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PERFORMANCE EVALUATION OF WAVELET-BASED ALGORITHM FOR PRINTED CIRCUIT BOARD (PCB) INSPECTION

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Abstract. Image difference operation is frequently used in automated printed circuit board (PCB) inspection system as well as in many other image processing applications. The inspection system performance depends critically on the speed of this operation, which is a common problem related to the image difference. The goal of our technique is to achieve real time inspection using wavelet transform. This paper presents a new wavelet-based algorithm for image difference, which computes image difference to the output of the wavelet transform. The results of applying the technique to PCB images showed significant improvement on the traditional image differencing.

Keywords: Image difference, wavelet transform, printed circuit board, inspection time

Abstrak. Operasi perbezaan imej seringkali digunakan dalam pemeriksaan papan litar bercetak secara automatik dan tidak terkecuali juga dalam banyak aplikasi pemprosesan imej yang lain. Pelaksanaan sistem pemeriksaan ini sangat bergantung kepada kelajuan operasi ini, di mana ia adalah masalah umum berkaitan dengan pembezaan imej. Matlamat teknik kami adalah untuk memperoleh pemeriksaan secara waktu nyata dengan menggunakan ubahan wavelet. Kertas kerja ini membentangkan satu algoritma baru berasaskan wavelet untuk pembezaan imej, dimana pembezaan imej dilakukan ke atas keluaran ubahan wavelet. Keputusan pelaksanaan teknik ini ke atas imej-imej papan litar bercetak menunjukkan pembaikan yang ketara berbanding dengan pembezaan imej secara tradisional.

Kata kunci: Pembezaan imej, ubahan wavelet, papan litar bercetak, masa pemeriksaan

1.0 INTRODUCTION

On-line inspection of PCBs requires acquisition and processing of gigabytes of image data in a matter of few seconds, especially when multi-layer and very high-resolution boards are used. It deals with detecting visual and functional defects on boards. Recently, there has been a lot of progress in automating the PCB inspection process. Advances in computers, pattern recognition, image processing and artificial intelligence have resulted in better and cheaper ways of inspecting PCBs. The

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availability of high processing power and high resolution imaging systems made visual inspection an integral part of the most manufacturing systems. Unlike the early days in which human operators were used for inspection, today, the inspection tasks are performed by automated systems, which employ computer vision and image processing techniques. Compared to human inspectors, computer based automated systems have many advantages: high speed, high inspection quality and low cost for labour. The rest of the paper is organized as follows. Section 2 specifically gives an outline of the PCB fabrication process in industry. Section 3 briefly describes the background of visual PCB inspection approaches and also the techniques chosen for this work. Section 4 shows the design of the proposed algorithm with a brief description of wavelet transform. The results are discussed in Section 5. Finally, Section 6 presents conclusions and outline the future work, followed by acknowledgements in Section 7.

2.0 PCB FABRICATION PROCESS: AN OUTLINE

Aithal *et al.* [1] gives a summary of the stages involved in the PCB fabrication process. Figure 1 shows the various stages in the PCB fabrication process. The paragraphs below briefly describe the corresponding stages.

