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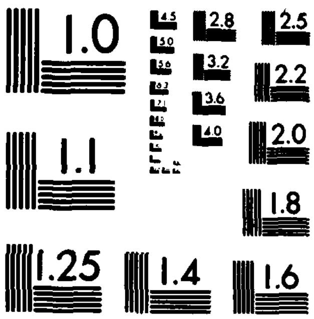

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ONE–STEP DIAGNOSIS ALGORITHMS FOR THE BGM SYSTEM LEVEL FAULT MODEL

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ABSTRACT

A one-step τ-fault diagnosable system is a system in which all faults may be identified from the test results, provided that the number of faults does not exceed τ. In this paper we present two algorithms that may be used for the one-step diagnosability of the system level fault model proposed by Barsi, Grandoni and Maestrini. The first algorithm may be used when the system is one-step τ-fault diagnosable and no two units test each other, and the second algorithm may be used whenever the system is one-step τ-fault diagnosable.

1. INTRODUCTION

In the past few years, a great deal of effort has been devoted to the presentation and analysis of system fault models. These models are characterized by the fact that they do not emphasize test generation, but rather emphasize the use of test results for the purpose of fault location and fault detection. The problems associated with system level fault models are (i) presentation and description of the fault models themselves; (ii) analysis of the diagnosability properties of the fault model under various assumptions concerning the fault-test relationships and the system testing interconnection network; and (iii) synthesis of diagnosis algorithms for fault detection, one-step diagnosis and sequential diagnosis.

Many fault models presently exist [2], [7], [8], [9], [14], and their diagnosability properties are essentially well understood [4], [5], [15-17]. The state of the art, as far as one-step diagnosis algorithms are concerned, is less satisfactory. The two most widely analyzed system level fault models are the PMC model, proposed by Preparata, Metze and Chien [14], and the BGM model proposed by Barsi, Grandoni and Maestrini [2]. There exist algorithms for the one-step diagnosis of the PMC model; unfortunately, they suffer from some serious drawbacks. The algorithms proposed by the author and Masson [10], [12] are only applicable to regular testing interconnection networks, and the ones proposed by the author [11], [13] have been shown to work only when the first Hakimi-Amin hypothesis [5, Theorem 1] is satisfied and the number of faults is limited. The algorithm proposed by Corluhan and Hakimi [3] depends on an unproved conjecture. The algorithms proposed by Allan, Kameda and Toida [1], [6] involve tree searching and backtracking.

The situation for the one-step diagnosis of the BGM model is even less satisfactory: no algorithm has been proposed to date. To remedy this situation, this paper presents two algorithms for the one-step diagnosis of the BGM model. The first identifies the set of faulty devices, provided that the first Hakimi-Amin condition is satisfied and the set of faulty modules is no greater than τ, where τ is the minimum number of system units that test each system unit. The second identifies the set of faulty modules whenever the system is one-step fault diagnosable. These two algorithms are easy to implement and their very existence is an *a posteriori* indication of the strength of the assumptions of the BGM model.

In the first part of the paper, the BGM model is described. Then the basic tenet of our approach, i.e., the partition of the system units into four subsets is presented, together with the properties of that partition. The first algorithm makes direct use of the basic partition properties, and its decoding properties are exhibited. Finally we perform an analysis of the failure mode of the first algorithm and present a remedy -- the second algorithm. We then show that this algorithm may be used to decode syndromes for the BGM model, provided that the model is one-step τ-fault diagnosable, and that the number of faulty modules is no greater than τ.

