PRINTED CIRCUIT BOARD INSPECTION USING WAVELET-BASED TECHNIQUE

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A thesis submitted in fulfilment of the requirements for the award of the degree of Master of Engineering (Electrical)

Faculty Of Electrical Engineering
Universiti Teknologi Malaysia

JUNE, 2002

UNIVERSITI TEKNOLOGI MALAYSIA PSZ 19:16

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To my family who loves me, especially to my parents for education they give me and also for their supports and understandings.

ACKNOWLEDGEMENT

First of all, thanks to Allah SWT for giving me the strength and the chances in completing this project.

Secondly, I wish to express my sincere thanks to my supervisors, Associate Professor Dr Syed Abdul Rahman Al-Attas and Mr Zulfakar Aspar for their guide and encouragement during this master project. I greatly appreciate their care and dedication in constructively criticizing my work, including my thesis. I have truly enjoyed working with them.

Millions of gratitude to other members of research group for their supports and advises. Also, I wish to thank the government for supporting this research via IRPA Grant: 72396.

Finally, I would like to thank my parents for their constant support, encouragement and understanding during my struggle away from home.

ABSTRACT

Malaysia is a well-known country with high quality productions in electronic manufacturing industry. One of the backbones in electronic manufacturing industry is the Printed Circuit Board (PCB) manufacturing. Current practice in PCB manufacturing requires etching. This process is irreversible. Printing, which is done before etching, caused most of the destructive defects found on the PCB. Once the laminate is etched, the defects, if exist would cause the PCB laminate to be of no use. Due to the fatigue and speed requirement, manual inspection is ineffective in inspecting every printed laminate. Therefore, manufacturers require an automated system to perform online defect detection which may occur during the printing. Hence, this project proposes an algorithm for automated visual PCB inspection that is able to automatically detect and locate any defect on a PCB laminate. Numerous approaches have been discussed in the literature so far but this work introduces a technique that is based on wavelets and multiresolution analysis. The inspection could be speed up by introducing wavelet-based algorithm for PCB defect detection and localization. The defect is detected by utilizing wavelet-based image difference algorithm. The detected defect is essential to locate the defective area on the tested PCB image. The ultimate goal of this project is to ensure the system can perform in a real-time environment with high performance.

ABSTRAK

Malaysia adalah sebuah negara yang dikenali dalam industri pembuatan elektronik yang bermutu tinggi. Satu daripada asas utama dalam industri pembuatan elektronik ialah pembuatan papan litar bercetak (PCB). Pembuatan PCB pada masa kini perlu melalui kikisan. Ini adalah proses satu hala. Percetakan yang dilakukan sebelum kikisan adalah penyebab utama kepada kecacatan pada PCB. Setelah PCB dikikis, kecacatan itu, jika ada menyebabkan PCB tidak berguna lagi. Disebabkan oleh keletihan dan keperluan kecepatan, pemeriksaan secara manual tidak effektif untuk memeriksa setiap PCB. Oleh itu, pengilang memerlukan sebuah sistem automatik untuk melakukan pemeriksaan kecacatan secara masa nyata yang mungkin berlaku semasa percetakan. Untuk itu, projek ini mencadangkan satu algoritma untuk pemeriksaan PCB automatik yang berupaya mengesan dan mengenal pasti lokasi sebarang kecacatan pada PCB. Pelbagai pendekatan telah dibincangkan setakat ini tetapi penyelidikan ini mencadangkan satu teknik berasaskan wavelets dan juga analisa pelbagai resolusi. Pemeriksaan boleh dipercepatkan lagi dengan memperkenalkan satu algoritma berasaskan wavelet untuk pengesanan dan pengenalpastian lokasi bagi sesuatu kecacatan PCB. Kecacatan tersebut akan dikesan dengan menggunakan algorithma pembezaan imej berasaskan wavelet. Kecacatan yang telah dikesan itu penting dalam mengenalpasti kedudukan kawasan kecacatan di atas imej PCB yang diuji. Matlamat terakhir projek ini adalah untuk memastikan sistem tersebut boleh beroperasi dalam keadaan yang sebenar dengan keupayaan yang tinggi.

