Int J Adv Manuf Technol (2005) 25: 940–946
DOI 10.1007/s00170-004-2299-9

ORIGINAL ARTICLE

H. Rau · C.-H. Wu

Automatic optical inspection for detecting defects on printed circuit board inner layers

Received: 13 February 2004 / Accepted: 11 June 2004 / Published online: 12 January 2005

Abstract This paper studies automatic optical inspection for detecting defects on the printed circuit board inner layer. The development of this study can be divided into five stages, they are reference image rebuilding, inspection image normalization, image subtraction, defects separation and defect classification. In the image subtraction stage, the difference between the reference image from the printed circuit board design and the inspected image is checked for defects. Each defect region is separated using a defect outer boundary tracing method. A boundary state transition method is proposed to classify the defect types. This system can recognize eight defect types, open, mouse bite, pinhole, missing conductor, short, spur, excess copper and missing hole. In addition, a comparison with the methods described in the literature is made, proving that the proposed method produces better results.

Keywords Automatic optical inspection · Defect · Printed circuit board

1 Introduction

Many important vision applications are found in manufacturing processes, such as inspection, measurement and some assembly operations. One of these applications is the automatic visual inspection of printed circuit boards (PCBs). The circuits on PCBs are becoming much finer and more complex, making human visual inspection a challenge. Comparing manual and automatic optical inspection (AOI), Moganti and Erical [1] pointed out that AOI relieves human inspectors of tedious jobs. They also showed that manual inspection is slow and costly, leading to excessive scrap rates and does not ensure high quality and that production rates for high-tech industries are so high that manual inspection is not feasible.

H. Rau (✉) · C.-H. Wu
Department of Industrial Engineering,
Chung Yuan Christian University,
Chungli, Taiwan 320, R.O.C.
E-mail: hsinrau@cycu.edu.tw

In addition, AOI has the following characteristics that contact testing lacks: it recognizes potential defects such as out-of-spaces, line widths, line spacing, voids and pinholes. AOI can inspect artwork and provides strict product control from the onset of production. AOI is a non-contact inspection method that avoids mechanical damage resulting from the inspection process.

There are six inspection stages in multi-layer PCB manufacturing process: (1) art-work masters, (2) photo-tools, (3) inner and outer layers after exposure and development, (4) inner layers after etch and strip, (5) outer layers after etching, and (6) inspection after machining and solder masking. The inner layers after the etching and strip stage is the point at which most of the visual inspection is invested in the multi-layer manufacturing cycle. This is the last inspection stage before lamination. After this point, a defective inner layer in a multi-layer board is not repairable. Therefore this study focuses on automatic visual inspection of the inner layer board.

In general, PCB inspection algorithms can be grouped into three categories: reference comparison methods, non-reference inspection methods, and hybrid inspection methods. This research belongs to the first category. The reference comparison methods require a standard image that is scanned from a "golden board" or PCB design CAD file. The inspected board is then scanned and compared to this standard image. These methods can easily detect defects such as missing conductors, opens and shorts. The limitations of these methods are the large required storage capability for the reference image, precise alignment, and that these methods are sensitive to illumination.

In the image comparison techniques field, Hamada and Nakahata [2] used inspected patterns for comparison with design patterns to achieve a highly reliable inspection method in 1990. They proposed a two-step image processing inspection. The first step is the coarse alignment between the detected patterns and the design patterns. The second step is the defect detection named the "local pattern comparison" method in which small defects up to 1.5 pixel-size can be detected without being influenced by pattern registration errors and sampling errors.

Ito and Nikaido [3] proposed a topological comparison method that compares the inspection graph obtained from the skeletons of the conductor and insulator images in an inspection PCB with those from the standard or reference board. The topological information incorporates weighted graphs composed of several types of nodes and edges, connections and their locations. The defects are detected using structural characteristics, which is not a direct image subtraction operation.

