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A Study of Built-In-Test Diagnosis Mistakes as a False Alarm Filter

Useful Redundant Techniques for Built-in-Test Related System[+]

Hyun Seung Oh*
Wang Jin Yoo**

ABSTRACT

Early generations of products had little to no inherent capability to test themselves. The technologies involved often required only visual inspection and limited probing to troubleshoot the system once it was turned over to maintenance personnel. However, as the complexity of military and commercial systems grew, symptoms of failure became less noticeable to the operator. Therefore, the procedure to access, inspect, repair and replace a component became complicated, the requirements for personnel skill and testing equipment increased, and it took too long of a time to maintain a system. Meanwhile, the need for availability became more mission-critical and maintenance become very expensive. The obvious solution was to design in-system circuits or devices to self-test the primary system, the Built-In-Test(BIT) was born. This approach has continued right on up through present systems and is an integral part of systems now being designed. The object of this paper is to present a state-of-the-art research for filtering out the BIT diagnosis mistakes using Bayesian analysis and develop the algorithm for Redundant systems with BIT to improve BIT diagnosis.

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* Department of Industrial Engineering, HAN NAM UNIVERSITY

Ⅰ. Introduction

1. General Concept of Built-In-Test

The term "Built-In-Test" refers to a subsystem whose major purpose is to test the operating state of the primary system. Briefly, BIT is the hardware and software that are integrated into a system to perform fault detection, diagnosis and isolation, and failure recording, along with possible reconfiguration or failure management[7].

BIT has attractive advantages, but some shortcomings as well. Today's technology cannot assure a perfect BIT. In fact, the improvements in BIT over the last decade and a half have, to a great extent, been canceled out by the increasing complexity of systems.

In addition, BIT is disastrously inefficient when applied to a high-reliability system : the high false alarm probability harasses maintenance personnel and designers a great deal. A breakthrough is needed to resolve this problem.

Malcolm has presented a new approach to this problem by using Bayesian analysis and the Bayesian processor[8, 9, 10, 11]. He has done an excellent job in this area. However, Malcolm's approach is not completely satisfactory and is not ready for used in real-world systems. His approach needs broadening, improvement, and refinement. This paper expends on Malcolm's approach, develops strict and complete mathematical models of the Bayesian processor.

Ⅱ. Bayesian Analysis of BIT Diagnosis Mistakes

1. General Source of Diagnostic Mistakes

Figure 1 is an event which depicts the essential properties of a test and illustrates the two types of diagnosis mistakes.

Theoretically, there are four path probabilities for a system under test. This implies that every test has a certain probability of calling a good system bad(false alarm) and a bad system good(missed fault). Obviously, this is also true for a system with BIT.

2. Bayesian Analysis of BIT Diagnosis Mistakes

Before we can analyze BIT diagnosis mistakes using the Bayesian approach, the following assumptions are essential and necessary :

(1) A complete failure modes and effects analysis has been done, i.e., all potential failure modes are specified and defined.

(2) The BIT is capable of recognizing all failure modes in the primary system.

Under the above assumptions, the effect of BIT on the primary system will be a random variable which follows a certain probaility density function, and the Bayesian processor can be realized.

In Figure 2, $\overline{F}$, represents the system under test when fault-free, and F represents the system under test when faulty.

In order to diagnose a system, we must to specify the upper and lower test thresholds, X_u and X_l. When a test result lies within the limits of the upper and lower thresholds, we call it a negative test result, denoted by T^-(BIT pass). Inversely, when a test result lies beyond the upper or lower thresholds, we call it a positive test result, denoted by T^+(BIT fail) (see Figure 2).

Malcolm only considered the case where there is one threshold for a test. In reality, there are uncountable phenomena for which we must set lower and upper thresholds to test or measure a system. Some examples are : the voltage of a convertor, tire pressure, the pressure of hydraulic circuit, thrust to adjust the altitude of an orbiting satellite, the diameter of a column, temperatures for heat treatment, turning frequencies, process time periods, etc.

