Detection and Location of Open Circuit Fault by Space Search

Space Search에 의한 회로의 단선 결함의 발견 및 위치 검색법

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ABSTRACT

In this paper, a space search technique is usedto detect and locate the faults of the circuit interconnections.

The circuit interconnections are represented by the tree structure and the tree space is searched to detect and locate the open faultsof the circuit interconnections. The breadth search is used to detect the open faults and reduce the space size. The depth search is used to locate the open faults

요 약

인공지능(AI)의 한기법인 Space Search 기법을 이용하여 회로의 단선 결함의 유무 및 결함위치를 찾아내는 방법을 제시하였다.

보통 회로의 결함은 단선 및 단락의 구조적 결함으로 나뉘어진다. 두가지 결함 모두 회로의 기능에 중대한 이상을 초래한다.

그중 단선에 의한 회로의 결함에 대하여 다루었다. 우선 회로를 net와 net의 연결 path에 따라 tree 구조로 변환하였다.

서로 독립된 net들은 서로 다른 tree의 node를 이루며 각각의 tree는 전기적으로 연결됨이 없다. 각 tree의 최상단부의 root node에 test vector를 입력하고 최하단부의 leaf node에서 vestor를 관찰하여 입력된 test vector와 비교한다. 그 비교 결과 동일 유무에 따라 결함의 유무를 판정한다. 결함이 있다고 판정된 leaf node는 depth search 방법에 의하여 root node 쪽으로 test vector를 관찰하여, 전기적 신호에 의하여 회로의 선로가 단선된 위치를 찾아내도록 하는 방법을 제시하였다.

Ⅰ. Introduction

Along with the technology advances, the more sophisticated and complex electronic equipment are being developed and PCB's(Printed Circuit Boards) are designed with the more thinner interconnect lines and layers.

The interconnect lines provide the signal paths among the components. The broken interconnect lines and the shorted lines change the signal paths and eventually change the function of circuit.

After the components are loaded and soldered on the PCB, it is very difficult to detect fault. Also, more Surface Mounting Devices(SMD) are used.

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Ⅱ. Faults of the circuit interconnections

Most of the faults of the circuit interconnection are divided into two categories and they are structural faults and parametric faults. The parametric faults change the frequency characteristics and the circuit performance and they are very critical to the time-critical circuits. The parametric faults happen much less than the structural faults in the interconnect wires and they are not handled in this paper.

Most of the faults in the interconnect wires are the structuralfaults and they are usually manufacturing or stuck-at faults. The structural faults are consist of the short circuit faults and the open circuit faults. Open circuit faults means the broken signal paths among the netsthat should be connected together and change the function of the circuit by blocking the signal paths. The broken path includes the broken through holes betweenthe different circuit layers.

Short circuit fault results from the unwanted sigcal paths among the nets that should be isolated from the other nets and change thefunction of the circuit by adding the unwanted signal flow. The short circuit fault results from the incomplete separation of the neighbor circuit paths and the through holes that haveunwanted contact with the circuit paths on the different layers whichshould be isolated.

The open circuit faults can be detected and located by probing thecircuit paths electrically. The short circuit faults can be detected by probing electrically but the faults can not be located by electrical test method becausethe electrical probing signals can be detected at any pointsof the circuit paths of the shorted interconnect wires. So the other test methods, such as automatic visual test(AVT), areused to locate the short circuit faults.

In this paper,we will handle the open circuit fault and discuss the detection and location of the open circuit faults of theinterconnect circuits. From the space search technique, the breadth search is used todetect the faults and the depth search is used to locate the faults.

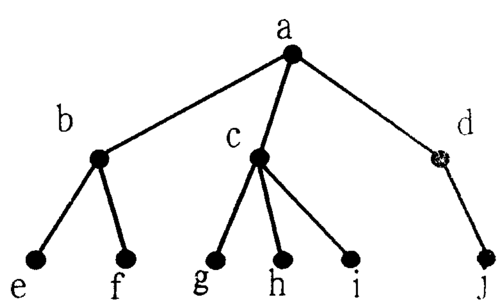

Figure 1. Example Tree Structure

Ⅲ. Tree representation of interconnect circuit

We can build a net group tree with nets and each node representsthe net of the circuit. In the net group tree representation, the tree shows the connection status of the nets but does not show the connection status of the through holes and test pins. And we trace the path between the involved nets to find the exact location of the open circuit fault.

