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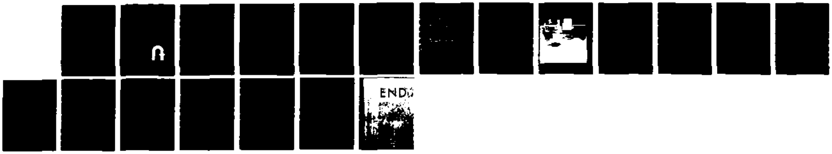

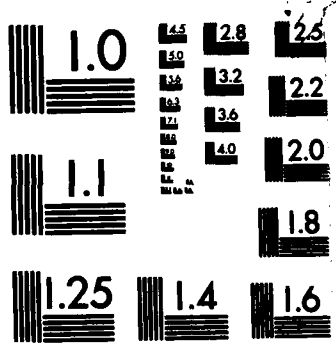

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AUTOMATIC INSPECTION FOR PRINTED WIRING

Robert Thibadeau, Mark Friedman and John Seto

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Pittsburgh, Pennsylvania 15213

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Automatic Inspection for Printed Wiring

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Paper presented at The Institute for Interconnecting and Package Electronic Circuits, Fall Meeting, San Diego, CA, October 3, 1982.

[1] Westinghouse Defense and Electronic Systems

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1. Introduction

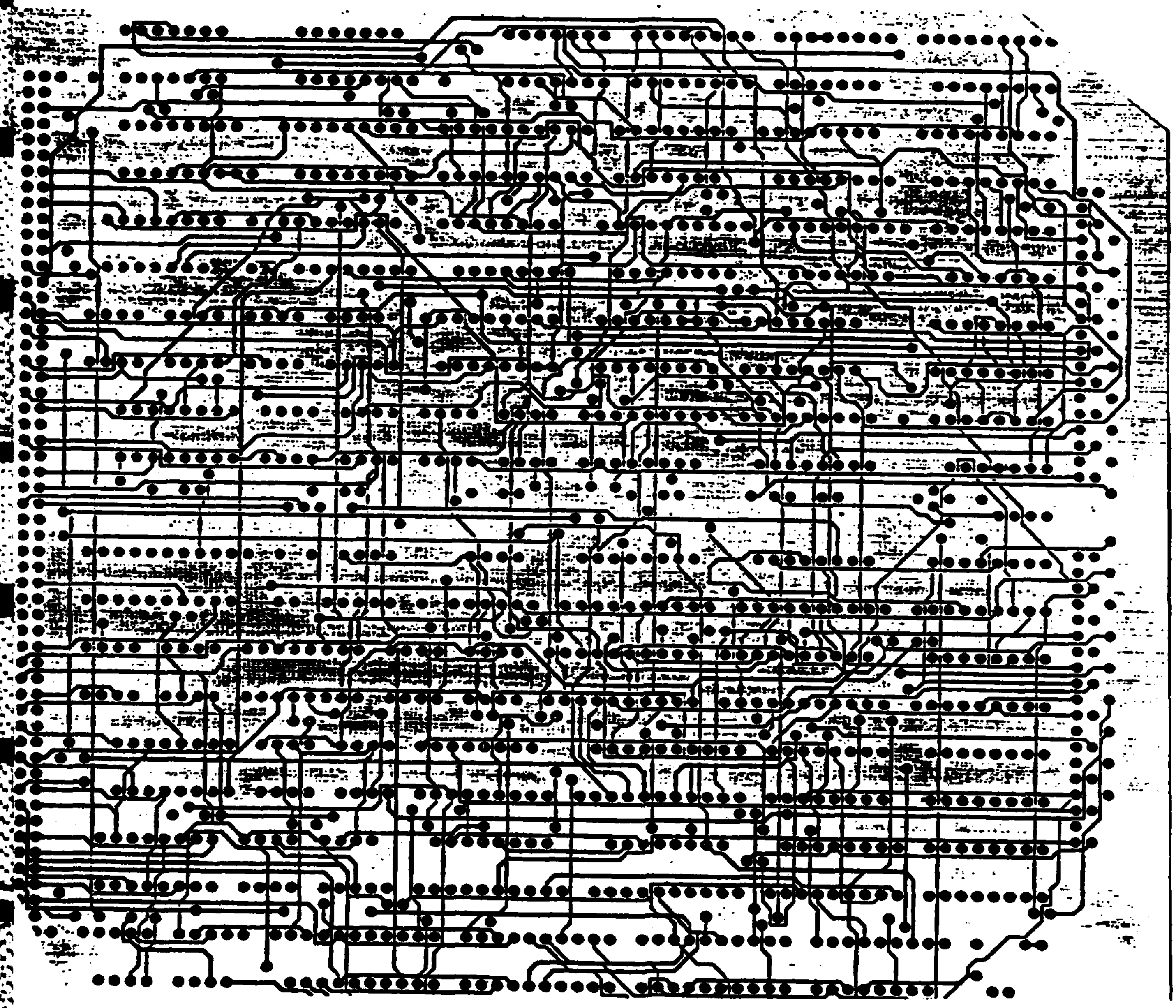
Twenty years ago the academic literature on computer vision contained many computer analyses of images of printed circuit boards. In fact even the most recent textbooks on image processing will illustrate several algorithms on pictures of printed circuits. As often as not the algorithm shows how to detect a defect in a printed circuit from the visual image of it. Every time, of course, the algorithm succeeds in detecting the defect. But for all these twenty years, and all those examples of defect detection, there has yet to be a successful commercial product for the visual inspection of printed circuits by machine. Perhaps the printed circuit industry lacked incentive for automated visual inspection. But now there is a need, and researchers are learning that automated printed circuit board inspection is a hard problem to solve.