When a test result is issued, should we believe it absolutely, believe it with reservations, or not believe it ? It is unscientific to answer this question impressionistically. We need a method to deal with the test result and get a believable and quantitative judgement. Bayesian analysis is such a method. Using Bayesian analysis, we can obtain a quantitative measure of the probability of truly having a failure or of having no failure when the test results are either positive or negative.

The Bayes formula for a positive test result case is given by :

$$\begin{aligned} P(F \mid T^+) &= \frac{P(F,\ T^+)}{P(T^+)} \\ &= \frac{P(T^+ \mid F) \cdot P(F)}{P(T^+ \mid F) \cdot P(F) + P(T^+ \mid \overline{F}) \cdot P(\overline{F})} \\ &= K_1 \cdot P(F) \end{aligned} \tag{1}$$

where

$$K_1 = \frac{P(T^+ \mid F)}{P(T^+ \mid F) \cdot P(F) + P(T^+ \mid \overline{F}) \cdot P(\overline{F})}$$

is a coefficient.

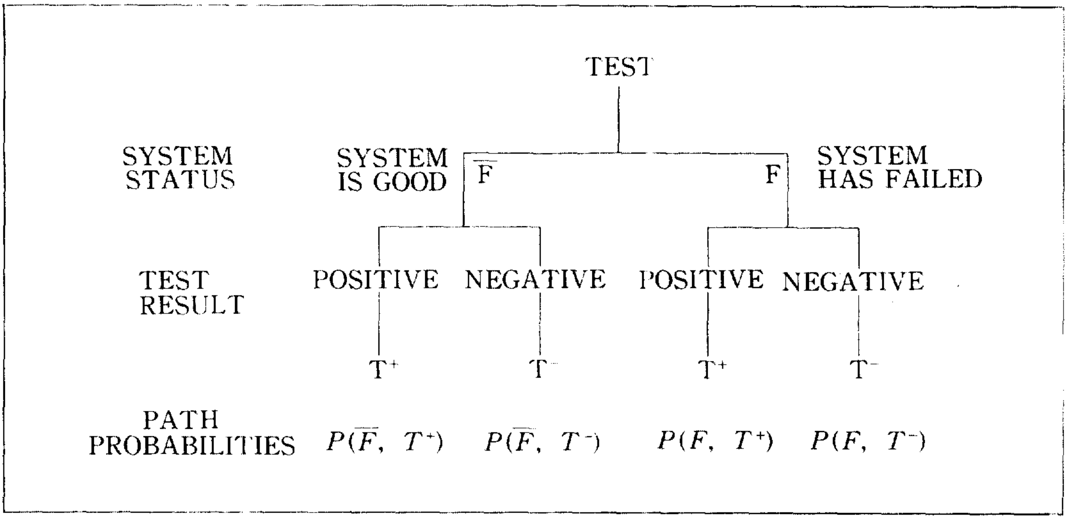

Figure 1. Essential Properties of a Test

The Bayes formula for negative test result case is given by

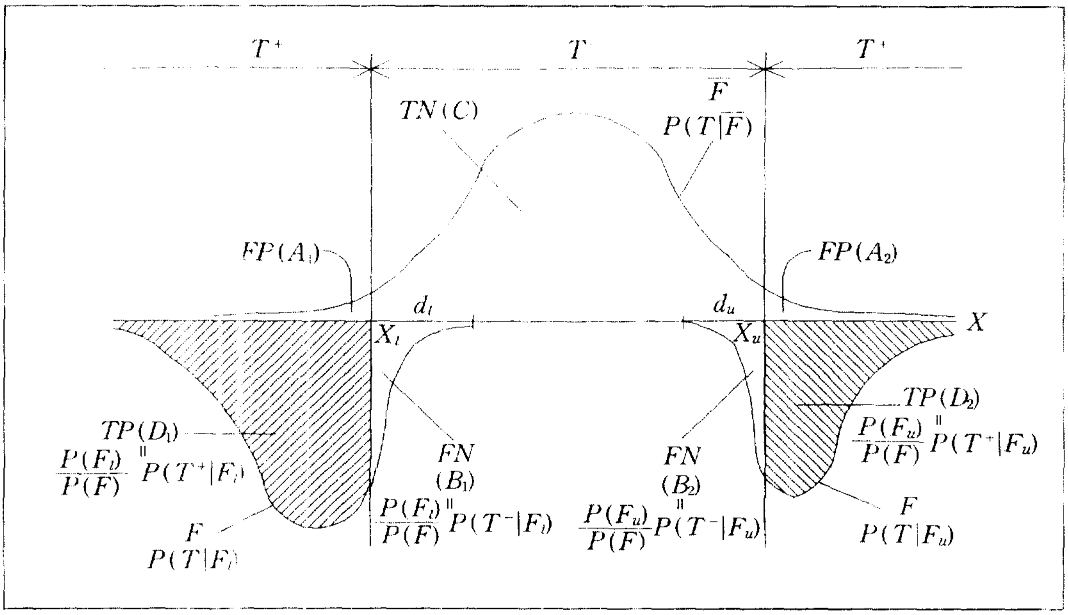

Figure 2. Test Result Probability Density Functions

$$P(F|T^-) = \frac{P(F, T^-)}{P(T^-)}$$

$$= \frac{P(T^-|F) \cdot P(F)}{P(T^-|F) \cdot P(F) + P(T^-|\bar{F}) \cdot P(\bar{F})}$$

$$= K_2 \cdot P(F) \qquad (2)$$

where

$$K_2 = \frac{P(T^-|F)}{P(T^-|F) \cdot P(F) + P(T^-|\bar{F}) \cdot P(\bar{F})}$$

is a coefficient.

In Eqs. (1) and (2), $P(F)$ is the prior probability that the system has failed, and $P(T^+|F)$ is the BIT detection probability. Another important BIT parameter, false alarm probability, is denoted by $P(\bar{F}|T^+)$, i.e., the Probability that a BIT will indicate a failure when there is no actual system malfunction. Because