2. THE BGM SYSTEM LEVEL FAULT MODEL

The BGM model proposed by Barsi, Grandoni and Maestrini [2] is a system level fault model closely related to the PMC model proposed by Preparata, Metze and Chien [14]. In the BGM model, a system S consists of n modules $U_0, U_1, \dots, U_{n-1}$ and a testing interconnection design TID, where

$$TID = \{ (i,j) \mid U_i \text{ tests } U_j \}.$$

It is assumed that no module tests itself, i.e., the diagonal does not belong to TID. A module is assumed to be either faulty or nonfaulty, and the state of each module in S is assumed to be constant during the application of the testing procedures. If (i,j) is in TID, then U_i tests U_j, and the test outcome $a_{i,j}$ is assumed to be either "0" (U_j passes the test) or "1" (U_j fails the test). The set of test outcomes $\{ a_{i,j} \mid (i,j) \in TID \}$ is the syndrome of the system. In the BGM model, the following relationships between fault and test outcomes are assumed:

(i) if (i,j) is in TID and U_i and U_j are nonfaulty, then $a_{i,j} = 0$;

(ii) if (i,j) is in TID, U_i is nonfaulty and U_j is faulty, then $a_{i,j} = 1$;

(iii) if (i,j) is in TID and both U_i and U_j are faulty, then $a_{i,j} = 1$;

(iv) if (i,j) is in TID, U_i is faulty and U_j is nonfaulty, then $a_{i,j}$ may take either the value 0 or 1.

Thus, the main difference between the PMC model and the BGM model is that if a module U_i is tested by a module U_j, and if $a_{j,i} = 0$, then the module U_i is nonfaulty.

A fault situation of the system S is described by the set F_S of the faulty modules in S. A set of possible syndromes corresponds to each fault situation. Given a fault situation, the computation of the corresponding syndromes is not difficult, but to compute the fault situations that are consistent with a given syndrome is not as easy. In this paper, we address the latter problem -- namely, syndrome decoding -- and we restrict ourselves to one-step τ-fault diagnosability in the sense of Preparata, Metze and Chien [14].

Definition 1: A system S is one-step τ-fault diagnosable if all faulty modules within the system can be identified without replacement, provided that the number of faulty modules does not exceed τ.

In the remainder of this work, s will be the index set that contains the indices of all the modules in S, i.e.,

$$s = \{0, 1, 2, \cdots, n-1\};$$

f_S will be the index set that contains the indices of all the faulty modules in S, i.e.,

$$f_S = \{i \in s \mid U_i \in F_S\};$$

and given an index set a, $\| a \|$ will be used to denote the number of elements in a.

3. IMPERFECT ONE-STEP DIAGNOSIS

Our approach to system diagnosis consists in partitioning the set s into four subsets (v, h_1, h_2 and h_3) that are easy to compute, and then to relate those four subsets to the set f_S which contains the indices of all the faulty modules in S.

The index set v contains the indices of all the modules in S that are tested by at least one other module in S and found to be nonfaulty by that module, i.e.,

$$v = \{ i \in s \mid j \text{ in } s \text{ exists so that } (j,i) \in TID \text{ and } a_{j,i} = 0 \}. \qquad (1)$$

Thus, if S is a BGM model, i.e., a fault model that satisfies the assumption of section 2, the module U_i is nonfaulty whenever the index i is in v.

The index set h_1 contains the indices of all the modules in S that are tested by at least one module U_j, j in v and found faulty, and the indices of all the modules in S that test at least one module U_j, j in v, and find it faulty, i.e.,

$$h_1 = \{ i \in s \mid j \text{ in } v \text{ exists so that } (j,i) \in TID \text{ and } a_{j,i} = 1 \} \\ \cup \{ i \in s \mid j \text{ in } v \text{ exists so that } (i,j) \in TID \text{ and } a_{i,j} = 1 \}. \quad (2)$$

One should note that if S is a BGM model, then the index sets v and h_1 are disjoint, and U_i is faulty whenever the index i is in h_1.

