TABLE I
THE 22 BASIC CONFIGURATIONS: THEIR BINARY (cf. FIG. 2) AND DECIMAL REPRESENTATION AND THEIR CONTRIBUTIONS $N_6^{(c)}$ AND $N_{26}^{(c)}$ TO N IN CASE OF 6- AND 26-CONNECTIVITY

configuration			contribution x4	
k(j)	c(j) binary	c(j) decimal	$4N_6^{(c)}$	$4N_{26}^{(c)}$
1	00 00 00 00	0	0	0
2	00 00 00 01	1	1	1
3	00 00 00 11	3	0	0
4	00 00 10 01	9	2	-2
5	10 00 00 01	129	2	-6
6	00 00 01 11	7	-1	-1
7	01 00 00 11	67	1	-3
8	00 01 01 10	22	3	-1
9	00 00 11 11	15	0	0
10	00 10 01 11	39	-2	-2
11	00 01 01 11	23	-2	-2
12	10 00 01 11	135	0	0
13	11 00 00 11	195	0	0
14	01 10 10 01	105	4	4
15	11 10 10 01	233	-1	3
16	10 11 11 00	188	-3	1
17	11 11 10 00	248	-1	-1
18	01 11 11 10	126	-6	2
19	11 11 01 10	246	-2	2
20	11 11 11 00	252	0	0
21	11 11 11 10	254	1	1
22	11 11 11 11	255	0	0

THE TABLE

There are 22 basic different possibilities to fill the $2 \times 2 \times 2$ cube among the 256 configurations. All the other ones can be produced by the symmetry operations of the cube. In Table I the binary and the decimal representation of each of the 22 basic configurations are given, together with the contributions $N_6^{(c)}$ in case of 6-connectivity and $N_{26}^{(c)}$ in case of 26-connectivity. The decimal representation provides an index to the table in which all the 256 possibilities are stored.

The configurations $k(j)$ ($k(j) = 1$ to 8) are complementary to the configurations $23 - k(j)$; configurations 9 to 14 are self-complementary.

CONCLUSION

Using the skeletonization algorithm described one can erode three-dimensional binary images preserving connectivity. the algorithm is a fast one because of the use of tables. It can also be implemented on our dedicated image processor (Gerritsen *et al.* [1]) for which typically 16 operations of 250 ns per voxel would be needed. Through the use of special purpose logic based on the $3 \times 3 \times 3$ neighborhood this might be shortened by a factor 3.

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A Method for Automating the Visual Inspection of Printed Wiring Boards

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***Abstract*—The application of pattern recognition techniques to manufacturing processes is a rapidly developing technology. Automatic verification of the quality of printed wiring boards (PWB's) using pattern recognition techniques is one potential application in this field. Qualitatively, this problem is finding small, irregular features in an environment of complicated, but larger and well-defined geometric features. In addition to the basic pattern recognition task, stringent performance requirements, both for throughput and accuracy, must be met if actual production usage is expected.**

The method employed in this study is based on characterizing 5×5 or 7×7 element binary patterns derived from the class of PWB's being inspected as good or defective. A database of 80 512×512 element images of PWB's was constructed and used to determine the number of unique patterns and their rates of occurrence. The major experimental result of this study is that *less* than 500 of the possible $(15/16)2^{24}$ 5×5 patterns are needed to describe *all* the border containing patterns in the 80 images. It is also apparent that more patterns would be required if the training database was larger.

The small number of patterns needed to represent virtually all of the normal border patterns suggests a two-stage inspection strategy. In the first stage, each border pattern from the PWB being inspected is compared to a previously prepared list. Those patterns not found in this list are passed to a second stage which employs a variety of techniques to determine if the pattern is indicative of a PWB flaw.

***Index Terms*—Automated inspection, pattern recognition, printed wiring boards.**

I. INTRODUCTION

The application of pattern recognition techniques to manufacturing processes, particularly for visual inspection, is a rapidly developing technology. One such application, inspection of printed wiring board (PWB) conductor patterns for small flaws has been the subject of several studies [1]-[5]. This paper will propose another method for accomplishing this task.

