The State of the Art in Printed Wiring Board Inspection

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Abstract

Automated visual inspection of printed wiring is providing research opportunities in completely utomated optical systems technology. This paper addresses device design considerations, articularly the important problem of turning an optical inspection device into a tool for lanufacturing process analysis and control.

1. Introduction

There is now an industry in the automated optical inspection of printed wiring boards, or what used o be called printed circuit boards. This industry is composed of research groups studying the basic irinciples of automated optical inspection, corporate groups developing devices for in-house valuation, and, most significantly, corporate groups developing devices for commercial exploitation. his paper provides a "state of the art" look into the future of printed wiring board inspection. The ommercial forces are compelling, and tend to exhaust available technologies. Fortunately, these ame forces are providing an opportunity for gains in basic research.

A few years ago, the dominant work in inspection was done by in-house corporate projects, with tore projects completed than publicized. Many, if not most, of the larger corporations doing ectronics packaging manufacture have experimented with the technology. One in-house device, jilt in 1978 by Warren Sterling for Xerox (Figure 1-1) used an X-Y translation table to move the inted wiring panel beneath a line-scan camera and a Xerox *Alto* as the central processor and ntrol element [1, 2]. Although it proved slow, this device represented one of the most technically iccessful of the 'software' approaches to inspection. A similar device using a modern variant on the *to,* a Perq Systems' *PERQ,* and bound only by a 2-4 million/second camera pixel rate was weloped in our laboratory for Westinghouse Electric Corporation (Figure 1-2). Also of importance e 'hardware' approaches. Interesting ones were pioneered by Ejiri for in-house use at Hitachi [3]. iri and his coworkers developed the now classic 'expansion-contraction' technique that assumes fects exist in a high, first-order spatial-frequency domain (viz., patterns that are small relative to the ceptable patterns). These projects once serviced internal company needs and have now dwindled, th most in-house projects leaning towards commercialization.

he research community has been involved in studying pattern recognition on printed wiring for my years [4, 5, 6]. Taken together with the in-house projects, many workable solutions to the blem of defect detection have been proposed. In fact, the problems of defect detection have been ved many times for the generic printed wiring board pattern such as the one illustrated in Figure / General methods that handle the great variety in actually observed patterns or that meet the most ingent requirements on inspection remain a research topic. However, the current research issue is t how to detect defects in printed wiring boards, but how to automatically interpret the defects. :er we will consider paradigms for advanced defect detection and interpretation, but first let us ter understand why there is such a commercial interest in the automated optical inspection of ited wiring.

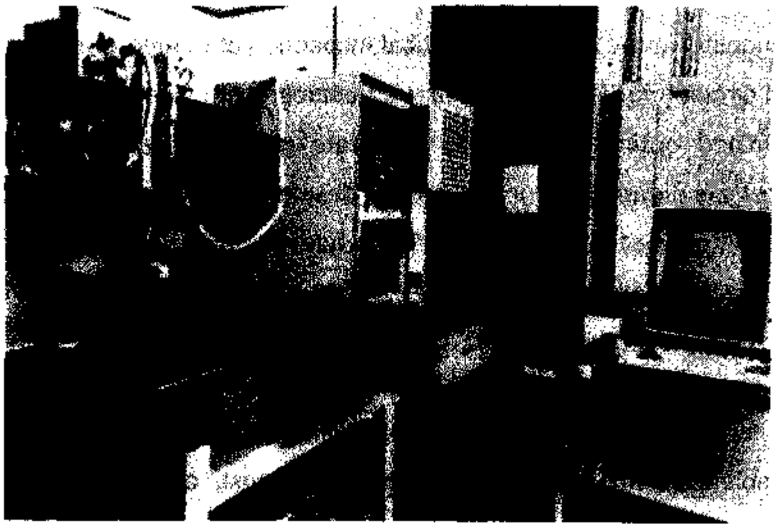
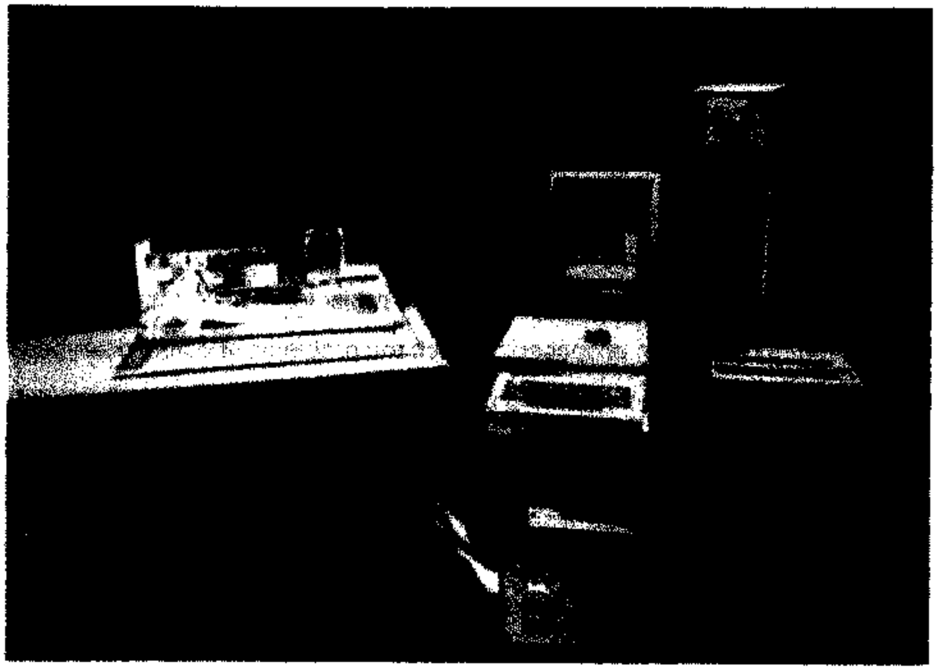