The index set h_2 depends on the cardinality of the sets $L(i)$, where, for every index i in $s - (v \cup h_1)$, the sets $L(i)$ are defined by

$$L(i) = \{ j \in s - (v \cup h_1) \mid (i,j) \in TID \text{ and } a_{i,j} = 1 \} \\ \cup \{ j \in s - (v \cup h_1) \mid (j,i) \in TID \text{ and } a_{j,i} = 1 \}.$$

Given an index i, it is possible that an index j exists so that the pairs (i,j) and (j,i) are both in TID, and $a_{i,j} = a_{j,i} = 1$. Obviously, in such a case the index j appears in $L(i)$ only once. The set $L(i)$ contains the indices of all the modules adjacent to the module U_i that must be faulty if the module U_i is actually nonfaulty. Given a scalar τ, the set h_2 consists of all the indices in s, but not in $v \cup h_1$ such that the cardinality of $L(i)$ is strictly greater than τ, i.e.,

$$h_2 = \{ i \in s - (v \cup h_1) \mid \| L(i) \| \geq \tau + 1 \}. \quad (3)$$

It is clear that if S is a BGM model and if at most τ modules in S are faulty, then U_i is faulty whenever i is in h_2.

The index set h_3 contains the indices of the remaining modules in S, i.e.,

$$h_3 = s - (v \cup h_1 \cup h_2).$$

In this section we will examine the properties of the sets h_1, h_2 and h_3 when every module is tested by at least τ other modules. We will then use those properties to synthesize a decoding algorithm that produces an index set f_A containing the indices of all the faulty modules and some nonfaulty ones, provided that the number of faulty modules $\|f_S\|$ is at most τ. We shall assume that the following assumption holds.

Hypothesis 1: Every module in S is tested by at least τ other modules in S.

The next lemma is a direct consequence of the properties of the BGM model and is given without proof.

Lemma 1: If S is a BGM model, if Hypothesis 1 is satisfied and if $\|f_S\| \leqslant \tau$, then the index sets h_1, h_2, h_3 and f_S satisfy

$$h_1 \cup h_2 \subseteq f_S \subseteq h_1 \cup h_2 \cup h_3.$$

Lemma 2: If S is a BGM model, if Hypothesis 1 is satisfied and if $\|f_S\| \leqslant \tau - 1$, then $\|h_1\| \leqslant \tau - 1$, $h_2 = \phi$, $h_3 = \phi$, and

$$f_S = h_1.$$

Proof: Let U_i be a nonfaulty module. By assumption, every module is tested by at least τ other modules and the fact that $\|f_S\| \leqslant \tau - 1$ implies that U_i is tested by at least one nonfaulty module, say U_j. Thus, if U_i is nonfaulty, an index j exists so that (j,i) is in TID and $a_{j,i} = 0$, and it follows that v contains the indices of all the nonfaulty modules in S.

Now let U_i be a faulty module. Hypothesis 1 and the fact that $\|f_S\| \leqslant \tau - 1$ imply that U_i is tested by at least one nonfaulty module, say U_j. Thus, if U_i is faulty, an index j in v exists so that (j,i) is in TID and $a_{j,i} = 1$, and it follows that h_1 contains the indices of all the faulty modules in S. Clearly, v and h_1 form a partition for s, and we may conclude that h_2 and h_3 are empty. □

Lemma 3: If S is a BGM model, if Hypothesis 1 is satisfied and if $\|h_1 \cup h_2 \cup h_3\| \leqslant \tau$, then

$$f_S = h_1 \cup h_2 \cup h_3.$$

Proof: If $\|h_1 \cup h_2 \cup h_3\| \leq \tau$, then either $\|f_S\| \leq \tau - 1$ or $\|f_S\| = \tau$. If $\|f_S\| \leq \tau - 1$, then Lemma 2 implies that $f_S = h_1 \cup h_2 \cup h_3$.
If $\|f_S\| = \tau$, the fact that $f_S \subseteq h_1 \cup h_2 \cup h_3$ implies immediately that f_S must be equal to $h_1 \cup h_2 \cup h_3$. □

Lemma 4: If S is a BGM model, if Hypothesis 1 is satisfied, if $\|f_S\| \leq \tau$, and if $\|h_1 \cup h_2\| = \tau$, then

$$f_S = h_1 \cup h_2.$$

Proof: If $\|f_S\| \leq \tau$ and if $\|h_1 \cup h_2\| = \tau$, then Lemma 1 implies immediately that f_S must be equal to $h_1 \cup h_2$. □

We will now show that if $\|f_S\| = \tau$ and $\|h_1 \cup h_2\| \leq \tau - 1$, the number of nonfaulty modules in h_3 is at most τ.