$P(\bar{F}|T^+)$ and $P(\bar{F}|T^-)$ are the complements of $P(F|T^+)$ and $P(F|T^-)$, respectively, we can easily derive the following equations:

$$P(\bar{F}|T^+) = 1 - P(F|T^+)$$

$$= \frac{P(T^+|\bar{F}) \cdot P(\bar{F})}{P(T^+|F) \cdot P(F) + P(T^-|\bar{F}) \cdot P(\bar{F})}$$

$$= K_3 \cdot P(\bar{F}) \qquad (3)$$

where K_3 is a coefficient.

and

$$P(\bar{F}|T^-) = 1 - P(F|T^-)$$

$$= \frac{P(T^-|\bar{F}) \cdot P(\bar{F})}{P(T^-|F) \cdot P(F) + P(T^-|\bar{F}) \cdot P(\bar{F})}$$

$$= K_4 \cdot P(\bar{F}) \qquad (4)$$

where K_4 is a coefficient.

From Eq. (1), if we assume that as long as the test result is positive, the system is faulty, $K_1 \cdot P(F)$ must be unity, i.e.,

$$K_1 = \frac{P(T^+|F)}{P(T^+|F) \cdot P(F) + P(T^+|\bar{F}) \cdot P(\bar{F})} = \frac{1}{P(F)}$$

or

$$P(T^+|\overline{F}) \cdot P(\overline{F})=0$$

$P(T^+|\overline{F})$ must be zero because $P(\overline{F})$ does not equal zero. That is, given a fault-free system, the test result will never be positive. Obviously, this is impossible. Therefore, the probability that the system is faulty given a positive test is less than 1. Or there is always some chance that even though the test result is positive, the system actually works well. This means that the test equipment has raised a false alarm.

From Eq. (3), because $P(T^+|\overline{F})>0$, $P(\overline{F})>0$, we get the same result that the conditional probability $P(\overline{F}|T^+)$, or false alarm probability, is greater than zero.