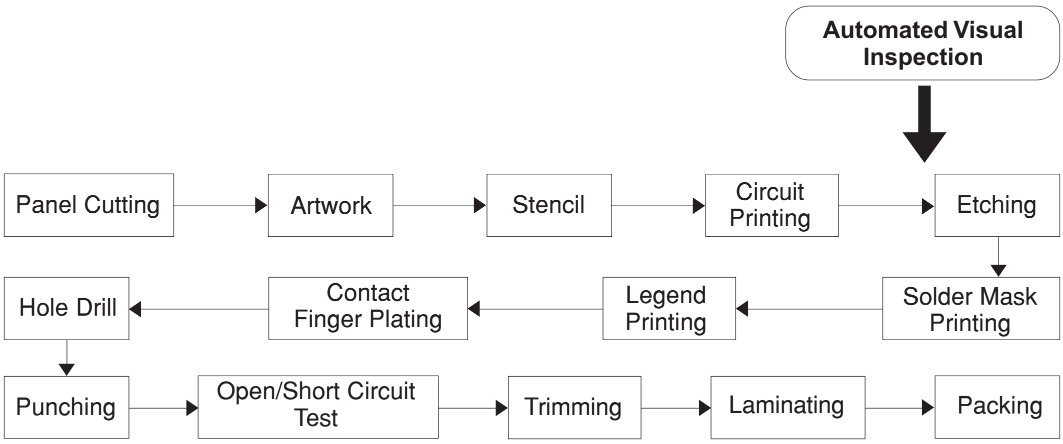


Figure 1 PCB Fabrication Process

Panel Cutting

Copper clad with thin layer of copper on one side used for fabrication of single-sided PCB. This copper clad is cut into pieces. These pieces of copper clad are called panels. Depending on the size of PCBs to be fabricated, a panel accommodate one or more than one PCB. Cutting these panels to the PCBs required size is done at the trimming stage of the process. On all the four sides of the panel, extra space is left which is required to hold the panel during different stages of fabrication process, without affecting the PCB area.

Artwork

An artwork is used for PCB manufacturing. Artwork is a negative film with the PCB pattern printed on it.

Stencil

Based on the artwork, stencil, that is a mask of circuit pattern, is build for circuit printing process.

Circuit Printing

Over the copper foil, circuit printing is done with blue ink, which acts as etch resist for subsequent etching stage to follow.

Etching

Once the pattern plating is done, the etching process takes place. This process is an irreversible process. This will bare the unwanted copper foil, which must be etched away to leave the copper pattern. Copper foil is etched by spraying the etchant to the panel as it moves on the conveyor.

Solder Mask Printing

Solder mask (green ink) printing is needed to make sure there is no short circuit occurred during soldering. It also reduces the ability of molten solder to adhere to the boards' surfaces. The solder mask is typically applied by screen-printing using solder mask film, which enables the entire board surfaces to be covered, except for the holes, pads and contact fingers.

Legend Printing

The legend or nomenclature is screen printed onto PCBs to identify the components, for assembling and testing purposes. This printing operation is performed using legend print film. Since legend is permanent, once it is dried, legend printed panels must also be checked for legibility and completeness of the printed image.

Contact Finger Plating

Contact finger plating is the next operation (optional) in the fabrication of PCBs.

Contact fingers is the rows of tabs along one or more edges of the boards. These tabs fit into connectors in the electronics equipment in which the PCB is used. They must be durable and resistant to tarnishing and oxidation.

Hole Drill

At the hole drill stage, the board is drilled with 2 holes only. These 2 holes are important for the alignment purpose either in assembly or inspection process.

Punching

Once the panel is drilled, the next stage is punching. Here, all necessary holes are created or punched at a certain temperature. Either Computerized Numerical Control (CNC) drilling or manual is used for this purpose. 99.5 % of the jobs are drilled on the CNC drilling machine and only 0.5 % of the jobs are drilled on optical drilling (manual). The main reason of manual drilling is one or more of the following:

(i) Very less ordering quantity
(ii) Non availability of drill data
(iii) Number of holes on the PCB is less than 1000

The panels are pinned together in stacks from one to four layers high, depending on panel thickness. These are loaded onto the drilling machine. NC part program is loaded into the CNC drilling machine and all required holes are drilled at proper locations, with correct drill size. Latest CNC drilling machines are equipped with automatic tool changer, which will automatically change drill bits when the holes size changes. Some CNC drilling machines are also equipped with multiple spindles, so that simultaneous multiple stacks of panels can be drilled.

Open/Short Circuit Test

The punched board goes to electrical test to check if there is any open or short circuit occuring on the board.

Trimming

During this stage of the process, the panels are cut to the required size of individual PCB.

Laminating

Finally, the PCB is laminated to prevent oxidation before packing.

Inspection

At various stages of the fabrication process inspection is carried out. If the panel is accepted at that stage, it is passed on to the next stage. Otherwise, it goes back to rework, to the same stage of operation. But in some of the cases, the panel is rejected. For such cases, the panel inspection is very important.

Current practice in PCB fabrication requires etching process. This process is an irreversible process. The printing process, which is done before etching process, caused most destructive defects found on the PCB. Any misprint will cause the etched board to be useless. Since laminated board constitute 70 % of the total production cost, it is important that the board is properly inspected before being etched. Otherwise, the wrongly etched board will be thrown away. To solve the problem, this paper proposes a system to detect online or in real-time any defect caused by the printing process.

3.0 BACKGROUND

Moganti proposed [2] three categories of inspection algorithm: referential approaches, rule-based approaches and hybrid approaches.