Very qualitatively, the PWB inspection problem examined in this paper consists of looking for small, irregularly shaped conductor defects in the context of the larger and well-defined conductor patterns. In most cases, the border between the conductor and substrate is of primary interest while the surface condition of the conductor is only of marginal interest.

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For any PWB inspection system to be useful it must have adequate throughput and accuracy. As an example, consider a flexible PWB being manufactured in a continuous, reel to reel fashion. A typical processing rate for such material is 1 in/s. An 8×10 in board may be conveniently fabricated with the long axis across the width of the material. Scanning this board at 1000 lines/in or with pixels 0.001 in in diameter, resolution appropriate for conductors 0.01 in in width, requires processing 10^7 pixels/s. The 8×10 in board is sensed as $1.6*10^8$ pixels (two sides); thus, to limit false error indications to one PWB in ten a maximum of 1 pixel in $1.6*10^9$ can be classified as defective. While this discussion is hypothetical, the magnitude of the data rates and the accuracy required to achieve acceptable automatic operation must be considered typical.

Two other considerations, crucial to the eventual production systems, image acquisition, and defect indication, will not be discussed in detail in this paper. Successful operation of the defect detection scheme is predicated on having an accurate binary (conductor/substrate) representation of the PWB being examined. While it now appears that high resolution linear CCD imaging arrays are the key to solving the image acquisition problem many specific parameters such as color and polarization of the illumination as well as possible control of the substrate properties must be correctly specified. Similarly, it appears that a method must be found to mark the defects found on the PWB in order that the inspection process may be monitored and to allow repair of mildly defective PWB's. These input and output problems are as important to the success of an eventual production inspection as the pattern analysis methods that are the subject of this paper. However, the technology required for their solution is sufficiently different that they should be considered as separate problems.

Briefly, the inspection method to be described in this paper consists of building a list of *good* patterns found in small windows, 5×5 or 7×7 pixels in size, and comparing the PWB under test on a pattern by pattern basis to this list. The list of good patterns is built by examining PWB's verified as good by independent means. If a pattern from the PWB being examined is not found in the list of good patterns it is considered to be a possible defect. A number of tests are then performed on the unmatched pattern to achieve a final classification. Since defects are defined and sensed only as small patterns this method does not require knowledge of the actual conductor pattern. Thus, it is applicable to a wide variety of PWB's without programming or other specialization operations.

This inspection method is a two-stage process. The first stage does the explicit pattern matching operation on individual patterns while the second, detailed analysis of individual patterns, is used to classify ones that are not found in the list of known good patterns. Because of the performance requirements for a production inspection system the first stage, pattern matching would be implemented as a hardware processor. The second stage, classification or detailed analysis, would be accomplished by a program executing on a minicomputer. The first stage can be viewed as a filter that limits the number of patterns examined in the classification stage to a manageable number. Statistics on pattern occurrences, the features evaluated for individual pattern analysis, and the details of a possible inspection system will be given in the following sections of the paper.

II. Observed Properties of Small Patterns in Binary PWB Images

A PWB image is represented as a two-dimensional bit array where "1"s represent the conductor pattern and "0"s represent the substrate. A *pattern* is defined as a 5×5 or 7×7 square array of pixels. The array is centered over each pixel of the PWB image to generate a set of patterns from the image. That the set of 25 or 49 bit patterns thus defined is a reasonable size for a collection of PWB images independently verified as defect free is the primary experimental result of this study. A reasonable size in this context is that the set can be stored and searched rapidly by currently available digital logic technology. Possible errors are indicated when patterns from a PWB being inspected are not found in the previously prepared list of defect free patterns.

A fundamental observation which results in this method being practical is that only a small fraction of all the possible patterns need be examined. Clearly, patterns composed entirely of substrate or conductor (all "0"s or "1"s) convey no information and need not be examined. Now consider an approximately vertically oriented edge. The same edge segment will appear in several horizontally adjacent windows. Thus, it will give rise to several unique patterns showing the same substrate to conductor transition. Since only the border region contains information relevant to the inspection process only one of the patterns arising from the translation need be examined to judge the quality of the border segment. Based on this discussion, a *border pattern* is defined as one where the center element is a "1" and at least one of the 4-connected neighbors of the central element must have the value "0." Only patterns that meet this definition of a border pattern will be considered in the following discussions.