Lemma 5: If S is a BGM model, if Hypothesis 1 is satisfied, if $\|f_S\| = \tau$, and if $\|h_1 \cup h_2\| \leq \tau - 1$, then h_3 contains the indices of at most τ nonfaulty modules and

$$\|h_1 \cup h_2 \cup h_3\| \leq 2\tau.$$

Proof: If an index i in h_3 corresponds to a nonfaulty module U_i, then U_i is tested only by faulty modules. By assumption, $\|f_S\| = \tau$ and $\|h_1 \cup h_2\| \leq \tau - 1$ and therefore, the index j of at least one faulty module is in h_3. The module U_j cannot test more than τ other modules in h_3 (otherwise j would be in $h_1 \cup h_2$), and it follows that the number of nonfaulty modules in h_3 is at most τ. The index set $h_1 \cup h_2 \cup h_3$ contains the indices of all the faulty modules and since h_3 contains at most τ nonfaulty modules, $\|h_1 \cup h_2 \cup h_3\| \leq 2\tau$. □

Lemmas 3 and 4 suggest the following decoding algorithm.

Algorithm 1:

Step 0: Compute the set v as in Equation (1).

Step 1: If $\|s - v\| \leqslant \tau$, let $f_A = s - v$ and stop; otherwise, go to Step 2.

Step 2: Compute the sets h_1 and h_2 as in Equations (2) and (3).

Step 3: If $\|h_1 \cup h_2\| = \tau$, let $f_A = h_1 \cup h_2$ and stop; otherwise, go to Step 4.

Step 4: Let $f_A = s - v$ and stop.

The properties of Algorithm 1 are easily obtained from Lemmas 3, 4 and 5, and are summarized below.

Theorem 1: Let S be a BGM model, let Hypothesis 1 be satisfied, let $\|f_S\| \leqslant \tau$, and let f_A be the set generated by Algorithm 1. If $\|f_A\| \leqslant \tau$, then $f_S = f_A$, and if $\|f_A\| \geqslant \tau + 1$, then $\|f_S\| = \tau$, $f_S \subseteq f_A$, and $\|f_A - f_S\| \leqslant \tau$.

In 1974, Hakimi and Amin [5] proposed two characterizations of the testing interconnection design that insure one-step τ-fault diagnosability for the PMC model. We will now examine the implications of the first of these assumptions on the sets h_1, h_2, h_3 and Algorithm 1. We begin our investigation by repeating the first Hakimi-Amin assumption.

Hypothesis 2: No two modules in S test each other.

Lemma 6: If S is a BGM model, if Hypotheses 1 and 2 are satisfied, and if $\|f_S\| \leqslant \tau$, then either $\|s - v\| \leqslant \tau - 1$ or $\|h_1 \cup h_2\| = \tau$.

Proof: If $\|f_S\| \leqslant \tau - 1$, then Lemma 2 implies that $f_S = s - v$, and therefore, $\|s - v\| \leqslant \tau - 1$.

If $\|f_S\| = \tau$, then h_3 is either empty or not. If h_3 is empty, then $f_S = h_1 \cup h_2$ and $\|h_1 \cup h_2\| = \tau$. If h_3 is nonempty, then let i be in h_3. The fact that no two modules test each other implies that no module in h_3 may test any other module in h_3. It follows that U_i is tested by exactly τ other modules that must be in $h_1 \cup h_2$, and we may conclude that $|h_1 \cup h_2|$ must be equal to τ. □

The result of Lemma 6 shows that Algorithm 1 generates the set of faulty modules in S whenever Hypotheses 1 and 2 are satisfied and the number of faulty modules is no greater than τ.

Theorem 2: Let S be a BGM model, and let Hypotheses 1 and 2 be satisfied. If $|f_S| \leq \tau$, then Algorithm 1 stops either in Step 1 or Step 3 and the set f_A that it generates satisfies

$$f_S = f_A.$$

It is clear from Theorem 2 that if S is a BGM model and if Hypotheses 1 and 2 are satisfied, then S is one-step τ-fault diagnosable.

