Performance Evaluation of Wavelet-based PCB Defect Detection and Localization Algorithm

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Abstract
One of the backbones in electronic manufacturing industry is the printed circuit board (PCB) manufacturing. Due to the fatigue and speed requirement, manual inspection is ineffective to inspect every printed circuit board. Hence, this paper presents an efficient algorithm for an automated visual PCB inspection system that is able to automatically detect and locate any defect on PCBs. The defect is detected by utilizing wavelet-based image difference algorithm. The coarse resolution defect localization algorithm, is also presented. The coarse resolution defect localization algorithm is applied to the coarse resolution differenced image in order to locate the defective area on the fine resolution tested PCB image. In addition, the performance of the algorithm is evaluated to verify the efficiency of the proposed algorithm in term of computation time. This new method turned out to be computationally less intensive than traditional image difference operation. One conclusion from this paper is that the second level Haar wavelet transform should be chosen for the application of automated visual PCB inspection.
Keywords: Automated Visual Inspection, Printed Circuit Board, Wavelets, Inspection Time

1. Introduction

There exist numerous algorithms, technique and approaches in the area of automated visual PCB inspection nowadays. As proposed by Moganti [1], these can be divided into three main approaches: referential approaches, rule-based approaches and hybrid approaches.

For the referential approaches, there are two major techniques. The first one is image comparison technique and the other one is model-based technique. Image comparison technique consists of comparing the tested PCB image against the reference PCB image using simple XOR logic operator. Model-based technique on the other hand, matches the tested PCB image with a predefined model.

Rule-based approaches test the design rule of the PCB traces to determine whether each PCB trace fall within the required dimensions or not. Mathematical morphological operation is frequently used where dilation and erosion are the basic operation.

Lastly, the hybrid approaches combines the referential approaches and the design-rule approaches to make use the advantages and to overcome the shortcoming of each approach.

This paper is organized as follows. Section 2 mentions the research methodology of this project. The proposed algorithm entirely can be divided into two stages: the defect detection and the coarse resolution defect localization. The wavelet-based PCB defect detection algorithm is addressed clearly in section 3. On the other hand, the coarse resolution PCB defect localization algorithm is described in detail in section 4. Section 5 contains the discussions and the analysis of the computation time of the proposed algorithm. Section 6 concludes the paper and lastly, the references of this research work are placed in section 7.

2. Research Methodology

Numerous techniques have been proposed under model-based method so far. Some of them are graph-matching technique, tree representation techniques [5], connectivity technique [6] and RLE-based technique [7].

This paper proposes a slightly different technique in such a way that the PCB images will be modeled by the use of two-dimensional Haar wavelet transform. Then, the image difference operation is applied to the images in the wavelet domain. The first advantage of the proposed technique is that wavelet transform can be treated as image-to-image transformation. This will enable each wavelet coefficient to be treated as a pixel image and thus allows the image difference operation to be carried out. After that, based on the coarse differenced image, the defect localization will be computed in the coarse resolution domain. However, the defective areas are marked on the fine resolution original image of the tested PCB. The proposed algorithm comprises of two major parts. The first one is wavelet-based image difference algorithm and the second one is coarse resolution PCB defect localization algorithm.

3. Wavelet-based PCB Defect Detection Algorithm

3.1 Wavelets

Wavelet is a zero mean function [8] and satisfies the so-called *admissibility condition* [4],

$$C_\psi = \int_{-\infty}^{\infty} \frac{|\hat{\psi}(\omega)|^2}{\omega} d\omega < \infty \qquad (1)$$

where ψ is a fixed function, called 'mother wavelet' and $\hat{\psi}$ is the Fourier transform of ψ. The constant c_ψ designates the admissibility constant. According to Mallat [9], the continuous wavelet transform (CWT) of a function f is given by:

$$f_\psi(a,b) = \int_{-\infty}^{\infty} f(t) \frac{1}{\sqrt{a}} \psi\left(\frac{t-b}{a}\right) dt \qquad (2)$$

The parameter a is called the dilation factor and has a constraint such that $a > 0$ and b, a real number, is the translation parameter. A wavelet transform decomposes a signal $f(t)$ into many coefficients, which are the function of scale (dilation) and position (translation).