Figure 1 provides an example of a printed circuit -- in this case an image taken at low magnification to give the idea of the patterns on a printed circuit board. The pattern is in copper and the reader may note the image from the copper on the other side of the board. Modern printed circuit boards (PCBs, or alternatively, printed wiring boards, PWBs) use wiring of finer design, greater density, and more printed layers to a single board. The image in Figure 1 is a layer of a twelve layer board. Already more than 15% of the labor force is likely to be involved in visually inspecting such layers. As line widths go from 20 mils to two mils, the cost of inspection is greatly affected. A major reason is that the tenfold decrease in line widths and spacing requirements is really a hundredfold increase in inspection area. Furthermore there is greater need to see the board under magnification. For 20 mil boards, a 3X magnifying glass is enough, but, for two mil boards, there is a need for 30X microscopic viewing. With such viewing the effective inspection area is ten thousand times larger.

This scaling effect is only a part of the problem. Finer line technologies promote more dependence on single boards. A single board becomes more valuable because more circuitry and components can be put on it, and this means the cost of missing a defect increases. Finally, current technology promotes the use of multilayer laminated boards. A 10% probability of a defect in a single layer translates to better than a 60% probability of a defect in a 10 layer laminate [5]. The effects of such a Bernouli probability process are quite scary, and (manufacturers are discovering) the fears are not at all relieved by current actualities.

Two years ago there were a few good research and development projects underway for inspection stations; now we count the projects in the tens. More than one large company is promising (or

A Picture of an Innerlayer PWB



strongly hinting at) commercially available inspection systems in the next months[1]. The prototype pictured in Figure 2 was just recently completed in the Inspection Laboratory of the Robotics Institute. Since only a few prototypes have yet been built and since such promises of production quality machines have been made before without result, there is reason to stand back from our claims. But there is a consensus among those who have looked at the problem in depth that robust inspection systems will be commercially available within a year.

The time has come to provide the PWB industry with what can reasonably be expected from state-of-the-art PWB inspection. The devices are inspection aids. They will not carry out autonomous inspection, as once hoped. Rather they will flag certain restricted problems with printed wiring boards, and a human operator *cum inspector* will still have to make the final decisions. The economic incentive for such stations stems from the fact that they succeed in aiding the human inspection task. This is largely because they will act to direct human attention to just those parts of the PWBs that are suspicious. We will not have to look in great detail at every part of the board. Machines will do much of the looking.

2. Guidelines for an Inspection Station

A valuable result of the cooperation between the Robotics Institute and Westinghouse Corporation has been the development of a set of guidelines or specifications for a PWB inspection station. Table 1 provides a synopsis, which has been altered slightly to be sensitive to industry standards rather than the needs specific to Westinghouse Defense and Electronic Systems and the Robotics Institute Inspection Laboratory. There have been several collaborations between corporate users and research and development groups which have resulted in the development of such guidelines. In our experience, the guidelines developed elsewhere have been similar.