Wu et al. [4] proposed an image comparison method that directly subtracted the template image form the inspection image, and then conducted an elimination procedure to locate the defects on a PCB. After finding defects, all identified defects could be classified into one of seven defect types using three indices: the type of object detected, the difference in object numbers, and the difference in background numbers between the inspected image and the template.

Model based inspection is also a branch of reference inspection methods. Tatibana [5] proposed a novel technique for PCB inspection based on a comparison of the connected table of a reference and a test image. This method is based on connected component analysis, which is a natural way to extract the connectivity information of the conductors on a PCB.

Borba and Facon [6] proposed a non-reference inspection method. This method could detect defects without considering a reference board. This research succeeded in verifying vertical, horizontal and 45-degree oriented traces.

This study chooses the image comparison technique as the principal inspection method for searching for PCB defects. Image subtraction is the simplest and most direct approach to the PCB inspection problem. The board to be inspected is scanned and its image is compared against the image of an ideal part. Because PCBs are fabricated using CAD data, the perfect reference image is rebuilt or directly transferred from the CAD data into the inspection system [7].

In this research, components such as a pad and track are obtained from a CAD file to make an ideal reference image. It is not always necessary for an inspection board to coincide completely with the standard board as long as some specified design rules are satisfied. This study therefore modifies ideal images that have a reasonable tolerance for the image subtraction process using PCB design rules stated in [6].

This study also adopted an outer boundary tracing process to separate defects, and proposes a boundary transition state method to classify defect types in the PCB inspection system. This inspection system can identify eight defect types that include the open, short, mouse bite, spur, missing conductor, excess copper, missing hole and pinhole. A comparison with the region merge method and the projection method is made, proving that the proposed method achieves better results.

The proposed inspection method is formulated in Sect. 2. This inspection method is then implemented and discussed in Sects. 3 and 4, respectively.

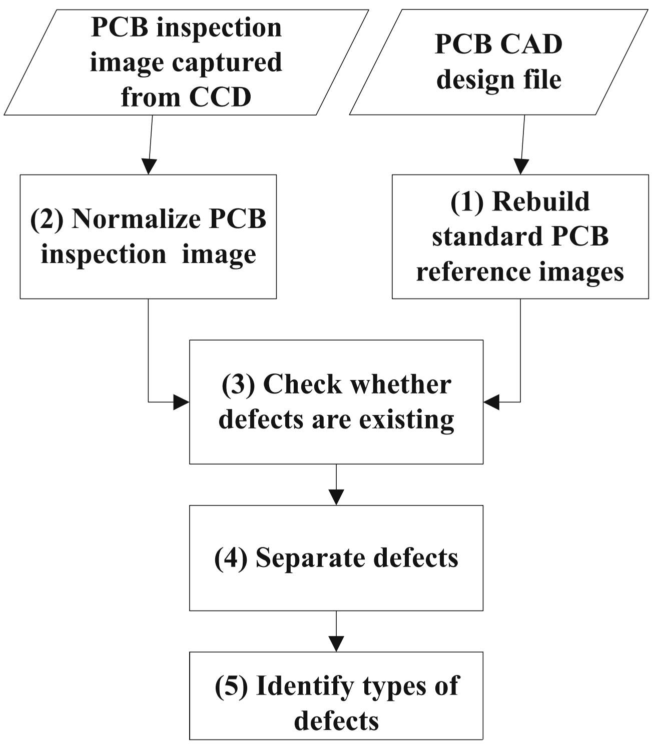


Fig. 1. PCB inspection

2 Proposed inspection method

The automated visual inspection system developed in this research for detecting defects on a PCB inner layer includes five major stages (see Fig. 1):

1. Read a CAD file for the PCB design and transfer the CAD data into ideal reference images.
2. Normalize the inspection image using a pixel coordinate transformation process. This includes rotation, scaling, and shifting operations.
3. An image subtraction process is used to search for defect areas.
4. A defect outer boundary tracing process is executed to separate the defects.
5. Classify defects using a boundary state transition method.