The referential approaches compare the reference PCB image to the tested PCB image. There are two major techniques: image comparison methods and model-based inspection. Image comparison, which is the simplest method, consists of comparing both images pixel-by-pixel using simple XOR logic operator. The operation is simple but the main difficulty is to determine 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 [2], 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 [2] and are based on the structural topological and geometrical properties of the image. The major difficulty of those methods is related to the matching complexity. Although Sun *et al.*, [3] proposed a technique called Pattern Attributed Hypergraph to make the method more practical, it still remains a complex and time-consuming method.

Rule-based approach on the other hand uses the complete knowledge of the circuit under test and determines whether each feature falls within the required dimensions or not. A PCB pattern is consider defective if it does not conform to the design specification standards. These method typically use morphological technique where erosion and dilation are the basic operation [4–7]. The main advantage of this approach is it does not require a reference model. But, it might miss large defects.

The hybrid approach is a combination of the reference-based and non-reference approaches. It has the advantages of these two approaches. However the approaches may be too complex and may result in high computational costs.

Wen-Yen *et al.*, [8] used the image difference operation for defect detection. The differenced image then goes to elimination procedure to get the residual image, which is used for defects classification. Since it involved with defect detection and classification procedure, the operation involves much time. Yet, the technique proposed by Wen-Yen can be improved to reduce the inspection time. The image difference operation can be applied on compressed images in order to achieve real time processing. This is done by Ercal *et al.*, [9] who apply the image difference between the reference image and the test image directly on compressed run length encoded (RLE) data in order to achieve fast processing in compressed domain. However, this technique is limited only to the PCB images, which is composed of primitive patterns.

Among the numerous approaches that have been proposed in the literature to date [2–7], image comparison approach is chosen due to its possibility for wavelet implementation. Wavelet-based algorithm is proposed to speed up the image difference operation used by Wen-Yen. The process is done on compressed image that employs wavelet transform. Unlike the work carried out by Ercal, the propose algorithm can be applied to any PCB images, not limited to the PCB images that is composed of primitive patterns.

4.0 WAVELETS AND PROPOSED ALGORITHM

According to Schremmer [10], a wavelet is a function $\psi \in L_2(R)$ that meets the admissibility condition:

$$0 < c_\psi := 2\pi \int_R \frac{|\hat{\psi}(\omega)|^2}{|\omega|} d\omega < \infty \tag{1}$$

where $\hat{\psi}$ denotes the Fourier transform of the wavelet ψ. The constant c_ψ designates the admissibility constant. It follows that a wavelet integrates to zero:

$$0 = \hat{\psi}(0) = \int_R \psi(t) e^{-2i\pi t0} dt = \int_R \psi(t) dt \tag{2}$$

Thus, the integral wavelet transform of a function $f \in L_2(R)$ is given by:

$$f \mapsto \tilde{f}_\psi(a,b) := \frac{1}{\sqrt{a}} \int_R f(t) \psi^* \left(\frac{t-b}{a} \right) dt = \int_R f(t) \psi^*{}_{a,b}(t) dt \tag{3}$$

where ψ^* is the complex conjugate ψ. $a > 0$ is called the dilation factor and b is the translation parameter, thus $\psi_{a,b}$ denotes a dilated and translated wavelet. A wavelet

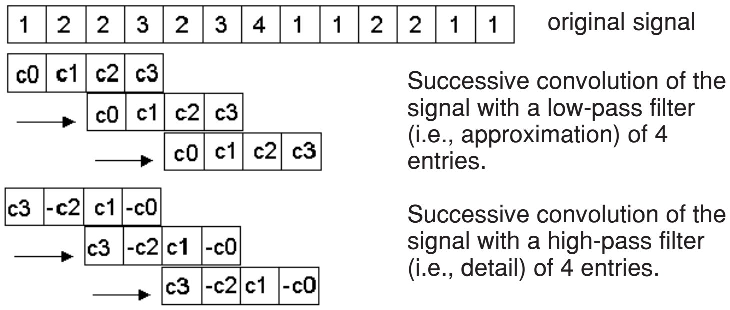


Figure 2 Computation of Two-dimensional Wavelet Transform.

transform decomposes a signal $f(t)$ into many coefficients, which are the function of scale (dilation) and position (translation). Unlike the Fourier transform, a transformation of a signal $f(t)$ from time domain to frequency domain, wavelets have a special capability to transform a signal $f(t)$ from time domain to both frequency and time domain.