Figure 1-1: The Xerox Inspection Device, circa 1978



Fi§ure 1 *2: The CMU-Westinghouse Inspection Device, circa 1982

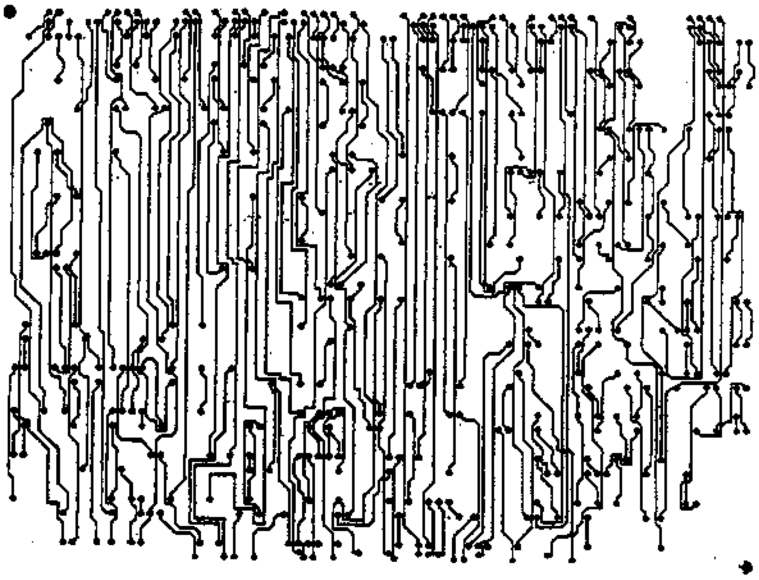


Figure 1-3: An example of a printed wiring pattern

2. The Commercial Interest in Inspection

The economic motivations are strong. Printed wiring board fabrication is a complicated multi-step process which involves steps as diverse as pressure plating of copper, chemical washing, stripping and etching, scrubbing, baking, solder bathing, and handling and transport. The result is a simple geometric pattern composed of lines and discs (or "pads"). Because there is a high possibility for process introduced defects, it is important to be able to study the defects even if only to tune the manufacturing process. Furthermore, with simple patterns it is generally believed that automatic devices for inspection should be practical.

A fact often overlooked is that printed wiring board inspection is most strongly motivated for multi-layer panels, where each individual panei is inspected before the panels are laminated together. The probability of a defect propagates as a Bernouli process: a 10% probability of a defect in one panel propagates to a better than 70% probability of scrap in a 10 layer laminate. Since individual panels are expensive, it is important to inspect before lamination to preclude throwing the good panels out with the bad ones.