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LIST OF ABBREVIATIONS

CAD	-	Computer-aided Design
CCD	-	Charge-coupled Device
CPS	-	Connectivity Preserving Shrinking
CWT	-	Continuous Wavelet Transform
DSP	-	Digital Signal Processing
DWT	-	Discrete Wavelet Transform
ECG	-	Electrocardiogram
FPGA	-	Field Programmable Gate Array
LED	-	Light-emitting Diode
MCS	-	Minimum Conductor Spacing
MCTW	-	Minimum Conductor Trace Width
MLW	-	Minimum Land Width
MRA	-	Multiresolution Analysis
MRLC	-	Modified Run Length Code
NAND	-	Not AND
NOR	-	Not OR
PCB	-	Printed Circuit Board
RLE	-	Run Length Encoding
RAM	-	Random Access Memory
ROM	-	Read Only Memory
STFT	-	Short Time Fourier Transform
VLSI	-	Very Large Scale Integration
XOR	-	Exclusive OR

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CHAPTER I

INTRODUCTION

1.1 Project Background

In this subsection, various stages involved in the PCB fabrication process are briefly described. In order to minimize scrap cause by the wrongly etched PCB panel, the automated visual inspection is proposed to be applied after the circuit printing and before the etching process. Also, 14 types of defect are outlined. These defects are expected to occur after the circuit printing process.

1.1.1 PCB Fabrication Process: An Outline

Aithal, et. al [1] gives the stages involved in PCB fabrication process in some detail. Following paragraphs briefly describe the stages involved in the PCB fabrication process. Figure 1.1 illustrates the various stages in the PCB fabrication process.

Boards with thin layer of copper on one side are used for fabrication of single-sided PCBs. These boards are cut into pieces. These pieces of board are called panels.

The input item for the PCB fabrication process is the artwork. Artwork is a film with the PCB pattern designed on it. Based on the artwork, stencil that is a mask of circuit pattern is built for circuit printing process. Here, the designed circuit pattern is printed over the copper foil with blue ink, which acts as etch resist for subsequent etching stage.

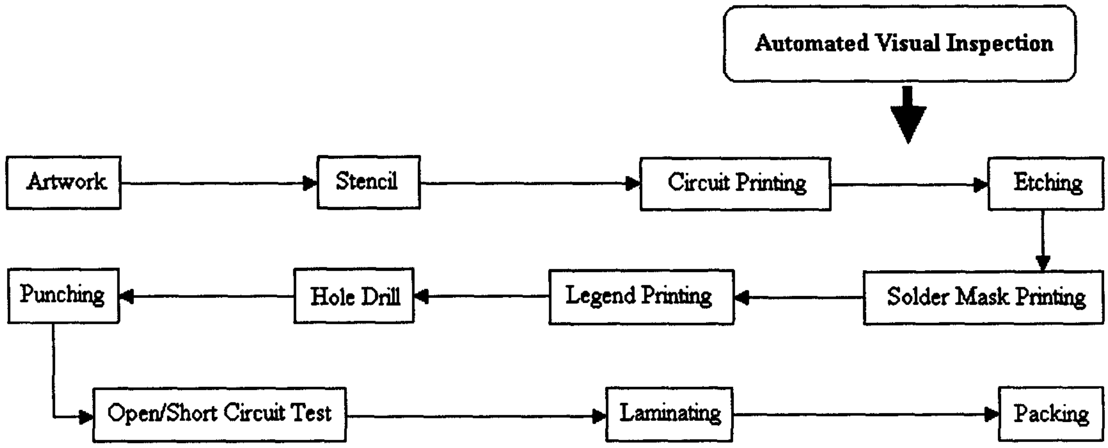


Figure 1.1 : PCB fabrication process

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

Solder mask (green ink) printing is needed to make sure there is no short circuit occurs during soldering. 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 and pads. Next, the legend is screen printed onto PCBs to identify the components. This printing operation is performed using legend print film.

At the hole drill stage, the board is drilled with 2 minimum holes. These 2 holes are important for the alignment purpose either in assembly or inspection process. Once the panel is drilled, the next stage is punching. Here, all necessary holes are created or punched. The punched board goes to electrical test to check if there is any open or short circuit occurs on the board. Finally, the PCB is laminated to prevent oxidation before packing.

1.1.2 Inspection

At various stages of the fabrication process, inspection is done. If the panel is accepted at that stage, it is passed on to the next stage. Otherwise, the panel 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 critically important.