Having defined a border pattern, the next step is to examine the collection of PWB images and tabulate the number of different border patterns and their rates of occurrence. To accomplish this a data base of 80 PWB binary images was prepared. A section of a PWB mask (Fig. 1) was used to create four 8×10 in black and white prints, each showing an approximately 2×2.25 in area of the PWB. The four prints were scanned on a Dest Data, Inc. DSD 120/240 page scanner to create four 2048×2620 binary element files. One pixel, therefore, corresponds to a resolution of 0.001 in in the original PWB mask. Each of these large files was divided into 20 separate 512×512 element files, inspected, and small artifacts due to dust or other minor digitization flaws removed using an interactive picture processing facility. The database was prepared in this manner in order that the pattern counting experiments would reflect the actual PWB patterns and not artifacts of the digitization process. The image acquisition problem referred to in the introduction has been bypassed by this procedure.

Using the PWB image database several statistical properties of the 5×5 and 7×7 border patterns were measured. These results are summarized in Table I. Fig. 2 shows the counting experiment results as the number of distinct patterns found as a function of the total number examined. The significance of Fig. 2 is that a relatively few of the possible patterns represent all the patterns observed. The four patterns that represent approximately 80 percent of the total of the 5×5 patterns are those that correspond to horizontal and vertical straight edges. This is to be expected from the predominately horizontal and vertical edge orientation in the data used (Fig. 1). From these plots it appears that the number of unique patterns is unbounded in a practical sense. However, using the same data and plotting the number of unique patterns required to represent 99.9 percent of the total patterns processed suggests that a fixed number is adequate. Unfortunately, the computational resources available did not allow the construction of a database large enough to more adequately determine these trends.

A simulation experiment was done to try to determine the behavior of the number of unique patterns as a function of the total number examined for numbers of patterns substantially greater than recorded from the PWB image database. The simulation consisted of creating 5×5 patterns corresponding to a straight edge and accumulating the same statistics as for the patterns observed in the PWB database. The patterns were generated by computing a 5×5 array of intensities for an edge with a specified width, adding noise using a normal random number generator, then comparing the intensities to a

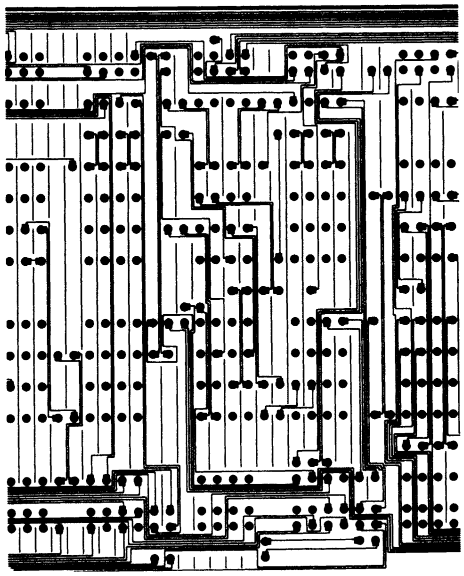

Fig. 1. The section of a PWB mask that was used to construct the data-base used in this paper.

TABLE I
STATISTICAL SUMMARY OF PATTERN COUNTING EXPERIMENTS

OBSERVED:	5x5		7x7	
A) Total Number of Patterns	20482880		20482880	
B) Border Patterns	700877	3.4%	700875	3.4%
C) Number of Unique Patterns	459		2550	
D) Number to Match 99.99%	404	88%	2480	97%
E) Number to Match 99.9%	301	66%	1872	73%
F) Number to Match 99%	169	36%	837	33%
G) Possible Patterns	$(15/16)2^{24}$		$(15/16)2^{48}$	
SIMULATED	**(5x5only)**			
H) Border Patterns	3410218			
I) Unique Patterns	2354			
J) Number of Unique Patterns Meeting Feature Value Limits Obtained From C)	761			
K) Total Patterns in J)	3371494	98.9% of H)		
L) Patterns Common to C),J)	444			
M) Occurrences in C) matched by J)	700785	99.9%		
N) Occurrences in J) matched by C)	3316633	98.3%		
O) Occurrences in I) matched by C)	3316633	97.2%		