The guidelines are broken down in four categories relevant to the end user. The **Layer Characteristics** represent a generalization of current PWB layer characteristics across a large number of companies. We assume, for example, that boards will not generally exceed 18 inches in width and that copper or copper treated patterns predominate. In one respect, namely the conductor or line width and spacing, we try to anticipate additive technology boards. It is likely that line widths below 4 mils (by spec) will be additive technology boards as opposed to the subtractively etched boards more common nowadays.

[1]We witnessed Hughes Corporation announce their "System 9126" automated inspection system at the IPC Conference, and we know that Itek Corporation, Automation Engineering Corporation, and Elron Ltd., are accepting orders of one form or another for 'off the shelf' technology

The CMU PWB Inspection Station

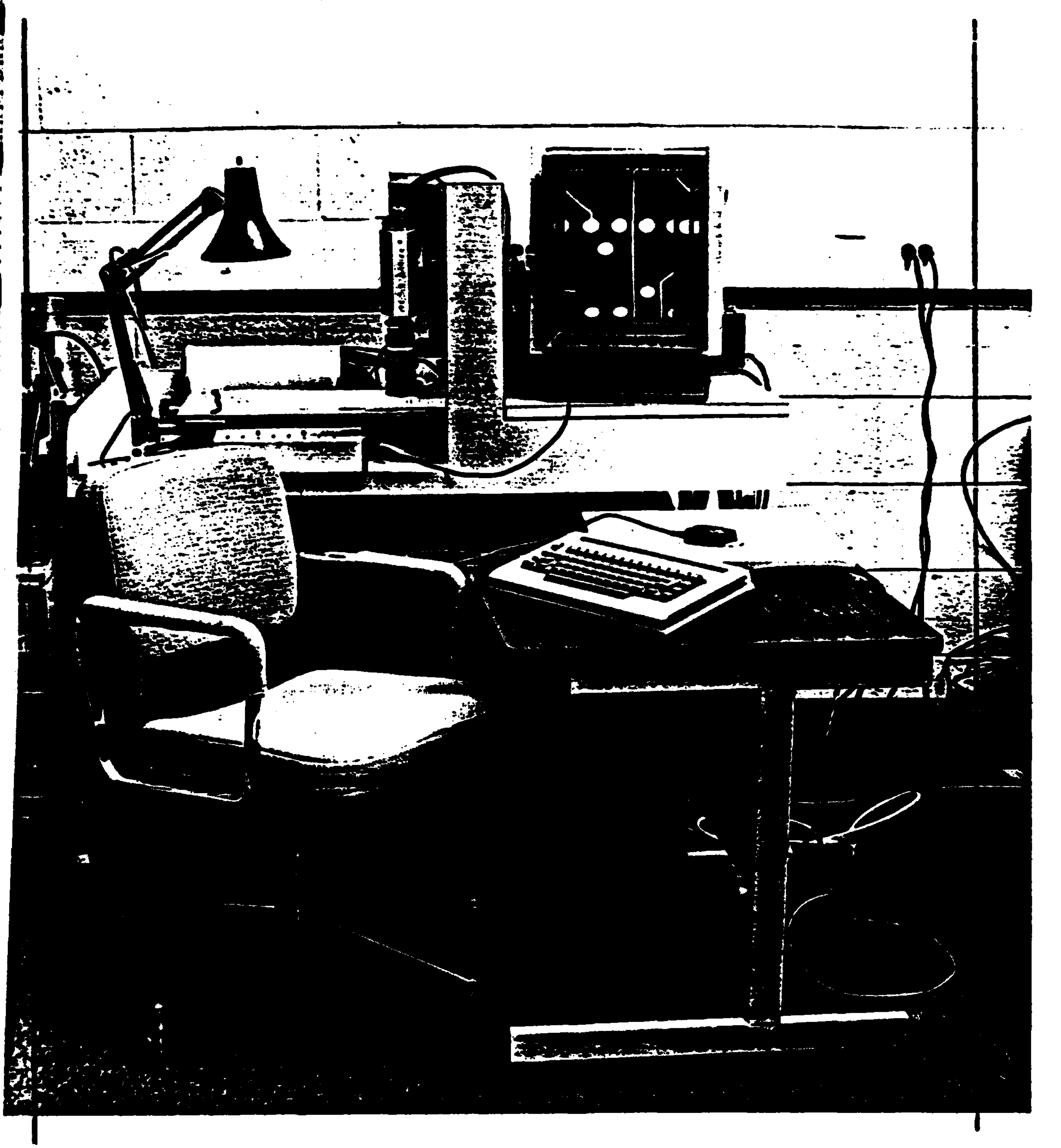


Table 1. PWB Design Rule Inspection Station Guideline

I. Layer Characteristics

a. 18"x24" panels (upwards of 300 sq. in. of inspection area per side)

b. Multiple images on a panel

c. Copper or (oxide) treated copper patterns

d. Substrate thickness >= 0.003" (epoxy glass, polyimide, teflon-based laminates)

e. Conductor patterns/groundplane/powerplane/solid copper

f. Conductor width/spacing >= 0.002"

g. Registration Techniques generally adaptable to pinning for registration

h. Subtractive or additive copper patterns

II. Defect Detection Requirements

a. Open conductor

b. Shorted conductor

c. Spacing below minimum

d. Conductor width below minimum

e. Locally reduced conductor width

1. nicks
2. pinholes

f. Spurious copper

g. Special Types: Measling, Additive Technique Gapping, etc.

III. Performance Requirements

a. Process both sides to keep up with Scheduling and Cost Requirements

1. Online Inspection (< 2 Minutes)
2. OffLine Inspection (< 15 Minutes)

b. <= 0.5% Escape Rate (number of defect escapes/total number of actual defects)

c. <= 5% False Alarm Rate (number of false alarms / [number of false alarms + number of total defects detected])

d. Identify types of defects and location

The **Defect Detection Requirements** focus on the two most significant classes of defects, opens

Table 1 continued.

IV. Inspection Station Features

a. Provide Performance Data in Machine Compatible Form

1. type of defect and quantity
2. part number
3. job number
4. disposition

b. Record location of defect on the innerlayer with ink

d. 98% availability (operational time/(operational time + down time))

f. Manual and Computer access of design data

i. Provision for meaningful operator interaction

j. Automatic load and/or unload capability (generally not yet available)