4. ONE-STEP DIAGNOSIS

At this stage, we have a decoding algorithm, Algorithm 1, that produces an index set f_A that is equal to f_S whenever $|f_A| \leq \tau$, and that contains the index of some nonfaulty modules whenever $|f_A| \geq \tau + 1$. If, in addition to Hypothesis 1, we assume that either $|f_S| \leq \tau - 1$ or that the first Hakimi-Amin hypothesis is satisfied and $|f_S| \leq \tau$, then $f_A = f_S$. In this section, we will modify Algorithm 1 so that it produces the set of indices of all the faulty modules when $|f_S| \leq \tau$ and the appropriate assumptions on TID are verified.

When Hypothesis 1 is satisfied and $|f_S| \leq \tau$, Algorithm 1 fails to produce a set f_A that is equal to f_S when $|f_S| = \tau$ and $|h_1 \cup h_2| \leq \tau - 1$. The only index set that presents a problem in that case is the set h_3. It is clear that if the index l is in h_3, the module U_l is tested by exactly τ other modules (otherwise i would be in $v \cup h_1 \cup h_2$). Thus, since $\|h_1 \cup h_2\| \leq \tau - 1$, at least one index $j(i)$ in h_3 exists so that the module $U_{j(i)}$ tests the module U_i. The fact that the index $j(i)$ is also in h_3 implies immediately that the modules $U_{j(i)}$ and U_i test each other. We are led to define the following index set w that depends only on the interconnection design.

Definition 2: Let w be the subset of s that contains all the indices i in s such that:

(i) the module U_i is tested by exactly τ other modules, and

(ii) an index $j(i)$ in s exists such that $U_{j(i)}$ is tested by exactly τ other modules in S, and U_i and $U_{j(i)}$ test each other.

In view of this discussion, we arrive at the result below.

Lemma 7: If S is a BGM model, if Hypothesis 1 is satisfied, if $\|f_S\| = \tau$ and if $\|h_1 \cup h_2\| \leq \tau - 1$, then

$$h_3 \subseteq w.$$

The set w given in Definition 2 may contain indices that correspond to nonfaulty modules. We must now define a subset x of w that possesses the desired property: a module U_i is faulty whenever i is in $h_3 \cap x$.

Definition 3: Let x be the set of all indices i in s such that:

(i) U_i is tested by exactly τ other modules;

(ii) an index $j(i)$ exists such that $U_{j(i)}$ is tested by exactly τ modules in s and U_i and $U_{j(i)}$ test each other; and

(iii) an index $k(i)$ in s exists such that the module $U_{k(i)}$ tests $U_{j(i)}$ but not U_i, and $U_{k(i)}$ is tested by at least one module that does not test U_i.

The set x given in Definition 3 depends only on the testing interconnection design; it may be computed once and stored. Its importance lies in that it may be used directly to find faulty modules in h_3.

Lemma 8: Let S be a BGM model, let Hypothesis 1 be satisfied, let $\|f_S\| = \tau$ and let $\|h_1 \cup h_2\| \leq \tau - 1$. If the index i is in $h_3 \cap x$, then i is in f_S.

Proof: Let i be in $h_3 \cap x$ and let $j(i)$ and $k(i)$ be indices that satisfy the assumptions of Definition 3. Suppose that U_i and $U_{k(i)}$ are both nonfaulty. All the modules that test U_i and those that test $U_{k(i)}$ are then faulty. The module $U_{i(k)}$ is tested by at least one module that does not test U_i and therefore, the assumption that both U_i and $U_{k(i)}$ are nonfaulty implies that at least $\tau + 1$ modules are faulty. This is impossible, and thus, if U_i is nonfaulty, $U_{k(i)}$ must be faulty. The module $U_{k(i)}$ does not test the module U_i, and the fact that i is in h_3 implies that U_i does not test $U_{k(i)}$. Thus, if U_i is assumed to be nonfaulty, we must conclude that at least $\tau + 1$ modules are faulty. Once again, this is impossible; Therefore, the module U_i must be faulty -- i.e., i is in f_S. □

Using the result of Lemma 8, we may modify Algorithm 1 to incorporate the fact that under the appropriate conditions, the set $h_3 \cap x$ is a subset of f_S.

