The Landscape of PCB Technology is changing rapidly. How Will AOI Testing Keep Up?

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Abstract
Ideas, manufacturing processes, materials and components that were in the realm of science fiction a few years ago are now being adopted into mainstream PCB products. Devices are getting smaller, boards are getting denser, and parts are getting more complex. Array packages are becoming more popular. On the near horizon we see the popularity of high density interconnect rising. Solder Jet printing and cold attachment rival traditional solder printing. Manufacturers are building smaller and smaller quantities – even batches of one! What does this all mean for traditional Automated Optical Inspection (AOI), which grew up in a world of technologies that might be superseded soon? In this paper, we discuss the strengths and weaknesses of AOI given these significant changes in PCB materials and manufacturing methods. We also examine alternative inspection methodologies that may complement or replace AOI.

1. Introduction

Over the past two decades we have seen some dramatic changes in PCB boards. The major ones include:

- the decrease in the use of through hole components
- decrease is size of parts and lead pitch
- increase in board densities
- the use of more complicated part geometries
- the placement of parts at irregular angles
- the adoption of lead-free solder
- the increase in use of array and chip scale packages
- radio frequency boards that require shields before reflow
- the decrease in board-lot size

Surprisingly, most Automated Optical Inspection (AOI) systems have been able to adopt to most these changes in PCBs without requiring a disruptive change in AOI technologies. However, we are seeing that customers are redefining how they may use AOI to inspect PCB boards based on the evolution of PCB technology. In this paper we will discuss the basics of AOI technology. We will discuss how most machines have been able to keep up with the changes we have seen over the past two decades. We will discuss some of the changes in where, in the line, AOI technology is being deployed. Finally, we will take a peek into the future. We'll look at new PCB materials, technologies, and process and discuss how AOI systems (and customers' use of them) must adjust to meet the coming needs.

2. Overview of AOI technologies

AOI stands for "Automated Optical Inspection. Typically what this means is that these machines "look" at the optical properties (visible portions) of a board in order to find defects and to measure attributes of the board and its elements. Most people distinguish AOI from AXI (Automated X-ray Inspection), of which the latter can look at different layers of the board. The truth is that AOI and AXI aren't as different as they seem. However, for purposes of this discussion, we will limit our comments to AOI machines and then briefly discuss AXI machines towards the end of the paper.

AOI machines are made up of three basic parts.

1) The image capture portion
2) The image processing portion and
3) The program generation portion (e.g. the methodology behind how a user creates and debugs a program).

The three are tightly bound together. It is rarely the case that the image processing and program generation portions of one system will work with an image capture system of a system, other than the one they were designed for.

The three parts are glued together by the system architecture which handles coordination of the hardware, software and program generation. While the system architecture is totally invisible to the customer, the architecture plays an important role in how adaptable an AOI machine is to required changes in any one of the three components or possible required additions to the basic building blocks of the system. (See Figure1.)

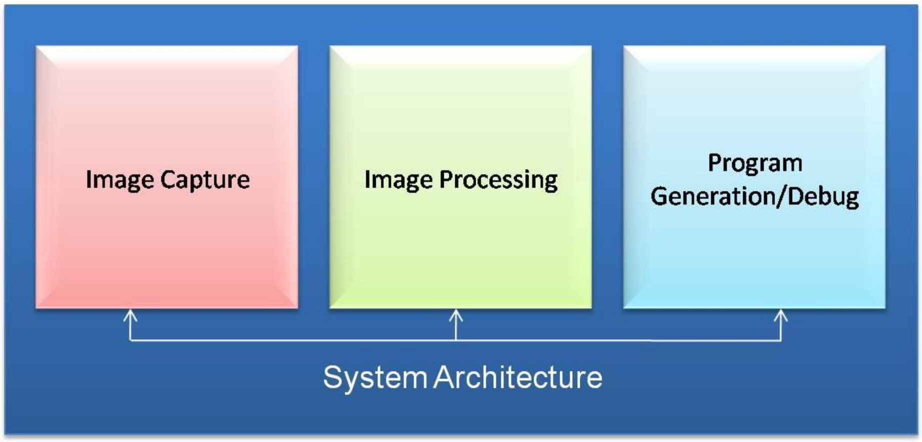

Figure 1- The three basic blocks of an AOI System: Image Capture, Image Processing, and Program Generation/Debug. These blocks are glued together by the system architecture which coordinates the actions of the entire machine.

The goal of most AOI machines is to look at the geometry of elements on the board such as the paste, parts and solder joints, to look at the optical properties of those elements such as orientation marks, labels, chips, and to look at the optical properties of the board to find such defects as foreign material, surface defects and gold finger defects.

There are three basic types of AOI systems that perform these tasks.

2.1 3D Systems: Three dimensional reconstruction systems use a form of structured lighting to illuminate the board. Based on the values the camera observers as a result of the lighting, the image processing attempts at each pixel (as seen by the camera) to try to determine the height of the object at that pixel. The main benefit of such a system is that it can produce a 3D rendering of the board in most locations. The pitfall of such a system is that they don't work very well on spectral features such as solder joints. In addition, most 3D systems don't offer the ability to look at the optical properties of elements on the board. Currently, the majority of 3D systems in the marketplace are laser based and are used to determine solder paste height, volume, and shape. Figure 2 shows a schematic of how a laser based system works to reconstruct height.

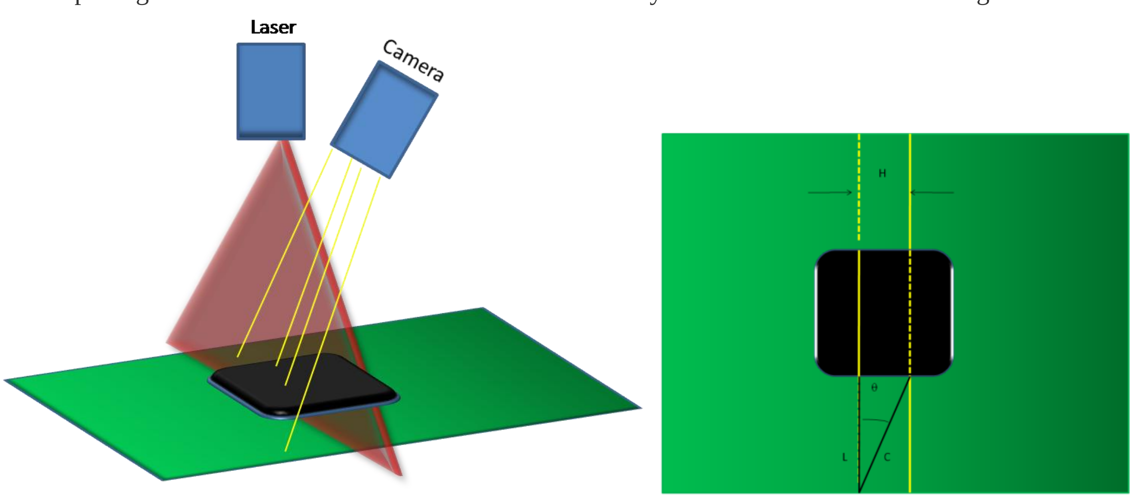

Figure 2 – Schematic of a 3D Laser Measurement System. The image on the left shows a simple configuration of a camera and laser. Given one laser stripe across the board, the system looks for offsets in the laser beam to determine if there is something above the ground plane of the board. For instance, in image on the right, the laser (solid) line, as viewed from the camera, moves to the left when the laser traverses the component. The offset between the expected line of the ground plane and the line on the component can be used to estimate the latter's height.