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 Figure 2. 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 Figure 3(a).

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 Figure 3(b). Again, same

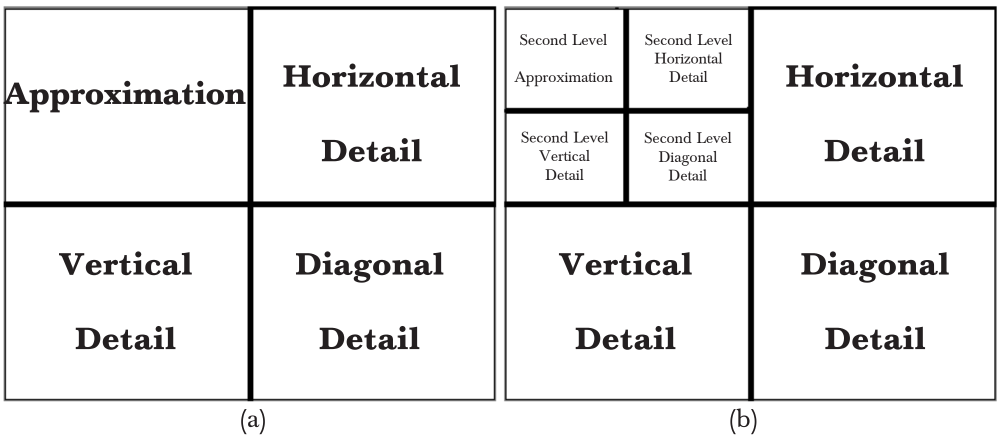


Figure 3 Wavelet Outputs (a) First Level (b) Second Level.

iteration is applied to the remaining approximation for the next level until the desired level is reached.

Haar wavelet transform has been chosen for simulation in MATLAB. Haar wavelet only has two filter entries [10] as shown in Table 1. Generally, filter length of another type of wavelet such as Daubechies is longer than the two entries. Table 2 demonstrates the analysis filter coefficient for Daubechies (db2.0) wavelet transform that is consists of four-filter entry [11]. By using the smallest filter entry (Haar wavelet), the processing time of inspection system can be minimized.

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

	Coefficient 1	**Coefficient 2**
Approximation (Low Pass) Filter	0.707	0.707
Detail (High Pass) Filter	0.707	–0.707

Table 2 Analysis Filter for Daubechies db 2.0 (4-filter entry)

	Coefficient 1	**Coefficient 2**	**Coefficient 3**	**Coefficient 4**
Approximation (Low Pass) Filter	0.48296291	0.8365163	0.22414386	–0.129409522
Detail (High Pass) Filter	–0.129409522	–0.22414386	0.8365163	–0.48296291

In this paper, a technique is presented, which is a slightly modification of image comparison technique for PCB inspection based on wavelet transform. Since, pure image difference operation is a time consuming process, the aim now is to reduce the inspection time. The flow of the traditional image difference algorithm and detailed wavelet-based image difference algorithm are well shown in Figure 4 and Figure 5 respectively. Next, Figure 6 demonstrates the overall design of the PCB inspection system.

5.0 SIMULATION RESULTS AND DISCUSSIONS

Two images are needed, the reference image and the test image. A CCD camera captures a non-defective board and the output that is a gray scale reference image is stored in memory. Third level wavelet transform is applied to the reference image and then the image and also the wavelet outputs are stored in memory. This step is operated offline as indicated by the dash line. The algorithm is tested on 600×800 PCB image. Figures 7(a) and 7(b) show the reference image and wavelet outputs of reference image, respectively.

During the online operation, the CCD camera captures the defective board and similar to the previous operation, third level wavelet transform is applied to the