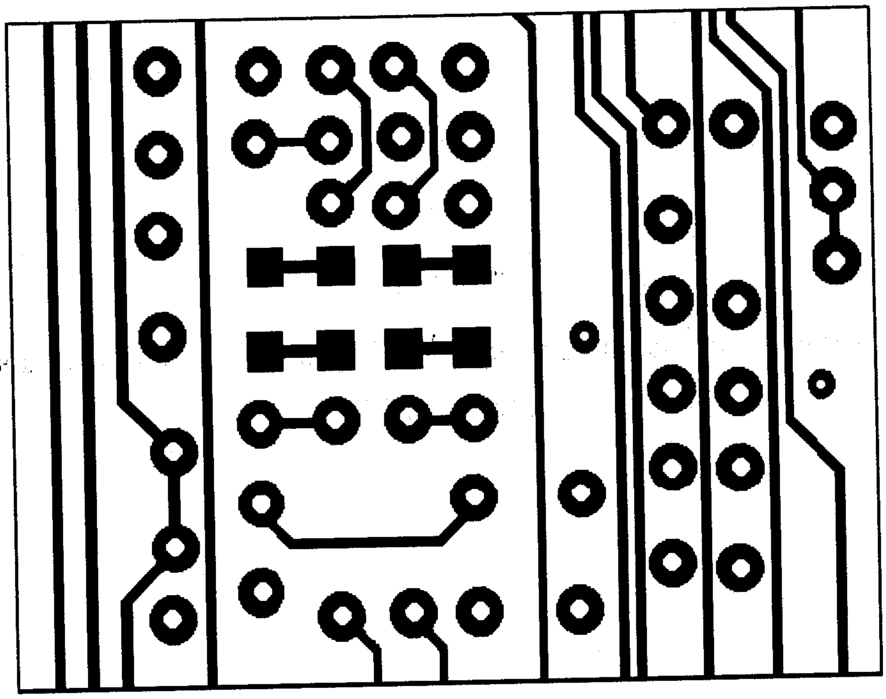
Current practice in PCB fabrication requires etching process. This process is an irreversible process. The printing process, which is done before etching process, caused most destructive defects found on the PCB. Any misprint will cause the etched board to be useless. Since laminated board constitute most 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. This, in return, requires a system to detect online or in real-time any defect caused by the printing process.

1.1.3 Defects

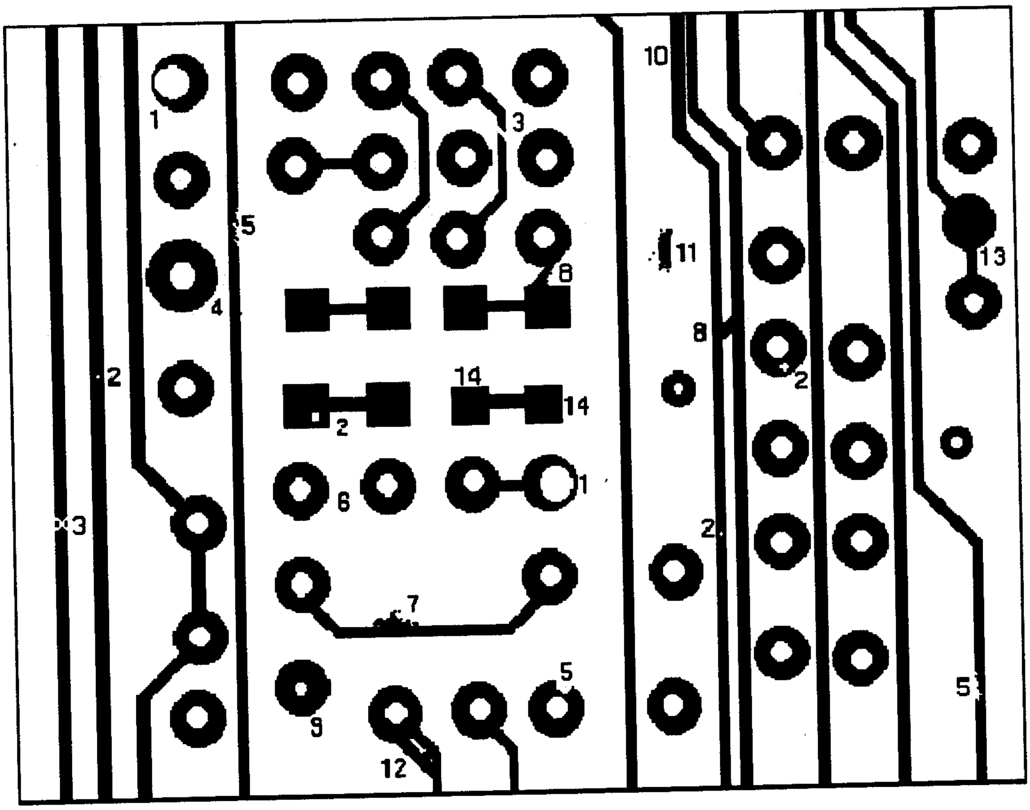
A variety of defects can affect the copper pattern of PCB. Some of them are identified as functional defects, whereas the others are visual defects. Functional defects seriously cause a damage to the PCB, meaning that the PCB does not function as needed. Visual defects do not affect the functionality of the PCB in short term. But in long period, the PCB will not perform well since the improper shape of the PCB circuit pattern could contribute to potential defects. Thus, it is crucial to detect these two types of defects in the inspection phase. Figure 1.2 (a) shows an artificial defect-free PCB image pattern. Figure 1.2 (b) shows the same image pattern as in Figure 1.2 (a) with a variety of defects on it. The printing defects and anomalies that will be looked at, for example, are 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. These defects are shown in Figure 1.2 (b).