The three contenders for inspection are electrical, optical, and human. The primary force pushing optical methods is the fine linework now common. With fine linework, human inspection becomes less feasible. Electrical testing requires contact probing: expensive in setup, subject to error, and as likely to do damage to the fine linework as to find the pre-existing defects.

Considerations which reject other approaches leave us with a default method, optical processing, which in this case might be preferable. An image of a defect is much more informative than any likely electrical result. Optical processing can detect defects before they become manifest electrically. Furthermore, as shown in Figures 2-1 and 2-2, electrically similar breaks have different significance to the manufacturing process. The former is flaking resist while the latter is a mechanical scratch with good resist adhesion. Figure 2-3 shows a pad defect which would not be revealed by an electrical test (because of pin placement) but indicates a likely artwork defect. If the machine can interpret the images it sees, the economics transcend simple inspection and bring us immediately to the possibilities of automatic process analysis, diagnosis, and control.

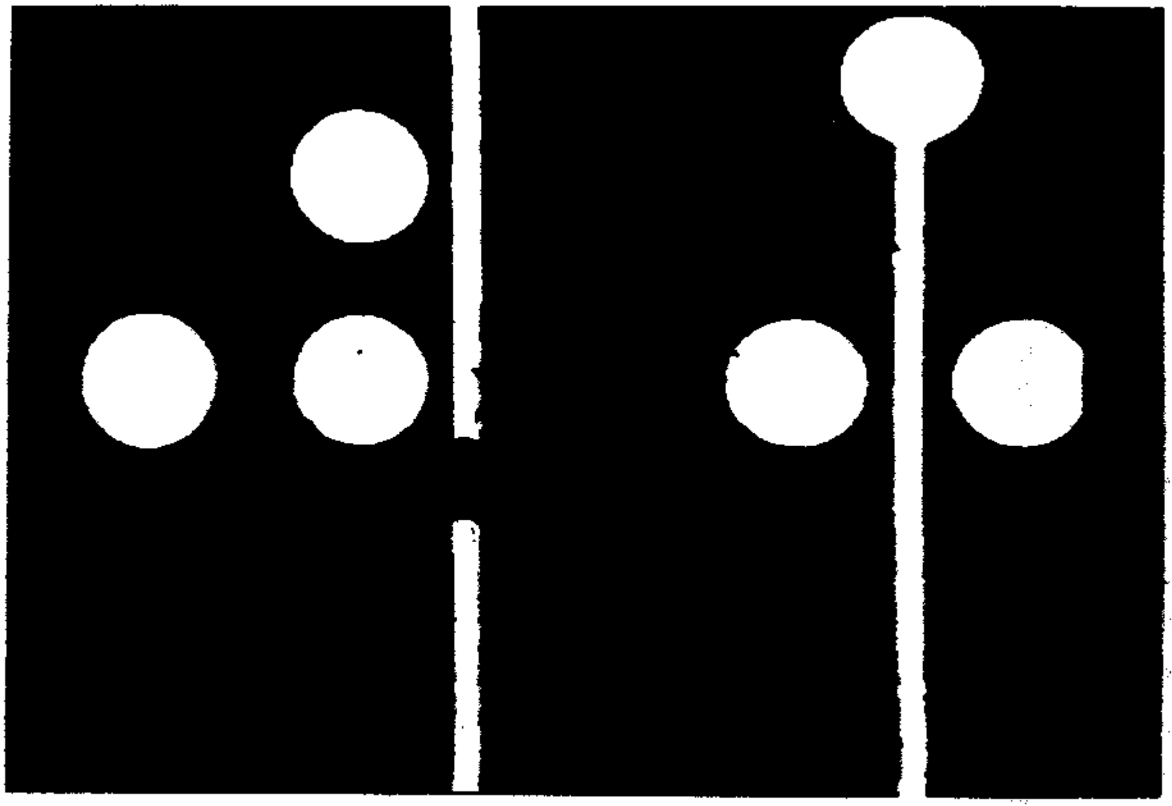


Figure 2-1: A break due to flaking resist

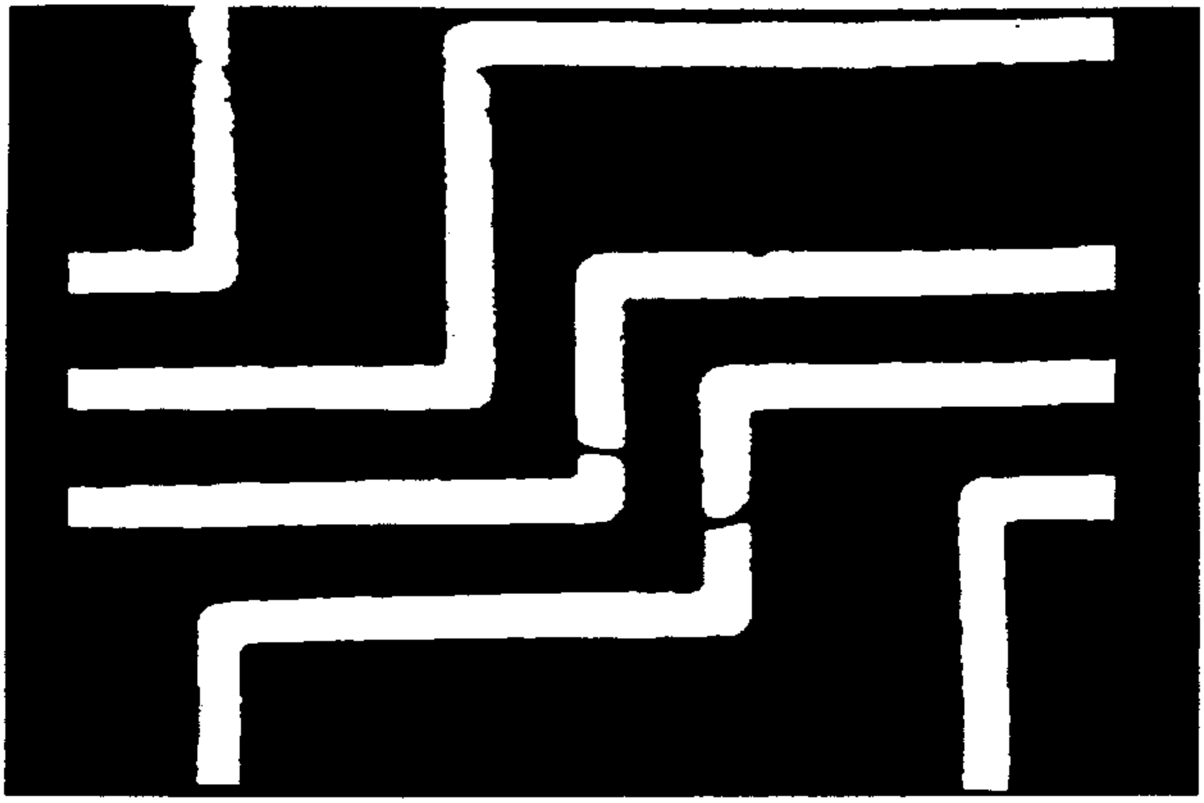
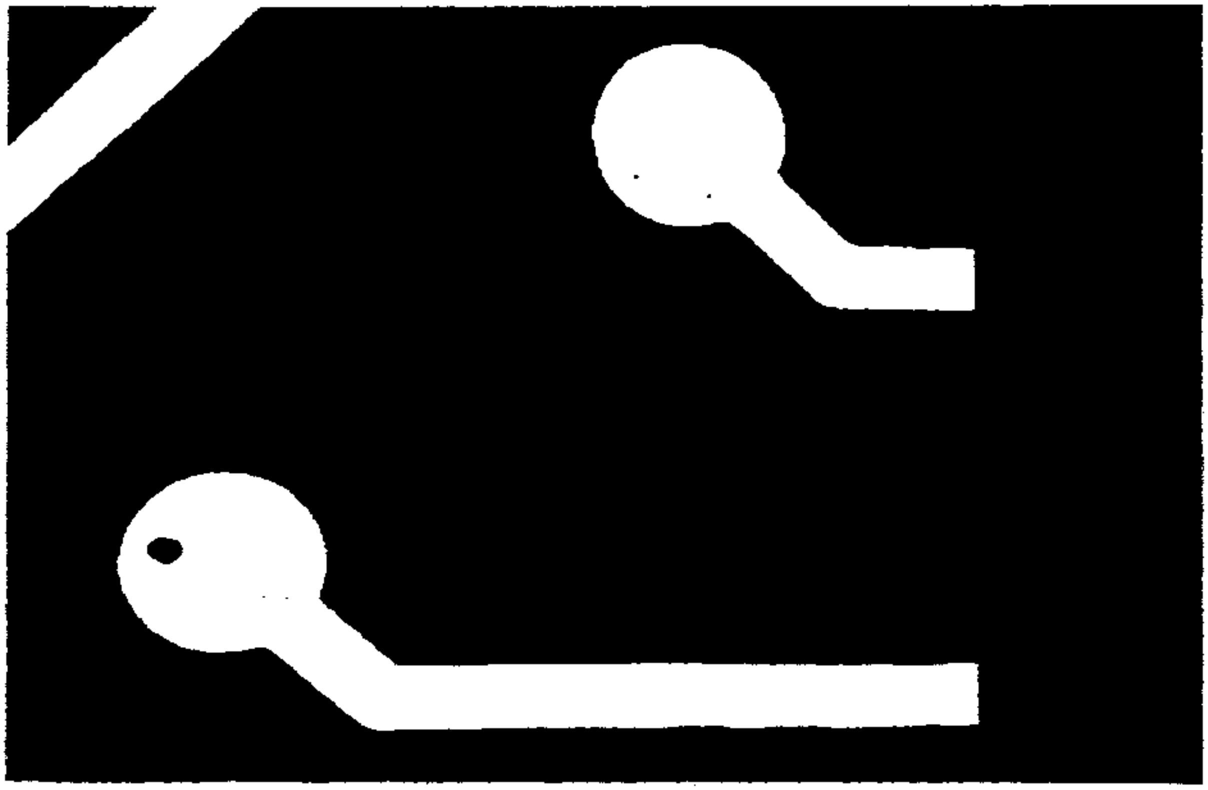


