Novel Automatic PCB Inspection Technique Based on Connectivity

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Abstract. This paper presents a novel technique for PCB inspection based on the comparison of the Connected Table of a Reference and a Test Image. The method is based on connected component analysis, which is a natural way to extract the connectivity information of the conductors of a PCB. The registration of the PCB holes, which is a common problem related to referential model techniques, is solved by the concept of zone of influence of each hole. This paper describes the method and its implementation using standard Morphology Image Processing techniques. A result of applying the technique to real images is shown.
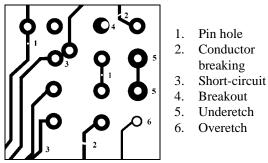
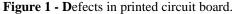**Keywords:** Printed Circuit Board Inspection, Morphology Image Processing.

1. Introduction

The technology of computer vision has been highly developed and used in several industry applications. One of these applications is the automatic visual inspection of printed circuit boards (PCB). The automatic visual inspection is important because it removes the subjective aspects and provides fast, quantitative and dimensional assessments. As PCBs normally contain complex and detailed patterns, manual visual inspection is very tiring and very subjective to errors. On the other hand, automatic systems do not get tired and are consistent.

1.1 Types of defects

Figure 1 illustrates the more common defects found in PCBs: conductor breaking and short-circuit, characterized as fatal defects; pinhole, breakout, overetch and underetch, which characterize potential defects. Fatal defects are those in which the PCB does not attend the objective they are designed for, and potential defects are those compromising the PCB during their utilization.

1. Pin hole
2. Conductor breaking
3. Short-circuit
4. Breakout
5. Underetch
6. Overetch

Figure 1 - Defects in printed circuit board.

1.2 Types of Visual Inspection

Moganti proposed in [Moganti et al. (1996)] three categories of inspection algorithms: referential approaches, generic properties methods (or project rules verification) and hybrid methods. In general, the referential proposal uses the complete knowledge of the circuit in test and generic property methods determine whether each feature falls within the required dimensions. As these methods normally use local neighborhood image processing techniques and do not require a comparison model, they are simpler and widely used but do not test the PCB connectivity features [Mandeville (1985)].

The referential methods compare the Reference PCB to the Tested PCB. There are two major techniques: image comparison methods and model-based inspection.

Image comparison, which is the simplest approach, consists of comparing both images pixel-by-pixel using simple logic operators such as XOR (*Symmetrical Difference*). The main difficulty found in these techniques is determining a precise alignment of the reference image and the test image, which makes its utilization difficult. More sophisticated proposals under the same idea, involve feature and template matching [Moganti et al. (1996)], but suffer from the same problem and normally require a large number of templates.

Model-based methods are techniques, which match the pattern under inspection with a set of predefined models. They are also called *Graph-Matching Methods* [Moganti et al. (1996)] and are based on the structural, topological,   and   geometrical
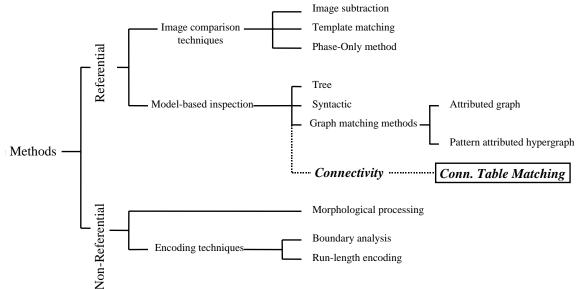
Figure 2 - Visual inspection algorithm classification**.**

properties of the image. The major difficulty of those methods is related to the matching complexity. Although [Sun et al. (1992)] proposed a technique called *Pattern Attributed Hypergraph* to make the method more practical, it still remains a complex and time-consuming method.

We present a new approach to the referential model PCB inspection method, based on the comparison of the conductor connectivity list. To understand how simple and powerful this technique is, we need to recall the main function of a PCB: to connect the leads of the electronic components based on the connectivity table generated from the schematic diagram. The connectivity table is a list of a list of connected holes.

The proposed method extracts and compares the connectivity tables from the Reference PCB and from the Test PCB. The connectivity extraction is done via the concept of connected components of binary images. The hole correspondence between the reference and the test images is solved by the zones of influence technique (Voronoi Diagram).

Although the novel method is simple, it can detect any discrepancy in the connected list of the PCB, which is its most important property.

Based on the classification of inspection algorithms proposed by [Moganti et al. (1996)], which is represented in the diagram of the Figure 2, our method is included a Connectivity Based Method, a new category under Model-based inspection *(shown in dashed lines and bold face).*

This paper is organized as follow. In section 2, the objectives of the methodology and its difficulties are presented. Section 3 describes the method and details its steps. Section 4 presents the application of the methodology using real examples of PCB. Finally, section 5 presents the conclusions of this work.