By including the nodes representing other points such as the through holes and the test pins in a net group tree representation, the open circuit faults can be identified by the nets, the through holes and the test pins. As a result, the open circuit faults can be identified by the nets, the through holes, and the test pins.

In the tree representation, the root node on the top and all the leaf nodes on the bottom level represent the nets, and all the other nodes in between represent the through holes and the test pins. The depth of the tree is the maximum number of paths from root node to the leaf nodes. The tree is to be searched to locate the open circuit faults of the net group by using the depth search. Any nets of the net group can be selected as the root node in the tree representation, but, the root node is recommended to be selected to minimize the depth and search time. For the minimum depth of tree, the root node is selected from one of the nets which are geometrically located in the center of the interconnect wires layouts.

Detection of a open circuit fault between the net and the through hold of a net group is to find the broken paths between the nodes in the tree representing the net group. To find the broken path in the tree, a test vector is applied at root node and breadth search is performed for all the leaf nodes on the bottom to observe the test vector. Then for the leaf nodes where the observed test vector is not the same as the applied test vector, the continuity of their parent nodes is tested by using the depth search starting from the faulty loaf nodes.

Ⅳ. Search technique for fault detection and location

To detect and locate the open circuit faults in a net tree, a set of two nodes is selected from a net tree and the continuity between those two nodes is tested. This test is repeated for all the possible combination sets of nodes. If the test procedure is performed sequentially, another set of two nodes is tested after one testing one set. This is an exhaustive test procedure and takes a long time. For the net tree with m nodes, all the possible combination sets of two nodes are :

$$mP_2 = \frac{m!}{(m-2)!} = m(m-1)$$

So, to check the continuity between m nodes, m(m−1) tests have to be performed.

The leaf nodes where the detected response are the same as the test vector are faultless leaf nodes and the leaf nodes have connected paths to root node. The leaf nodes where the detected responses are not the same as the test vector are faulty leaf nodes and there are broken paths between the leaf nodes and root node. We can start search from those initial state of faulty and faultless leaf nodes to find the broken path. In the tree structure of a net group, we can reduce the state search space of finding the broken paths positions of a net group tree by eliminating the branches which are not involved in the open circuit faults.

V. Fault Detection and Space Reduction by breadth search

The search techniques are used to detect and locate the open circuit faults in a net group tree. It is mentioned that all the nodes of a net group are normally connected and the connection status can be known from the netlist and the interconnection circuit layouts. figure 2 shows an example of the net tree.

The nodes are labeled as from N1 to N45. A root node N1 and leaf nodes N26, N27, ..., N45 represents the nets of a net group. The rest of nodes, N2, N3, ..., N19, and N25 represents other pins in the same net group, such as through holes or other test points.

At the root node N1, a test vector is applied for the net group and responses are observed from the leaf nodes at the bottom (N26, N27, ..., N44, N45). The observed responses are breadth-searched at the bottom level from left to right or from right to left. If we select breadth search from left to right, the responses at the leaf nodes level will be examined in the order N26, N27, N28, ..., N44, N45.

The breadth search is performed at the bottom level of the net group tree to check if the test vector applied on the top of the tree is transferred to the bottom level through all the intermediate nodes [illegible] and reach the leaf nodes.

Since the root node and the leaf nodes represent all the nets of a net group, if the observed response at the leaf nodes are the same as the applied test vector, all the paths from the root node to the leaf nodes are connected and the net group does not have any open circuit faults.

The test vector is applied at the root node and the responses are observed at the leaf nodes. If there exists any broken path between the root node and the leaf node, the applied response vector can not be observed from the leaf node. And we know that there exists a broken path between the leaf node and its parent nodes or between any of its ancestor nodes at the upper levels. So, by searching and examining the bottom level only, we can detect the open circuit faults of a net group. After the leaf nodes at the bottom level are searched in breadth, the leaf nodes can be divided into two categories, faulty leaf nodes and faultless leaf nodes. The faulty leaf node means that there exists at least one broken path between the root node and the faulty leaf node and all the ancestor nodes at the upper levels should be searched to find the broken paths between the faulty leaf node and the root node. Figure 3 shows the leaf nodes at the bottom level after the responses from the leaf nodes are examined. They are labeled as On for a faultless leaf node and Fn for a faulty leaf node. The