In a similar way, from Eq. (2), if we require that negative test results assure a fault-free system, $K_2 \cdot P(F)$ must be zero, i. e.,

$$K_2=\frac{P(T^-|F)}{P(T^-|F) \cdot P(F)+P(T^-|\overline{F}) \cdot P(\overline{F})}=0$$

as $P(F) \neq 0$.

Or we must have $P(T^-|F)=0$, which implies that for a given faulty system, there will never be a chance that the test result is negative. This is clearly impossible, because diagnostic technology cannot deliver perfect test equipment. From Eq. (4), the same result will be drawn.

Example of the false alarm probability in high reliability system:

Assume a very high true positive rate of 99% and a very low false positive rate of 2%, and that 3% of the items to be tested are faulty. Referring to Figure 2, where TP means true positive, the corresponding areas are D_1 and D_2 ; for FP(false positive), the areas are A_1 and A_2 ; for TN(true negative), the area is C ; for FN(false negative), the areas are B_1 and B_2.

Substituting the above data into Eq. (1), we have

$$P(F|T^+)=\frac{0.99\times 0.03}{0.99\times 0.03+0.02\times(1-0.03)}$$
$$=0.60$$

Hence, the false alarm probatility is

$$P(\overline{F}|T^+)=1-P(F|T^+)=1-0.60=0.40$$

This result may seem surprising, but it reflects reality.

The preceding analysis explains why high reliability sytems will tend to have testability problems which occur primarily as false alarms [14, 15]. Since the overlapping of the $F-pdf$ curves and the $\bar{F}-pdf$ curve is generally unavoidable, the false alarm problem is an unavoidable fallout.

Researchers used to focus their efforts on improving the test circuits as a means of reducing false alarms, and increasing detection probabilities. Unfortunately, their efforts have not been very effective [1, 2, 5]. The preceding analysis shows that even when the test equipment is excellent, it is still difficult to assure lower false alarm probability. The solution to improving BIT may be found outside the framework of individual tests, i.e. outside the basic BIT configuration.

This approach constitutes a new direction in the improvement of BIT diagnosis techniques. However, in the case where some failure modes in a system have not yet been defined, or have not been considered for testing by BIT, the above Bayesian analysis may not be applicable. The proper approach to this problem is the utilization of an intelligent data processor, such as an expert subsystem [3, 4] or integrated diagnosis system with human capabilities [16, 17].

III. Bayesian Processor-A False Alarm Filter

The major shortcomings of BIT are false alarms and lack of fault coverage, i.e., diagnostic problems. These shortcomings must be recognized as a very complex problem with involves many aspects.

Current techniques make it possible to detect a faulty system with high reliability, say greater than 99%, and fail to avoid false alarms. Desensitizing basic BIT circuits for the purpose of reducing false alarms is generally a mistake, because this will increase the probability of missing faults and will mask intermittents. Indeed, we need a breakthrough to solve BIT diagnostic problems, especially false alarms [12].

1. Principle of False Alarm Filter

Bayesian analysis of an individual test was demonstrated in Section I [13]. However, before replacing the LRU which is indicated as failed by BIT, maintenance personnel will usually test it again. Then the question is, How can we integrate the multiple test results? Further, how can we incorporate the prior failed data which we may also receive from field statistics? The Bayesian processor allows us to use every piece of information we can get, and obtain the probability of failure after the n^{th} test. The BIT false alarm probability could, therefore, be greatly reduced.

2. Mathematical Models

Before deriving the mathematical models for the Bayesian processor, we must make the assumption that the time to failure for both the primary system and the BIT itself is exponentially distributed.

To make the mathematical models more nearly complete, to match the real world, we will consider the situation that the primary system may fail more at one threshold than the other. Consequently, we must consider the trend of the BIT results at the lower and upper thresholds separately.

Let us define :

*$P(F_l|T^-)$ is the probability that the primary system has failed at the lower threshold, given a positive test result.

