LINE SCAN VISION SYSTEM

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The automation of inspection tasks has always been of prime concern to process engineers. Until recently, the technology was not available to automate anything but the simplest tasks. With advances in machine vision and computer technologies, many visual inspection tasks can now be automated. This paper describes an AT&T development that can be used as an efficient tool for automating the inspection of printed circuit board assemblies. Significant increases in reliability are achievable as compared to current methods, namely human inspectors.

Background—Customer Need

Since the advent of printed circuit boards (PCBs) in the late 1950s and early 1960s, the verification of completed assemblies has been and continues to be a major concern in the electronics industry.

As the technology progressed through the 1970s and now into the 1980s, we could assemble more circuits and, therefore, more components per square inch of PCB than ever before. But smaller components and, in many instances, increased lead densities have brought assembly verification to the point where human inspection is less than 80 percent reliable.

Operator fatigue also decreases the reliability of any inspection, and leads to human discomfort and dissatisfaction with the work environment.

All these factors have led to the development of expensive electronic testers for verifying PCB assemblies. Although the testers are effective, their operation is costly—the initial expense of equipment and fixtures, labor to operate the equipment, and labor to repair defects. Therefore, improved quality of the assembly operation and reduced costs of verification remain primary objectives of the electronic industry.

Assembly defects can be classified into three major categories:

- *Wrong or missing components*—These defects can be attributed to operator error or malfunctions of insertion equipment. As more automation is used in assembly, these defects tend to be minimized. But
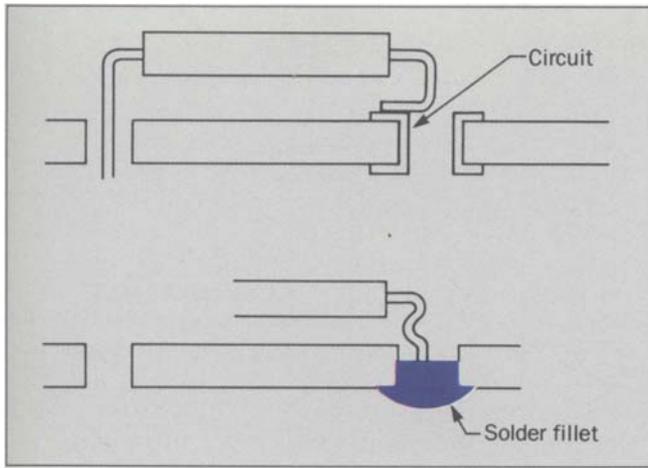
Figure 1. A new defect type emerging from automated assembly of printed circuit boards. Top, a folded-under lead; bottom, a hiked or crumbled lead.

a new defect type is emerging: a crumbled lead, or a lead that is not inserted correctly into its hole in the PCB (Figure 1). Often, electronic testers do not find this type of defect because the lead may still make contact with the circuit but is not soldered to it. This defect will eventually cause an electrical failure days and sometimes months after the unit is in the field.

- *Wrong polarity*—This type of defect usually results from operator error, but can also result from mixed orientation within the component packaging. Once again, assembly automation will tend to minimize this type of defect. But operator error in loading the components and random defects in packaging will always exist. Thus, the need for verification will always be present.
- *Solder defects*—These defects are generally classified as shorts and opens. They are mainly caused by variability of the automated soldering process, cleanliness of metallic components, and the PCB's design. As the technology advances, these defects are also being eliminated and, as some engineers feel, may eventually become negligible. However, most processes are not yet at this level.

For at least the last 20 years, the assembly verification process has been a target for improved methods.

Visual aids and overlays have been and continue to be used with some success. But these technologies are slow and subject to human inefficiencies. Optical comparator processes have also been attempted with similar results. For example, Teradyne, Hewlett-Packard, and Fairchild, among others, have developed post-solder electrical verifiers to address these problems.

These electrical testers generally will find almost all the typical assembly defects, except the curled-up lead or lead partially through the hole. Although electrical verifiers are efficient in identifying defects, they are extremely expensive (hundreds of thousands of dollars each). They also require intricate fixturing and programming to isolate and evaluate complicated circuits.