2. PCB Inspection by Comparison of Connectivity Tables

The novel method of PCB inspection consists of extracting and comparing the connectivity list of two PCB images: the **Reference** image and the **Test** image.

The method is explained by an illustrative example shown in Figure 3a and Figure 3b representing, respectively, the Reference image and the Test image. The Reference image has 7 holes and 3 conductors while the Test image has the same number of holes, but with two conductors broken, resulting in 5 conductors. The holes are the round pads where the component leads are normally soldered. It is important to note that there is a natural correspondence of *conductors* in the PCBs and *connected components* of the image.
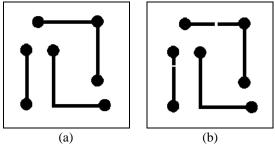

(a)   (b)
Figure 3 - (a) Reference Image and (b) Test image.

The output of the proposed inspection algorithm is visualized through a color code as shown in Figure 4. Each conductor can be classified as correct, broken, short-circuit, and conductor with no holes. In the case of

Figure 4, the black conductor is the one without defects and the light-gray conductors are broken.
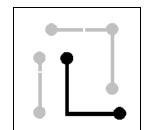

Figure 4 - Result of the defects detection.

In the following paragraphs, we describe the idea and the difficulties associated with the method.

The labeling operator does the identification of the conductors of a PCB. It identifies each connected component (each conductor) of the binary image and assigns a unique number to its pixels, here called *conductor label*. Labeling is one of the keys of the proposed method, as the labeling uses the concept of connected components, assigning a unique value to pixels belonging to the same connected region of the binary image. Figure 5 shows the labeling of the images of Figure 3. We can identify that the reference image has 3 conductors and the test image has 5 conductors.
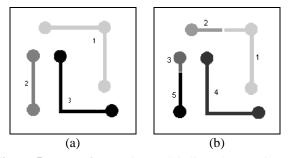

(a)   (b)

Figure 5 - (a) Reference image labeling, (b) Test image labeling.

From the labeled images, and the coordinates of the centroid of the hole pads, we can build the *Holes Connected Table*. This table associates each hole coordinates to a conductor label. Table 1 and Table 2 show the conductor label of each of the 7 holes of the Reference image and the Test image respectively. Note that the holes centroid coordinates of the Reference and the Test images are not exactly the same due to small misalignments during the image digitization and capture.

To appreciate the effect of the misalignment, in Figure 6, we show the symmetrical difference (XOR) of the Reference image and the Test image. This is one of the general problems in working with referential

methods. In our proposed method, each hole center is identified to its *zone of influence*. Zone of influence of a point is the region where all the points are nearer to that point than any other point in the image.

Coordinates		Connection
X	y	Conductor label
191	39	1
70	40	1
46	97	2
101	98	3
191	159	1
46	207	2
206	209	3

Table 1 – Reference Connected Table.

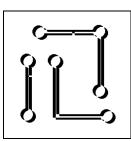| Coordinates		Connection
X	Y	Conductor label
197	43	1
76	44	2
52	101	3
107	102	4
197	163	1
52	211	5
212	213	4

Table 2 - Test Connected Table.

Figure 6 - Symmetrical Difference of Reference and Test Images.

Each connected Table is then converted to the Zone of Influence Connected Table, solving the misalignment problem elegantly.

The final step in the proposed method is the comparison of the two Connected Tables to find possible defects. This test presents no special difficulty as discussed in the next section.

3. Description of the Method

The Figure 8 presents a general view of the method of PCB inspection based on the comparison of the connectivity table. The input images are binaries and in the number of four: two from conductors (Reference and Test) and two from the holes (Reference and Test).

The conductor images are labeled and have their Connected Table extracted using the centroids of the holes. These tables are based on the coordinates of the holes. The zone of influence is taken from the centroids of the Reference Image and used to convert the Connected Tables to refer to zones instead of holes coordinates. Finally the region based connected tables are compared and the resulting color codes are visualized on the Test image.

Each individual morphology image-processing operator used in the method is described in the next subsections. The reader is encouraged to follow the Figure 8 to see the relationship of the operators in the whole process.

3.1 Labeling

Labeling transforms a binary image in an image where each pixel is assigned a unique value related to its connected component. The output labeled image is directed related to the identification of the conductors in the PCB image. Each conductor component is assigned a value, here called conductor label (Figure 5).