Figure 2-2: A break due to scratch



Figy re 2-3: A pad defect unlikely to be detected electrically

3. "Big" Current Problems

The big three problems are imaging, algorithms, and speed. Paraphrased: how to get the spatial sensor to sense the object of interest, how to get a computer to interpret the resultant image in order to classify the object of interest, and finally, how to have the system do this quickly. These are difficult problems, and their solutions are more special-purpose and inflexible.

Major efforts are underway to develop the general-purpose flexible inspection device that could be bought off the shelf to solve many inspection problems in electronics packaging. While algorithm and speed developments are of great importance, it appears that general algorithms are forthcoming, and speed Is increasing yvith current advances in computational architectures and electronics fabrication capabilities. Of the big three problems in inspection, only the optical requirements for image acquisition seem to admit no immediate breakthroughs in design. There is still a need to specially compose optics and lighting for each inspection, and to discover by trial and error what works best. For example, different lighting and optical schemes are required for each of the following: (a) etched clean copper, (b) oxide coated copper, (c) blue photoresist, (d) red photoresist, (e) solder before reflow, (f) solder after reflow, (g) layers that are opaque, (h) thin transparent layers (single sided), and (i) phototools. If we specify the many ways patterns can appear (i.e., 'pattern material[1] and 'substrate material[1]) the optical-lighting problem can be solved with a fixed set of mounts, lights, lenses, and filters; but the manufacturers are not able to constrain this rapidly changing technology in these regards. The same systems which do printed wiring board inspection might just as well do hybrid circuit Inspection, photomask inspection, and microwave assembly inspection, were it possible to build the universal optical-Sighting assembly.

Other current big problem are even more mundane and less academic. Nevertheless, their influence is important enough to be mentioned. One problem is thai of access to Computer Aided *Design* information which would permit integration of the inspection systems with the printed wiring design systems* The newer 'comparator* type systems, which not only inspect conductors for width but for placement as we'L, require information exchanges between the design and inspection computers. SfcnHariy, increased interpretive capability calls for the interaction between the inspection compuiers and process centre! computers*

The Influence of such mundane* commercial problems has stimulated rather titan hindered research. This is largely dim to tie greater depth afforded research by having more powerful systems available, and because experience with these systems has motivated much more sophisticated views of what automated visual inspection should provide.

