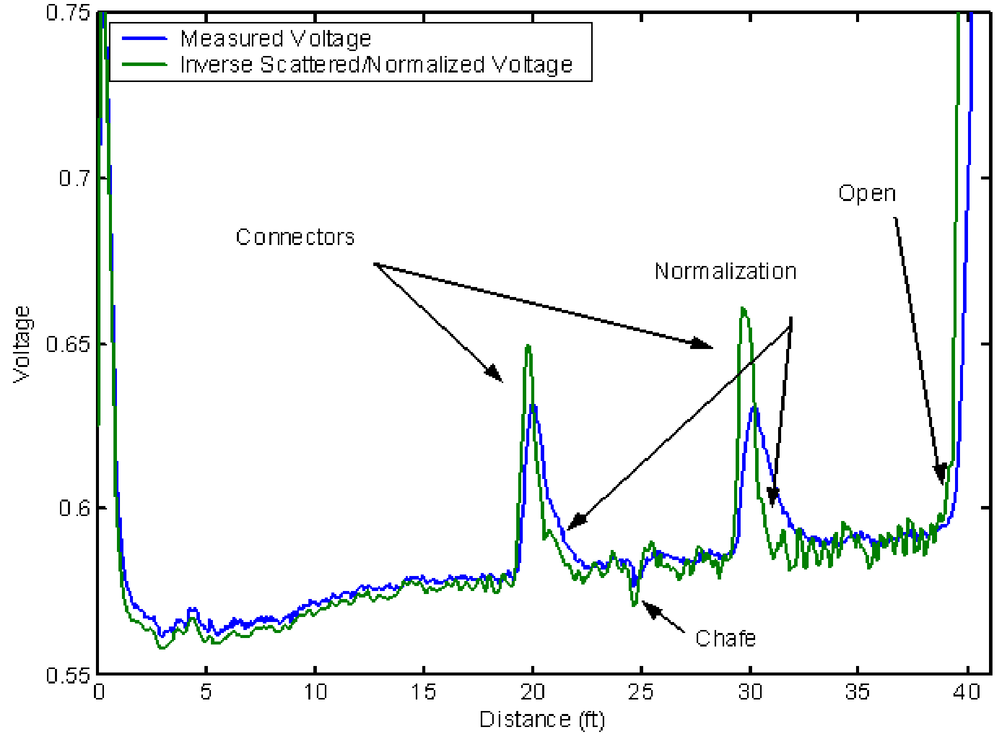

Figure 3 Example of Twisted Shielded Pair

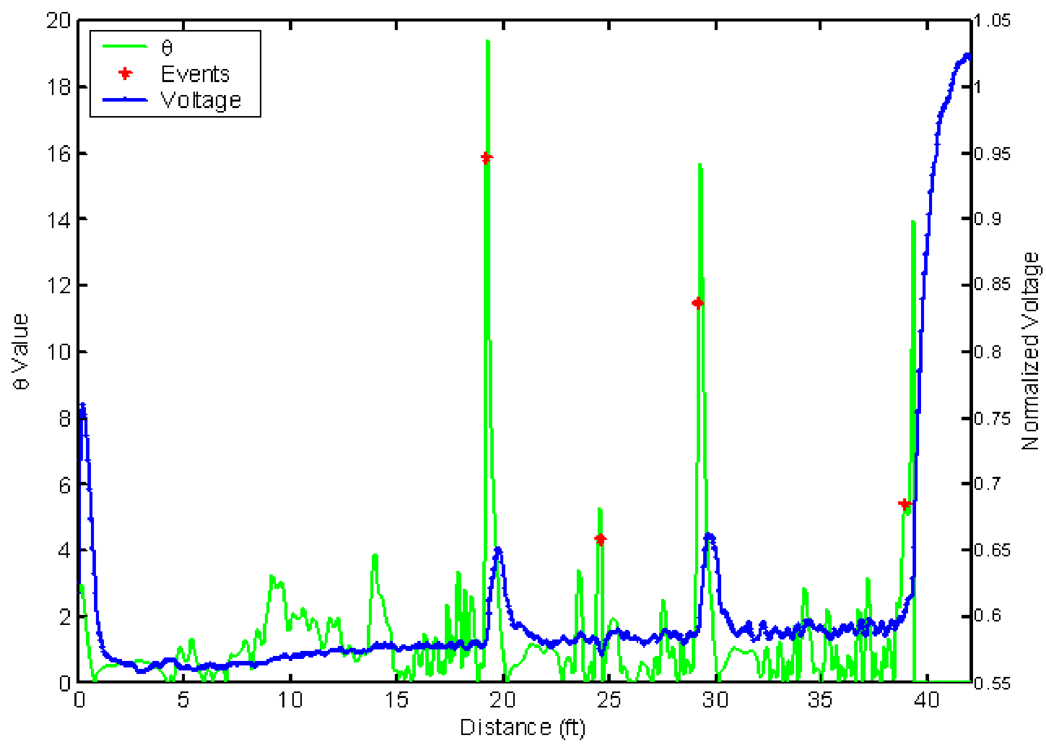

Figure 4 Theta Values, Events and Voltage for Damaged Twisted Shielded Pair

The decision problem consists of partitioning this observation space into n regions, Φ_0 (unknown event) or $\Phi_1 \ldots \Phi_{n-1}$ (some other know feature). When θ falls within Φ_0 then H_0 is defined as true and when θ falls within Φ_1, then H_1 is defined as true. When the decision that has been made that is made is not valid, an error has occurred.

This is the essence of a hypothesis test. The goal is to create a decision region that minimizes the error with the given observation space Φ. In the general case, the observation space consists of a set of parametric observations $\boldsymbol{\theta} = (Z_i, Z_{i+1} \ldots Z_{i+m})$ with some joint probability density function $p(Z_i, Z_{i+1} \ldots Z_{i+m})$.

Modeling the Observation Space as the Test of a Hypothesis

$P(H_i|\theta)$ is defined as the probability that H_i was the true hypothesis given a measured observation. Then the correct hypothesis is the one corresponding to the largest probability of the n hypotheses. The decision rule will be to choose H_0 if:

$$P(H_0|\theta) > P(H_1|\theta), P(H_2|\theta), \ldots P(H_m|\theta).$$

For the binary case, the rule becomes:

$$\frac{P(H_1 | \theta)}{P(H_0 | \theta)} \underset{H_0}{\overset{H_1}{\gtrless}} 1$$

This is the maximum a posteriori probability criterion, wherein the chosen hypothesis corresponds to the maximum of two posterior probabilities1. Using Bayes' rules to write the criterion gives:

$$P(H_i | \theta) = \frac{p(\theta | H_i) P(H_i)}{p(\theta)}, \quad i = 0,1$$

where P(Hi) is the probability of Hi in the observation space, such that:

$$\frac{P(H_1 | \theta)}{P(H_0 | \theta)} = \frac{p(\theta | H_1) P(H_1)}{p(\theta | H_0) P(H_0)}$$

This allows the test to become:

$$\frac{p(\theta | H_1)}{p(\theta | H_0)} \underset{H_0}{\overset{H_1}{\gtrless}} \frac{P(H_0)}{P(H_1)}$$

The ratio $l(\theta) = p(\theta|H_1)/p(\theta|H_0)$ is defined as the likelihood ratio. If the likelihood ratio is assumed to be well behaved and everywhere continuous and differentiable, then without loss of generality, the natural logarithm of both sides can be taken. The logarithm is a monotonically increasing function so that the inequality holds. The terms of the log-likelihood ratio become:

$$\mathbf{ln}\, l(\theta) \underset{H_0}{\overset{H_1}{\gtrless}} \mathbf{ln} \frac{P(H_0)}{P(H_1)}$$

In making a decision in a binary hypothesis-testing problem (e.g. an unknown event vs. a connector event), there are four possible outcomes:

Say H_0, and it is true that the component is healthy;

Say H_1, and it is true that the component is faulted;

Say H_1, but the component is healthy; and

Say H_0, but the component is faulted.

The third condition is a type I error and is referred to as a false alarm. The forth condition is a type II error and is referred to as a missed detection. The probability of detection (PD) is 1 minus the probability of missed detection (PM).