Because testing includes electrical measurements, the assembly must be soldered before test. When a defect is found, it generally requires analysis before being verified and repaired. The cost of this procedure, including repair, can average anywhere from $100 to $500 a day for every 1 percent of defectiveness.

The industry yield for first pass testing of electronic assemblies averages 75 percent, with half the defective assemblies failing because of workmanship or noncomponent-failure defects. Detection and repair of these defects can cost from $250,000 to several million dollars a year, depending on the volume and yields of the assembly process. Improved yields also reduce retest requirements, which means a savings in test equipment.

As these examples show, there is a strong force to increase test yields, and improved inspection reliability is one way to achieve this.

AT&T is expending much effort to improve performance in this area. Increased automation and modernization of our processes are the first priority in most of our factories. Improved test yields—which translates into shorter intervals and, therefore, reduced inventories—is a driving force for modernization.

Assembly processes are being designed to move the product forward constantly in an *in-line* fashion. Processes are also being networked with a shop flow computer to provide a flexible manufacturing information database—e.g., computer-aided design and manufacture (CAD/CAM)—and a mechanism for implementing process control.

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Figure 2. The line scan vision system. A custom interface connects the line scan camera to the rest of the system.
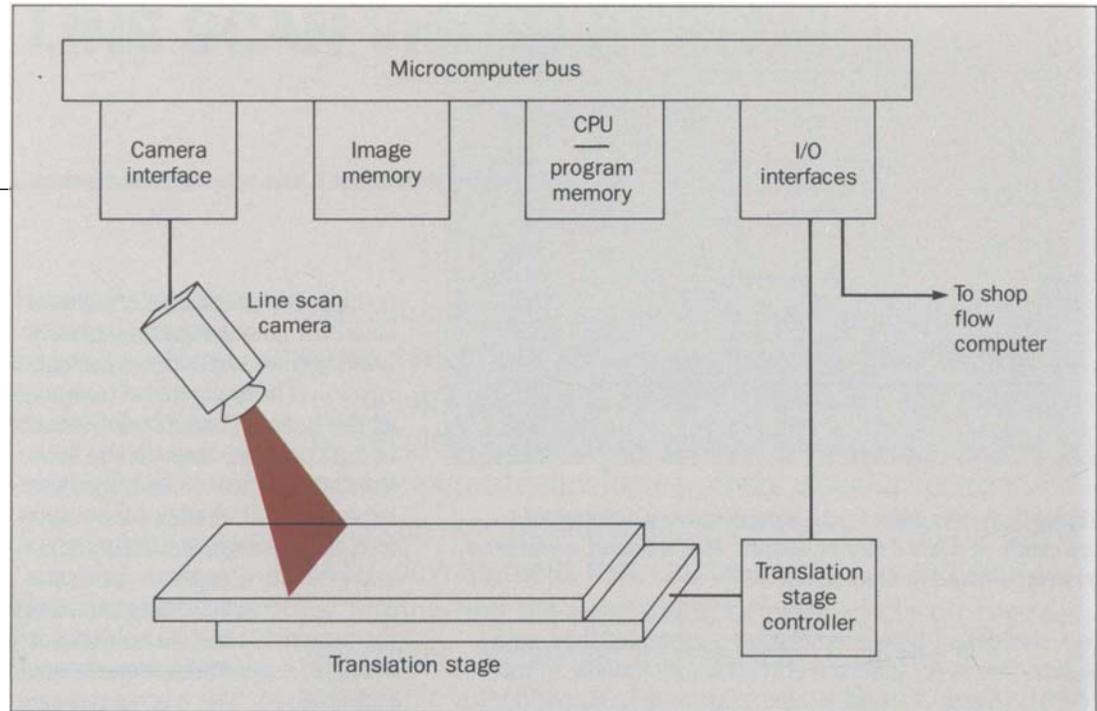
Many companies are using machine vision, a developing technology, to address the reliability problem of verification and provide the database needed to evaluate the process and control those areas that generate the problems.