2.2 Multiple camera and or multiple lighting mode systems: Multiple cameras and/or multiple lighting modes can be used to infer the geometry of parts and solder joints. Systems that employ this methodology don't attempt to get a precise measure of a part or solder joint height at every pixel. Instead, they try to create signatures that indicate the rough geometry of the components under test. Using multiple illumination sources to perform this task is commonly known as "shape from shading". Using multiple cameras to perform this task is a less stringent variant of "stereo vision" or "structure from motion". These systems have the benefit of working well on spectral materials, such as solder joints. They also can assess the optical properties of parts and boards. Finally, with multiple image capture options (and a permissive user interface); they can give the user flexibility to inspect for new types of defects without a redesign of the image capture head and image processing.

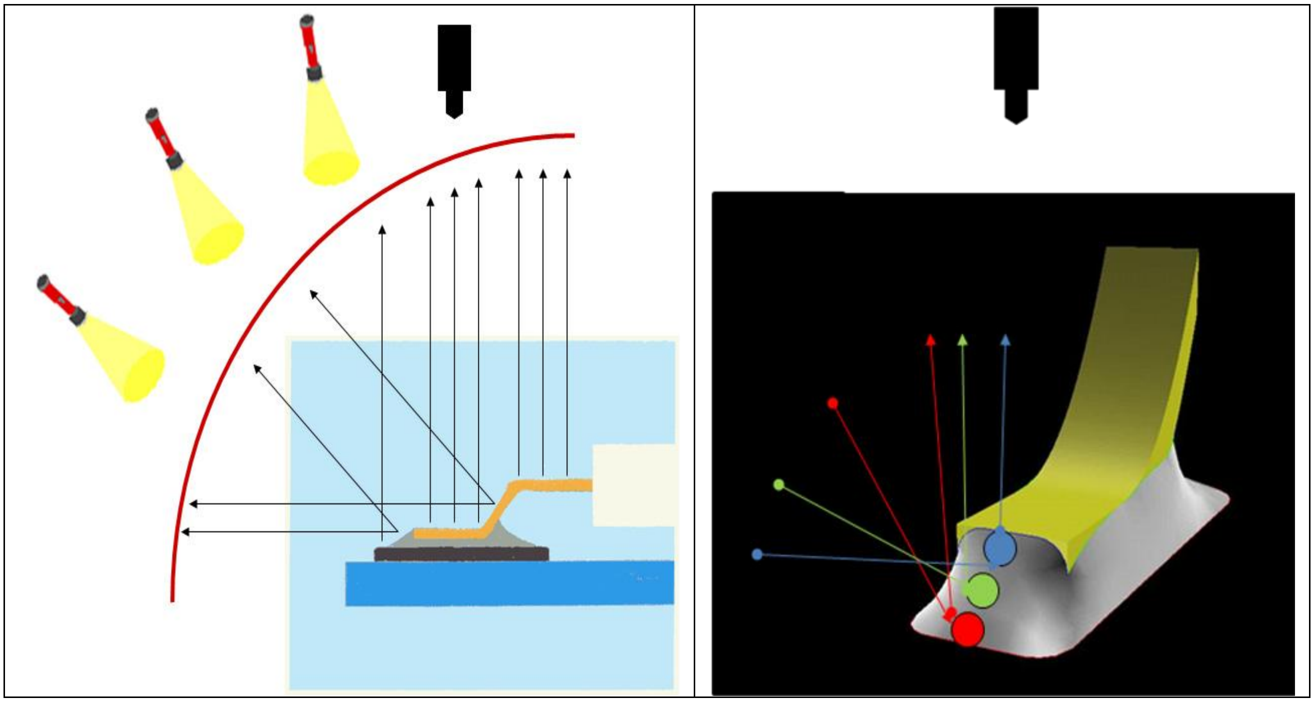

Figure 3- (Left) Schematic of a system with multiple lighting angles. (Right) Example of how the 3-D shape of a solder joint can be approximated by the use of multiple angled light sources. For instance, low angle lights (depicted as a blue arrow) may indicate high curvature points on the solder joint. In contrast, high angle lights (depicted as a red arrow), may indicate low or flat curvature points on the joint. (With a sufficient number of narrow angled light sources, it is theoretically possible to reconstruct the 3D profile of the joint.) The Landrex Optima™ 7300 series uses this type of system architecture to find defects.

2.3 Single camera systems/fixed lighting modes: Most single camera systems are color based. These systems rely on the difference between the board colors and the part colors to infer part geometry. They also use shading from the light source to infer solder joint integrity. If the image processing is sophisticated enough, these systems are often the simplest to use because they do not require the user to modify the hardware settings for each part or solder joint. Such systems are also commonly used for 2D paste inspection.

Figure 4 – Example of how a system with a single camera and one lighting mode can use color to separate a parts from its background. The middle image shows a dark black BGA on a primarily dark green background. The left image shows the results of a standard image contrast enhancement technique, which results in an undesirable highlighting of the text on the part and traces and vias on the board rather than the part boundaries. The results from a more sophisticated image analysis algorithm, generated from Landrex Optima™ 7200 series and shown on the right, can delineate the part neatly from the background. The main point is that more sophisticated algorithms are required for a single color camera system with fixed lighting.

2.4 Image Processing: The description above focuses on the image capture portion of the AOI systems. However, each type of AOI system must have image processing capabilities that are suited to the types of images the systems receive. For instance, the image processing used in a 3D system must find the height at each image pixel. If we are considering paste bricks, it then must create an area, height/shape map for each brick. Finally, it must use limits to determine if the area, height or shape constitutes a defect. In contrast, systems that use multiple cameras and/or multiple light modes create patterns on the image that indicate a defect. It is the job of the image processing software to determine if that pattern is visible or not. In the third case, color processing, for instance, is used to find the boundary between the board and the part to determine if the part is in the correct location. Thus, broadly speaking, color image processing algorithms are required.

2.5 Program Generation: A separate design piece of each system is responsible for how a user programs the hardware (if required) and the software to find defects and adjusts the program if it makes a mistake (false accept/false reject). Systems fall into a continuum from those that require the user to choose the hardware configuration and/or software algorithms for each type of defect on each part to those that have an intrinsic knowledge about how to inspect PCB boards or a well defined library that has the most widely used parameters to inspect the board. The benefit of the former is that the user is given ultimate flexibility in how he/she decides to use the system to inspect PCB boards. However, this has the drawback of increasing the programming time. In the latter case, the programming is simplified because the system decides how to inspect each type of defect. This has the benefit of short programming time (even on a board lot of one). However, its drawback is limited flexibility to adapt to new defect classes. Certainly, a balance between these two extremes is desirable. One solution is to create adaptive machines. Such machines have built-in knowledge for inspecting PCB boards but have the ability to automatically adapt to the current board conditions. Figure 5 illustrates this tradeoff.

Figure 5: AOI system design involves a trade-off between flexibility and programming time.