*$P(F_u|T^+)$ is the probility that the primary system has failed at the upper threshold, given a positive test result.

*$P(\overline{F}_l|T^-)$ is the probility that the primary system has not failed at the lower threshold, given a positive test result.

*$P(\overline{F}_u|T^-)$ is the probility that the primary system has not failed at the upper threshold, given a positive test result.

For negative test result, let us define :

*$P(F_l|T^-)$ is the probability that the primary system has failed at the lower threshold, given a negative test result.

*$P(F_u|T^-)$ is the probability that the primary system has failed at the upper threshold, given a negative test result.

*$P(\overline{F}_l|T^-)$ is the probability that the primary system has not failed at the lower threshold, given a negative test result.

*$P(\overline{F}_u|T)$ is the probability that the primary system has not failed at the upper threshold, given a negative test result.

According to the definition of the conditional probability theorem, we have

$$P(F_l|T^+)=\frac{P(F_l,\ T^+)}{P(T^+)}$$

$$=\frac{P(T^+|F_l)\cdot P(F_l)}{P(T^+)} \tag{5}$$

and

$$P(\bar{F}_l \mid T^+) = \frac{P(\bar{F}_l,\ T^+)}{P(T^+)} = \frac{P(T^+ \mid \bar{F}_l) \cdot P(\bar{F}_l)}{P(T^+)} \qquad (6)$$

From Eqs. (5) and (6), we obtain

$$\begin{aligned}\frac{P(F_l \mid T^+)}{P(\bar{F}_l \mid T^+)} &= \frac{P(T^+ \mid F_l) \cdot P(F_l)}{P(T^+ \mid \bar{F}_l) \cdot P(\bar{F}_l)} \\ &= \frac{P(T^+ \mid F_l)}{P(T^+ \mid \bar{F}_l)} \cdot \frac{P(F_l)}{P(\bar{F}_l)} \\ &= L_l^+ \cdot O_{ol} \qquad (7)\end{aligned}$$

where

$$L_l^+ = \frac{P(T^+ \mid F_l)}{P(T^+ \mid \bar{F}_l)} \qquad (8)$$

and

$$O_{ol} = \frac{P(F_l)}{P(\bar{F}_l)} \qquad (9)$$

L_l^+ is called the likelihood ratio when the test result at the lower threshold is positive. The likelihood ration L_l^+ represents the ratio of the true positive rate to the false positive rate for a BIT fail at the lower threshold.

O_{ol} and $\frac{P(F_l \mid T^+)}{P(\bar{F}_l,\ T^+)}$ are called initial prior and posterior odds of failure at the lower threshold, respectively.

Therefore,

$$\left\{\begin{matrix}\textit{Posterior} \\ \textit{Odds of Failure at} \\ \textit{the Lower Threshold}\end{matrix}\right\} = \left\{\begin{matrix}\textit{Likrlihood Ratio} \\ \textit{for Positive Test} \\ \textit{Result at the Lower} \\ \textit{Threshold}\end{matrix}\right\} \times \left\{\begin{matrix}\textit{Prior Odds of} \\ \textit{Failure at the Lower} \\ \textit{Threshold}\end{matrix}\right\}$$

In a similar manner, we will have

$$\frac{P(F_u|T^+)}{P(\bar{F}_u|T^+)}=\frac{P(T^+|F_u)}{P(T^-|\bar{F}_u)}\cdot\frac{P(F_u)}{P(\bar{F}_u)}$$
$$=L_u^+\cdot O_{ou} \tag{10}$$

where

$$L_u^+=\frac{P(T^+|F_u)}{P(T^+|\bar{F}_u)} \tag{11}$$

and

$$O_{ou}=\frac{P(F_u)}{P(\bar{F}_u)} \tag{12}$$

and for negative test result, we have

$$\frac{P(F_l|T^-)}{P(\bar{F}_l|T^-)}=\frac{P(T^-|F_l)}{P(T^-|\bar{F}_l)}\cdot\frac{P(F_l)}{P(\bar{F}_l)}$$
$$=L_l^-\cdot O_{ol} \tag{13}$$