System Description

Based on the above requirements, a set of image-acquisition specifications for a machine vision system can be developed.

The system's resolution must be at least as small as the smallest feature of interest. For presolder lead inspection, this is about 5 mils. Because a typical or practical scanning area for PCB inspection is about 10 inches by 10 inches, this implies that the system's linear resolution must be better than one part in 2000. The system must also be able to inspect a PCB (including acquiring and processing the image) in about 10 seconds, the dwell time of typical in-line assembly processes.

The Sensor. The critical element of such a system is the sensor; in our case, a line scan camera was selected.

A line scan camera consists of a single row of image sensing elements (pixels) and associated electronics, integrated with an appropriate lens system. The analog charge proportional to the intensity of the incident light that strikes each element is amplified and strobed serially out of the camera.

Line scan cameras are available commercially, and have from 256 elements to 2048 elements. One with 2048 elements meets the linear resolution requirement described above.

However, the image must be built up by acquiring line images. This is done by moving the camera relative to the object in a direction perpendicular to the linear array. The speed of this motion depends on several factors; the most critical is the amount of incident illumination.

If we assume maximum available illumination, the data rate of a 2048-element line scan camera can be as high as 9000 lines/second. For a scanning resolution of 5 mils/line, this equates to 45 inches/second, well over ten times more than the requirement for this application.

Therefore, a line scan camera meets all the requirements for the sensing element of a PCB inspection system. As will be illustrated later, the camera has some additional advantages when used for presolder lead inspection.

Camera Interface. While the sensor is an important component in the system, careful attention must be given to system integration to meet the processing time requirement.

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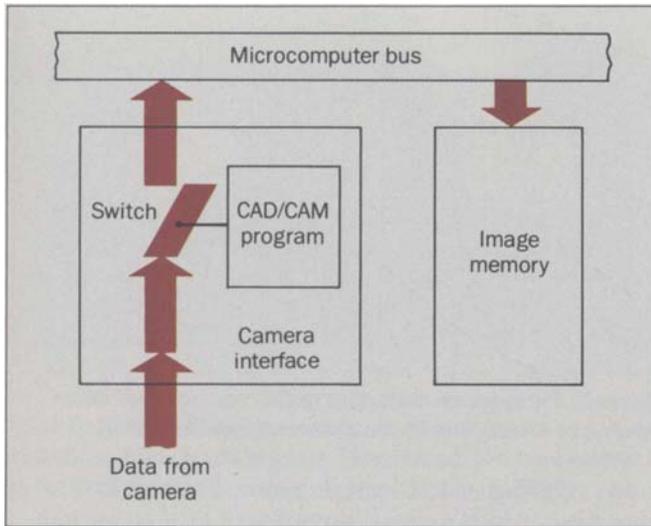
Figure 3. The camera interface for the line scan vision system. Information in the CAD/CAM program operates the switch that enables image data from the camera to reach memory.

Figure 2 is a block diagram of the line scan vision system. The line scan camera is connected to the rest of the system through a custom camera interface. In addition, a minimum system has an image memory, a central processing unit (CPU) with program memory, and input/output (I/O) interfaces, all interconnected via a bus.

We selected a commercial, nonproprietary bus for this application called the VME bus. The CPU controls and synchronizes the camera interface with the translation stage through an I/O interface and translation stage controller. The CPU also has access to the shop flow computer where PCB code and CAD/CAM information reside.

The operation of the camera interface is the key to efficient image acquisition and processing.

First, it is not practical or necessary to store each frame of the entire PCB image. For presolder lead inspection, the locations of all leads are available from the CAD/CAM database. Therefore, a more effective technique is to use this CAD/CAM database to define *windows,* or small regions of interest, that contain the pertinent image data of the PCB. Each window would include a small area surrounding each PCB hole that has a component lead inserted through it.