We should note that no AOI system, no matter how intelligent or dynamic, can anticipate all possible uses of the machine. Thus, it is desirable to have flexible system architecture so that the designers of the system can add more intelligence into the system in order to adapt it for more defect classes without a redesign of the entire platform.

2.6 Evaluating an AOI Machine- the whole is more than the sum of the parts: When evaluating AOI systems, most customers focus on the system hardware specifications. The simple reason is that this piece is visible and quantifiable.

Most customers find it difficult to determine if the image processing portion of the system can effectively use the images from the image capture module to find defects and allow the system to be easily programmed. However, it is crucial that customers attempt to examine each of the three pieces, the image capture portion, the image analysis, and the program generation, and their combination via the system architecture in order to truly determine whether an AOI machine can meet the inspection criteria.

3. Where are AOI technologies used in a PCB Line?

There are three obvious places in the PCB line to employ AOI inspection. The first is after paste deposition, the second is after one or more of the placement machines (e.g. after the chip shooter and before fine pitch placement or after all parts have been put on the board), and the third is post-reflow.

Historically, the primary place for AOI inspection has been after solder reflow or "post-production". The cost of automated inspection at a single point is low. More importantly, post-reflow AOI can inspect for most types defects (solder, placement, board defects, etc.) at one place in the line with one system. Bad boards are reworked and good boards sent to the next stage of test. (Along with reflow, some customers employ optical paste inspection right after paste deposition. In fact, 2D paste inspection is integrated into many of the paste deposition machines.) This is a traditional test strategy - to test after the boards have been built. The disadvantage of end of line inspection is higher costs of repair and higher WIP.

An alternative strategy, which is gaining popularity due to a variety of factors, is to deploy AOI earlier in the process, e.g. at place inspection and/or to deploy AOI at multiple points in the process ("pre-production"). At post-place it is easier to prevent defects from re-occurring, ensure first articles are correct and detect process errors, such as loading the wrong part during part replenishment, while WIP is small. It is also safer than reworking after the boards have been reflowed. In addition, some customers are using measurement data from the AOI machines to look for trends to try to predict the defects before they occur. Thus, more boards get build correctly and the need for rework is reduced. The use of measurement information to look for trends or to diagnose issues is often called "process control". It involves the use of variable data analysis. *Knowing that what you are building now is correct is preferable to knowing what you built wrong already*. Figure 6 shows the two different types of test strategies (conventional post-production test, and distributed pre-production test). Figure 7 shows how measurement data can be used to improve the process.

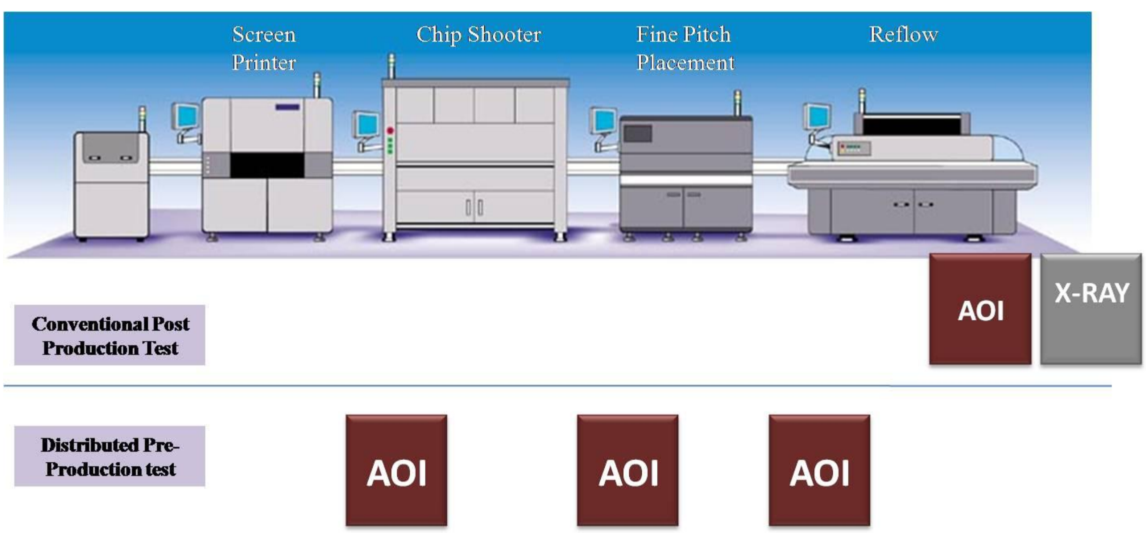

Figure 6 – Different options for AOI placement. The top schematic shows test (AOI or X-ray) after the boards have been built. The bottom schematic shows distributive test earlier in the line at post-paste, after the chip-shooter and before fine-pitch placement, and after placement but before reflow. There are advantages and disadvantages to both strategies, but, as we discuss in the text, the distributed approach appears to be more amenable to the coming advancements in PCB manufacturing.

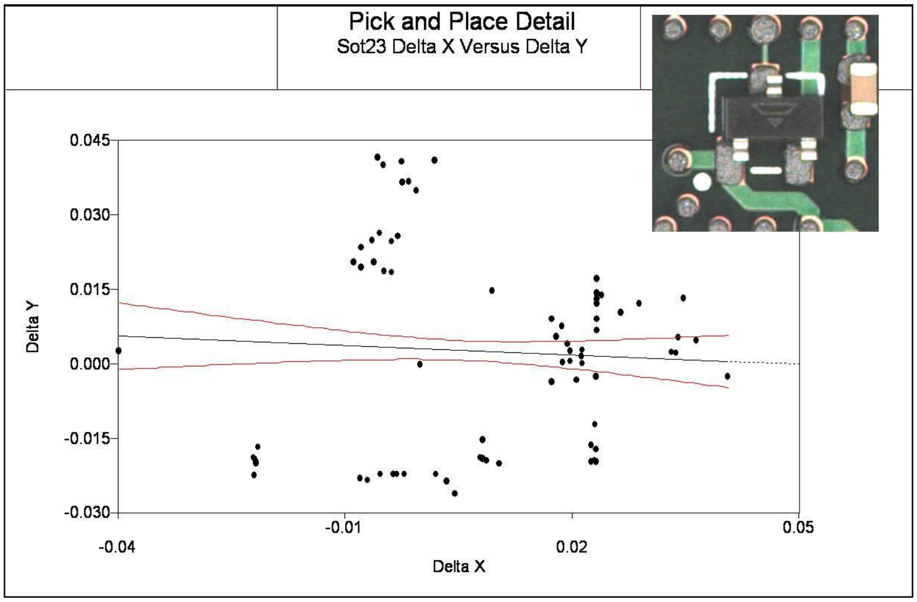

Figure 7 – Example of use of pre-reflow measurement data at a customer site: A sot-23 was being misplaced at multiple locations across the board. By eye, the misplacements looked random. However, by measuring the part position (dx, dy) and reviewing the data for this part type across one board and multiple boards, we found that the sot displacements were at a radial distance from the expected position. This led to a diagnosis of a bent nozzle and was confirmed by the pick and place operator. Using measurement data helped to diagnose the problem. Finding the issue earlier in the line (at post-place) and feeding the information back to the pick and place system resulted in fewer defective boards being built.