threshold value to obtain the 5×5 binary pattern. The resulting patterns were subjected to the border test and those that passed were accumulated on the appropriate lists. The edge segment was rotated and translated in order that all edge configurations were possible. The data from the simulation are summarized in the second part of Table I. Approximately five times as many patterns were generated in the simulation as were found in the 80 PWB images. Note the commonality between the sets of patterns given in lines *C*) and *J*). The simulation has given essentially the same set of patterns as were observed from the PWB images. The simulation data are also shown in Fig. 2 in the form of the number of unique patterns as a function of the total number of occurrences. The last decade of this curve (from 0.3 to 3 million observed patterns) appears to define a linear relationship on the semilog plot. This strengthens the conclusion reached from the actual image data that the number of defect free patterns is essentially unbounded.

Another estimate of the number of valid border patterns can be obtained from

$$P = 4(n - 1)2^n$$

where $4(n - 1)$ is the number of distinct line orientations or peripheral cells in the n^2 pattern and 2^n is an estimate of possible variations of the line. This latter term is very approximate as one cell is constrained while the other border defining cells may occupy more than two positions. For the 5^2 case, $P = 512$ which is only slightly more than than the observed number of patterns and somewhat less than the number of patterns found in the simulation. For the 7^2 case, $P = 3072$ which is about 50 percent more than the observed number of defect free patterns.

Summarizing, the patterns required to represent all the verifiably good PWB border configurations appears unbounded in a practical sense. That is, the number of such patterns will increase without limit as the total number of patterns processed increases. More importantly, the number of patterns required to represent 99.9 percent or any specified fraction of the total number observed appears to be bounded, or if not bounded, then the number required increases at a comparatively slow rate. In any case, a list of *all* defect free patterns cannot be prepared. Because of this, the simple pattern matching method cannot be used by itself as the basis for an inspection system. Therefore, the pattern matching process must be viewed as a filter that reduces the number of patterns subjected to detailed analysis to a manageable number.

In addition to the pattern counting experiments, *features*, characteristics, or properties of individual patterns that can be evaluated to a numerical values, can be identified and measured. Conductor *area*, that is the number of "1"s in a pattern, is one of five features that have proven useful. The others used are the *length* of the boundary within the pattern, the *ratio* of the boundary length squared to the conductor area and the number of distinct *regions* within an individual pattern. The fifth feature used in this study is the number of *sides* of the square pattern that are all "0"s. This latter feature gives some indication of the curvature of the border segment. It is these five features that provide the basis for the classification of patterns that are not found in the defect free lists. This classification, or detailed analysis step, is required because the absence of a particular pattern in the defect free list is not a sufficient condition to label the pattern as a defect indicator. Each of the five features has been evaluated on the set of good patterns. The fifth feature, number of regions, is two for all good patterns. The detailed analysis of a pattern not found in the defect free list consists of determining its five feature values and comparing them to the limits obtained for the same features in the set of good patterns. If all five feature values are within these limits the pattern is considered good. The limit values were set to the maximum and minimum obtained from tabulations made for each feature from the good pattern set. If any feature is outside the limits it is taken to be an indication of a defect.

The data given in this section of the paper are sufficient to allow the conceptual design of a PWB inspection system. One possible system will be described in the following section.

III. An Inspection System

The experimentally observed facts about small (5×5 or 7×7) patterns in binary representations of PWB images allow the design of a specific inspection system. The general concept, as outlined in the Introduction, is a series of processing steps starting with simple operations running at the maximum desired processing rate to a final classification step running at comparatively slow rates in a conventional minicomputer. Each stage in the processor removes a fraction of the patterns from the stream thus reducing the average data rate for the following step. Given a system processing rate, the rates for each section can then be determined. Obviously, some queuing of data between the stages must be done to match the processing rates of the various stages.