We designed the camera interface with these concepts in mind. This interface is a programmable switch that writes the serial image data from the line scan camera

to the image memory. The program stored in this interface is derived from the CAD/CAM database for a particular PCB code. Because the program contains the information required to operate the switch, only image data from these predefined windows are stored in the image memory (Figure 3). The data are then available to the CPU for later processing.

The major advantage of this technique is it significantly reduces the image memory size required to achieve high resolution over a large area. However, two conditions must be met for its successful implementation.

First, we must have information available about *where to look.* This is usually found in a CAD/CAM database. Second, the board must be placed accurately with respect to the start point of the camera. This is not a problem for PCB inspection, because tooling holes are available and are used to register a PCB accurately in other steps of the manufacturing process. Typical placement accuracy for PCB inspection might be plus or minus 5 mils (one pixel).

Thus, the two conditions that would limit the use of this technique in other inspection applications are easily overcome for circuit board inspection.

Processors and Memory. In integrating the camera interface into the system, the concepts of multiple processors and shared memory are important to overall system performance.

When acquiring an image, the camera interface accesses the bus and image memory as just another CPU on the bus (Figure 2). This access occurs only when the preprogrammed switch is *on*; i.e., when regions of interest are being scanned by the camera. Therefore, the CPU can read and process data already stored in image memory during the *off* times of the scan. On a typical PCB, this is a large percentage of the scan time.

Concurrent processing is an important, but not obvious, advantage of using a windowing technique to acquire the images. If one large image is stored as a single frame, processing cannot begin until the camera interface relinquishes the bus and image memory, i.e., at the end of the scan.

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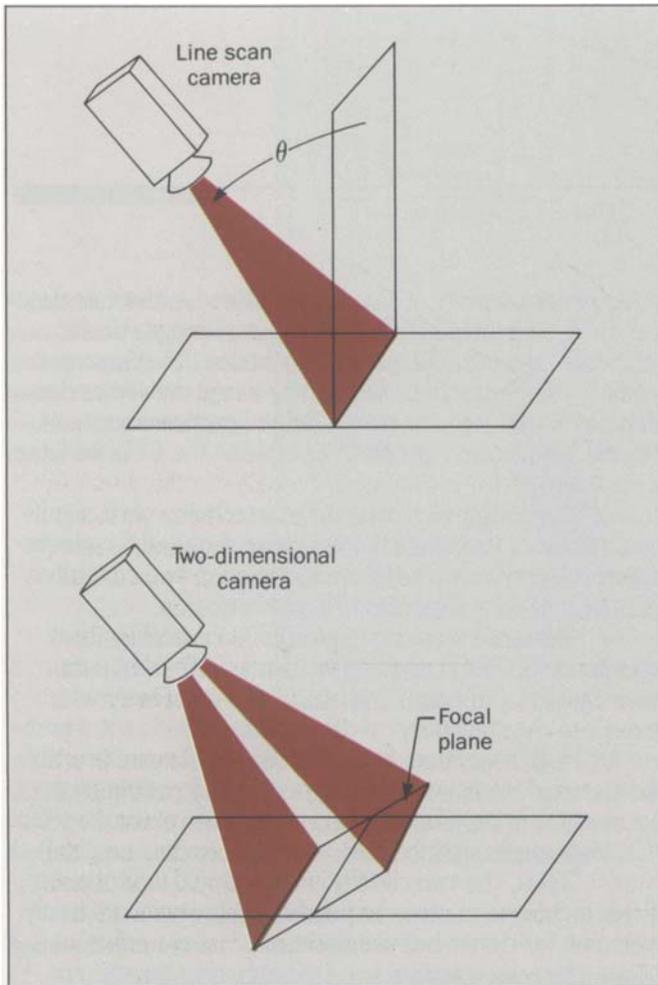
Figure 4. Angular viewing with a line scan camera and a two-dimensional camera. The line scan camera's image is a line, and the viewing angle rotates about this line. A two-dimensional camera's image is a plane, which when rotated, can create focusing and distortion problems.