4. How have AOI systems adjusted to the PCB technologies from the last two decades?

Let's now return to our list of how PCB technology has changed over the past two decades and how AOI machines and customer use of AOI machines have evolved to deal with these changes. We can classify the changes listed in the Introduction in seven sections.

1) Change from through hole to surface mount
2) Change in size and density
3) Change in part complexity and mounting angle
4) Change in optical properties of solder
5) Increased use of array packages
6) Increased use of shields
7) Decreased number of boards in lot.

4.1 Change from through hole to surface mount: This change has had two effects on AOI systems. The first, and most obvious, is that the need to inspect through-hole components was significantly reduced or eliminated. The result was that algorithms and lighting modes used for through-hole inspection were no longer required.

However, the change from through hole to surface mount had a great impact on PCB technology changes #2 and #3 as listed above. The replacement of through-hole components by equivalent SMT packages has allowed boards to become <u>smaller and denser</u>. But the major impact of this was felt by PCB design and fabrication companies. Buried and blind vias increased and the number of layers increased to accommodate the new routings between parts and pins. As a result, PCB layout and routing has become almost entirely automated. The CAD auto routing software commonly places <u>parts at angles</u> to increase density and allow for complex trace routes.

4.2 Smaller parts, denser boards: The decrease in discrete component sizes has been driven by lower power consumption requirements, now 1/32W with 01005s. The decrease in pin pitches and corresponding increase in pin count has been a result of more complex semiconductor designs. The decrease in size of components, decrease in component pitch and increase in densities of boards has had a significant impact on AOI machines. Most AOI systems have addressed this in the Image Capture and Image Processing modules of the AOI system.

Figure 8 shows an example of a 0402 discrete, which was the smallest, commonly used part a decade ago, as compared to a standard pencil. Now the smallest commonly used part is a 01005, which is 16 times smaller! Figure 9 shows how boards have increased in density over the past 10 years. The left image is a portion board from the year 2000. The right image is a portion of a more recent board. Both images were taken at the same resolution. Certainly, the parts are smaller and closer together on the image on the right. One result of this is that electrical testing of boards is more difficult and, therefore, the reliance on AOI has increased.

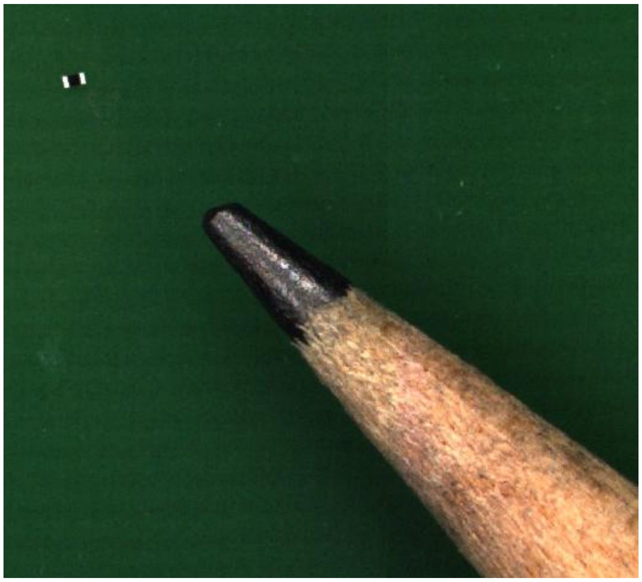

Figure 8 – The pictures shows and image of a 0402 next to a pencil. The smallest discrete size that is now used in production is 1/16 the size of the 0402.

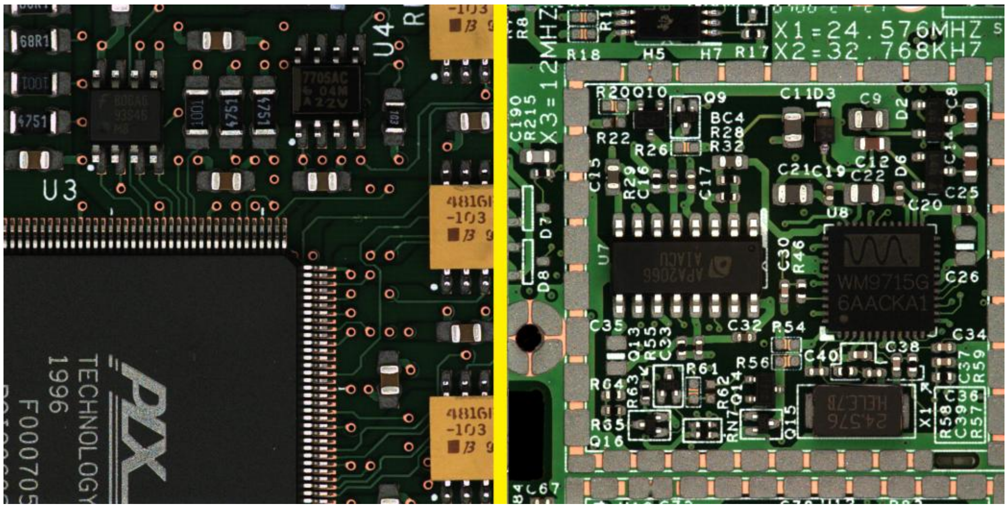

Figure 9 – Two images taken of different PCB boards with the same image capture setup. The board on the left is from the year 2000. The board on the right is more recent. With devices, such as cell phones, getting smaller and more complex, real estate on PCB boards is becoming more valuable.

To inspect smaller parts and denser boards, the Image Capture System (lens and the camera sensor size) can be changed to add more resolution which effectively means smaller pixels. The benefit is that there are more pixels available for analysis on the small parts and spacing between the parts. However, there are significant downsides to adding resolution. The first is that one camera frame now constitutes less of the board. This means more frames may be required to cover the entire board, which often increases the image capture time. Also, with more pixels to process, increased resolution also increases the image processing time. More pixels at higher resolution can increase the signal to noise ratio. Finally, as parts get smaller, the distracter elements of a PCB board, such as silkscreening, vias, traces, etc., become more problematic for AOI systems resulting in higher false calls and false accept.

Let's now look at some of the ways AOI designers addressed these issues. To improve the image capture time, one option is to increase the camera sensor size (e.g. going from 1 megapixel to 4). Other options include adding multiple cameras and increasing the speed of the stage. On the image processing side, algorithms can be developed to utilize super-resolution and sub-pixel techniques which lessen the requirements on how many pixels are required to inspect a part.

To address the processing time issue, there are three commonly used solutions. Parts can be inspected with resolutions that are decided “on demand”. Only the smallest parts or finest pitch parts require fine resolution for processing. Two resolutions can also be achieved either in hardware by using a low resolution and high resolution camera or in software by down sampling images as needed. Additionally, algorithms can be developed to be scalable according to the number of processors in the system. With computing power on the rise and the associated costs on the decrease, adding computer power is no longer a barrier to solving this problem.

To address the signal to noise ratio decrease, there are several possibilities. Lighting can be modified to try to better distinguish the part and joints from the board. Image enhancement algorithms can be improved to try to reduce some of the general noise. However, more sophisticated image analysis algorithms are required to ignore the distracters and to increase repeatability. The latter has proved to be a most difficult problem and we will continue to see work on this area for many years to come.