In the following, each stage will be discussed in detail.

2.1 Rebuild reference image

The PCB design file is obtained from the PCB design software PROTEL. This method uses two basic components, pad and track, from a CAD file generated in the PCB design software to make ideal reference images. Reasonable tolerances used in design rules for PCB manufacturing are considered in this method. Borba and Facon [6] pointed out the following inspection rules, adopted in our study. They are:

1. The width reduction of a trace must be less than 30% of the nominal width.
2. The size of the copper lacks in the pads must be less than 2/3 of the nominal diameter.

3. Any reduction in the distance between two elements (pad and trace) must be less than 30% of the nominal distance.

Two ideal images are used in this method: expansion and contraction from the original design image for the image subtraction process. Image expansion is used for detecting excess pixel defects such as shorts, spurs, excess copper and missing holes. Image contraction is used for detecting missing pixel defects such as opens, mouse bites, pinholes and missing conductors.

2.2 Normalize inspection image

The image normalization process is a very important stage in PCB inspection. In this process, some reference points should be searched first allowing the inspection image to be mapped onto the ideal image using reference points. Three geometric transformations for the image normalization process are rotation, scaling and shifting. Their operations can be checked in reference [8] for details.

2.3 Subtract image

The image subtraction method is one of the reference-based inspection methods. It is simple, quick and effective in finding defects. Although the overall defects can be detected using this method, it suffers from a serious problem that it would make inspection errors when noise occurs. The environment or information transformation process could introduce this kind of noise. The proposed method expands or contracts the source images by including reasonable tolerance according to the design rules discussed in [6]. This method can easily reduce the noise problem.

The resultant images can be separated into two groups: missing pixels and excess pixels after the image subtraction operation with expansion or contraction of the ideal reference images. The missing pixel image group $Missing(x, y)$ can be derived using Eq. 1. The result is shown in Fig. 2. Defects of this kind are opens, mouse bites, pinholes and missing conductors. The excess pixel image group $Excess(x, y)$ can be derived using Eq. 2. The result is shown in Fig. 3. These defects include shorts, spurs, excess copper, and missing holes.

$$Missing(x, y) = \begin{cases} 0 & Contraction(x, y) = O \& Inspection(x, y) = B \\ 1 & otherwise \end{cases} \tag{1}$$

$B : Background \quad O : Object \quad 1 : White \quad 0 : Black$

$$Excess(x, y) = \begin{cases} 0 & Expansion(x, y) = B \& Inspection(x, y) = O \\ 1 & otherwise \end{cases} \tag{2}$$