Using multiple processors in this architecture increases system performance at minimum cost. For example, assume that an inspection algorithm for presolder lead inspection operates at a speed of 100 leads/second. (An inspection algorithm is a subroutine or subprogram that processes the image data and returns a numeric value to identify an acceptable or defective condition.) If the dwell time of the manufacturing process is 10 seconds, a single processor inspects 1000 leads/dwell time at this rate.
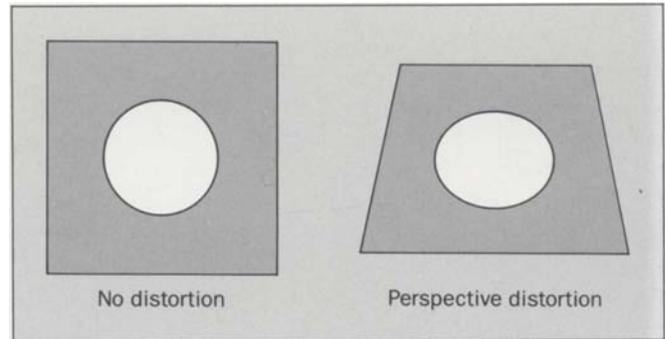
Figure 5. Perspective distortion (right) encountered when viewing at an angle with a two-dimensional camera.

Adding an additional processor doubles the throughput, which permits inspection of PCB codes with up to 2000 leads/dwell time. The cost of the hardware for this increase in speed is about 5 percent of the overall system cost.

It is easy to visualize how these processors operate in parallel. Each processes successive, alternate images (windows of data), so they are relatively independent of each other. Almost double the speed is achieved because only a small percentage of system processing overhead is used for this approach.

Presolder Lead Inspection

We selected presolder lead inspection as an initial application of the system. Some technical issues regarding this application will be reviewed here to point out the advantages of using a line scan system.

Many components inserted in PCBs have leads that are left unclinched as part of the normal manufacturing process. The most common example of this is a multileaded component with only its corner leads clinched. Because this is an acceptable condition, an automated inspection system must be capable of reliably detecting the lead both in the clinched and unclinched state.

For example, typical leads on an integrated circuit are 5 mils by 15 mils and protrude 50 mils from the lower surface of the board.

Because a clinched lead presents a significant cross section to the camera, the lead's image contains a large amount of useful information. However, an unclinched lead presents a small, almost undetectable cross section to the camera when the viewing angle is normal (perpendicular) to the PCB. To increase the cross section of an unclinched lead, we can use a higher resolution ($<$ 5 mils/
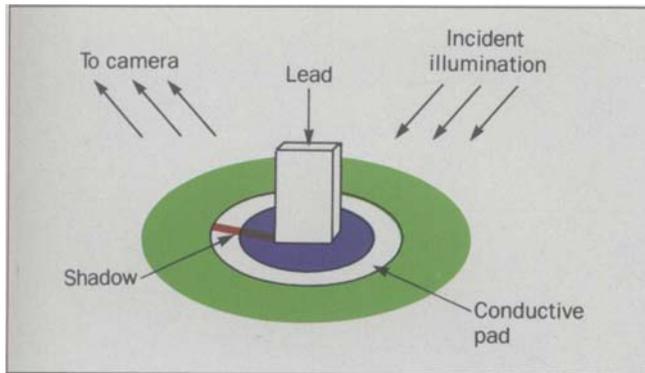
Figure 6. Illumination and viewing conditions for an unclinched lead. When properly illuminated, the lead blocks the incident light and casts a shadow on the conductive pad.

pixel) or view the lead at an angle.

Viewing at an angle is a simpler solution and, when set up properly with a line scan camera, does not have the imaging disadvantages associated with a two-dimensional camera.

Figure 4 illustrates the differences of angular viewing with a line scan camera and a two-dimensional camera. Two effects are avoided because the image is *a line* and the angle of view is rotated about this line.