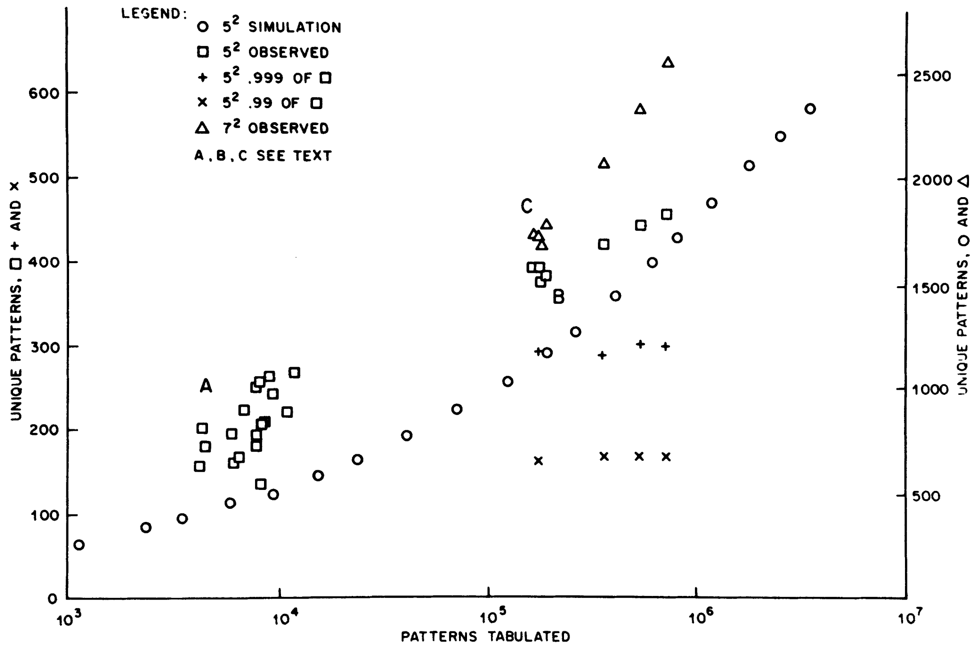

Fig. 2. The number of unique patterns found plotted as a function of the total number of border patterns observed. Data are included for observations made with the database and from a simulation.