$B : Background \quad O : Object \quad 1 : White \quad 0 : Black$

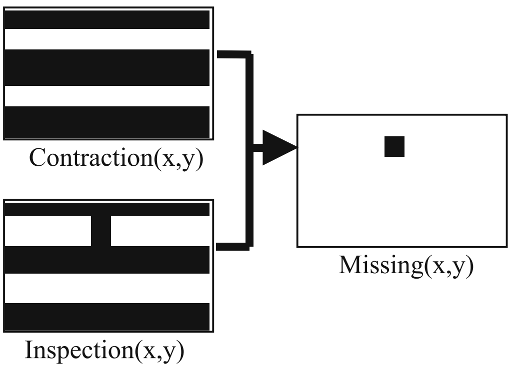


Fig. 2. Image operation of missing pixel

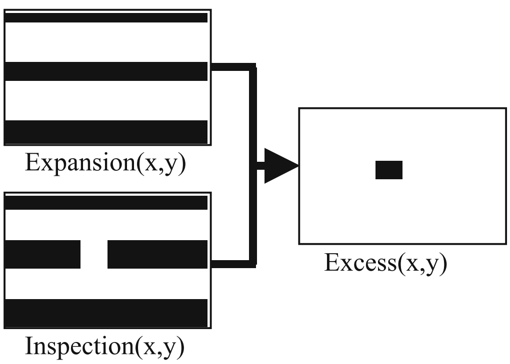


Fig. 3. Image operation of excess pixel

2.4 Separate defects

Basically, image separation can be divided into two kinds of methods: region scanning and boundary tracing. Wu et al. [4] used region scanning. This study selected boundary tracing for the better performance, as discussed in Sect. 4. The defect outer boundary tracing method, described in [8], was used here to separate defects. A 4-connectivity logic operation is used to determine the outer boundary of objects in a binary image. A sample of the outer boundary is detected as shown in Fig. 4. In the test image inspection shown in Figs. 2 and 3, outer boundary tracing was used to detect missing and excess pixels, as shown in Fig. 5.

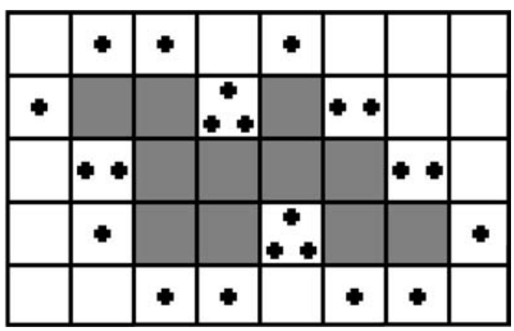


Fig. 4. Example of outer boundary tracing [8]
• denotes outer boundary elements

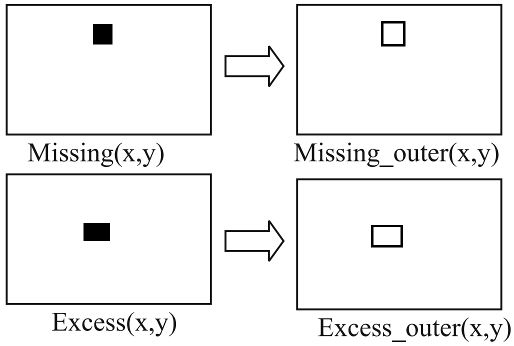


Fig. 5. Outer boundary tracing result for missing and excess images

2.5 Classify defects

After the defects are separated, they can be classified using method called boundary state transition (BST). BST can detect eight types of defects. The BST method traces the defects outer boundary and checks the boundary state, which is either object or background. It then counts the number of state transitions (NOST) for detecting defect types. The method is described in the following algorithm:

1. Search the image from the top left until a pixel for a new boundary for a defect is found and denote this starting pixel in the boundary as P_0. Define a variable *POS* that stores the position of P_0.
2. Define a variable STA_n that stores the state (object or background) of the image at the position P_n, $n = 0, 1, 2, \ldots$. Define a variable *NOST*, and its initial value is 0.
3. Start from P_0 to search the neighborhood pixel P_{n+1} using a 3×3 mask of the P_n along with the boundary and in the counterclockwise (or clockwise) direction. If STA_{n+1} is not equal to STA_n, then $NOST = NOST + 1$ (see the illustration in Fig. 6).
4. Repeat step 3 until P_0 is reached again.
5. Identify the defect type as missing or excess, *NOST*, and record the boundary state in STA_n.
6. Return to step 1 for another defect.