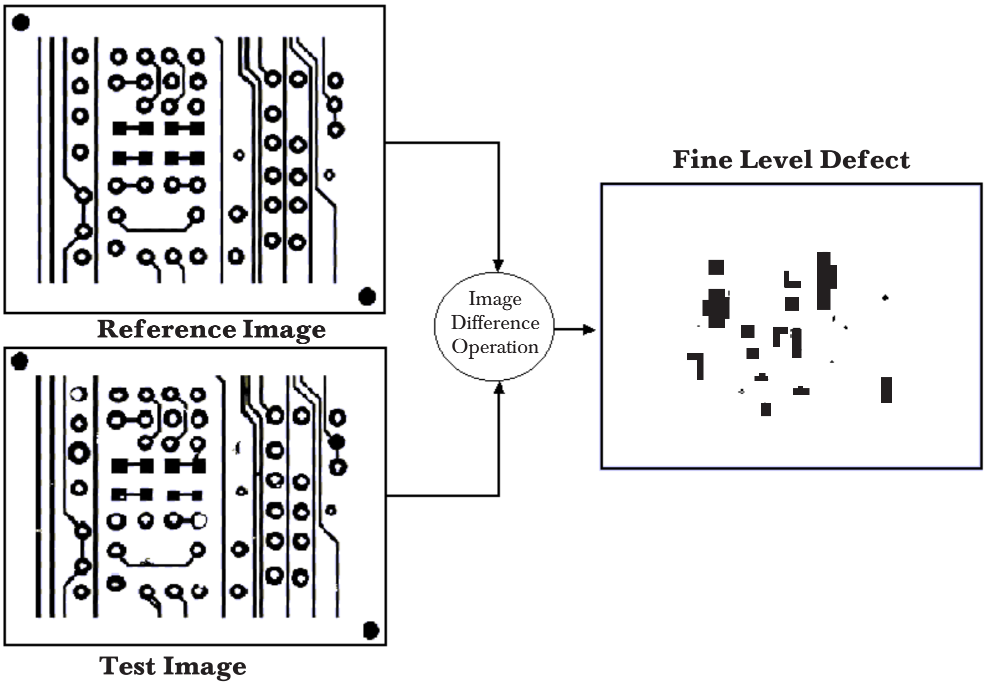


Figure 4 Traditional Image Difference Algorithm

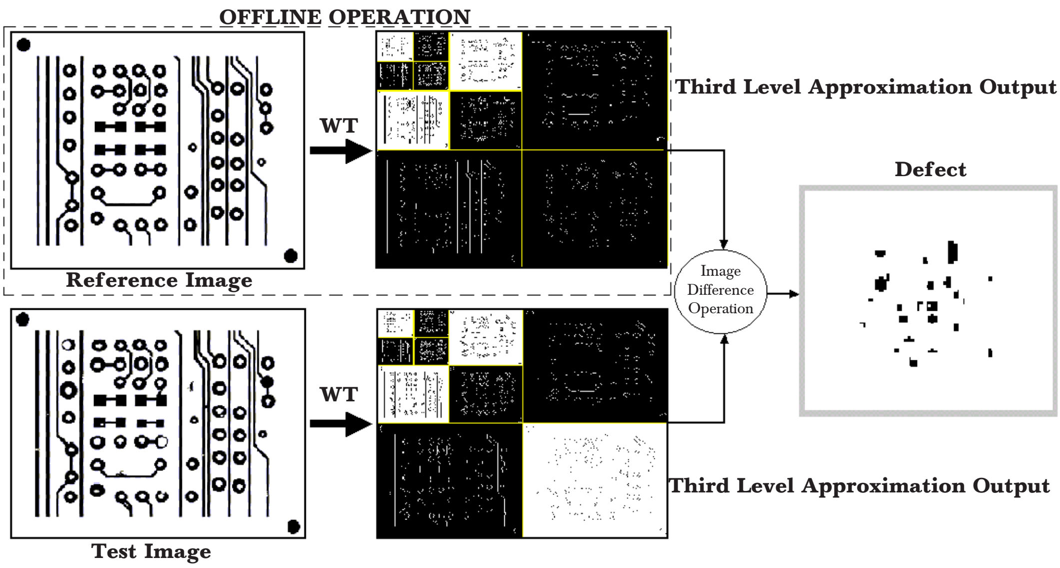


Figure 5 Wavelet-based Image Difference Algorithm