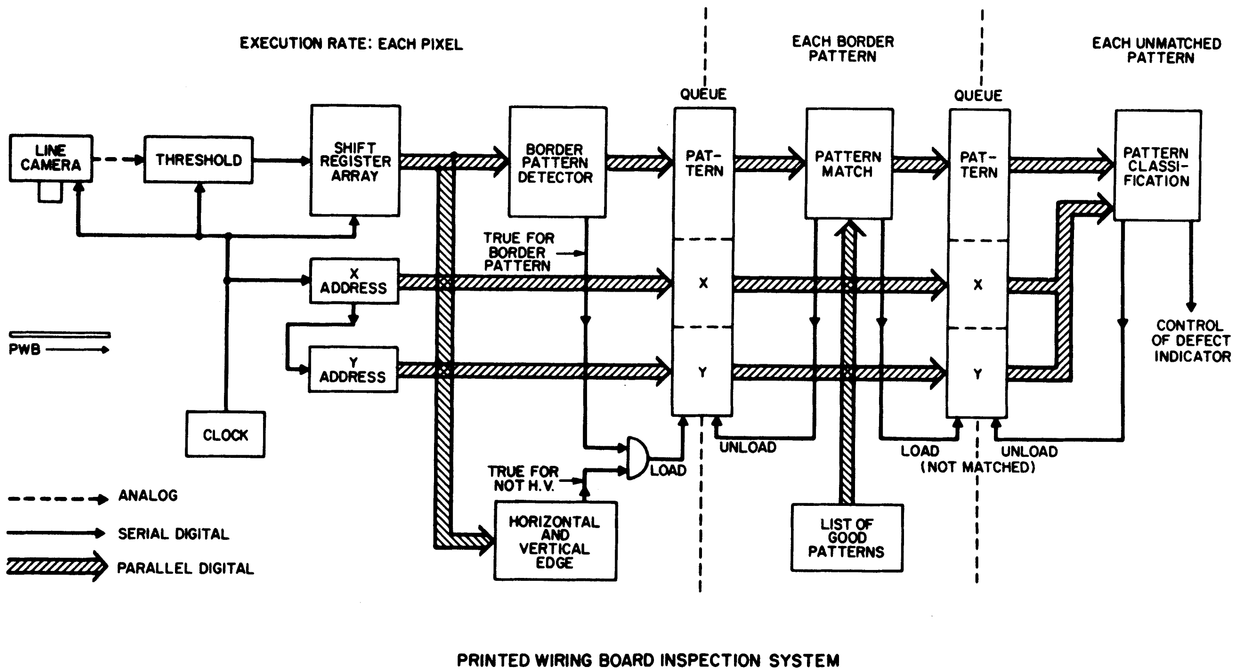

Fig. 3. Hardware outline of a possible inspection system.

The apparatus diagrammed in Fig. 3 was designed to accomplish the inspection. This apparatus partitions naturally into four subsystems. The first, which includes all the video processing, thresholding, the conversion of a sequential stream of bits into an array, and the border detector must operate at the maximum desired data rate. The second section includes the pattern matching phase and operates on each pattern passed by the border detector. The third section performs a final classification of the patterns not found in the defect free list by the explicit matching operation. Typically, this step would be implemented as a program in a mini- or microprocessor programmed to evaluate and compare the features discussed in the previous section to preestablished limits determined from the examination of a set of defect free patterns. The fourth major component is a detector for horizontal or vertical edges and is logically part of first processing section. The utility of this component, which must operate at the maximum pattern rate, will be discussed in the following paragraph.

Using the data given in Table I and Fig. 2 typical data rates in this system may be determined. First assume an input data rate of 3 million pixels/s. From the fraction of observed border elements, 3.4 percent, the average data rate in the pat-

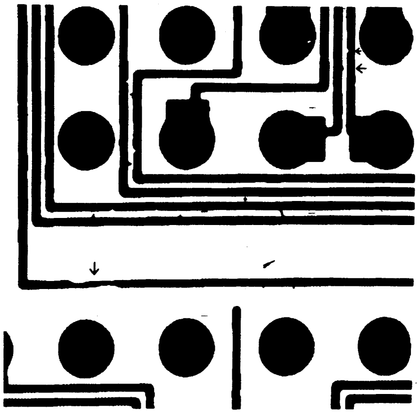

Fig. 4. A test image containing various defects that was prepared from one of the images in the database.