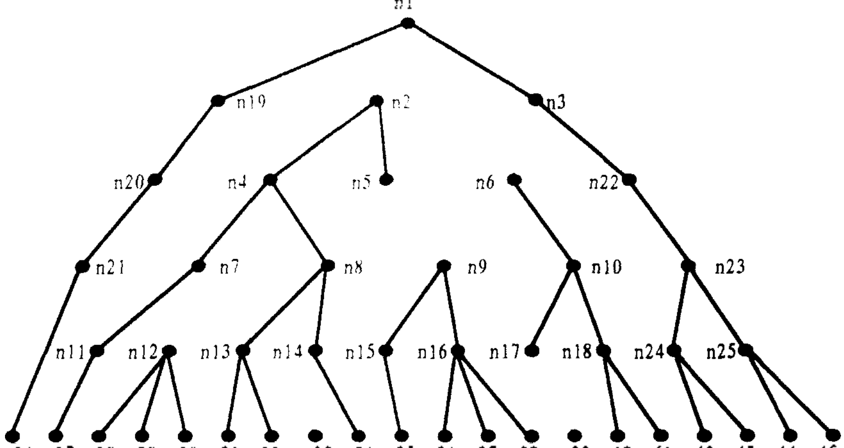

Figure 2. Example of a net tree representation

state space of all the nodes of a net group tree forms the net group space and this can be constructed from a net group tree by tracing back the ancestor nodes of the leaf nodes toward the root node. Table 1 shows the net group space for Figure 3. From the examination of the leaf nodes at the bottom level, the leaf nodes are divided into faultless leaf nodes and faulty leaf nodes. Here, we will call the set of faulty nodes, all their ancestor nodes to the root node, and their paths as the faulty space. And the faultless leaf nodes, their ancestor nodes to the root node, and their paths are called as the faultless space.

For a net group tree, there can be a case where there is a broken path in the tree but we can observe the test vector from every leaf node due to a short circuit path provides a redundant path for the broken path. If we test the connections between only the nets in a net group, the continuity test between the root node and the leaf nodes at the bottom level detects all the faults. The nodes at the intermediate levels represent the through holes and test pins.

For a net group with K nets and H through holes and test points, the corresponding tree representation has a root node, K−1 leaf nodes,and H intermediate nodes and the total search state space is H + K−1 nodes. Also, if the net group tree has B average children nodes and n levels, the total state space is Bn, and if there are P average children nodes that are not involved in the open circuit faults at n levels, the size of the state space of faultless nodes is Pn and this space can be eliminated from the total state space (B∗n) and only (B∗n−P∗n) nodes in the state space need to be searched to locate the fault positions. So, in the net group tree, the search space for the depth search. This means, the faultless space can be eliminated from the net group space and we can detect all the faults of the net group by searching only faulty space.

Locating the Faults by depth search In most cases, the circuit boards under test may have open circuit faults in their net groups and all the nodes of the net group tree would be searched to locate the open circuit faults of the net group. In a net group tree representing K nets and H through holes,every node except the root node has a path connected to its parent node and the net group tree with K + H nodes has K + H −1 paths connecting the nodes. From the breadth search at the bottom level of the net group tree, the faults can be detected for the given net group tree. And if faults are detected on the leaf nodes, the ancestor nodes of the faulty leaf nodes are searched to locate the fault positions.

As we described before, the paths from the root node to the faultless nodes can be eliminated from the depth search space. We do not have to perform additional search in the faultless space and only the faulty space should be searched to locate the open circuit fault positions of the net group.

From Figure 3, we make Table 1 that shows the net group space and the depth relationships of the nodes for each level. Table 2 shows the faultless space. Table 3 shows the search state space of the nodes involved in the faulty leaf nodes, which is the faulty space. In Table 3, depth search can start from either the leftmost or the rightmost faulty leaf node. Figure 4 and Figure 5 show the depth search space