Even with the most sophisticated inspection equipment, the choice of where to inspect the PCB becomes more crucial with smaller parts and denser boards. As discussed above, most AOI systems that have been deployed are post reflow systems. However, smaller parts, increased pin count, and increased part count means that it becomes more critical to deposit the paste correctly and to place the parts correctly in order to get a good solder joint. Additionally, the density of the boards and size of the parts makes rework quite difficult. Thus, the need for AOI inspection earlier in the line becomes more obvious. Because one defect can cause significant problems, we are seeing customers use not only defect detection at place and paste, but also measurement information for use in process control to reduce or prevent defects from occurring (as previously described in Figure 7).

4.3 More complex parts, parts mounted at complex angles: As discussed above the increase in complexity of part types and their positioning relative to the board axes was driven initially by the elimination of through-hole PCB technology. However, as time goes on the desire to use more complex parts is now fueled by the need to reduce real-estate usage by packing more complexity into one device.

Counter-intuitively, the ratio of “simpler parts” to “more complex parts” has decreased. The ratio was roughly 40/60 in the 90’s. In the early part of this decade the ratio was nearer 30/70. Now the ratio is more like 20/80. However, the overall component count on a board has increased. It is now common to have several hundred or even several thousand parts on a PCB. Thus, the end result is that there are a greater absolute number of parts on the board, and therefore, a greater absolute number of parts with complex geometries.

AOI manufacturers have adapted to parts with complex geometries at complex angles (e.g. not the canonical 0, 90, 180, 270 degrees) by augmenting the System Architecture and Image Processing portion of the AOI system. Changes in the System Architecture offer the ability to inspect parts at any rotation. Additionally, the Image Processing module has been augmented in most AOI machines to offer a special inspection capability for oddly shaped parts, called the “odd-shaped tool”. This is the catch-all tool for parts whose shape cannot be anticipated by the system designers or library builders. Due to demand, the inspection capabilities of odd-shaped tools have increased dramatically. Figure 10 shows an example of processing via an odd shaped tool.

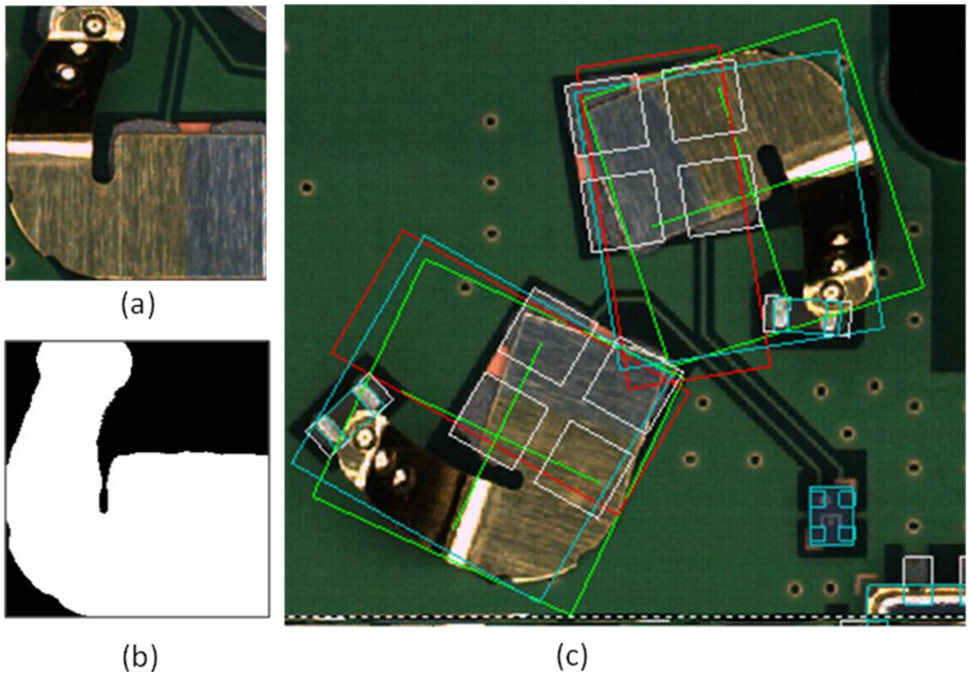

Figure 10 – The "odd-shaped" tool. (a) Example of an oddly shaped part. (b) Results from the sophisticated image segmentation algorithms from the system mentioned in figure 4. The outline of the part is automatically generated without any knowledge of the part shape and colors. (c) Examples of the system finding the location of the part of the board. Note the part is placed at an odd angle. The green box shows the found location of the part.

4.4 Transition to lead free solder: The transition to lead free solder was driven by legislation, not technology. Early chemistries such as Sn/Bi, Tin-Bismuth oxidized rapidly and had a mottled appearance and rough surfaces. This made it quite difficult for AOI to inspect solder joints, since most AOI relies on homogenous, consistent appearances. However, current lead-free pastes such as Sn/Ag/Cu, Tin, Silver and Copper have a more consistent but less reflective appearance.

While the increase in homogeneity decreases noise, the less reflective appearance can be a problem. Most AOI solder inspection systems are built upon the principle that they can project different light patterns on the solder joint and the solder joint will reflect unique signatures back to the camera to indicate "good", "excess", and "insufficient" diagnoses. It is paramount that the solder joint reflect back the signature with clarity and intensity. As a result, most AOI systems which inspect lead-free solder have had to adjust their light intensity (or exposure duration) and algorithm thresholds to account for the change in reflectivity.

One issue that customers are reporting is that lead-free materials are more difficult to rework. They require higher processing temperatures that may stress or cause significant damage to heat-sensitive PCB materials and components. If rework becomes undesirable, then the inspection of boards must occur before reflow, at paste deposition and placement. Additionally the use of process control, to try to catch defects early and to prevent defects before they actually occur at paste and place, is gaining popularity.

4.5 Increased use of array packages: Array package types are also becoming more commonplace. One subset of Array packages that is commonly used is the Ball Grid Array (BGA). With a relatively small size and thermal footprint, they can be designed to give more complex functionality than traditional parts. (Figure 11 shows a recently designed board where a significant portion of the real estate is devoted to array packages, indicating their popularity.) However, the majority of the leads and pads are hidden with this package type. In addition, these package types are very delicate, meaning they are not very amenable to rework, and expensive to replace.

Thus, there are only two realistic methodologies, which are not mutually exclusive, to inspect this type of part. The first is to use X-ray inspection. X-ray inspection allows one to see cross-sections of the hidden joints. Thus, one can inspect for cracks, voids, and other "non-visible" solder related issues. Because X-ray is slow and relatively expensive, many companies employ X-ray machines solely for array package inspection and often just inspect on a sampling basis to validate the process. However, X-ray inspection is naturally used after the part has been reflowed. Once the defects are found, it may not be feasible to fix them. Thus, X-ray can only be used as an indicator that something is wrong in the process.

The second method for inspecting array packages is to use pre-reflow AOI. If the paste is deposited correctly, if there are no dropped parts after the chip-shooter and before fine pitch placement, if the array package is placed correctly, and if the oven profile is correct, there is a high probability that the package will not have a defect after reflow. Additionally, if there is a problem at paste deposition or placement, these defects can be corrected.