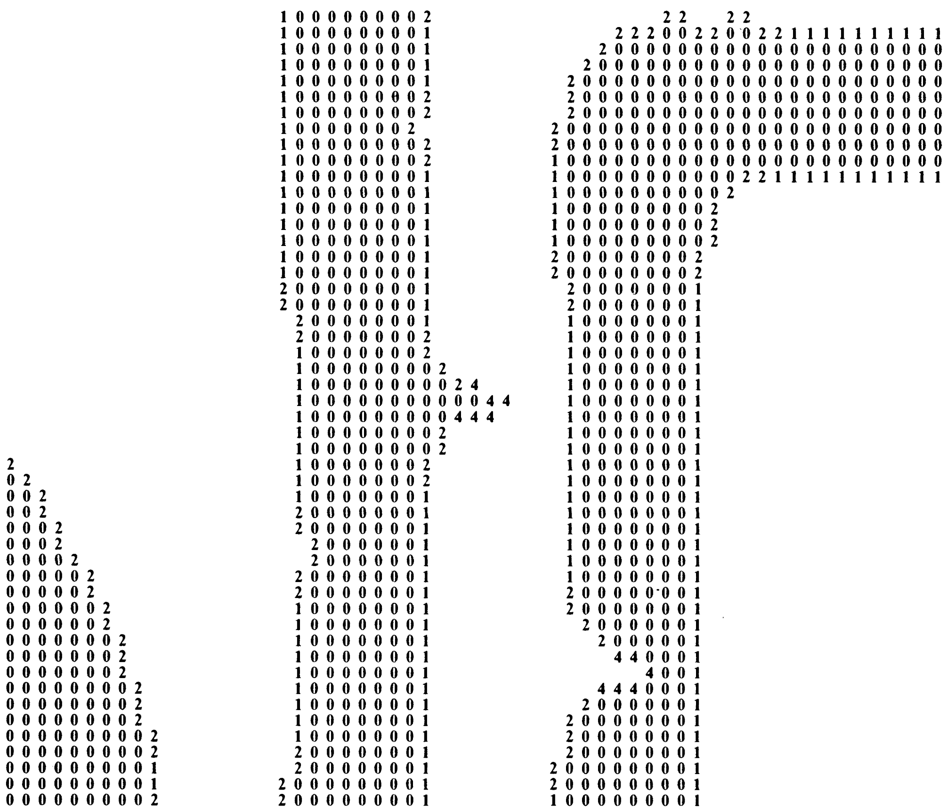

Fig. 5. A small area of Fig. 4 showing the processing results for two defects. The meaning of the cell labels is given in the text.

tern matching section is about 10^5 operations/s. Assuming that the detailed pattern evaluations can be done at 100 operations/s the pattern matching section must match 99.9 percent of the samples presented to it. From Fig. 2 we determine that this requires approximately 300 samples in the list of defect free patterns. If the PWB's being examined contain primarily horizontal and vertical edges, like those used in this study, the use of a specific detector for these four predominant patterns would reduce the data rate in the matching section to about 20 000 samples/s. Conversely, the input sample rate could be increased to about 15 million samples/s while maintaining the 10^5 sample/s rate in the pattern matching phase.

With the exception of the pattern matching stage all the operations to be performed at high speeds are simple logic operations. However, there may be a substantial amount of equipment involved as much of the processing is done on data paths that are 24 bits wide (5×5 patterns). One solution to the pattern matching operation is the binary search [6]. The patterns are considered as arithmetic quantities and are stored in the lookup table in increasing value. The binary search lookup can be accomplished with less than or equal to $\log_2(N)$ operations where N is the number of stored values. N in this case is in the range of 300–500 for the 5×5 pattern set. Each iteration of the algorithm, which includes a 24-bit subtraction and two 10-bit additions as its basic operations, can be easily done in a microsecond. Thus, it appears that a hardwired binary search table lookup processor with a processing rate of 10^5 lookups/s is feasible.

In Fig. 3 the coordinates of the pattern are also carried

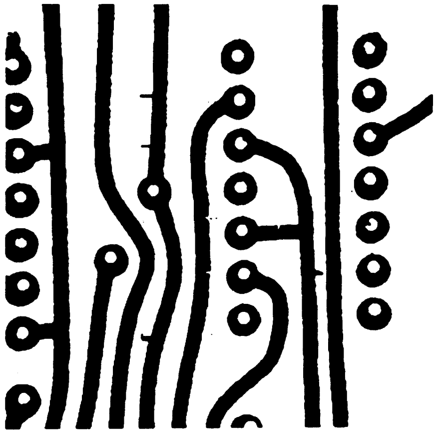

Fig. 6. A test image not derived from the PWB image database.