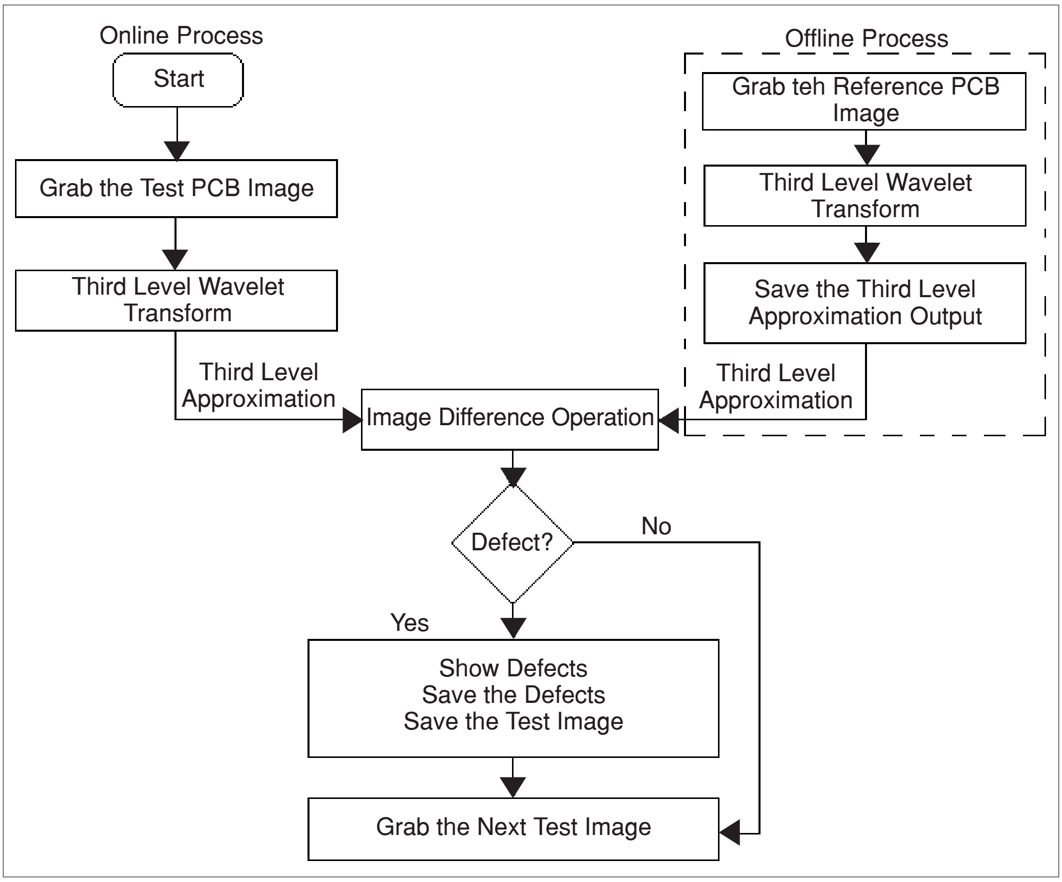


Figure 6 Overall Design of the PCB Inspection System

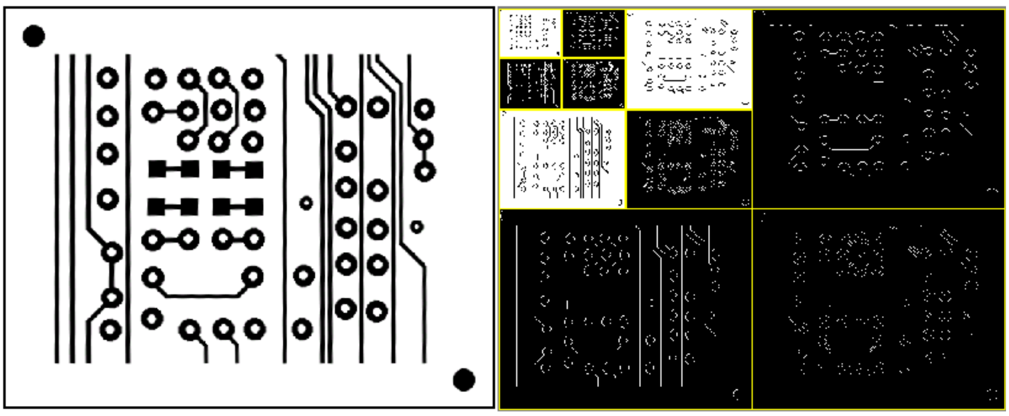
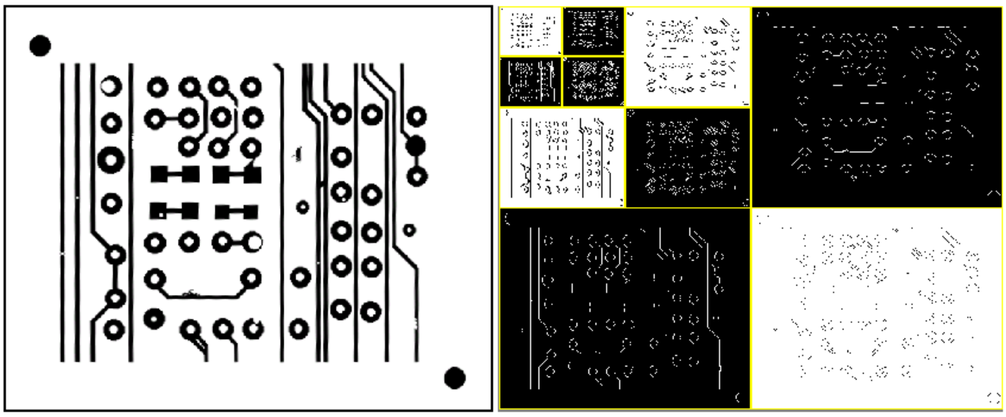