The computation of the wavelet transform of a two-dimensional signal, an image, is applied as a successive convolution by a filter entry of row/column followed by a column/row as depicted by Fig. 1. Thus, for two-dimensional wavelet transform, after the first level wavelet transform operation, the input image can be divided into 4 parts: approximation, horizontal detail, vertical detail and diagonal detail where the size of each part is reduced by the factor of two compared to the input image as depicted by Fig. 2.

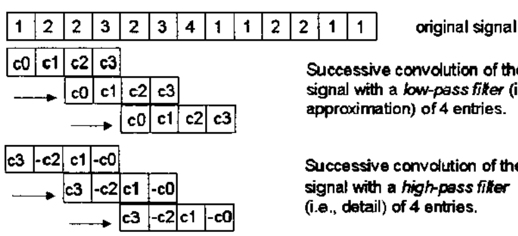

Fig. 1 Successive Convolution of Wavelet Transform

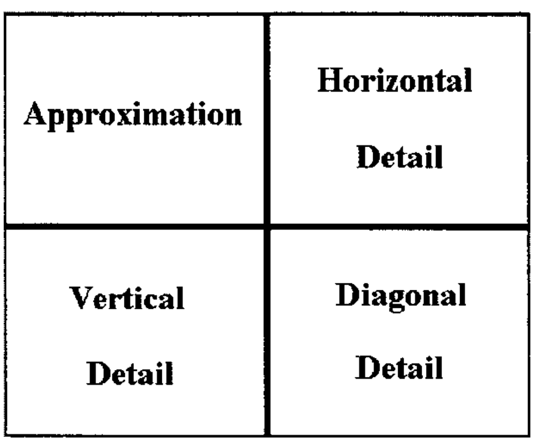

Fig. 2 First Level Wavelet Transform

Approximation is a compressed and coarser part than the original input image. Meanwhile, the horizontal detail, vertical detail and diagonal detail contain the horizontal, vertical and diagonal components of the input image. When the second level wavelet transform is applied, the approximation part of the first level will be further decomposed into four components as depicted by Fig. 3. For the higher level, the iteration is done in the same way until the desired level is reached.

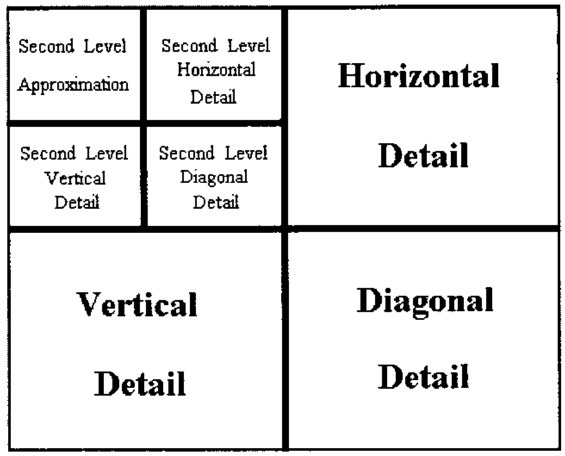

Fig. 3 Second Level Wavelet Transform

Haar wavelet transform has been chosen for simulation in MATLAB. Haar wavelet has two filter entries [10] as shown in Table 1. By using the Haar wavelet for wavelet-based image difference algorithm, no boundary solution is required. Also the computation of wavelet transform can be applied as a moving average operation within the original image.

Table 1 Analysis Filter for Haar Wavelet (2-filter Entry)

	Coefficient 1	Coefficient 2
Approximation Filter (Low Pass)	½	½
Detail Filter (High Pass)	½	½

3.2 Image Difference Operation

Consider two binary images named as *Img1* and *Img2* of size *M* x *N* where *M* is the length and *N* is the height of the image respectively. For each pixel at corresponding location *(x,y)* that is *x* from 1 to *M*, *y* from 1 to *N* where both *x* and *y* are integers, *Img1[x,y]* and *Img2[x,y]* has a value of either one or zero. In this case, it is assumed that one is identified as background pixel, whereas zero is identified as foreground pixel.