where

$$L_l^-=\frac{P(T^-|F_l)}{P(T^-|\bar{F}_l)} \tag{14}$$

and

$$\frac{P(F_u|T^-)}{P(\bar{F}_u|T^-)}=\frac{P(T^-|F_u)}{P(T^-|\bar{F}_u)}\cdot\frac{P(F_u)}{P(\bar{F}_u)}$$
$$=L_u^-\cdot O_{ou} \tag{15}$$

where

$$L_u^-=\frac{P(T^-|F_u)}{P(T^-|\bar{F}_u)} \tag{16}$$

In the general case of a test result(either positive T^+ or negative T^-), and we do not care whether the primary system fails or not, or at which threshold. From the conditional probability theorem,

$$P(F|T)=\frac{P(F,T)}{P(T)}=\frac{P(T|F)\cdot P(F)}{P(T)} \tag{17}$$

and

$$P(\bar{F}|T)=\frac{P(\bar{F},T)}{P(T)}=\frac{P(T|\bar{F})\cdot P(\bar{F})}{P(T)} \tag{18}$$

Hence,

$$\begin{aligned}\frac{P(F|T)}{P(\bar{F}|T)}&=\frac{P(T|F)}{P(T|\bar{F})}\cdot\frac{P(F)}{P(\bar{F})}\\&=L\cdot O_o\end{aligned} \tag{19}$$

where

$$L=\frac{P(T|F)}{P(T|\bar{F})} \tag{20}$$

is called the likelihood ratio, and

$$O_o=\frac{P(F)}{P(\bar{F})} \tag{21}$$

is called the prior initial failure odds.

Therefore,

$$\left\{\begin{matrix}\mathit{Posterior}\\ \mathit{Odds\ of\ Failure}\end{matrix}\right\}=\left\{\begin{matrix}\mathit{Likelihood}\\ \mathit{Ratio}\end{matrix}\right\}\times\left\{\begin{matrix}\mathit{Prior}\\ \mathit{Odds\ of\ Failure}\end{matrix}\right\}$$

If a positive test result is given, we will find

$$\begin{aligned}\frac{P(F|T^+)}{P(\bar{F}|T)}&=\frac{P(T^+|F)}{P(T^+|\bar{F})}\cdot\frac{P(F)}{P(\bar{F})}\\&=L\cdot O_o\end{aligned} \tag{22}$$

where

$$L^{+}=\frac{P(T^{+}|F)}{P(T^{+}|\overline{F})} \tag{23}$$

is called the likelihood ratio when the test result is positive.

Similarly, if a negative test result is given, we will find

$$\begin{aligned}\frac{P(F|T^{-})}{P(\overline{F}|T^{-})}&=\frac{P(T^{-}|F)}{P(T^{-}|\overline{F})}\cdot\frac{P(F)}{P(\overline{F})}\\&=L^{-}\cdot O_o\end{aligned} \tag{24}$$

where

$$L^{-}=\frac{P(T^{-}|F)}{P(T^{-}|\overline{F})} \tag{25}$$

is called the likelihood ratio when the test result is negative.

From Eqs. (8), (11), (14), (16), (23) and (25), we believe that the likelihood ratio L takes the same sign(superscript) as the test result T, and the same sign(subscript) as the system $\overline{F}$ or F.

In Eq. (21), note that $P(F)$ is the prior cumulative probaility that the system has failed, i. e.,

$$P(F)=F(t),\ t\geq 0$$

where $F(t)$ is the cumulative failure distribution function, and t is a random variable denoting the time to failure, and

$$P(\overline{F})=1-P(F)=1-F(t)$$

then the prior initial odds are also expressed by

$$O_o=\frac{F(t_o)}{1-F(t_o)} \tag{26}$$

where t_o is the test start time.