and shorts, and on military specification (generally tighter than commercial specification). We would like to regard II.g., **special defects**, as a catch-all class of defect patterns not of immediate concern to inspection aids. True inspection devices must, of course, even detect that improbable human hair that appears in the substrate causing a short between conductors.

The **Performance Requirements** were selected because we believe that current technology provides at least this level of system performance. A caution is in the area of identifying the types of defects. The "types" of defects current stations are likely to identify may be somewhat different from the "types" of defects cited in quality control manuals.

The **Inspection Station Features** have to do with man-machine interaction and are generally meant to provide a baseline criterion for performance. A number of assumptions have been made which may not be pertinent to a given application. The general aim in these features has been to point up a very important capability for PWB inspection stations. This is to provide information to affect quality control, process control, and process capability studies. A significant benefit of automated, viz., computer based, PWB inspection stations is that they can be made to provide information about the inspections without additional human involvement. We will return to this point later.

3. Types of Inspection Stations

Generally there are two classes of inspection station, the comparator station and the design rule station. Both have their place. The comparator station can look at a PWB with knowledge about the proper location and orientation of every feature of the board. It does a one-to-one comparison of the features of a known 'good' board to the board in question. A recent published description of such a station is [2].

The design rule station requires considerably less information and less precision and is, therefore, more economic. It detects whether a board in question contains features which violate design rule specifications. Such specifications are similar to those found in quality control documents; for example, that a line must end in a pad. The stations currently on the market are all design rule systems. Relevant research publications include [1], [3], and [4].

A comparator station is more powerful in principle, since it also detects whether general design rules are met by virtue of the fact that these are an attribute of the specific design. Comparisons of an artwork master against the CAD database for the printed circuit will detect whether a line was left out or misplaced. Comparisons of a printed circuit board against master or CAD database entry will determine whether the manufactured printed circuit board mirrors the master copy. A final type of comparison capitalizes on the fact that in some settings a single board may contain two ostensibly identical prints side by side later to be routed out as separate PWBs. These ostensibly identical prints can be compared.