Figure 7 (a) Reference Image (b) Wavelet Transform of Reference Image

captured image. As an example, Figure 8(a) shows a test image captured by the CCD camera and Figure 8(b) shows the wavelet output of this test image.

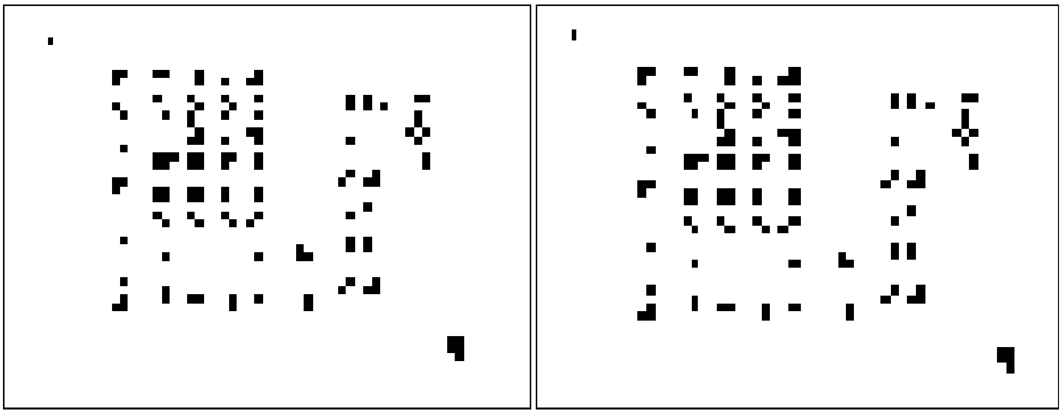
Refer to Figure 7(a) (reference image) and Figure 8(a) (test image). The size of each image is 600 x 800 pixels and each image is called a fine image. Referring to the wavelet outputs in Figure 7(b) and Figure 8(b) of the images, this technique uses the third level approximation only. Figure 9 shows the third level approximation of the reference image and the test image.

These two compressed images are named as coarse images and the size of each image is much reduced by a factor of 8 according to its original image to 75×100



(a) (b)

Figure 8 (a) Test Image (b) Wavelet Transform of the Test Image

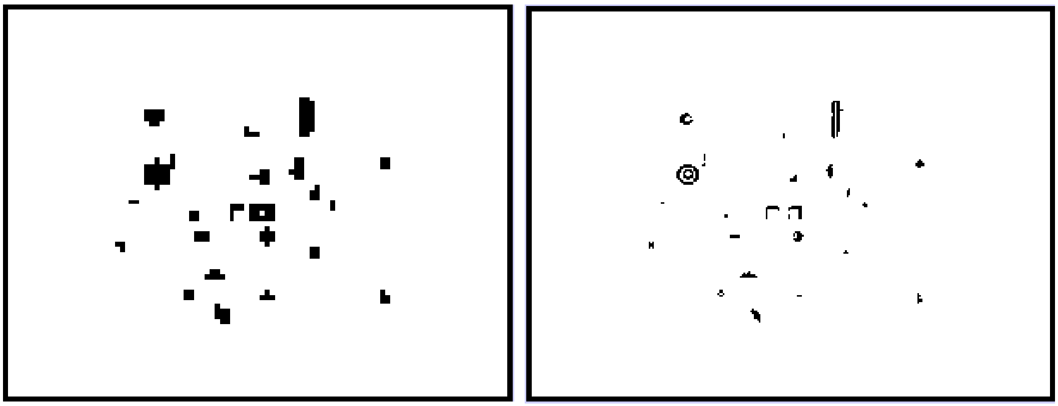


(a) (b)

Figure 9 (a) Third Level Approximation of the Reference Image. (b) Third Level Approximation of the Test Image pixels. Normal human visual system is not able to differentiate between the coarse reference image and the coarse test image. Furthermore it is impossible for human visual system to detect and locate the defects occur on coarse test image.