Algorithm 2:

Step 0: Compute the set v as in Equation (1).

Step 1: If $\|s - v\| \leq \tau$, let $f_B = s - v$ and stop; otherwise, go to Step 2.

Step 2: Compute the sets h_1 and h_2 as in Equations (2) and (3).

Step 3: If $\|h_1 \cup h_2\| = \tau$, let $f_B = h_1 \cup h_2$ and stop; otherwise, go to Step 4.

Step 4: Let $f_B = h_1 \cup h_2 \cup (h_3 \cap x)$ and stop.

At this point, it is clear that when the appropriate assumptions are satisfied, Algorithm 2 generates a set f_B that is a lower bound for f_S.

Lemma 9: If S is a BGM model, if Hypothesis 1 is satisfied and if $\|f_S\| \leq \tau$, then the set f_B generated by Algorithm 2 satisfies

$$f_B \subseteq f_S.$$

In their 1976 paper, Barsi, Grandoni and Maestrini [2] proposed a condition on TID that insures one-step τ-fault diagnosability. Using our notation, we will now repeat that assumption and show that it may be used to insure that f_S is found.

Hypothesis 3: If the indices i and j are in w and if U_i and U_j test each other, then i or j or both are in x.

Lemma 10: If S is a BGM model, if Hypotheses 1 and 3 are satisfied, if $\|f_S\| = \tau$ and if $\|h_1 \cup h_2\| \leq \tau - 1$, then

$$\|h_3 \cap x\| = \tau - \|h_1 \cup h_2\|.$$

Proof: The set h_3 contains at least $\tau - \|h_1 \cup h_2\|$ indices and therefore, if all the indices in h_3 are also in x, then

$$\|h_3 \cap x\| \geq \tau - \|h_1 \cup h_2\|.$$

If at least one index, say i, is in h_3 but not in x, then U_i is tested by at least $\tau - \|h_1 \cup h_2\|$ other modules with indices in h_3. All the modules with indices in h_3 that test U_i are also tested by U_i. Hypothesis 3 implies that they are all in x and therefore,

$$\|h_3 \cap x\| \geq \tau - \|h_1 \cup h_2\|.$$

Lemma 9 implies that all indices in $h_1 \cup h_2 \cup (h_3 \cap x)$ are in f_S, and using the assumption that $\|f_S\| \leq \tau$, we obtain

$$|h_3 \cap x| = \tau - |h_1 \cup h_2|. \square$$

The results of Lemmas 3, 4 and 10 show that, when the appropriate conditions are satisfied, Algorithm 2 generates the set of indices of all the faulty modules in S.

Lemma 11: If S is a BGM model, if Hypotheses 1 and 3 are satisfied and if $|f_S| \leqslant \tau$, then the index set f_B produced by Algorithm 2 satisfies

$$f_S = f_B.$$

Note that Lemma 11 implies that if S is a BGM model that satisfies Hypotheses 1 and 3, then S is one-step τ-fault diagnosable, i.e., the the result given in [2, Theorem 2, p. 585] is retrieved.

It is known that if a BGM model is one-step τ-fault diagnosable, then Hypotheses 1 and 3 are satisfied [2]. Hence, we obtain the main result of the paper.

Theorem 3: Let S be a one-step τ-fault diagnosable BGM fault model and let F_S be the set of faulty modules in S. If $\|F_S\| \leqslant \tau$, then the index set f_B generated by Algorithm 2 satisfies

$$F_S = \{ U_i \mid i \in f_B \}.$$

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The paper presents an analysis of the BGM system level fault model of Barsi, Grandoni and Maestrini based on system partitioning. The properties of the partitioning are then used to synthesize two algorithms for the decoding of the syndromes produced by the BGM model.

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