Comparator systems fail when defects are hidden by imprecision in aligning or correlating the test board against the known good board. Unfortunately, alignment is extremely difficult for printed wiring. More often than not, to get a comparator system to detect defects, one must also accept a very high false alarm rate. Comparator systems are designed to flag everything which is different than the master. However, the sensitivity is often too high because of uncontrolled conditions and this results in false alarms. Too many false alarms and you might as well put a human inspector back on the task.

Design rule systems are advantageous when there is a question of monetary cost and inspecting artwork masters is less an issue. These systems guarantee that certain abstract features of the boards agree with specifications. Rarely is there as much need in such systems for the precise registration of boards. Access to a design database is less critical in the use of such stations. Most admirably, such stations are less likely to give high false alarm rates.

In their crude forms neither type of system has the capability of differentiating among different types of defects or of differentiating severe from less severe defects. But, in practical fact, they permit some primitive level of defect classification. Comparator systems that do raw comparisons are the worst in this regard. About the most we can expect from them is telling us whether something was 'extra' on the board or 'missing' -- not even what that something is. Current comparator schemes work because the comparison is not done between images, per se, but between abstract features derived from images.

The work at The Robotics Institute has focused on design-rule systems for a number of reasons. A major reason is that workable comparator systems tend to borrow from design-rule technology. Gleaning abstract features from an image is the basic work to be done in a design rule system. Another reason is that rapid defect detection will inevitably have a heuristic component. That is to say, there will be some defects that will be missed and some patterns that will be identified as defects but for the wrong reasons. No method, or combination of methods, we have encountered detects all the copper defects which can occur on printed wiring boards.

Current technology suggests that design rule systems are what you can buy today. Tomorrow, expect comparator systems which borrow on the methods developed in the design rule research and development.

4. How Design Rule Systems Work, and Don't Work

It is important to understand that design rule systems do not faithfully reproduce the will of their creators. The technology is such that the limitations enforced by experience, time, and cost affect the performance of the system. Typically a design rule system is built around a single method, or algorithm, which has a characteristic response to a restricted number or class of spatial patterns. Defects are, often, non-predictable in shape and severity. The machine may look for defects or for deviations from the spatial patterns which are deemed "good". A given algorithm may work well in finding breaks in the conductors, but may fail miserably in finding shorts between pads and conductors. An overview of a number of algorithms and their characteristic responses can be found in [5].

There appear to be two classes of design rule algorithm in current machines. The first is associated with a "software" approach and the second with a "hardware" approach. It is unclear whether the functionality of the machines can be distinguished by a hardware or software approach, and the problems of getting software to work rapidly enough are largely surmountable nowadays. The user may never know whether he has a "software" or a "hardware" machine. Nevertheless the principles of operation tend to be quite different and are worth noting.

A hardware machine will typically take several "masks"[2] in rapid succession and apply the masks, left-to-right, top-to-bottom, across every part of the image of the circuit. If a mask at some point matches the image to some criterion or in some logical way, the mask is deemed to account for the pattern.If a copper pattern is present but no mask matches it, or a mask sensitive to a type of defect matches, then the system registers a defect. For example, consider a mask made up of concentric circles. The mask detects pinholes when the center circle is filled with substrate (or background), but the outer one is filled with copper (or foreground). Masks can be worked out to detect legitimate geometries and types of defects in this fashion. Unfortunately, this approach often yields a strange categorization of defects. Several masks may detect a defect, each implying a different manisfestation.

A "software" machine does not work rapidly enough to apply the mask approach. Such a machine will typically work to characterize areas of copper on the basis of some computationally simple criterion or set of criterions. For example, the software machine may formulate regions of copper and ask questions about the local horizontal width of a region. If the width is too small and the context indicates the *region* is a vertical line. then the inference is that the line is too thin. A round pad will cause problems since it too may contain a line across it which is very short (at the top and bottom for horizontal lines drawn across the pad). Such software systems use ingenious ways to avoid false alarming like this on legitimate geometries.