1.2 Motivation

This thesis is motivated mainly by the need for more efficient techniques in inspection of the PCB panel in PCB fabrication process. Normally, a couple of operators are assigned in each station to manually check the PCB panels. This technique is not economic in a long run as it takes many man hours. In addition, humans are prone to make error especially due to fatigue. Moreover, it is impossible to check the entire PCB panels at every location without any delay. Instead, the printed laminate is sampled for a certain interval of quantity for manual inspection.



(a)



1. Breakout 2. Pin Hole 3. Open Circuit 4. Underetch 5. Mousebite
6. Missing Conductor 7. Spur 8. Short 9. Wrong Size Hole 10. Conductors too close
11. Spurious copper 12. Excessive Short 13. Missing Hole 14. Overetch

(b)

Figure 1.2 : (a) An example of good PCB patterns (b) An example of defective PCB patterns

As the electronic circuitary technology advances, the PCB pattern becomes denser and complicated to facilitate smaller end products. Thus, manual inspection is not applicable anymore. Meanwhile, the advances in computers in term of high speed, large memory and low cost have resulted in better and cheaper equipment for image processing. Hence, there exist a possibility of introducing and implementing an automated PCB inspection system to remove the subjective aspects of manual inspection. At the same time, the automated PCB inspection system provides real time assessment of the PCB panel.

From the literature review, it is noted that there has been an increasing number of applications for wavelets and multiresolution analysis including (but not limited to) image compression [2], image denoising [3] and edge detection [4]. Up till now there is still no clear advantages of wavelets in industrial inspection application, especially for PCB inspection. This is a secondary motivating factor for the thesis.

The emphasis here is on the improvement of inspection time using wavelet-based technique. The algorithm proposed in this thesis has been tested on three PCB sample images. The classification or analysis of the defects detected is beyond the scope of this thesis.

1.3 Objective

The objective of this thesis is to design and develop an algorithm for automated visual PCB inspection that will automatically detect and locate the printing defects occurred on printed circuit boards laminate. The primary concern of this project is to make use the advantages of wavelet, related to multiresolution analysis (MRA) in order to detect and locate the printing defects with a minimal inspection time experimentally. The technique proposed should produce the output that is suitable for defect classification stage. Once the algorithm is developed, it will be tested with samples of PCB pattern. However, the defect classification and the actual implementation of the entire system are not covered in this thesis.

1.4 Scope Of Work

In designing and developing a new defect detection and localization algorithm for automated visual PCB inspection, the scopes of the project have been defined as follows:

1. The whole PCB manufacturing stages comprise of bare-board fabrication, loaded board assembly and soldering process. For every stage, an automated visual inspection can be applied to facilitate the reliability test of the product. The algorithm is designed for the inspection of bare PCB panels only. Apart from the area, research work related to the component insertion inspection and solder joints inspection can be revised in [5-10].

2. There are three types of printed circuit boards available today [1]. They are:

   - Single sided boards: where the entire circuit is laid on one side of the board and the holes should be drilled on the board for mounting of components or for interconnection of components.
   - Double sided boards: with the circuit on both sides of the board and electrical connection is establish by drilling holes through the board and plating copper through the holes.
   - Multilayer boards: two or more pieces of PCB panel are stacked up together. Electrical connections are established from one side to the other and to the inner layer by drilled holes, which are subsequently plated through with copper.