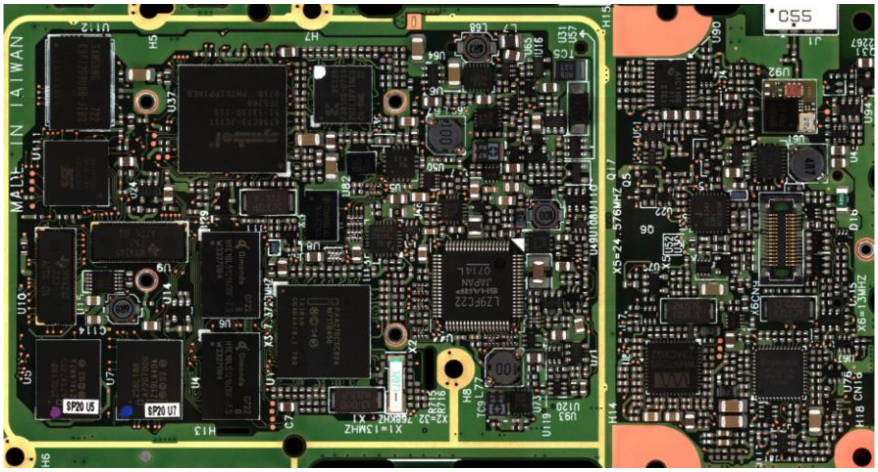

Figure 11- The use of array packages has increased significantly. This recent board devotes approximately 40% of its real-estate to array packages.

Determining if an array package (or any part) has been placed correctly requires fine measurement accuracy and repeatability. This measurement function is often called metrology. Most AOI systems who offer metrology have modified both their Image Capture modules and Image Processing modules to deal with the significant issues associated with metrology.

4.6 The increased use of shields- Mobile phones and other devices that use an RF component require shields before reflow. This means that many of the parts cannot be viewed at post-reflow inspection since they are covered. Shields additionally block lighting and camera views. Also, rework of shielded components is quite difficult. Thus, AOI must be deployed prior to shield attachment. Figure 12 shows an example of a board with one shield placed and pasted pads/land patterns ready to receive other shields.

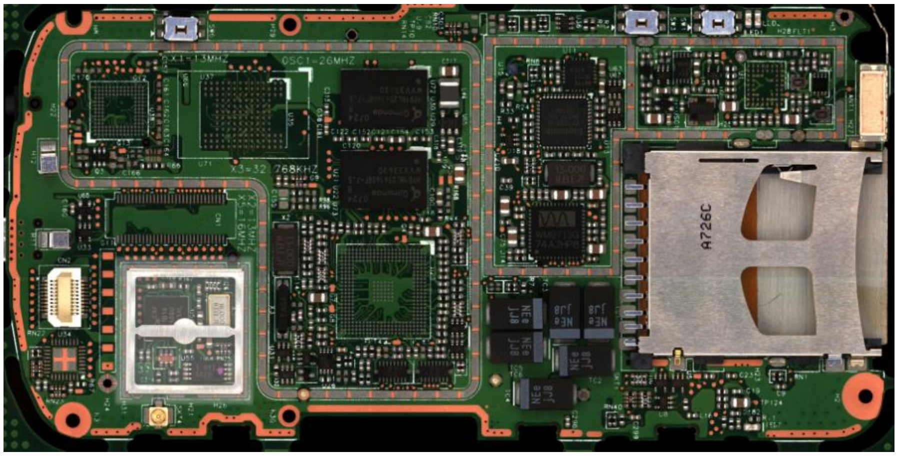

Figure 12 – Example of the use of shields – The board in this figure has one shield placed in the lower left corner. However, there are land patterns that show that shields will eventually cover 70% of the board, making it difficult to do post-reflow inspection.

4.7 Decrease in board lot size: Ten years ago, high volume manufacturing dominated the PCB landscape. It was commonplace for a company to set up a PCB line for one particular board and to run that particular board for an extended period of time. In the past 10 years things have changed dramatically. Board mix has increased and board volumes have decreased. New revisions of the board are constantly introduced. Manufacturing customers are asking for more custom boards.

Older AOI technology was prone to significant false failures and false accepts and constant tweaking of the machines was required to keep them at a stable inspection level. It was common for one to “tune” an AOI program to inspect a board for weeks or months. While this process was labor intensive, it was still feasible to use the program once the variations were all managed in a high volume environment. Such a process is no longer tolerated or feasible.

Thus, designers of AOI machines have performed significant work on the program generation piece of the system. Most AOI systems compiled a library of the best settings for the Image Capture module and the Image Processing module based on their experience with customer boards. This library gives a “head start” because it is a known good place to start the debug process. More sophisticated machines employ a learning process that automatically adjusts to each board type, whether it is a new board or revision. This allows the system to provide a good inspection plan for the exact board undergoing test. It also allows the program to adjust over time as normal variations in the PCB creation process occur. In our experience, we have found that this can significantly reduce programming time and create a more stable program without significant debug work. (Figure 13 contrasts the status quo of programming a board ten years ago with the new programming and debug requirements based on a number of factors including smaller lot sizes.)

Decreased board lot size also means there is significant pressure to find defects before too many boards have been built. It would be undesirable to build a lot of 20 and to find at reflow that all had defects. Thus, high-mix, low-volume manufacturers are also seeing the benefits of using AOI pre-reflow to find defects at the point at which they occur. Additionally, by using measurement (metrology) data from their pre-reflow machines, we found they can decrease their setup time by 50% and monitor the process to reduce future defects.