4. Functions of Inspection

When inspection is made automatic and it performs well, the dividing line between product inspection and process control is less clear. Rarely is there much difficulty in finding one or more loops which should be closed in the process once the possibility of on-line, 100% inspection becomes a reality. The progressive functions of increasingly sophisticated printed wiring board inspection devices illustrate how inspection turns to process control:

1. Defect Detection. Defect detection is the mainstay of printed wiring board inspection. Basically, the goal is to identify the spatial coordinates of every defect on a layer. There is usually a criterion of point defect density so that points which lie very close together are counted as a single point defect. The Optrotech Vision 104 System [7], which is the only system to have been sold in quantity to date, goes no further than reporting point defects in a way fully analogous to the earlier systems generated out of our laboratory [4,6]. The evaluation of this system is simple: you score the defects detected, and downgrade tie detected defects by the amount of time and effort wasted in flagging "point defects" that are not defects (false alarms). The Optrotech System, like ours, will "hit[11] on the order of 85-95% of true defects, and false alarm on the order of 5-20% of the reported hits. This is better than human performance, but not better than more modern methods.

2. Defect Summary. Defect summary applies a level of classification to the defects and provides a defect summary for the board. The Itek System, which is commercially available [8] but has not been widely tested in the market, provides such a defect summary. Generally, there are two kinds of summaries: (a) one summary is based on categories corresponding to how the board is analyzed computationally, and (b) a second summary is based on categories which mimic human classification. Itek is of the former style, and the result is that some of the categories are more meaningful than others. A few years ago, IBM developed a system which used a simple classifier excess versus missing copper [9]. This is extremely potent in some circumstances, but usually too weak to be of much use. Our laboratory, and reportedly some commercial outfits, are working on more readily interpretable classifiers: the standard "break", "short", "pinhole", "mousebite", "overetch", "scratch", etc. A machine that reports point defects places onerous burdens on its users unless it can also list the types of defects in a way that people will use for analysis.

3-True Gauging. Technology for visually inspecting for defects is different from the technology for gauging conductor and pad widths. Gauging widths for inspection is merely confirming that the widths are within some, usually liberal, range. Measuring the widtbs with precision is an important function which current device technology does not address very well. In order to hold performance high, defect detection devices place only 10-18 light sensors across the minimum conductor width. One interesting, very general problem is associated with proper binary thresholding of an image in order to permit a focusing error without affecting gauging accuracy. A less general, but more challenging, problem is pixel interpolation for the specular gradient between the dull substrate and shiny copper. Gauging by a single measurement is out of the question for present day devices because camera speeds or electronics computations cannot support the resolution required in the time available. But cameras take thousands of measurements every second, and this can be exploited to yield precise measurements over short regions (e.g., .01 inch). Often it is more useful for process engineers to know that tie conductors are progressively changing width in a certain direction than for them to know that a particular serious defect has just occurred. In fact, many facilities that show 98% fresh lot yield on easily manufactured printed wiring boards could still justify an "inspection device" that gauges the patterns on every board.

4. Process Analysis. The gauging and the defect summary capabilities are precursors to a full process analysis tool. Alone, these capabilities provide valuable tools for analyzing the fabrication process, but devices can be designed with these features, and others, in a coherent working framework. Such devices may be used for statistical or even full-audit process analysis. Among the other desirable features of such a system is a statistical analysis package and the capability to judge defect repetition. Defect repetition combined with a visual categorization is often sufficient to determine the cause of the defect and what can be done to stop its recurrence.

5. Process Diagnosis and Control. A reliable system that reports with sufficient detail for a person to make a causal judgement should also be capable of making that causal judgement itself. We have found that the process engineers familiar with the particular fabrication process can attribute a cause for approximately 80% of the point defects on a printed wiring panel. I suspect that a machine which makes a correct judgement of defect cause only 50% of the time, and hardly ever false alarms, would be an invaluable contribution to the process control capabilities of a printed wiring board fabrication facility.

   Causal judgements involve knowledge in such a way that it is unlikely that we could build a machine (under a uniform theory of perception) which outperforms the approximate 80% rate of engineers. People are extremely good at extracting spatial cues for object recognition. An engineer evaluates what a defect looks like in the context of where it is, what was supposed to be there, the board style, what machines were involved, who was involved, what supplies were used, and even the weather outside. The reasons that an engineer may use to make a decision are not always available to a mere computer. However, computers can bring considerable knowledge to bear on an interpretation problem, so there is reason to be ambitious in having the computers conservatively come to conclusions.