Although it is possible to apply the proposed algorithm for the inspection of multi-layer boards and also the double-sided boards, this project concentrates more on the single sided boards inspection for experimental purpose.

3. In real implementation, an actual PCB images are acquired by using a single or multiple CCD camera. Thus, the individual camera takes the whole or a part of the PCB image. However, in this thesis, the PCB images used for the experiments are either taken from the previous research work or synthetically generated.

4. Automatic PCB inspection algorithm is designed to detect any one of the 14 types of defects mentioned previously. These 14 types of defects are expected to occur after the printing process. Thus, the defects caused by design-rule violation and the defects classifications of defects detected are beyond the scope of the project.

5. The project emphasis on the development of an efficient and fast algorithm for hardware implementation. However, it is beyond the scope of the project to evaluate or design the actual system hardware.

1.5 Thesis Contributions

The main contribution of this thesis is the wavelet-based technique for industrial inspection application. The wavelet-based algorithm for PCB defect detection and localization that will be proposed in this thesis proves that wavelets can be used in an automated visual PCB inspection. In fact, wavelets provide an effective way for the computation of the defect detection and defect localization. From the wavelets point of view, Haar wavelet is chosen with the aim to speed up the inspection of PCBs by looking at the number of filter entry with no boundary solution to avoid the complexity of the wavelet computation.

REFERENCES

1. Aithal, K. S., Narahari, Y. and Manjunath, E. (1999). "Modeling, Analysis, and Acceleration of a Printed Circuit Board Fabrication Process." Technical Report, Electronic Enterprises Laboratory, Department of Computer Science and Automation, Indian Institute of Science.

2. Meyer, F. G., Averbuch, A. Z. and Stromberg, J. (2000). "Fast Adaptive Wavelet Packet Image Compression." *IEEE Transactions On Image Processing*. **Vol. 9. No. 5.** 792 – 800.

3. Guoliang, Fan and Xiang-Gen, Xia (2000). "Wavelet-Based Statistical Image Processing Using Hidden Markov Tree Model." *Proceedings of the 34th Annual Conference on Information Sciences and Systems, Princeton University, Princeton, New Jersey.* TA5-31 – TA5-36.

4. Rao, R. L. (1995). "Multiresolution Techniques in Image Processing." Louisiana State University: Ph.D Thesis.

5. Pau, L. F. (1983). "Integrated Testing and Algorithms for Visual Inspection of Integrated Circuits." *IEEE Transaction on Pattern Analysis and Machine Intelligence.* **Vol. PAMI-5. No. 6.** 602 – 608.

6. Driels, M. R. and Nolan, D. J. (1990). "Automatic Defect Classification of Printed Wiring Board Solder Joints." *IEEE Transaction on Components, Hybrids, and Manufacturing Technology.* **Vol. 13. No. 2.** 331 – 340.

7. Kishimoto, S., Kakimori, N., Yamamoto, Y., Takahashi, Y., Harada, T., Iwata, Y., Shigeyama, Y. and Nakao, T. (1990). "A Printed Circuit Board (PCB) Inspection System Employing the Multi-lighting Optical System." *8th International Symposium on Electronic Manufacturing Technology (IEMT), Baveno, Italy.* 120 – 129.

8. Han, C., Mazouz, K. and Saravanan, N. (1993). "A Printed Circuit Board Inspection System Using Artificial Neural Network." *Twenty-Fifth Southeastern Symposium on System Theory, Tuscaloosa, Alabama.* 238 – 242.

9. Chen, T. Q., Zhang, J., Zhou, Y. and Murphey, Y. L. (2001). "A Smart Machine Vision System for PCB Inspection." *14th International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems (IEA/AIE), Budapest, Hungary.* 513 – 518.

10. Teoh, E. K. and Mital, D. P. (1995). "A Transputer-based Automated Visual Inspection System for Electronic Devices and PCBs." *Optics and Lasers in Engineering.* **Vol. 22.** 161 – 180.

11. Moganti, M., Ercal, F., Dagli, C. H. and Shou, Tsunekawa. (1996). "Automatic PCB Inspection Algorithms: A Survey." *Computer Vision and Image Understanding.* **Vol. 63. No. 2.** 287 – 313.