3.2 Centroid

Centroid extracts the coordinates of each hole in the PCB image. A PCB hole image can be seen in Figure 7a. The output of the Centroid is a list of coordinates and an image with single pixels at the centroid position (Figure 7b). The lists of the coordinates of the Reference and Test images of Figure 3 are shown in Table 3.
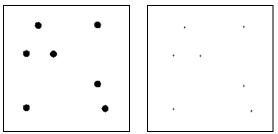

Figure 7 – (a) Holes image, (b) Centroids.

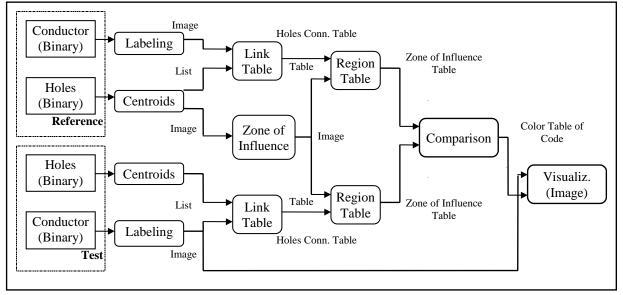| Coordinates of the holes centroids			
Reference		Test	
X	Y	X	Y
191	39	197	43
70	40	76	44
46	97	52	101
101	98	107	102
191	159	197	163
46	207	52	211
206	209	212	213

Table 3 - List of Centroids Coord.

Figure 8 – PCB Connected Table Comparison Method.

3.3 Link Table

The Link Table operator extracts the Connected Table of a PCB from its conductor labeled image and the list of the coordinates of the holes centroids. The Connected Table of the Reference and Test images can be seen in Table 1 and Table 2 respectively. This operator uses the coordinates of the centroids to get the pixel values (conductor label) of the labeled image.

3.4 Zone of Influence

Given an image of the centroids of the holes such the one shown in Figure 7b, the Zone of Influence operator partitions the image in the same way a Minimum Distance Classify does. Each partition has a correspondent centroid and all the coordinates within that partition have a smaller distance to this centroid than to any other centroid in the image. This partition is also called Voronoi Diagram.

There are many ways to determine this zone of influence image. Using Morphology Image Processing operators, one can find the Watershed of the Distance Transform of the negation of the centroids image. Figure 9a shows the Distance Transform and Figure 9b shows the watershed with the partitions assigned a unique label which identifies the zone of influence of each centroid.

This operator is applied to the Reference image, generating an image of the zone of influence of the centroids of the Reference holes.
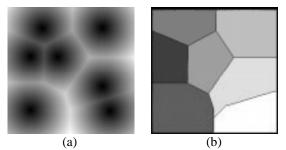

<center>(a)   (b)</center>

Figure 9 - (a) Distance Transform (Euclidean) and (b) Watershed.

3.5 Region Table

The Region Table operator converts the Connected Table of the holes centroids coordinates to zone of influence of the holes of the Reference image. This is the key to make the correspondence between holes in both images. The maximum amount of misalignment allowed between the images is half of the distance between the two closest holes of the PCB image.

This operator generates the Connected Table of the zones of influence of the Reference image. It changes

the coordinates of the centroids in the table by the correspondent value of the zone of influence image at that coordinate. Table 4 and Table 5 show the correspondent connected tables of Table 1 and Table 2 converted to the Reference Holes Regions.

This operator can check for two possible errors: a) the existence of two or more holes in same zone of influence; b) the lack of hole in any zone of influence.

3.6 Comparison

The Comparison operator accepts the two connected tables of the Reference and Test images based on zone of influence and outputs a table with a color code for each conductor label of the Test image. Applying this color code as a color table to the labeled conductor Test image gives the desired output result of the inspection method (as seen in Figure 4).

Ref. Zone of Influence	Conductor label
6	1
4	1
2	2
5	3
7	1
3	2
8	3

Table 4 - Connected Table of the **Reference** image based on the reference zone of influence.

Ref. Zone of Influence	Conductor label
6	1
4	2
2	3
5	4
7	1
3	5
8	4

Table 5 - Connected Table of the **Test** image based on the reference zone of influence.

This operator is explained using the illustrative example of the Table 4 and Table 5, which refer to the images of Figure 3:

1. Obtain the number of conductors of the Test table. This number is the size of the output colormap table that is used to store the defects color code. In the example, the number of conductors is 5;

2. Initialize the colormap table with value 4 which is the code for a conductor with no holes;

3. For each reference zone of influence in the reference connected table which is not marked do:

Mark this zone and find and mark all the other zones connected to this one. Look at the conductor label associated to this zone and then look for all other zones associated to this conductor. In the illustrative example, the zone is 6 and the zones connected to it are 4 and 7, all associated to conductor 1.