A problem for any inspection approach is what we will call the "put and punch" method of PWB fabrication. One puts on a pattern and then punches out some parts of it by drilling. A difficult problem in present technology is to inspect boards with drilled-through pads in which one allows a certain degree of "break-out" -- the drill hole creates a half-moon of the pad. The reason this is difficult is that the drill hole upsets the geometry of the pattern unpredictable ways. If we require that the drill hole leave a ring of copper around it, then many detectors will work. But the difference between a sharp edge of copper caused from a drill hole misaligned on a pad and a sharp edge of copper caused by overetch is very difficult for such systems to "see". We do not expect this difficulty to remain forever, but, the reader may note, even comparator systems will have to deal with "put and punch" playing havoc with otherwise orderly geometries.

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[2] The term "masks" is just one of many that have been used: We might just have well used a mathmatical sense of "operator" or "window" as we did in our oral presentation. The most precise term is "operator".

A major point of this section has been to emphasize that the manner in which the inspection station views the circuitry is quite different from the manner in which we, as humans, view it. The method is typically quite simple, although ingenious. It does not guarantee defect detection unless the defects meet certain specifications themselves. We all know that defects are not planned, and therefore some will remain elusive.

5. What happened to Truly Automatic Inspection Stations?

Ten years ago, which is at least ten years after academics began talking in earnest about the problem, automated PWB inspection was a common thought in the PWB industry. That idea, though, was an ambitious one. The inspection was to be a *real inspection* by computer. The computer would look down on the printed wiring board and decide what was going right or wrong with the manufacture. Defects would be routinely trapped, fabrication processes automatically tuned, and a description of defects and actions taken sent to management personnel. No one would question whether the dauntless machine would miss a defect. No one would worry that the machine would cry wolf one too many times. The only questions that might arise would be questions of bad programming or defective hardware.

Needless to say, a long time has passed. We believe much of the problem lay in the fact that in both academics and industry the problem has been severely underrated. PWB inspection is a hard problem. Furthermore, it is not all simply a problem of taking a technology and applying it. It is not a hard problem simply because one engineer may disagree with another about a defect. There are fundamental research issues which require satisfactory resolution before the dream of real automated PWB inspection stations will come to pass.

The most fundamental of those research issues concerns *defect understanding*. When an engineer looks at printed wiring and sees something is amiss, he will carefully size up the problem. He is interested in saving the board, evaluating the performance of the fabrication process, and, over time, evaluating process capability and the potential for better productivity in his plant. An experienced engineer, the person we would like the automated inspection station to emulate, sizes up the problem very quickly. Most of the time, he simply looks and knows what is happening. He is doing something that humans do very well. This form of visual recognition requires finding the defining visual attributes of an object. The objects in our case are "a short", a "line break", a "case of overetch", a "speck of dust on the artwork master", and so forth. Despite the many quality control documents explaining these 'objects' to people, it is far more difficult to explain these 'objects' to computers. The defining attributes are, to put it bluntly, a total mystery.

The traditional example of this problem is recognizing a dog. Few of us have difficulty seeing a dog as a dog. But what is it about the vision of the dog that makes it clear that the thing is a *dog* and not a cat or a wolf, for example? Dogs take on a veritable infinity of shapes and sizes, yet we have no difficulty seeing them for what they are. To date, we still do not have good ways of having machines do this primitive kind of visual recognition. We hold that it is precisely this kind of recognition that the engineer uses, and it is precisely this kind of recognition that an automated PWB station will require to perform well.

In contrast to other technologies where a problem was underrated, we believe that PWB inspection technology can address this very fundamental question quite directly. The first machines will do economically viable jobs of detecting most defects most of the time. Defect categories, like line breaks and shorts will be distinguished, but the distinctions may not always agree with common sense. They will reflect hard, and most often oversimplified, definitions programmed into the automated inspection aid. Nevertheless, these machines will provide the economic incentive to build better machines. As long as circuit patterns remain reasonably constant (aside from any changes in scale), the development of PWB inspection methods can build on experience. With attention to the problem, something very close to an ideal PWB Inspection Station will be a technical and economic possibility.