12. Wu, Wen-Yen, Mao-Jiun, J. Wang and Chih-Ming, Liu. (1996). "Automated Inspection of Printed Circuit Boards Through Machine Vision." *Computers in Industry.* **Vol. 28. Issue 2.** 103 – 111.

13. Jarvis, J. F. (1980). "A Method for Automating the Visual Inspection of Printed Wiring Boards." *IEEE Transactions on Pattern Analysis and Machine Intelligence.* **Vol. PAMI-2. No. 1.** 77 – 82.

14. Hara, Y., Akiyama, N. and Karasaki, K. (1983). "Automatic Inspection System for Printed Circuit Boards." *IEEE Transactions on Pattern Analysis and Machine Intelligence.* **Vol. PAMI-5. No. 6.** 623 – 630.

15. Ja, H. Koo and Yoo, Suk I. (1998). "A Structural Matching for Two-Dimensional Visual Pattern Inspection." *IEEE International Conference on Systems, Man, and Cybernatics, San Diego, California.* **Vol. 5.** 4429 – 4434.

16. Tatibana, M. H. and Lotufo, R. de A. (1997). "Novel Automatic PCB Inspection Technique Based on Connectivity." *Proceedings of the 10th Brazilian Symposium on Computer Vision and Image Processing, Campos do Jordo, Brazil.* 187 – 194.

17. Ninomiya, T., Yoshimura, K., Nomoto, M. and Nakagawa, Y. (1992). "Automatic Screen-Printed Circuit Pattern Inspection Using Connectivity Preserving Image Reduction and Connectivity Comparison." *Proceedings of 11th IAPR International Conference on Pattern Recognition, The Hague, Netherlands.* **Vol. 1.** 53 – 56.

18. Ouslim, M. and Curtis, K. M. (1995). "PCB Inspection Based on a Variant of the N-tuple Technique." *Proceedings of the Fifth International Conference on Image Processing and its Applications, Edinburgh, UK.* 677 – 681.

19. Ouslim, M. and Curtis, K. M. (1996). "Automatic Visual Inspection based upon on Variant of the N-tuple Technique." *IEE Proceeding on Vision, Image and Signal Processing.* **Vol. 143. No. 5.** 301 – 309.

20. Ji-joong, Hong, Kyung-ja, Park, and Kyung-gu, Kim. (1998). "Parallel Processing Machine Vision System for Bare PCB Inspection." *Proceedings of the 24th Annual Conference on the IEEE Industrial Electronics Society (IECON 98), Aachen, Germany.* **Vol. 3.** 1346 – 1350.

21. Ercal, F., Bunyak, F., Hou, Feng and Lei, Zheng. (1997). "A Fast Modular RLE-based Inspection Scheme for PCBs." *Proceedings of SPIE – Architectures, Networks and Intelligent Systems for Manufacturing Integration.* **Vol. 3203.** 45 – 59.

22. Ercal, F., Bunyak, F. and Hou, Feng. (1998). "Context-sensitive Filtering in RLE for PCB Inspection." *Proceedings of SPIE – Intelligent Systems and Advanced Manufacturing.* **Vol. 3517.**

23. Ercal, F., Allen, M. and Hou, Feng. (2000). "Proof of Correctness and Performance Analysis of a Systolic Image Difference Algorithm for RLE-Compressed Images." *IEEE Transaction on Parallel and Distributed Computing Systems.* **Vol. 11. No. 5.** 433 – 443.

24. Hou, Feng, Ercal, F. and Bunyak, F. (1998). "Systolic Algorithm for Processing RLE Images." *Proceedings of IEEE Southwest Symposium on Image Processing and Interpretation, Arizona, U.S.A.* 127 – 131.

25. Nam-Hyeong, Kim, Jae-Young, Pyun, Kang-Sun, Choi, Byeong-Doo, Choi and Sung-Jea, Ko. (2001). "Real-time Inspection System for Printed Circuit Boards." *IEEE International Smposium on Industrial Electronics (ISIE), Pusan, Korea.* **Vol. 1.** 166 – 170.

26. Seyfullah Halit Oguz and Onural, L. (1991). "An Automated System for Design-Rule-Based Visual Inspection of Printed Circuit Boards." *Proceedings of the IEEE International Conference on Robotics and Automation, California, U.S.A.* 2696 – 2701.