In this project, image difference operation is applied onto the output of the second level wavelet transform and not on the binary image. The input data is no longer an integer value but rather a floating value. Therefore, for every pixel of *Img1* and *Img2*:

- For *Img1*, grab a pixel value at location *Img1(x,y)* and named it as *PixVal1*.
- For *Img2*, grab a pixel value at location *Img2(x,y)* and named it as *PixVal2*.
- If *PixVal1* is equal to *PixVal2*, assign the corresponding pixel at location *Difference(x,y)* as background pixel.
- If *PixVal1* is *not* equal to *PixVal2*, assign the corresponding pixel at location *Difference(x,y)* as foreground pixel.

3.3 PCB Defect Detection Algorithm

Two images are needed in this project, the reference image and the test image. Wavelet transform is applied to the reference image and then the image and also the wavelet outputs are stored in memory. This step is done offline once only as indicated by the dash box in Fig. 4.

For the test image, as same as the ideal reference image, wavelet transform is applied. The flow of the algorithm, which is illustrated in Fig. 4, consists of an example of a reference image, a test image, the resultant wavelet transform output and also the defect detected in the output image of image difference operation. The output image is called the coarse resolution differenced image.

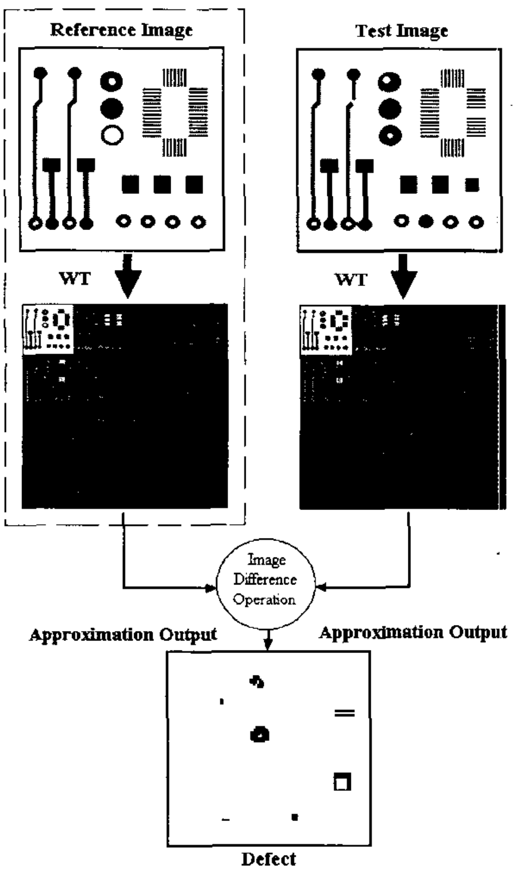

Fig. 4: Wavelet-based Image Difference Operation

4. Coase Resolution PCB Defect Localization Algorithm

The purpose of the defect localization algorithm is to highlight the defective areas on the tested PCB image. The defect localization is important in order to mention the users about the location of the defects detected for further procedures such as defect classification and defect marking.

The input for the defect localization algorithm is the coarse resolution differenced image. The input comes from the wavelet-based image difference algorithm. The defect localization algorithm consists of four core operations named as connected-component labeling operation, window coordinates searching operation, mapping operation and windowing and defect extraction operation.

4.1 Connected-component Labeling Operation

The connected-component labeling operation returns the information of the coarse differenced image (a binary image) to identify each object in the image. The output of the connected-component labeling operation is a two-dimensional output array named as labeled image. The size of the labeled image is exactly the same as the coarse differenced image, which the objects in the coarse differenced image are distinguished by different integer values in the labeled image.

In this paper, the 8-connectivity pixel for the connected-component labeling operation is selected to minimize the number of the identified object.

4.2 Window Coordinates Searching Operation

The most important objective of this operation is to search four coordinates of each object after the connected-component labeling operation for the defective area windowing. The four coordinates of each object are named as: *RowMin, RowMax, ColMin* and *ColMax* correspond to minimum row, maximum row, minimum column and maximum column respectively. Note that this operation is done on the coarse resolution image.

4.3 Mapping Operation

According to the coordinates obtained in the previous operation, a number of windows are drawn on the fine resolution tested image. Recall that these four coordinates of each object is defined in a coarse resolution image. Hence, some sort of mapping equation is needed to map the coordinates in the coarse resolution image to the fine resolution image. The determination of the mapping equation is critical in the sense that ineffective mapping equation will cause the distortion problem happened to the individual drawn window. In order to solve this matter, four equations are used for the mapping operation.