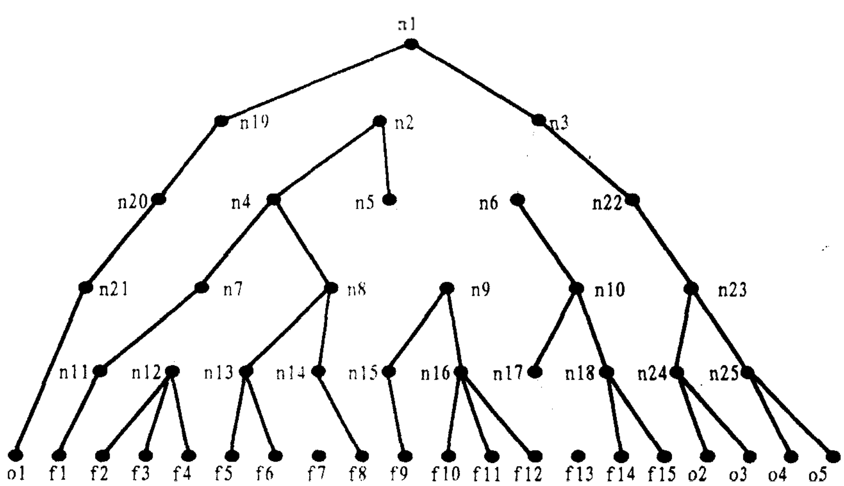

Figure 3. Faulty and faultless leaf nodes after the breadth search

Table 1. Net group space and the depth relations with upper nodes

level 1	n1	n1	n1	n1	n1	n1	n1	n1	n1	n1
level 2	n19	n2	n2	n2	n2	n2	n2	n2	n2	n2
level 3	n20	n4	n4	n4	n4	n4	n4	n4	n4	n5
level 4	n21	n7	n7	n7	n7	n8	n8	n8	n8	n9
level 5	o1	n11	n12	n12	n12	n13	n13	n14	n14	n15
level 6	o1	f1	f2	f3	f4	f5	f6	f7	f8	f9
LEVEL	good			bad						
level 1	n1	n1	n1	n1	n1	n1	n1	n1	n1	n1
level 2	n2	n2	n2	n3	n3	n3	n3	n3	n3	n3
level 3	n5	n5	n5	n6	n6	n6	n22	n22	n22	n22
level 4	n9	n9	n9	n10	n10	n10	n23	n23	n23	n23
level 5	n16	n16	n16	n17	n18	n18	n21	n24	n25	n25
level 6	f10	f11	f12	f13	f14	f15	o2	o3	o4	o5
LEVEL			bad					good		

Table 2. Faultless net group space

level 1	n1	n1	n1	n1	n1
level 2	n19	n3	n3	n3	n3
level 3	n20	n22	n22	n22	n22
level 4	n21	n23	n23	n23	n23
level 5	o1	n24	n24	n25	n25
level 6	o1	o2	o3	o4	o5
LEVEL	good node				

Table 3. Faulty net group space

level 1	n1	n1	n1	n1	n1	n1	n1	n1
level 2	n2	n2	n2	n2	n2	n2	n2	n2
level 3	n4	n4	n4	n4	n4	n4	n4	n4
level 4	n7	n7	n7	n7	n8	n8	n8	n8
level 5	n11	n12	n12	n12	n13	n13	n14	n14
level 6	f1	f2	f3	f4	f5	f6	f7	f8
LEVEL			bad node					
level 1	n1	n1	n1	n1	n1	n1	n1	
level 2	n2	n2	n2	n2	n3	n3	n3	
level 3	n5	n5	n5	n5	n6	n6	n6	
level 4	n9	n9	n9	n9	n10	n10	n10	
level 5	n15	n16	n16	n16	n17	n18	n18	
level 6	f9	f10	f11	f12	f13	f14	f15	
LEVEL			bad node					

when all the leaf nodes are assumed to be faulty and all the nodes of the net group tree have to be searched.

In the worst case, we may have to search from the leaf node to deep into the root node level. The search space for a tree with breadth W, and depth D, is W* D, and we have the biggest depth search space for the given net group tree.

Figure 4 shows the depth search space starting from the leftmost node and Figure 5 shows the depth search space starting from the rightmost leaf node. Both cases have the same space size, since they are searching the same tree. We will consider only the depth search starting from the leftmost faulty leaf node.