27. Ahmed M. Darwish and Jain, A. K. (1988). "A Rule Based Approach for Visual Pattern Inspection." *IEEE Transaction of Pattern Analysis and Machine Intelligence.* **Vol. PAMI-10. No.1.** 56 – 58.

28. Qin-Zhong, Ye and Danielson, P. E. (1998). "Inspection of Printed Circuit Boards by Connectivity Preserving Shrinking." *IEEE Transaction on Pattern Analysis and Machine Intelligence.* **Vol. PAMI 10. No. 5.** 737 – 742.

29. Jelloul El Mesbahi and Mohamed Chaibi. (1993). "Printed Circuit Boards Inspection Using Two New Algorithms of Dilation and Connectivity Preserving Shrinking." *Proceedings of the 1993 IEEE-SP Workshop on Neural Networks for Processing, New York.* 527 – 536.

30. Borba, J. F. and Facon, J. (1996). "A Printed Circuit Board Automated Inspection System." *Proceedings of the 38th Midwest Symposium on Circuits and Systems, Rio de Janeiro, Brazil.* **Vol. 1.** 69 – 72.

31. Charette, C., Park, S., Williams, R., Benhabib, B. and Smith, K. C. (1998). "Development and Integration of a Micro-Computer based Image Analysis System for Automatic PCB Inspection." *International Conference on Computer Integrated Manufacturing.* 129 – 135.

32. Moganti, M and Ercal, F. (1998). "Segmentation of Printed Circuit Board Images into Basic Patterns." *Computer Vision and Image Understanding.* **Vol. 70. No. 1.**

33. Ramirez, R. W. (1985). "The FFT: Fundamentals and Concepts." New Jersey: Prentice-Hall, Inc.

34. Sarkar, T. K. and Su, C. (1998). "A Tutorial on Wavelets from an Electrical Engineering Perspective, Part 2: The Continuous Case." *IEEE Antennas and Propagation Magazine.* **Vol. 40. No. 6.** 36 – 49.

35. Torrence, C. and Compo, G. P. (1998). "A Practical Guide to Wavelet Analysis." *Bulletin of the American Meteorological Society.* 61 – 78.

36. Mallat, S. (1996). "Wavelet for a Vision." *Proceedings of the IEEE: Special Issue on Wavelets.* **Vol. 84. No. 4.** 604 – 614.

37. Misiti, M., Misiti, Y., Oppenheim, G. and Poggi, J. (1997). "Wavelet Toolbox: For Use with MATLAB." USA: The Math Works. Inc. 1-1 – 1-36.

38. Mandal, M. K., Aboulnasr, T. and Panchanathan, S. (1999). "Fast Wavelet Histogram Techniques for Image Indexing." *Jurnal of Computer Vision and Image Understanding.* **Vol. 75. No. 1/2.** 99 – 110.

39. Stollmitz, E. J., Derose, T. D. and Salestin, D. H. (1995). "Wavelets for Computer Graphic: A Primer, Part 1". *IEEE Computer Graphics and Applications.* **Vol. 15. No. 3.** 76 – 84.

40. Vetterli, M. and Kovacevic. J. (1995). "Wavelets and Subband Coding." New Jersey: Prentice-Hall, Inc. 260.

41. Schremmer, C., Esser, C., Kuhmunch, C. and Effelsberg, W. (2001). "A Wavelet Transform Applet for Interactive Learning." Technical Report TR-00-004, Department for Mathematics and Computer Science, University of Mannheim, Germany, 2001.

42. Schremmer, C. (2001). "Empirical Evaluation of Boundary Policies for Wavelet-based Image Coding." Springer Lecture Notes of Artificial Intelligence (LNAI), Hong Kong, China, 2001.

43. Niblack, W. (1986). "An Introduction to Digital Image Processing." Second Edition. London: Prentice-Hall International (UK) Ltd. 16 – 17.

44. Anderson, R. G. (1990). "Data Processing. Volume 1: Principle and Practice." Seventh Edition. London: Pitman Publishing. 53.

45. Schremmer, C., Kuhmunch, C. and Esser, C. (2001). "Wavelet Filter Evaluation For Image Coding." Technical Report TR-01-006, Department for Mathematics and Computer Science, University of Mannheim.

46. Quaid, A. and Hollis, R. (1996). "Cooperative 2-DOF Robots for Precision Assembly." *Proceedings of the IEEE International Conference on Robotics and Automation, Minneapolis, Minnesota.* **Vol. 3.** 2188 – 2193.