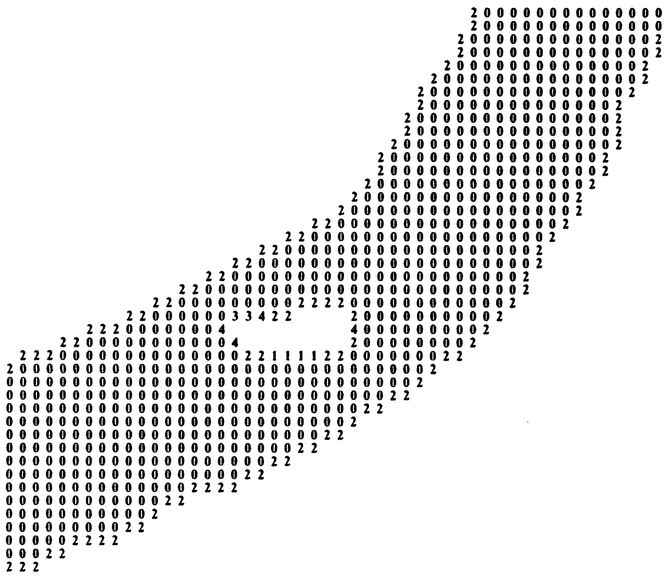

Fig. 7. A small area of Fig. 6 showing processing results for one defect. The cell labels are explained in the text.

through the various processing steps. These data are needed to allow the analysis of possible errors by proximity as well as the display of errors. Since it is likely that the error rate will be, in fact must be, small an explicit y value need not be carried through the processor. In practice, sufficient vertical accuracy should be achieved by computing a coordinate in the processor from interrupts at the line scan rate.

The hardware description in the preceding paragraphs was given to establish the feasibility of building a PWB inspection system using the method of local pattern matching. Furthermore, the system appears to be capable of running at potentially useful data rates.

A possible problem with this method is the length of the pattern queues, particularly the one between the border detector and pattern matcher (table lookup). If the scan line is parallel to an edge in the PWB image this queue can get arbitrarily long. The exact length of such queues is a sensitive function of the relative speeds of the pattern matcher and system processing rate. One possible way to prevent excessively long queues would be to place the scanners at a slight angle away from the predominately found directions of edges in the PWB's.

One test of the method, using 5×5 patterns, was made by creating a PWB image containing a number of "defects" and is shown in Fig. 4. In this case the defects were drawn onto one of the 80 original binary images based on actually observed defects. In this example 211 of 12 222 total border patterns were not matched. Of these 211 patterns, 193 were classified as defective by the detailed pattern examination phase. The inspection method detected 20 of the 23 drawn defects in this example. The three defects not detected are indicated by the arrows in Fig. 4. A portion of the original image showing two of the flaws is displayed in Fig. 5. In this figure pixels labeled "0" correspond to interior conductor cells. Those labeled "1" are horizontal or vertical boundary cells. Those labeled "2," "3," and "4" were input to the pattern matching operation. Cells labeled "3" correspond to unmatched patterns while those labeled "4" are for patterns that have failed the final pattern classification step. The cells labeled "2" are those that were matched by the pattern lookup procedure. Cell with a label of "4" are the indicators of PWB errors.

A second PWB image, Fig. 6, not part of the original training set, was also processed. One of the defects contained in this example is shown in detail in Fig. 7. In this figure the cell labels have the same meaning as in Fig. 5. In this case, a few isolated cells (label "3") correspond to nominally good patterns have been found and classified as good by the detailed checking step of the process.

IV. Conclusions

This paper has described a method for the detection of flaws in PWB conductor patterns. The inspection method is based on the empirical result that only a small fraction of all the possible patterns in 5×5 or 7×7 arrays describe all the defect free conductor-substrate border configurations. A much larger PWB sample than used in this study, including actual defects, would have to be analyzed to determine if the added complexity of processing the larger patterns is justified. For this or any other method to be useful, solutions to the input and output problems must also be found. The input problem is the acquisition of an accurate, noise free, binary image of the PWB being inspected. The output problem is the marking of discovered defects on the PWB so auditing of the inspection process and repairs may be accomplished.

The sensitivity of the local pattern matching method can be enhanced by controlling the details of the PWB layout. In particular, a design rule specifying a *minimum* radius for all corners in the conductor pattern could be expected to increase the discrimination between defects and normal patterns.

Clearly, there is a big gap between the successful demonstration of a method on carefully controlled data and a functioning system in a manufacturing environment. The method described, however, appears to be adequate in terms of processing accuracy and rate to allow the construction of a fully automatic PWB visual inspection system.

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