When there are multiple tests, we can treat the $(n-1)^{th}$ test result as a prior for the n^{th} test. The result of the n^{th} test is a variable denoted by T_n where n=1, 2, ……

It is obvious that T_n can be either positive T_n^+ or negative T_n^-. In this case, the prior odds given the former (n−1) test results will be

$$O_{n-1}=\frac{P_{n-1}(F|T_{n-1})}{P_{n-1}(\bar{F}|T_{n-1})} \tag{27}$$

We could then use a unified equation instead of Eqs. (22) and (24) :

$$\frac{P_n(F|T_n)}{P_n(\bar{F}|T_n)}=L_n\times\frac{P_{n-1}(F|T_{n-1})}{P_{n-1}(\bar{F}|T_{n-1})},\quad n=1,\ 2,\ \cdots \tag{28}$$

where L_n should take the same superscript sign as T_n and the subscript sign as F and $\bar{F}$.

IV. Prior and Posterior Failure Odds and System Failure Probability P_n

When we begin testing, i.e., $n=1$,

$$\frac{P_1(F|T_1)}{P_1(\bar{F}|T_1)}=L\times\frac{P_0(F|T_0)}{P_0(\bar{F}|T_0)} \tag{29}$$

where $\frac{P_0(F|T_0)}{P_0(\bar{F}|T_0)}$ is called the initial prior odds. We note also that

$$\frac{P_0(F|T_0)}{P_0(\bar{F}|T_0)}=\frac{P(F)}{P(\bar{F})}=O_0 \tag{30}$$

which can obtained from prior field data.

The likelihood ratio, L, represents : (1) the ratio of the true positive rate to the false positive rate for a BIT failure at either the lower or upper threshold(L_l^+ or L_u^+) ; or (2) the ratio of the false negative rate to the true negative rate for a BIT pass at either lower or upper threshold (L_l^- or L_u^-).

If the prior odds $\frac{P(F)}{P(\bar{F})}$ and the likelihood ratio L are given, the posterior odds after the n^{th} test will be readily obtained from Equation(28).

Denote the posterior odds after the i^{th} test, $\frac{P_i(F|T_i)}{P_i(\bar{F}|T_i)}$, by O_i. Then

$$O_i=\frac{P_i(F|T_i)}{P_i(\overline{F}|T_i)}=L_i\cdot\frac{P_{i-1}(F|T_{i-1})}{P_{i-1}(\overline{F}|T_{i-1})}=L_i\cdot O_{i-1},\ \ i\geq 1. \tag{31}$$

The posterior odds after the n^{th} test will be

$$O_n=L_n\cdot O_{n-1}=L_n\cdot L_{n-1}\cdot O_{n-2}=\cdots=\prod_{i=1}^{n}L_i\cdot O_o \tag{32}$$

where L_i can be L_l^+, L_u^+, L_l^- or L_u^-, O_0 is the initial prior odds, and

$$O_0=\frac{P_0(F|T_0)}{P_0(\overline{F}|T_0)}=\frac{P(F)}{P(\overline{F})}=\frac{F(t_0)}{1-F(t_0)} \tag{33}$$

Denoting the probability that the system is faulty given the i^{th} test result, $P_i(F|T_i)$, by P_i and noting that $\overline{F}$ is complementary to F, we have

$$\begin{aligned}P_i&=P_i(F|T_i)\\&=\frac{P_i(F|T_i)}{P_i(F|T_i)+P_i(\overline{F}|T_i)}\\&=\frac{P_i(F|T_i)/P_i(\overline{F}|T_i)}{1+\{P_i(F|T_i)/P_i(\overline{F}|T_i)\}}\\&=\frac{O_i}{1+0_i}\end{aligned} \tag{34}$$

Obviously, the probability that the system is faulty after the n^{th} test will be

$$P_n=\frac{O_n}{1+O_n} \tag{35}$$

V. Further Topics to Improve BIT Diagnosis-Algorithm for Redundant Systems with BIT

Shao & Lamberson [7, 12] have developed a set of mathematical models to deal with cold standby, k-out-of-n, shared load and majority voting system with BIT. A complete algorithm for the mathematical models and sensitivity analysis is needed in this topic.