The advantage of wavelet transform is that it still preserves most of the information of the fine image in the coarse image. It is possible to detect the defects occur on coarse test image by simply applying the image difference operation between the coarse reference image and coarse test image. That is why only the third level approximation part is chosen for image difference. Figure 10 shows the result of coarse level image difference for wavelet-based algorithm and fine level image difference for traditional algorithm.

By evaluating Figure 10(a) and Figure 10(b), it is clearly shows that the proposed algorithm is able to maintain the accuracy of defect detection with the size as small as 1 pixel. The coarse image processing is only applied to defects detection procedure. However, the defects localization should be highlighted on the test image for better visual perception.



(a) (b)

Figure 10 Image Difference Outputs (a) Wavelet-based (b) Conventional

The cost of processing depends on the size of the input image. So, the proposed algorithm is expected to get better performance in terms of inspection time due to the size of input image for image difference operation. Tables 3 and 4 show the different performance in term of inspection time for each the traditional image difference, the Daubechies (db2.0) – based algorithm and also the Haar-based algorithm. Note that the inspection time given is achieved from simulation, the real inspection time can be obtained by the implementation of the inspection system later.

Table 3 shows that, for traditional image difference operation, the overall inspection time is 13.30 s. 11.92 s is used for image difference operation. Meaning that, 89.62 % of the overall inspection time is spent on image difference operation.

Table 3 Performance of Traditional Image Difference

	Operation	Time, s
1	Grab the test image	00.77
2	Set the difference parameter	00.33
3	Image difference operation	11.92
4	Show the defect	00.28
	Total	13.30

Table 4 Performance of Daubechies (db2.0) – Based Image Difference Algorithm

	Operation	Time, s
1	Grab the test image	0.77
2	Third level wavelet transform	2.58
3	Set the difference parameter	0.00
4	Coarsest image difference operation	0.22
5	Show the defect	0.11
	Total	3.68

Table 5 Performance of Haar-Based Image Difference Algorithm

	Operation	Time, s
1	Grab the test image	0.77
2	Third level wavelet transform	2.14
3	Set the difference parameter	0.00
4	Coarsest image difference operation	0.22
5	Show the defect	0.11
	Total	3.24

Table 4 on the other hand shows much inspection time reduction by using the proposed algorithm based on 4-filter entry Daubechies db2.0 wavelet. The overall inspection time can be much reduced to just 3.57 s. It takes 2.47 s for third level wavelet transform and 0.22 s for image difference operation. Thus, by introducing wavelet transform to image difference operation, the overall inspection time can be decrease up to 72.33 % where 98.15 % of reduction is achieved on image difference operation.

However, the speed of inspection can be further increased by utilizing the smallest filter length by replacing the wavelet used in the proposed algorithm. For this reason, Haar wavelet (2-filter entry) is used. Table 3 clearly shows that for Haar-based algorithm, the overall inspection time now is 3.24 s where 2.14 s and 0.22 s is spent on third level wavelet transform and image difference operation respectively. Again, when traditional image difference is taken for comparison, the overall inspection time can be decreased up to 75.64 %. Same as Daubechies db2.0 – based algorithm, 98.15 % of reduction is achieved on image difference operation. Meaning that, for PCB inspection application, Haar wavelet is better than another wavelets. Thus, Haar wavelet is selected to minimize the inspection time.

6.0 CONCLUSIONS

Automatic PCB inspection is needed to inspect the PCB for defect, anomalies and fault. Among the variety algorithms, this paper emphasizes the image difference operation to get better improvement by introducing wavelet transform into image difference operation. The major improvement of performance in term of the inspection time has been achieved. This technique maintains the possibility to detect the defects with the size as small as 1 pixel and at the same time minimize the inspection time.

It is important to note that the proposed algorithm did not take into account the image registration problem, which is commonly occurred in pure image difference operation. Current research activity is about aligning the reference image and the test image before executing the third level wavelet transform in order to solve the image registration problem.

7.0 ACKNOWLEDGEMENTS

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