5. Paradigms

Printed wiring board inspection provides marry paradigms which are interesting for their academic merit For example, the camera systems employed will commonly generate between 1QG ami 600 mliion pixels for each image of a printed wiring board panel. While most groups are designing to *mmS* storing these large images, there *m* great utility in keeping them -- perhaps even keeping them In color {which could triple the storage requirement). This problem generates interesting paradigms in dataflow in electronics Hardware.

Another interesting paradigm is forced by the current shift in technological focus from "design rule" devices to ^inemciry comparator[1]* devices. The critical difference is that memory comparator devices not only respond to design ryte violations, they also respond to the proper spatial positioning of each conductor and pad. An interesting problem is to design a device which can be both a design rule and a comparator device, depending on the information available about a particular panel and perhaps the speed desired for inspection. The interesting paradigm is in discovering image processing algorithms which are opportunistic and will use all available design information about each panel individually.

A final paradigm concerns the intelligent automatic perception and interpretation of defects and defect patterns. We have already established that the problem is interesting. Let us now turn to developing a deeper understanding of this paradigm.

6- The Paradigm of Interpretation

In this section, I will discuss two methods of defect interpretation which I find interesting. They differ in intent: one labels the quality while the other labels the significance of defects directly (as an engineer might do). As suggested earlier, many labeling schemes are possible, and are determined by what the inspectors and engineers are trained to see rather than by what the inspection device must do to detect defects quickly.

6.1. Common Labeling

The goal of labeling is to produce labels for point defects or clusters of point defects. The labels people usually want are of the following defects: (a) line break (or "open"), (b) short, (c) pinhole, (d) scratch, (e) overetch, (f) underetch, (g) spurious (or "excess") copper, (h) mousebite (or "nick"), and (i) pad defect. In our laboratory, machine implementation of common labeling is to the following classes: (a) line break, (b) short, (c) pinhole, (d) thin conductor, (e) overwidth or thick conductor, (f) spurious copper, and (g) pad defect Figures 6-1 and 6-2 illustrate examples of this automatic labeling.

Such labeling is not simple pattern abstraction. A defect, by definition, is not predictable in its pattern - there is no a *priori* shape even to a pinhole or short, let alone a piece of spurious copper or a damaged pad. A segmentation method for defect interpretation would be as follows: (a) The defect is viewed as a physically defined region in the printed wiring because it is possible, under virtually any defect detection scheme, to point to the location of the defect The label is derived by evaluating the physical context of this defective region of copper, (b) Context evaluation identifies particular fines and pads that can be seen in the context (c) Context evaluation also determines shared borders between defect regions and the labeled line and pad regions, (d) And, finally, context evaluation determines whether the defect region Is Inside or outside the projected area of the line or pad (essentially "missing" or "excess" copper).

An image processor which provides this low-level information can provide input into a rule system which labels defects. The rules used to evaluate defects of the classes shown in Figures 6-1 and 6-2 are simple but reasonably powerful. A hole is identified as a region of substrate not connected with an image border. A thin conductor is a defect region within the projection of two line regions, whereas a thick conductor is outside that projection. A break is a defect region within the projection of one line region. A short is a defect region outside the projections of a line and a pad but connecting both together. Finally, spurious copper is excess copper not connected to any line or excess copper on a pad.