First, when viewing at an angle with a two-dimensional camera, the image focal plane is now at this angle with respect to the object. Unless the depth of focus is very large, different areas of the image are in and out of focus. Rather than image a *plane* (the case with the two-dimensional camera), a line scan camera images only a line. Because the two-dimensional image is built up through relative object-camera motion, this line is always in focus thus avoiding the depth of focus problem.

Second, when a two-dimensional camera images an object while viewing at an angle, the image has perspective distortion (Figure 5). A line scan camera avoids this distortion because each line is the same size in the two-dimensional image that is built up from successive one-dimensional scans.

With angular viewing, if the lead is properly illuminated, two pieces of information about the lead can be detected in the image: the lead itself, and its shadow. Figure 6 illustrates this effect.

The angle of incident illumination is set equal to the viewing angle. Thus, the conductive pad that surrounds the hole reflects the incident illumination. If a lead is present, it blocks the light coming from the upper part of the pad and casts a shadow on the lower part of the pad.

Figure 7a, a gray scale plot of an image of an unclinched lead through a hole, illustrates this effect. Figure 7b is an image of a 45° clinched lead under the same conditions, while Figure 7c shows a defective condition, a missing lead.

Algorithms. It is beyond the scope of this paper to discuss the algorithms for determining passing versus defective conditions for this application. However, some general statements should be made using presolder lead inspection as an example.

The lead count of a typical PCB code is easily about 1000 per PCB. Also, there can be a large variation in the images of the leads, because of their different shapes and clinch angles.

If we use the architecture described here, practical algorithms must run at a speed of 100 inspections/second. In addition, the algorithms must be robust.

Generally these two conditions conflict; i.e., the faster the algorithm, the less robust it is, and vice versa. However, if the front end illumination and viewing techniques just described are used, simple, fast but effective algorithms can be applied.

A histogram of the probability that acceptable and defective sites will occur versus the quantitative result of an algorithm provides insight to the meaning of robust. Figure 8 illustrates two probability densities, one from a fully populated board and another from a defective or bare board. Robustness is related to the separation of these curves. The more separated they are, the easier it is to establish a threshold that differentiates between acceptable and defective sites.

However, the two curves generally overlap at some point. Establishing a threshold for this condition leads to the terms false accept and false reject rates. The *false accept rate* is the percentage of defective sites indited as good. This is represented as the tail of the defective curve that crosses the threshold into the acceptable regime. The *false reject rate* is the percentage of acceptable sites indited as defective, and has a similar, but opposite