The Bayes Classifier for the Normal Distribution— Under many circumstances, the Normal distribution is a valid model of the data. In the case of an n-dimensional observation space, due to the Central limit theorem, the Normal distribution should be the default distribution. For the generalized n dimension decision space, the hypothesis H_0 is defined as the mean of the impedance vector space, m_0, representing an unknown event and the probability distribution function of the impedance vector, θ, given H_0 is defined by the Normal distribution (centered on m_0)

$$H_0 : m_0 = E\{\boldsymbol{\Phi}_0\}$$

$$p(\theta | H_0) = \frac{1}{(2\pi)^{n/2}} |\Sigma_0|^{-1/2} \mathbf{exp}\left[-\tfrac{1}{2}(\theta - m_0)^T \Sigma_0^{-1} (\theta - m_0)\right]$$

while the alternative is;

$$H_1 : m_1 = E\{\boldsymbol{\Phi}_1\}$$

$$p(\theta | H_1) = \frac{1}{(2\pi)^{n/2}} |\boldsymbol{\Sigma}_1|^{-1/2} \mathbf{exp}\left[-\tfrac{1}{2}(\theta - m_1)^T \Sigma_1^{-1} (\theta - m_1)\right]$$

where Σ is the covariance. Now define the normalized distance squared between θ and any m, being the mean of the given decision space:

$$d^2 = (\theta - m)^T \boldsymbol{\Sigma}^{-1} (\theta - m)$$

The log likelihood ratio test is then:

$$\tfrac{1}{2}\left[d_0^2 - d_1^2\right] + \tfrac{1}{2} \ln\left(|\Sigma_0| \big/ |\Sigma_1| \right) \underset{H_0}{\overset{H_1}{\gtrless}} \ln \frac{P_0}{P_1}$$

where |Σ| is the determinant of the covariance. This states that if the normalized distance squared between **θ** and m_0 (plus a threshold offset) is greater than the normalized distance between **θ** and m_1, then accept the alternate hypothesis, H_1.

5. EXAMPLE

Using the twisted shielded pair example, configuration data was taken by extracting mean value and covariance for chafe and connectors. This template data was then used in the Baysian classifier. The results are:

Event Type	Event @ 19.2 ft	Event @ 24.6 ft	Event @ 29.2 ft
Φ_1 (Connector)	**6196**	-4665	**7223**
Φ_2 (Chafe)	1394	**208**	2277

NOTE THAT IMPLICITLY ONLY M-1 TESTS ARE CONDUCTED. BY DEFAULT, IF NO TEST SCORE IS GREATER THAN ZERO, THE NULL HYPOTHESIS IS NOT REJECTED. THE TEST REJECTS THE NULL HYPOTHESIS IF THE SCORE IS GREATER THAN 0 AND CHOOSES Φ_I THAT IS LARGEST. IN THIS EXAMPLE, THE FIRST EVENT IS CLASSIFIED AS A CONNECTOR, THE SECOND EVENT IS CLASSIFIED AS A CHAFE AND THE THIRD EVENT IS CLASSIFIED AT A CONNECTOR. ONE ASPECT OF A BAYSIAN CLASSIFIER IS THAT THE TEST DOES NOT IMPLY THAT THE EVENT IS A HYPOTHESIS, ONLY THAT IT IS MORE LIKE ONE HYPOTHESIS THAN ANOTHER. FROM A PARTICLE STAND POINT, THIS SUGGESTS THAT DEVELOPING A TEMPLATE REQUIRES A SMALL CLASS OF EVENT TYPES – IN THE CASE GIVEN, ONLY THREE: NOMINAL LINE, CONNECTOR OR CHAFE.

6. DISCUSSION

We have gained a better understanding of modeling wire response, event detection and classification. Acceptable detection and classification have been observed; certain model violations reduce the potential performance of the system. For example, the inverse scattering problem assumes a perfect step function, but frequency attenuation causes this model to be less perfect as the length of wire increases. Additionally, frequency normalization does not take into account the deleterious effect of connectors. Finally, a better method for estimating noise (e.g. threshold setting) needs to be developed. These suggestions are tweaks to the basic system.

Finally, other decision models should be investigated. For example, when testing a wire such as a twisted shielded pair, there are six potential tests that can be done:

Wire A to Wire B
Wire B to Wire A
Wire A to Shield
Shield to Wire A
Wire B to Shield
Shield to Wire B

These tests are correlated, and any damage should be correlated as well. Testing of this type may improve the probability of detection for a given false alarm rate.

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BIOGRAPHY

Dr. Bechhoefer is retired Naval aviator with a M.S. in Operation Research and a Ph.D. in General Engineering, with a focus on Statistics and Optimization. Dr. Bechhoefer has worked at Goodrich Aerospace since 2000 as a Diagnostics Technical Lead. He has previously worked at The MITRE Corporation in the Signal Processing Center.

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