4. Verify which conductors in the Test connected table are associated to the set of connected zones found in item 3.

a) If the conductor labels are all equal, verify if there are any other zone with the same conductor label;

    i) If none is found, then that conductor is correct. Assign the code 0 to that conductor label;

    ii) If other zones are found, then a short circuit occurred. Assign the code 8 to that conductor label;

b) If the conductor labels are different, it means there is a break in the conductor. For each conductor label, verify if there are any other zones with the same conductor label:

    i) If none is found, then this conductor has a break. Assign the code 6 to it;

    ii) If other zones are found, then the conductor also has a short circuit. Assign code 10 to it.

In the illustrative example, the conductors of the Test image associated with zones 6, 4 and 7 are 1 and 2. So, there is a break in conductors 1 and 2.

Repeating the algorithm for the next non marked zone; we get zones 2 and 3, corresponding to conductors 3 and 5 (another break). Finally, zones 5 and 8 correspond to conductor 4, which is correct.

3.7 Color Code

The color code used to show the results of the classification of each conductor label is the following table:

Classification	Color Code
Correct	0
No holes	4
Broken	6
Short Circuit	8
Broken and Short Circuit	10

4. Implementation and Results

The inspection technique is implemented using MMach – A Mathematical Morphology Toolbox for the Khoros system [Barrera et al.].

Figure 10 and Figure 11 show a real situation example. Figure 10 is the Reference image and Figure 11 is the Test image. The result of this inspection is show in Figure 12. There are a few short circuits and broken conductors as indicated by the color code and by the highlighted areas in the Figure.

Although the objective of this work was not to create a fast implementation, we include below the total execution time of the technique running the Khoros cantata workspace applied to the example shown in Figure 12. The PCB image has more than 600.000 pixels, 431 holes and 287 connections. The total execution time was 53 seconds running in a Sun Sparc5 with 32 MB of memory including the time to read and write all intermediate files usually associated with the workspace execution.

We believe that by creating a tailored implementation of the proposed inspection algorithm, avoiding reading and writing files and including more than one operator in the same raster image scanning, the total time can fall to around 5 seconds.

5. Conclusions

A novel PCB inspection algorithm based on the connectivity of the conductors is proposed and implemented using classical Morphology tools. The two most important tools used in the technique are labeling and zone of influence. Labeling extracts the conductor connectivity of the PCB image and zone of influence is used as an aid to register the holes of the Test image to the holes of the Reference PCB image.

This new technique falls in a new class of inspection algorithm under the classification proposed by Moganti [Moganti et al. 1996]. It is a referential method based on connectivity.

We have demonstrated the technique, by implementing it using the MMach Toolbox and applying to real PCB images. The proposed inspection algorithm has the simplicity of many non-referential PCB based inspections algorithms, but the powerful analysis of complex model-based techniques.

Figure 10 - Reference PCB.
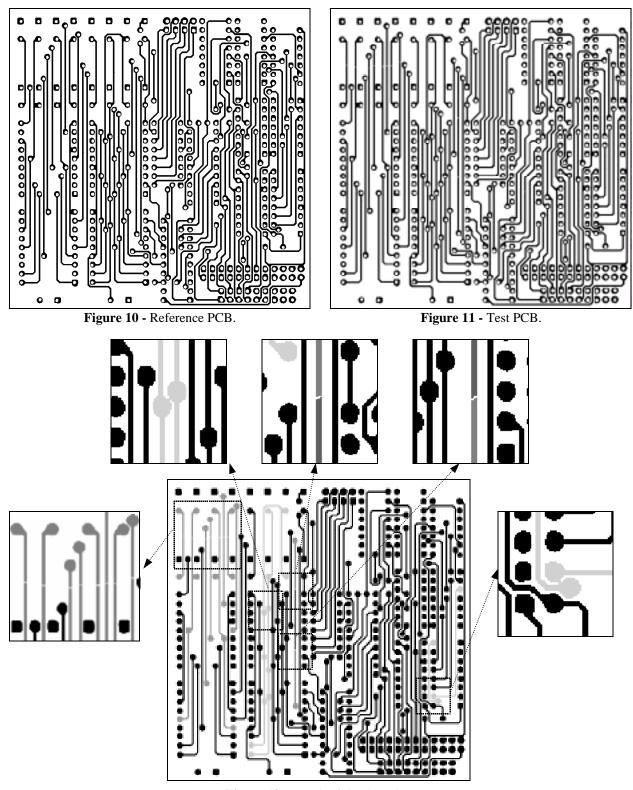

Figure 11 - Test PCB.

Figure 12 - Result of the detection.

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