Suppose that if each coordinate *RowMin, RowMax, ColMin* and *ColMax* on the coarse resolution image is to be mapped into *RowL, RowH, ColL* and *ColH* on the fine resolution image, then:

$$RowL = (RowMin)(2^L) - (2^L - 1) \quad (3)$$

$$RowH = (RowMax)(2^L) \quad (4)$$

$$ColL = (ColMin)(2^L) - (2^L - 1) \quad (5)$$

$$ColH = (ColMax)(2^L) \quad (6)$$

where L denotes the iteration or level of wavelet transform used in the wavelet-based image difference algorithm.

4.4 Windowing And Defect Extraction Operation

For each *RowL, RowH, ColL* and *ColH* represent to each defective area, a boundary line representing a window can be drawn on the fine resolution tested PCB image. Each window marks the defective areas where the defects are actually occurred. After the defective areas are windowed successfully, it is possible to segment each defective area for defect extraction where each defective area is shown in an individual image.

The result of the defect localization is depicted in Fig. 5. The black windows on the gray pattern highlight the defective areas on the tested PCB image. The flow of the coarse resolution defect localization algorithm is well shown in Fig. 6.

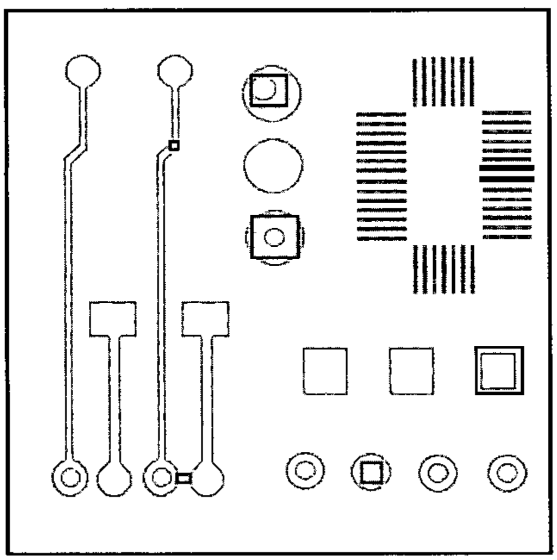

Fig. 5 Defect Localization

5. Computation Time

The defect detection and localization algorithm is tested on different resolution images. The different resolution images is gathered by executing the first level wavelet transform, second level wavelet transform and third level wavelet transform onto the input images. As time is one of the industries major factors, it is essential to see the performance of the propose algorithm in term of inspection time. The computation time is achieved by the use of MATLAB as a platform. The inspection time of the proposed algorithm based on the full resolution operation (without wavelet transform) and wavelet-based technique are given in Table 2 and Table 3 respectively.

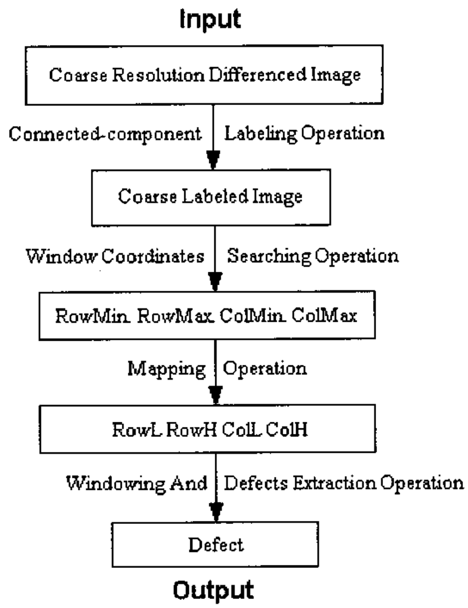

Fig. 6 Coarse Resolution Defect Localization Algorithm

Table 2 Inspection Time of the Full Resolution Operation

Operation	Inspection Time (s)
Read Input	00.020
Image Difference	07.251
Labelling	00.060
Window Coordinate Searching	17.846
Mapping And Windowing	00.050
Defect Extraction	00.812
Show Output	00.150
Total	26.189

According to the results given by Table 2 and Table 3, the data of the overall computation time is plotted in order to simplify the analysis. The graphs of the computation time reduction are shown in Fig. 7. These graphs obviously show the slope of the inspection time reduction by applying zero, first, second and third level of wavelet transform. Note that the zero level wavelet transform means that no wavelet transform involves in the image difference operation and the computation of the algorithm is done on the original full resolution of input images.