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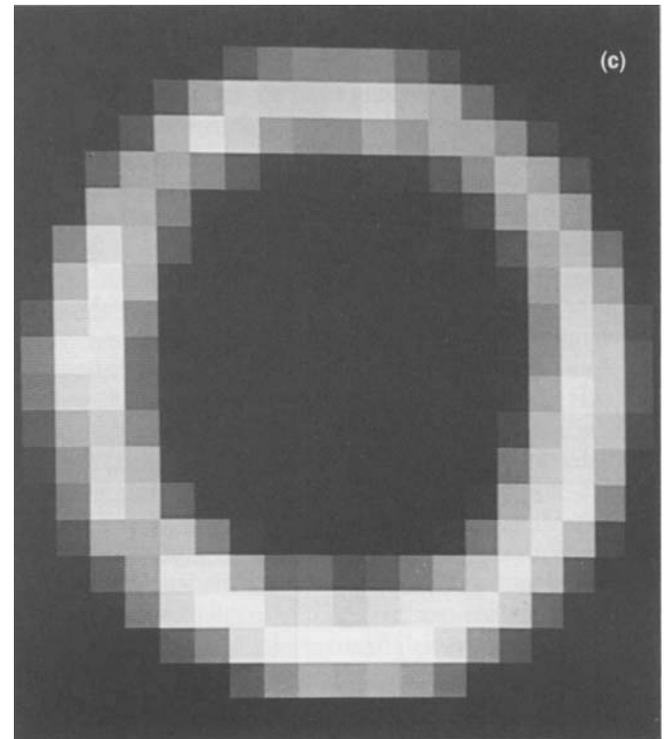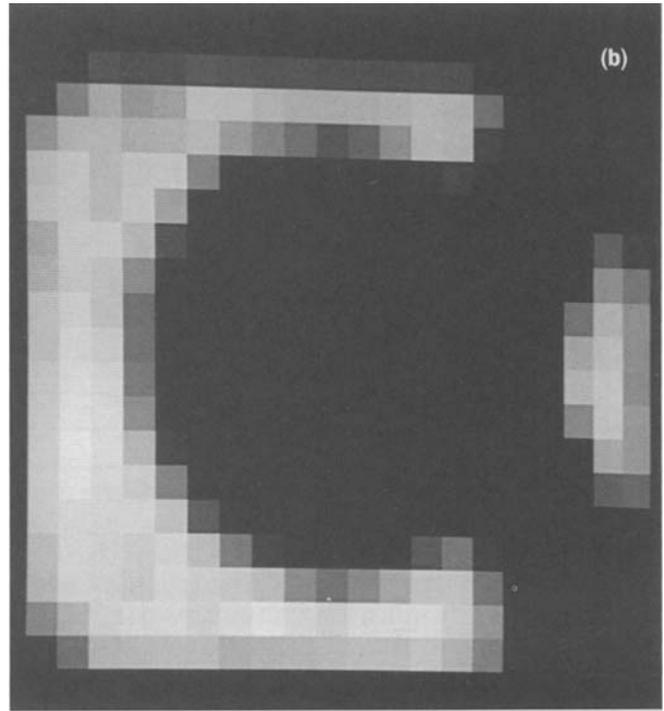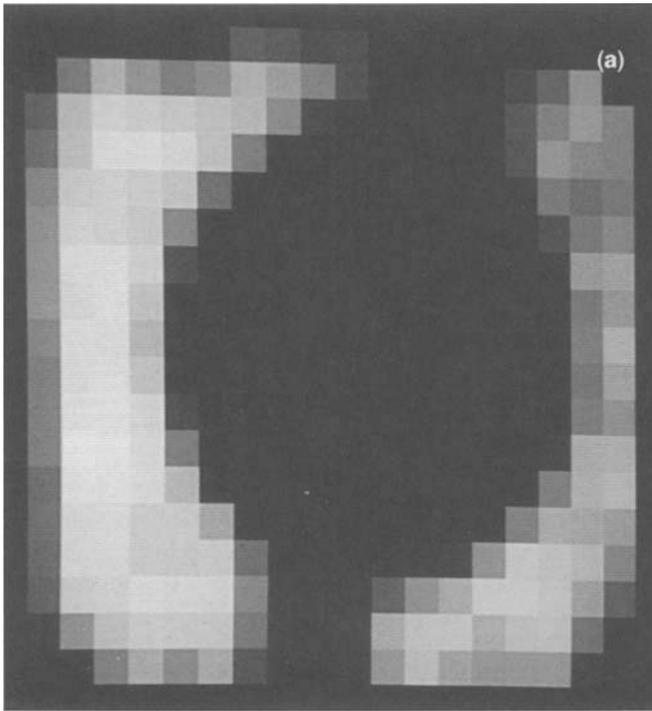
Figure 7. Gray scale images of a PCB hole illustrating the effect of angular viewing: (a) an unclinched lead, (b) a 45° clinched lead, and (c) a hole with a missing lead.

representation on the acceptable curve.

Let us quantify what we mean by robust in terms of these rates. Assume that there are 2000 leads per PCB with a miss insertion rate of one in 10,000 leads (a typical performance of an insertion process). Figure 9 is a simplified plot of the average number of PCBs that pass through the repair loop of an automated lead inspection system as a function of false reject rate.

If we assume perfect operation (zero false rejects), 20 percent of the PCBs would pass through the repair loop (have real defects). However, if the inspection system is not perfect, it falsely indites other PCBs, which loads the repair loop.