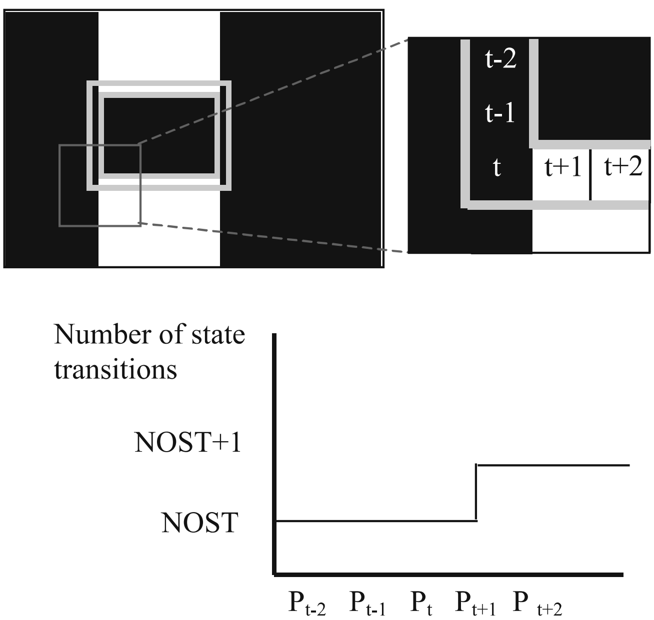


Fig. 6. Boundary state transition method

2.6 Results of defect detection

Based on the discussion in the previous sections, defect types can be detected. First, we use an image subtraction process. Defects are identified for their existence, but we do not yet know which type of defect and how many of each type. Identified defects can be divided into two groups: missing pixels and excess pixels. One defect can be separated from another using an outer boundary tracing process. Finally, defects can be classified using the proposed BST method with the help of which group, missing

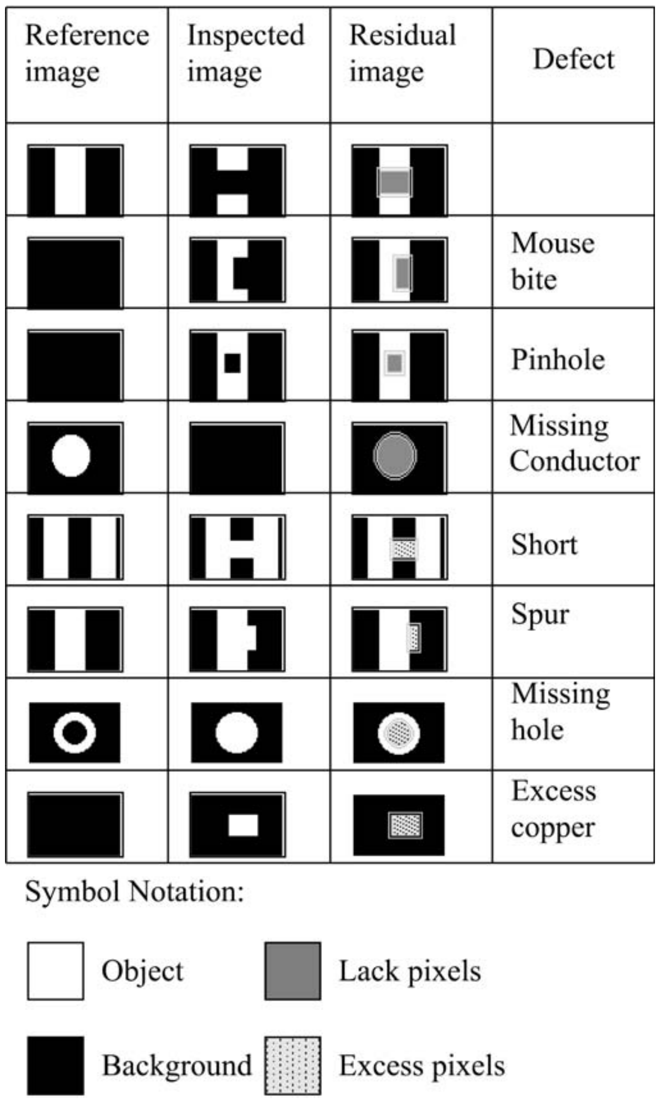


Fig. 7. Eight types of defects on the PCB inner layer

Table 1. PCB defect detection by boundary state transition method

Defect type	Missing	Excess	NOST	Boundary state
Open	√		4	
Short		√	4	
Mouse bite	√		2	
Spur		√	2	
Missing conductor	√		0 (all in background)	
Excess copper		√	0 (all in background)	
Pinhole	√		0 (all in object)	
Missing hole		√	0 (all in object)	