Recall that the principle goal of this project is to meet the online processing requirements for the PCB inspection. Undoubtedly, the overall inspection time is successfully reduced. Due to the sample, the inspection time reductions by using the first level wavelet-based technique with respect to full resolution computation is about 67.69%. Meaning that more than half of the overall computation time acquired by fine resolution operation is saved.

Table 3 Inspection Time of the Wavelet-based Technique

Operation	Inspection Time (s)		
	First Level Wavelet Transform	Second Level Wavelet Transform	Third Level Wavelet Transform
Read Input	0.030	0.030	0.030
Wavelet Transform	1.582	1.162	1.092
Image Difference	0.781	0.200	0.050
Labelling	0.010	0.020	0.020
Window Coordinate Searching	5.048	1.993	1.082
Mapping And Windowing	0.030	0.030	0.030
Defect Extraction	0.801	0.990	0.941
Show Output	0.180	0.261	0.260
Total	8.462	4.686	3.505

Up one level ahead, the percentage of the overall computation time reduction is increased. The percentage of reduction based on the full resolution processing by using the second level wavelet transform is 82.11%. From a different view, the increment of the overall computation time reduction (in percentage) with respect to the overall computation time, where the first level wavelet transform is chosen is about 14.42%.

When the third level wavelet transform is selected in the proposed defect detection and localization algorithm, the percentage of the overall computation time reduction is increased to 86.62%. However, the percentage of the overall computation time reduction might be poorer and unacceptable when the data is compared to the overall computation time based on the second level wavelet transform. The increment is about just 4.51%.

The result is unacceptable in the sense that it is not worthy to utilize the third level wavelet transform in order to reach just a little bit improvement in the overall computation time and at the same time, the more expensive hardware is required. In reality, wavelet transform is an expensive task when the transformation is going to be implemented on hardware such as Field Programmable Gate Array (FPGA), Digital Signal Processing (DSP) Processor or Very Large Scale Integrated-Circuit (VLSI). Based on the argument, second level wavelet transform is recommended for the implementation.

From the proposed algorithm point of view, cost comparison between wavelet-based and non-wavelet processing with respect to time requirements suggests that wavelet-based processing provides considerable advantage over the non-wavelet one.

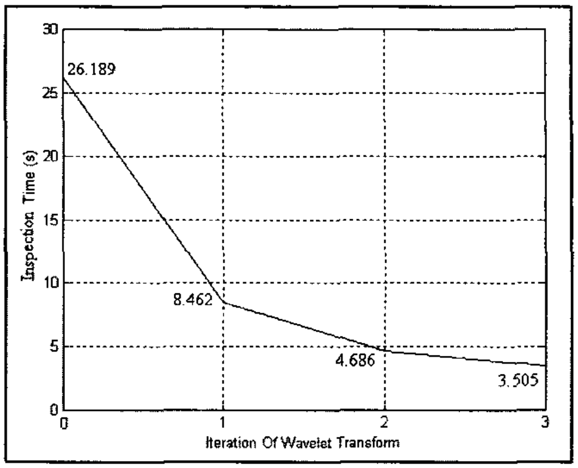

Fig. 7 Inspection Time Reduction

6. Conclusions

This paper proposes an algorithm for PCB defect detection and localization for an automated PCB inspection system. Due to these all results, the proposed algorithm is expected to detect and localize successfully several types of printing defects such as breakout, short, pin hole, wrong size hole, open circuit, conductor too close, underetch, spurious copper, mousebite, excessive short, missing conductor, missing hole, spur and overetch. The localized area in these figures will be used as the inputs to the classification stage, which is the subsequent stage after the defects detection had been achieved.

As a conclusion, it can be said that the wavelet-based PCB defect detection and localization is better than the existing PCB defect detection algorithms in term of computation time. The continuation of this research is to implement the algorithm on hardware to ensure that the automated PCB inspection system can perform in a real-time environment with high efficiency. The proposed algorithm could be used for an automated visual PCB inspection system to achieve real time inspection of PCBs.

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