At a false reject rate of just over 0.04 percent, the repair loop transforms from a repair loop to a reinspect line because all the product is going through it. Therefore, a false reject rate of less than 1/10000 (out of 10,000 acceptable sites, one is falsely rejected) quantifies a robust in-line inspection system. Typical commercial two-dimensional systems falsely indite one defect out of 1000 acceptable sites.
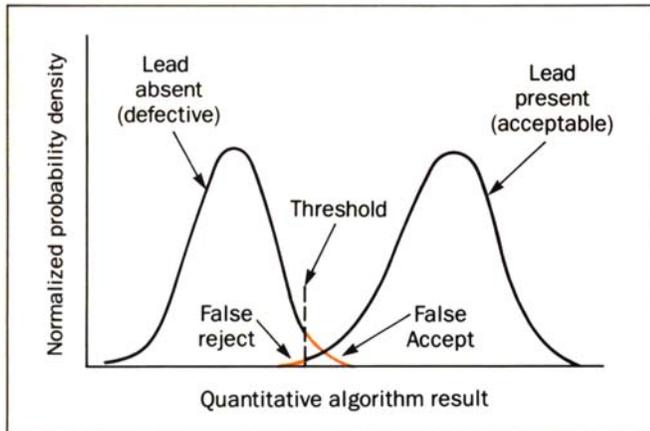
Figure 8. Normalized probability density functions for acceptable and defective sites. The false reject or false accept rate represents where the tail of the curve crosses the threshold into the other regime.

Figure 9. Average number of PCBs through repair loop (with 2000 leads/pack) versus false reject rate. Commercial two-dimensional inspection systems typically exhibit a 0.1-percent false reject rate with mixed-technology circuit packs.
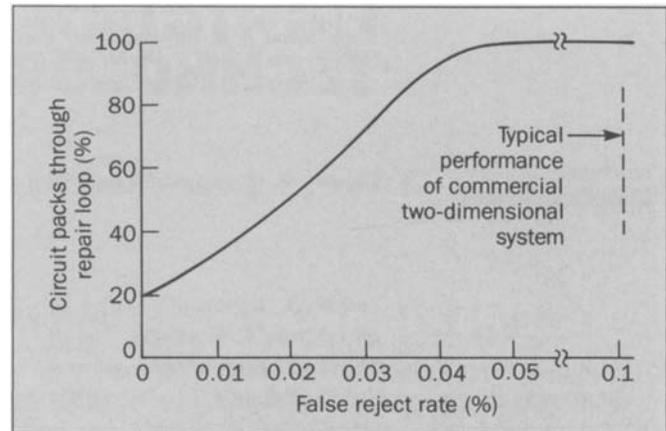
If Figure 8's curves overlap, there is obviously a tradeoff between the false accept and reject rates. Initially, one might assume that the false accept rate should be about zero, or the same order of magnitude as the false reject rate. However, this may not be practical or even necessary.

For the example given above, a simple calculation shows that for a false accept rate as high as 1/50, only one out of 250 PCBs will have a defect that is not detected. This seems to be a reasonable false accept rate for an in-line inspection system.

A line scan vision system with the architecture described here can be effective at achieving these goals for a robust inspection. The major reason for this is the large amount of information used in the analysis. Most of it comes from the large number of pixels or data available for the algorithm to process.

For a given scan time, a line scan system acquires over ten times more pixels than two-dimensional systems. For presolder lead inspection, additional information (the shadow) is available about the presence of a lead. Furthermore, the CAD/CAM database also identifies the type of lead (flat IC lead, axial lead, etc.) and its clinch angle.

The more significant the information available to the algorithm, whether image data or CAD/CAM data, the more separable are the curves in Figure 8. Thus, this results in a more robust inspection.

Conclusions

The complexity of today's electronic designs is pushing the limits of performance of the manufacturing process. Machine vision can provide the technology to monitor this performance effectively by automating assembly verification.

We described a machine vision system specifically designed to address efficiently the problem of PCB inspection. It has several features that provide improved performance over current methods. Although we only described the use of the system for presolder lead inspection, it is not limited to this function. Future uses of the system will involve other PCB inspection applications.

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