Table 2. Result of PCB sample inspection

Defect_No	Part_No	Defect_Type	X	Y
1	1	(Open circuit), 1	114	161
2	1	(Pinhole), 3	115	102
3	1	(Mouse bite), 2	280	53
4	1	(Missing pattern), 4	414	39
5	1	(Short circuit), 5	601	40
6	1	(Excess copper), 7	713	195
7	1	(Spur), 6	944	139

or excess, they belong to. Eight types of defects are recognized by this method. The result is summarized in Table 1. Figure 7 presents the eight defects of the inner PCB layer. Open, mouse bite, pinhole, and missing conductors belong to the missing pixel group. The excess pixel group includes shorts, spurs, excess copper and missing holes.

3 Implementation

A PCB automatic inspection system is tested using real PCB patterns on a Pentium II PC with a PV-910PC frame grabber, shown in Fig. 8. A 1240×720 pixel PCB image with various defects is displayed in Fig. 9b. A defect-free image is shown in Fig. 9a. The tested source image was inspected using the five stages that discussed in the previous section. After inspection the defects are

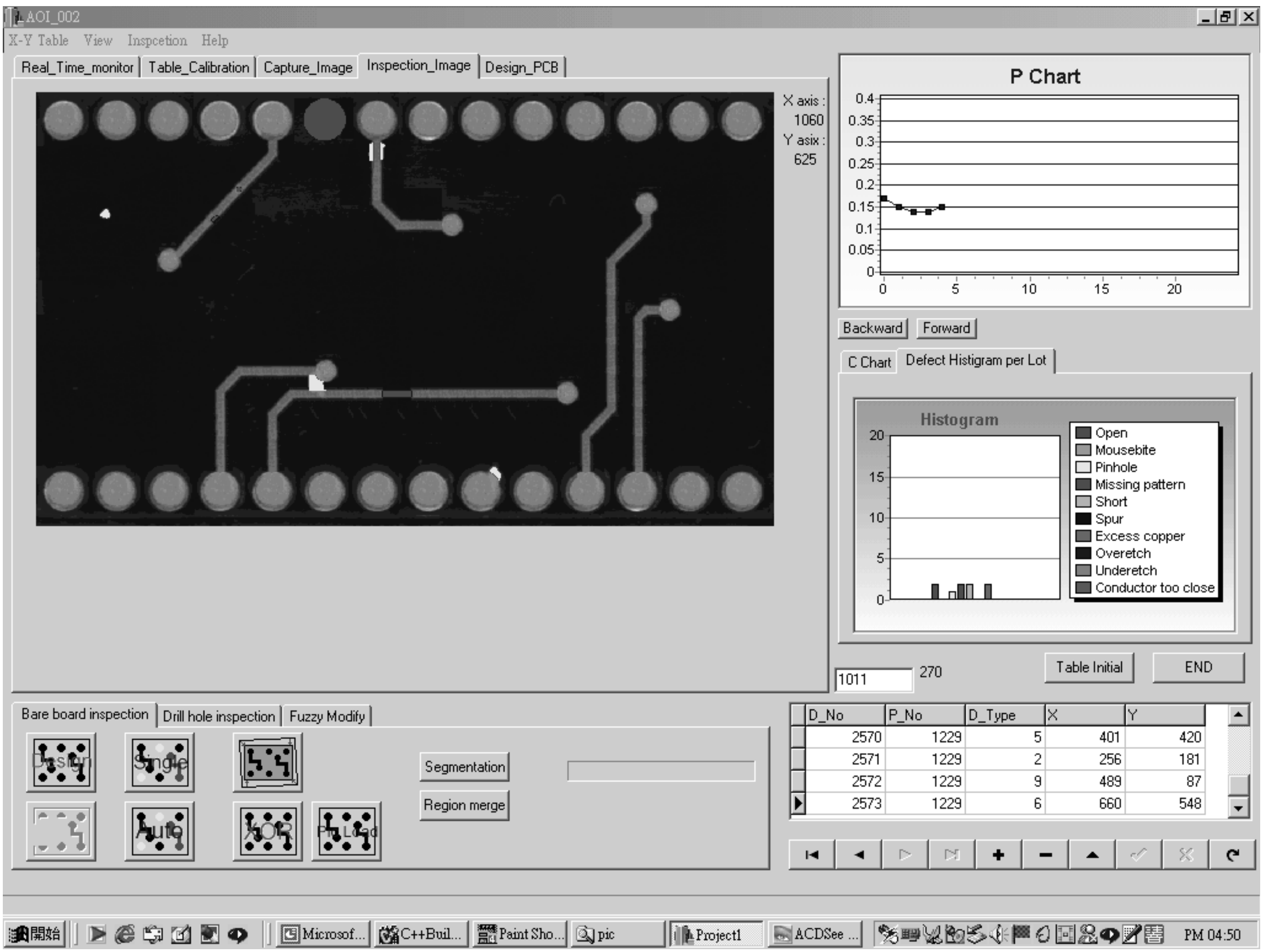
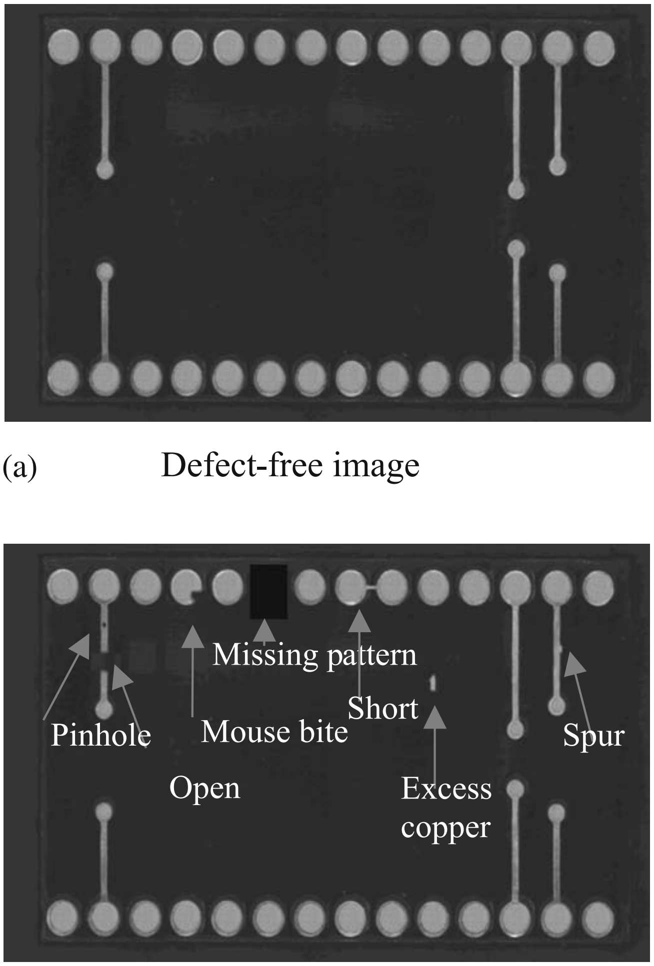


Fig. 8. PCB automatic inspection system



(a) Defect-free image

(b) Inspected image

Fig. 9. PCB etching sample images

detected. Because the sample has only gone through the etching stripping process, the defect of missing hole would not be shown on it.

This PCB inspection system can also detect defect positions using the center of gravity calculation method for a two-dimensional image. The inspection result is shown in Table 2. Defect positions are useful information that can help an operator to fix defects easily using PCB defect reading equipment. This defect inspection information can be used to perform statistical analysis for controlling the manufacturing process. As we can see, all defects occurring on the tested sample were successfully detected using this inspection system.