6. Flexible if not Ideal Stations

As market forces come into play, PWB inspection stations are likely to become spare and rather stripped down beasts of burden. But there are hidden costs to computer technology (and fairly well hidden advantages) which deserve open discussion before we strip the beast of all its purported luxuries. A major issue is in how to exercise the process control capability of PWB inspection stations. We do not want another information engine on the factory floor which spits out enormous quantities of detailed information. We would rather have decisions that the process and quality control engineers would make; supposing they had the time and resources to study all that information. This high-level information is better if the system can also explain the decisions.

The inspection device developed at the Robotics Institute is constrained to provide for two stage processing [5]. The first fast-flagging, or coarse analysis, stage implements a state-of-the-art inspection aid, as has been described above. Using the "software" approach, defects are flagged for attention by the station operator. The operator can then examine the board at specific locations to determine the disposition of the board. The inspection devices currently available and likely to be available in the next couple of years are going to require at least this level of operator intervention.

However, we also provide a second machine processing stage which is distinguished by cropping the image of the defective area and submitting that image to more intensive, finer, image processing. This processing can exhaustively measure line widths and pad features and can also proceed to classify the defect patterns in a more motivated way than is available with simple ingenious algorithms. In our view, the fast-flagging stage can be implemented as either a "hardware" or a "software" inspection aid, but, in either case, it is appropriate to make provision for a "software" second stage, or follow-up analysis by the machine. This second stage should not simply have available the result of the first stage -- it should also have available the information, the image, which was examined by the first stage. It is important to emphasize that this second stage is not meant to 'make up for the sins of the first'. If the first stage fails to detect a defect, the second stage will not have the opportunity to see the defect (research needs to continue in first stage analysis, of course). The purpose of the second stage is to provide a logical interface between the way the machine coarsely scans a board and the engineer's need to understand the 'experience' of the machine.

A natural question is why not do this second stage analysis while one is doing the first stage analysis. The second stage analysis takes enough time that it is unreasonable, even with special purpose hardware, to apply that analysis to every square inch of the PWB. Consider the size of the image that the machine is dealing with: For boards with 10 mil line widths, one is likely to use a system in which the smallest picture element, or *pixel*, is 2/3 of a mil square (the considerations on pixel size have to do with the capacity to measure minimum line width violations). Four hundred square inches of inspection surface means that approximately a billion picture elements will require inspection in, say, 100 seconds. The data-rate for this specification is 10 million picture elements a second. This is a sizable data-rate by present standards. We cannot expect an inspection system to do much more than flag potential defects at this data-rate.

The flexibility of inspection is improved with two stages. The flexibility is in defining defect categories and in adjusting the level of report to the end user. It is clear that PWB manufacturing plants have different ideas about defect patterns. A good example is "spurious copper". One group may consider "spurious copper" to be any copper that is found on a board out of place, while another group may consider "spurious copper" to be copper which is out of place but only in a position to cause a short when the board is drilled (copper causing a directly observable short is typically just called a "short"). Inspection aids will flag the spurious copper, but it is more economic to catch the difference between definitions in the second stage analysis.

The end user wants the inspection station to provide not only the service of inspection but a measurement of conductor and spacing dimensions as well. Do not expect current technology devices to be 'measuring' in the same way a quality control document stipulates. Current devices may check whether a line width is within a range, but may never actually compute the average number of mils for that line width. The second stage analysis is a natural place for such measurement. Furthermore it is natural to permit some adjustment or selection among second stage tasks. If an engineering decision is made to do a process capability study, perhaps on a new etching method, the engineer can set the inspection device to do a more careful analysis. This extra analysis costs time. Perhaps more time than is acceptable on a routine inspection. The value of the device is the combination: its capability to do fast, routine, work, and more time consuming process control studies.

7. Conclusions

(printed wiring boards)

Automatic visual inspection of PWBs is a technology which is just about to arrive. A new machine will appear on the factory floor which actually looks at what it is doing. The arrival of this machine has been marked by years of research, and it is likely that years more of research will be invested in its perfection. But for now, a practical and economically rewarding device is available. As in any new technology, it is important to consider the long-term goals as well as the short-term rewards. PWB inspection stations primarily serve quality control functions, but they hold great potential in serving process control functions. We are on the verge of having devices which can bring tireless and intelligent vision to the process of PWB fabrication.

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