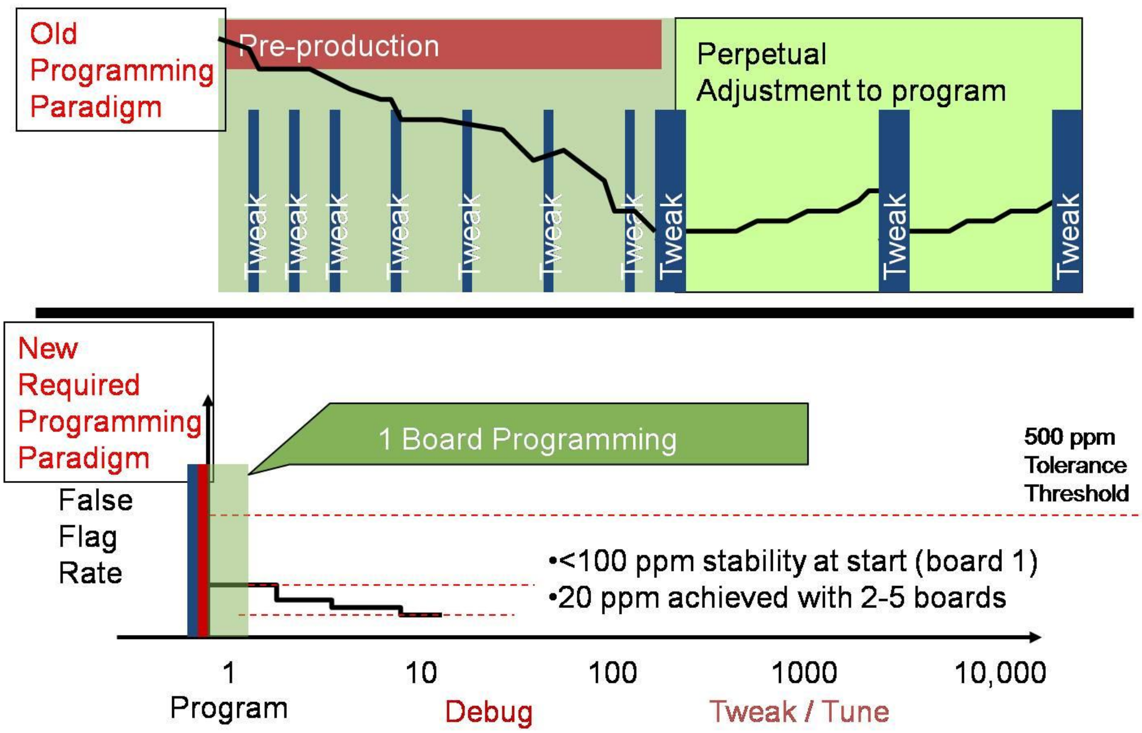

Figure 13 – Contrast between the programming/debug practices from 10 years ago and the programming/debug practices that are required today. The top schematic depicts the behavior of older AOI machines whose programming methodology required significant examples of boards in the pre-production stage and constant “tweaking” or modifications in the production stage to meet and maintain acceptable false accept/false reject ppm levels. Smaller lot sizes and the desire to reduce labor costs have put significant pressure on AOI designers to develop methodologies to reduce programming time and to develop more stable programs requiring significantly less “tweaking” over time.

4.8 Summary: We touched on 7 major changes in PCB board technology that have occurred over the last two decades. Table 1 shows a summary of how the components in an AOI machine that have changed to adapt to these technologies, how customers are changing their use of AOI machines, and how customers are changing the technology they use to inspect PCB boards.

Change in PCB technology	Image capture	Image processing	Programming paradigm	System architecture	Change in place in line	Use of process control	Cross platform integration	Change in technology (e.g. X-ray)
Reduction of through hole components		☑						
Smaller parts, denser boards	☑	☑			☑	☑		
More complex parts, complex mounting angles		☑		☑				
Transition to lead free solder	☑	☑			☑	☑		
Increased use of Array Packages	☑	☑			☑	☑		☑
RF boards					☑	☑		
Decreased board lot size			☑		☑	☑		

Table 1 – Summary of changes in AOI technology and AOI usage over the past ten years.

5. What are the changes in PCB technology that AOI systems will have to face in the future?

We spent the prior section talking about how AOI has adapted to PCB technological changes that have already occurred. Now let's look to the future. We see 4 major classes of changes in PCB technology that are coming in the next several years. These are:

1) Changes in component packaging
2) Changes in PCB materials
3) Changes in attachment materials and methods
4) Changes in the use of output data from AOI machines
5) Increased sharing across platforms

The sections below discuss these major changes and the implications on AOI technology and how AOI systems are used. This section is not intended to be exhaustive. The main idea is to illustrate some of the significant changes we see on the horizon.

5.1 Component Packaging: PCB component packages are evolving at an exponential rate. So far, the newly developed packages that we discussed above are amenable to the type of image capture and image analysis that is possible with AOI machines. As we see new packages, both the AOI machines and how customers use AOI will need to continually adapt or change. Below we discuss three types of new package classes.

One good example of a new component type is stacked configurations commonly called PoP or Package on Package. PoP was developed based on the need to reduce space and thickness, especially for handheld devices. One example of PoP consists of cost logic processors as a base with stacked memory directly on top. The manufacturing challenges of utilizing PoP include accuracy of paste deposit, flux dipping, placement accuracy, reflow profile and rework. The bottom package is placed on standard paste deposit, the top part is dipped in flux and then the combination is reflowed at the same time. The AOI challenges are three fold. The first is that pre-reflow AOI must be able to inspect the paste deposition and placement of the bottom layer. It then must be able to inspect the flux deposit and placement of the top layer, relative to the bottom layer. Post-reflow AOI must be able to inspect any visible joints from the bottom layer. Inspecting one layer relative to another layer will require a significant change in how AOI machines work. Currently, all placement inspection is performed and evaluated relative to the board or panel fiducials. In addition, most AOI machines expect to evaluate a part's position relative to its transition to the board or pads. Now AOI machines will need to inspect part layers relative to other layers underneath. This will require a change in the machine's software infrastructure and in the image processing algorithms. Customers will need to redouble their efforts pre-reflow because this part needs to be inspected prior to reflow in stages. Additionally, because the cost of these stacked parts is double or triple the cost of the standard package, verifying the paste/flux and paste pre-reflow are critical to avoid having to scrap this part later in the process.

Another example of a new package type is wafer level chip scale package (WL-CSP) or a wafer level package (WLP). This package type has pads that are etched directly onto the silicon. Conductive adhesive is used to connect the part to the PCB board. The part itself is generally very small, approximately 1.5 x 1mm. (Figure 14 shows two examples of this package type.) The major issue with this type of part is that once it is adhered to the board, the part cannot be reworked. Thus, the burden of inspecting this type of part falls on the post-adhesive inspection and the post-place inspection. Probably the most significant change to AOI systems would be in the post-adhesive inspection. This type of conductive adhesive looks different from paste and normal adhesive. 3-D measurements are difficult and not-required. An optical system that can distinguish the adhesive from the board is required.

(a)

(b)

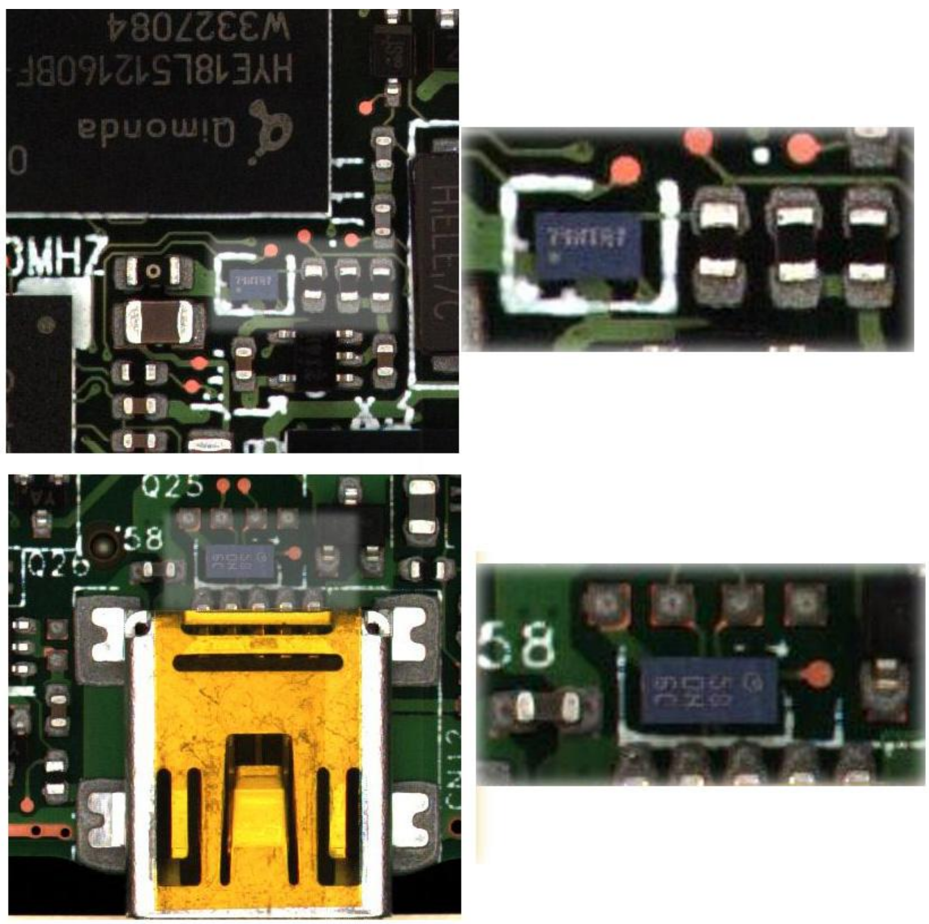

Figure 14 – Two examples of wafer level chip scale packages (WL-CSP). In each case, the color of the wafer level chip scale package is blue. The images on the left show the packages in context on the boards. The images on the right show magnified views of the packages and some surrounding parts. The packages shown are very small, similar in size to a 0402.