4 Discussion

This defect inspection system uses an image subtraction process to locate the defects, followed by processes to separate and classify the defects. As mentioned before, there are two kinds of separating methods: region scanning and boundary tracing. These two methods can deal with more general cases. Another method, the projection segmentation method, can handle certain special cases. This study compares these three methods. In this comparison the proposed BST method is used to follow up the boundary tracing method.

In the image projection method the image is projected onto the horizontal and vertical axes. This is the fastest way to separate objects in an image. However it can only be used in a special case in which any two objects can be separated using either horizontal or vertical projection.

Sonka et al. [8] pointed out a region merging function, shown in Eq. 3:

$$\begin{aligned} &(a)\text{Find S regions}: H(R_i) = TRUE \qquad i = 1, 2, \ldots, S \\ &(b)\text{Merge regions}: H\left(R_i \cup R_j\right) = TRUE, \qquad i \neq j \\ &\qquad\qquad\qquad\qquad\qquad\qquad \text{and } R_i \text{ adjacent to} R_j\,, \end{aligned} \tag{3}$$

where S is the total number of regions in an image, and $H(R_i)$ is a binary homogeneity evaluation of the region R_i. Initially, s regions are located. The regions are then merged. When R_i and R_j are adjacent and $\mathrm{H}(\mathrm{R}_i \cup \mathrm{R}_j) = \mathrm{TRUE}$, then R_i and R_j will execute the region merging process.

The outer boundary tracing method is used to separate defects. This study proposes the boundary state transition method for classifying defects. Using these two methods, less time is required to separate and classify defects than in the region scanning method. The above-described methods are tested using several image samples that had different numbers of defects. When the number of defects increases, the region merging method takes much more time to separate and classify defects than the outer boundary tracing method. The time needed for these three methods to detect defects is compared in Fig. 10. As we discussed before, the projection method can only take care of special cases. Separating the defects using the projection method is the most efficient way. But for general cases, the outer bound-

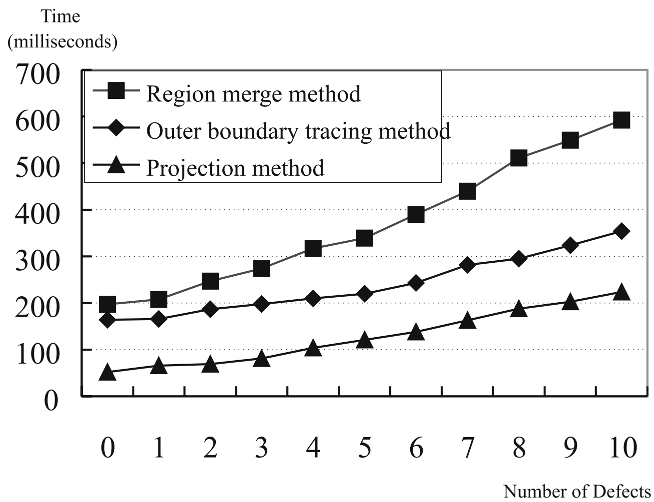


Fig. 10. Time needed for various methods

ary tracing method plus the boundary state transition method is better.

5 Conclusion

This research studies automatic optical inspection for detecting defects on the printed circuit board inner layer. This study uses image subtraction operation that includes reasonable tolerance according to design rule in the expansion and contraction process for comparing the inspected images against reference images. The outer boundary tracing and BST methods are then used to identify the defect types. The developed inspection system can detect eight types of defects, which include opens, shorts, mouse bites, spurs, pinholes, excess copper, missing conductors and missing holes. A real PCB pattern was tested using the proposed method. A comparison between the proposed method and two other methods was conducted. The proposed method was proven to have more general use and detected defects more efficiently.

Acknowledgement The paper was partially supported by National Science Council (NSC) of Taiwan, R.O.C., under contracts NSC 89-2218-E-033-002 and NSC 89-2218-E-033-012.

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