From Figure 4, it is shown that the upper level nodes are not searched if they are already searched at a previous depth search. This accomplishes additional reduction of the depth search space. For example, from a leaf node F1, its ancestor nodes N11,

n1	n1	n1	n1	n1	n1	n1	n1	n1	n1	n1	n1	n1	n1	n1
n2	n2	n2	n2	n2	n2	n2	n2	n2	n2	n2	n2	n3	n3	n3
n4	n4	n4	n4	n4	n4	n4	n4	n5	n5	n5	n5	n6	n6	n6
n7	n7	n7	n7	n8	n8	n8	n8	n9	n9	n9	n9	n10	n10	n10
n11	n12	n12	n12	n13	n13	n14	n14	n15	n16	n16	n16	n17	n18	n18
f1	f2	f3	f4	f5	f6	f7	f8	f9	f10	f11	f12	f13	f14	f15

Figure 4. Breadth search starting from the leftmost leaf node

n1	n1	n1	n1	n1	n1	n1	n1	n1	n1	n1	n1	n1	n1	n1
n2	n2	n2	n2	n2	n2	n2	n2	n2	n2	n2	n2	n3	n3	n3
n4	n4	n4	n4	n4	n4	n4	n4	n5	n5	n5	n5	n6	n6	n6
n7	n7	n7	n7	n8	n8	n8	n8	n9	n9	n9	n9	n10	n10	n10
n11	n12	n12	n12	n13	n13	n14	n14	n15	n16	n16	n16	n17	n18	n18
f1	f2	f3	f4	f5	f6	f7	f8	f9	f10	f11	f12	f13	f14	f15

Figure 5. Breadth search starting from the rightmost leaf node

N7, N4, N2, N1 are searched and the open circuit faults in those nodes can be detected and located. Them, from the next leaf node F2,its parent node N12 is searched and then node N7 is searched and depth search stops for leaf node F2. Since all the ancestor nodes of node N7 are already searched at the previous depth search from node F1, we can stop additional searches above node N7 and eliminate the duplicated searches from node N7 to node N1. In the same way, from node F3, F4, only node N12 is searched since the nodes above N12 were searched at previous search from node F2.

For node F5, its ancestor nodes N13 and N8 are searched and search stops at node N4, since the upper level of node N4 is searched at the previous search. For node F13, all of its ancestor nodes (N17, N10, N6, N3, N1) are searched since none of its ancestor nodes are searched at previous depth searches. So, by the depth search of the faulty leaf nodes at the bottom level, we can locate all the multiple open circuit faults of the given net group.

In the depth search from the leaf nodes, we start searching from the obseved faulty responses and the search proceeds toward the upper level locating the open circuit faults. The conventional depth search technique may search the whole search space, net group search, to find the goal. We divide the search space into faulty space and faultless space. The goal, open circuit faults, does not exist in the faultless space and the depth search is applied to search only the faulty space and locate the fault positions.

The location of open circuit faults using the depth search in the faulty space is implemented as the following procedure. The list OPEN contains the faulty leaf nodes and list CLOSE will have the least of the upper level nodes already searched and list FAULT LIST will have the list of node pairs where the open circuit faults are located.

Search Flow

```
PROCEDURE OPEN_CIRCUIT_FAULT_LOCATION
INITIALIZE : OPEN = [FAULTY_LEAF_NODES]
          CLOSE = [ ]
          FAULT_LIST = [ ]
          STOP = FALSE
WHILE OPEN is NOT [ ]
REPEAT
      S = the LEFTMOST LEAF_NODE from OPEN
      REMOVES S FROM OPEN
      ADD S to CLOSE
      X = S
      WHILE STOP is NOT TRUE
      REPEAT
      P = the PARENT_NODE of X
      CHECK PATH between X and P
      IF OPEN_CIRCUIT_FAULT EXIST
      THEN
         ADD[X-P] to FAULT_LIST
      ELSE
         NO OPERATION
      IF P EXISTS in CLOSE
```

```
THEN
  STOP   TRUE
ELSE IF P is ROOT NODE
  THEN
    ADD P to CLOSE
    STOP   TRUE
  ELSE
    ADD P to CLOSE
    X ← P
```

VI. Conclusion

In this paper, we discussed a space search technique for the detection of the structural faults of the circuit interconnections. We handled the detection of open-circuit faults detection and we showed that the circuit interconnection can be represented by a tree structure and by searching the tree space, the open circuit faults can be detected and the fault locations can be identified,too. Multiple faults were allowed in this study.

The application of state space search techniques is from Artificial Intelligence and was studied to detect and locate the open circuit faults in the test. Breadth search detects the list of nets disconnected. The connected nets and their paths were removed from the search space and the reduced search space reduced the search time for depth search. With the faulty nets and their paths,depth search was performed to find the locations of broken circuit paths.

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