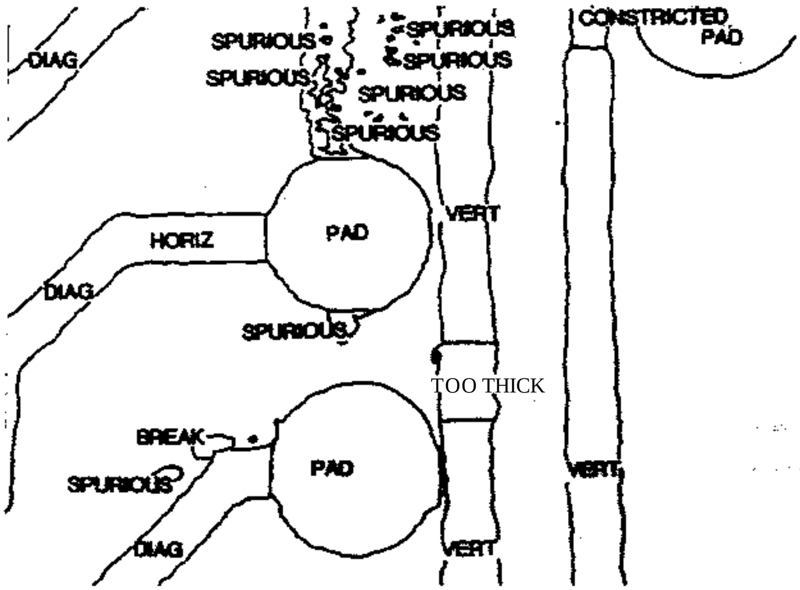


Figure 8-1: Serious yndereteh labeled autoniaticatty. {Re-drawn from tie color original).

These rules establish a labeling scheme which can 'be characterized as "local". That Is* the rules depend only on the regions Immediately adjacent to a defect region. However, this toads to bizarre behavior cm some occasions* For example, *Wmm* is a region labeled as a^m*bmak*^{w} in Figure '6-1 which may not be a bm«k because of consequent spacing design violations should the line be extended. Such schemes wif also fail to see more global features, such as the underetch In Figure 6-1 as opposed to tie underetoh in Figure 6-2, which may be inferred from the "short^1* label

Despite such problems, local labeling schemes may prove useful in automated visual inspection environments. Aggregates of labels will remain approximately correct and will provide useful ififematioa The *me* Just illustrated is capable of working in real-time environments since the computations are simple and very well defined.

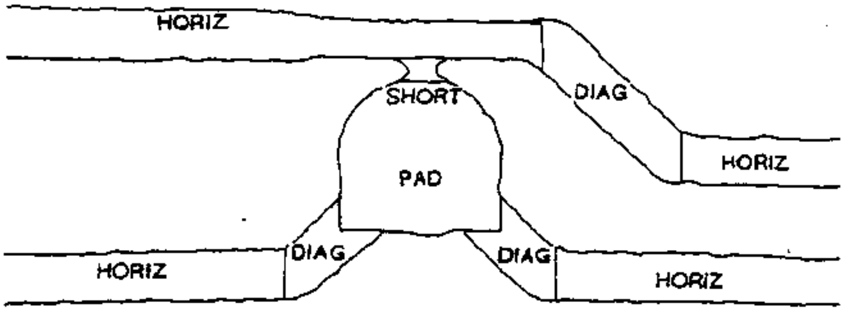


Figure 6-2: A simple short labeled automatically.
(Re-drawn from the color original).

6.2. The Perception of Causation

A much more powerful method was derived by interviewing quality engineers and developing the scenario for an expert system. Our study included sessions on over 500 images of natural defects in printed wiring. The engineers provided their interpretations of the defects and what may have caused them.

Because the analysis and system design on this work is in progress, it can only be discussed cursorily. Basically, we find that the image processing required to reach the level of an "expert," interpreting about 80% of the images without making errors, can be obtained by image processing methods which are simple if taken individually. For example, flaking resist is a defect which can be characterized as a conductor break which is broad, whereas a mousebite is a polynomially simple nick out of a conductor. These are computationally quite distinct although the computation in either case is rather simple (but interesting!). The significant observation appears to be that every causal attribution has its own distinct image processing requirements. A system that can make causal attributions on the basis of visual information will have to draw on extremely diverse image processing resources. In fact, the likelihood is that every manufacturing facility will have to have a tailored system for making causal attributions and that the specialization will reach down to the basic image processing building blocks.

On the more positive side, it is clear that there are ways of making extremely useful causal attributions completely mechanically. Our current research aims to describe how to do this.

7. Closing

The "state of the art" in printed wiring board inspection is rapidly changing. There are many interesting domains of study which are sufficiently well grounded and well disciplined to attract academic interest. Our single most important observation is that this domain, like some to be found in medical and military imaging, provides both breadth and depth to academic problems in optics, sensors, computer systems, computer vision, and artificial intelligence. Furthermore, the problems are, in general, not so simple as to be uninteresting applications of existing knowledge and not so difficult as to require a restructuring of our academic base to conform. Thus, printed wiring board inspection is a nearly ideal applied problem, because it complements, without detracting from, a number of basic research problems.

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