Some typical sets of BIT parameter data will be input to the computer program and the corresponding reliability, maintainability and availability results of redundant systems can be readily obtained, and a series of curves can be drawn.

The algorithms would be very applicable for engineers, designers and reliability analysts of any redundant system because a redundant system without BIT actually is the same system with a perfect BIT.

In addition, this is a good way to validate and refine upon Shao and Lamberson's mathematical models if necessary. It is possible that this task can be extended as commericial software package because I have not seen a satisfied mathematical model which represents a redundant system considering both undetection and false detection.

VI. Conclusion

As long as we know the initial prior odds O_0(which can obtained from prior field data or development testing data, laboratory testing data could be used to replace field data as an approximation) and the likelihood ratios L_l^+, L_u^+, L_l^- and L_u^-(which play a key role in the Bayesian processor must be carefully determined, based on laboratory testing and statistical techniques), the probability that the system is faulty given the n^{th} test result, P_n, will be readily obtained. A systematic and integrated approach which consists of several methods is needed for solving BIT diagnostic problems thoroughly. Algorithms for Redundant systems(such as Overlapping Technique, Other Redundant BITs) will be developed based on this paper. A computer program and Case study is needed to show that how algorithms work on BIT related systems.

REFERENCES

1. Buswell, S. M. And Sesto, P. A. (1989), "*An Expert System to Facilitate Fault Isolation*", Proceedings of Annual R&M Symposium, pp. 74 - 81
2. Chee, C. W. J. and Power, M. A. (1990), "*Expert System Maintainability*", Proceedings of Annual R&M Symposium, pp. 415 - 418
3. Goodall, A. (1985), The Guide to Expert Systems, Learned Information(Europe) Ltd, Oxford, England
4. Hart, A. (1989), Knowledge Acquisition for Expert System, Kogan Page Ltd, London
5. Hollnagel, (1989), "*The Reliability of Expert Systems*", FLLIS HORWOOD LIMITED, Chichester, West Sussex, England
6. Kapur, K. C., and Lamberson, L. R. (1977), **Reliability In Engineering Design**, John Wiley & Sons, Inc., NY
7. Lamberson, L. R. and Shao, J. (1989),

"*Built-In-Test Technology in Commercial System*", Proceedings of International Industrial Engineering Conference, Toronto, Canada, pp. 357—362

8. Malcolm, J. G. (1981), "*Analysis of Built-In-Test(BIT) False Alarm Conditions*", AD-A108752
9. Malcolm, J. G. (1982), "*BIT False Alarm : An Important Factor In Operational Readiness*", Proceedings of Annual R&M Symposium, pp. 206—212
10. Malcolm, J. G. (1983), "*Practical Application of Bayes' Formulas*", Proceedings of Annual R&M Symposium, pp. 180—186
11. Malcolm, J. G. and Foreman, G. L. (1984), "*The Need : Improved Diagnostics -Rather than Improve R*", Proceedinga of Annual R&M Symposium, pp. 315-322
12. Shao, J. and Lamberson, L. R. (1988), "*Impact of BIT Design Parameters on Systems RAM*", Reliability Engineering and System Safety, Vol. 23, pp. 219—246
13. Shao, J. and Yoo, W. (1989), "*Effect of self-Test on the Reliability of an Automatic Control system*", Proceedings of China-Japan International Symposium on Instrumentation, Measurement and Automatic Control, Beijing, pp. 230—235
14. Yoo, W. (1988), "*BIT PERFORMANCE PARAMETERS*", Technical Notes
15. Yoo, W. (1988), "*BUILT-IN-TEST : The General Concept and The Application*", Technical Notes
16. Yoo, W. (1988), "*Effects of BIT on System*", Technical Notes
17. Yoo, W. (1988), "*FURTHER INVESTIGATION FOR BIT TECHNOLOGY*", Technical Notes