A third example of a new package type is embedded passive designs. These are components that are not surface mounted, but embedded in the board itself. They will become common in order to reduce circuit size and increase circuit density. Imbedded passives can reduce circuit size by more than 50%. The inspection requirements of these embedded passives are to determine if the printing of the passive is the right size and in the right location. This may require a change to the image processing algorithms used by AOI machines. The problem of inspecting these passives is more similar to bare board inspection than surface mount inspection. Algorithms from the former can be adapted to this new type of part.

5.2 PCB material changes: Just as PCB components are changing, the underlying PCB substrate is also changing. Most AOI machines are used to standard FR4 PCB boards. However, we are seeing a rise in two types of new board technologies.

The first is high density Interconnect (HDI). HDI boards are boards that have three-dimensional wafer-scale packaging of integrated circuits. Patterns of interconnect layouts and micro-via holes are written or drilled out by lasers. Chips can be connected to each other using standard semiconductor fabrication methods. The wafer-scale components are stacked and interconnected at their edges. As a result, HDI changes PCB boards from “large” two-dimensional surfaces into very “compact” three-Dimensional spaces.

Inspection of traditional PCB components on the surface of an HDI board is difficult because of the number of distracters on the board. There are substantially more traces and vias than on normal “two-dimensional” boards. This substantially decreases the signal (part, paste, joint) to noise (distracter elements on the board) ratio. The image processing component of some AOI machines may need to be modified to ignore the distracters.

The second material change is the use of flexible film circuit technology. Components are mounted onto the flexible material using conductive adhesives, which are flexible, reduce the need for traditional connectors and cables and allow for more creative designs, switching and interface panels.

AOI systems will have to adapt in three ways as a result of this new flexible film material. Imaging techniques will be needed for post conductor printing, post placement and post reflow. As we discussed above the conductive adhesive looks different from both the paste and flux that are traditionally used and may require changes to the image capture process and the image processing portion of the AOI systems.

Flexible films themselves are a challenge for the image capture and image processing portion of AOI machines. The substrate itself is very shiny and reflections from the board may increase false calls. It is possible that different illumination techniques in addition to changes in the image processing may be required to inspect these boards. To compound the problem, flexible films are by definition flexible. In order to build loaded boards, the films are pinned to a rigid substrate. Generally, the result is that the flexible surfaces are not very flat in random portions of the boards. This creates visual non-uniformities that decrease the signal to noise ratio and cause problems for laser based systems that attempt to map the depth and distortion of the board prior to inspection.

Flexible films also have different inspection needs than traditional PCB boards. Customers are requiring bare board inspection of the lines in the conductive path to look for such defects as “rat bites”. (If the “rat bites” are found they can be fixed by adding some conductive ink on the path. Adding elements of bare board inspection to surface mount AOI inspection systems may require changes to the Image Processing and Program Generation module.

Thus, PCB material changes may require changes to all of the components of an AOI system. They may be the disruptive driving force which forces the invention of a new class of AOI systems. Additionally, they will force customers to rely on pre-reflow inspection for most of their AOI tasks.

5.3 Attachment: As described above, new component types and new materials are driving the attachment methods away from traditional solder paste and flux to conductive adhesive. Traditional solder paste inspection relies on the reflection of laser light. Traditional solder joint inspection is based on reflective properties of materials. New attachment materials do not have the same shape, reflectivity or laser opaque properties of solder. Thus, the image capture and image processing modules may need to be substantially changed to inspect the adhesives.

The adhesive is more likely to be completely covered by the pins and end caps of SMT components. Additionally, once attached to the component, they cannot easily be reworked. Altogether, pre-reflow inspection seems much more relevant than post-reflow inspection for this type of attachment method.

We are also seeing a rise in the use of stencil free solder printing techniques. The advantages are obvious in terms of flexibility, cost reduction, reduced changeover and elimination of waste.

Whether printed by piezoelectric pistons, rotary pump or time/pressure, the appearance of the resulting solder deposits are very different. Pad-shapes may also be modified to improve the reflow characteristics of the new joint. As with adhesives, this means inspection systems that rely on rectangular brick shaped deposits, will need to change. And, implied volume calculations will be less accurate.

5.4 Sharing of Data: Based on the upcoming adoption of new PCB board technology and component technology, we anticipate it will be a requirement to inspect boards and parts at multiple stages of the assembly. As distributed inspection become more common, it will be desirable to share data across all the inspection machines. Additionally, we project that correcting defects after rework will become less and less feasible. Thus, boards need to be built right the first time. Direct feedback of variable data is necessary to reduce the occurrence of assembly defects and requires the development and incorporation of standard data interface and exchange. In the past, third party SPC and proprietary SPC data analysis have been common. New standards for CAD, part descriptions and assembly data are being developed by IPC, EIA/JEDEC, IEEE and RosettaNet promoted and proposed by iNEMI. These standards will allow for a common data exchange and lead to improved manufacturing and process feedback.

5.5 Cooperation: A new awareness of the benefits of cooperation and exchange of information and ideas is underway. Driven by the economic instability of global markets, suppliers who have not always been open to communication are now aggressively pursuing relationships with competitors. Less business and smaller profits are leading brand competitors to work together. Duplications of efforts in R&D among AOI companies with nearly identical applications are prohibitive given the low margins. Also, with the need for very different types of inspection systems, usually meaning several different suppliers in a production line, AOI systems must be able to communicate with each other across platforms for input programming and distributed data analysis. As the best AOI techniques are comparable in terms of their ability to perform inspections, the competition is between the best support organizations and the best programming processes rather than the best technology.

5.6 Summary

Table 2 shows a summary of how we believe AOI systems must evolve in the future to meet the new changes in PCB technology.

Change in PCB technology	Image capture	Image Analysis	Programming paradigm	System Architecture	Change in place in line	Use of process control	Cross platform integration	Change in technology (e.g. X-ray)
Component Packaging	☑	☑	☑	☑	☑	☑		☑
PCB material changes	☑	☑	☑	☑	☑	☑		
Attachment	☑	☑	☑		☑			☑
Data					☑	☑	☑	
Cooperation				☑			☑	

Table 2- Summary of theorized future changes to AOI systems and their usage to meet the coming changes in PCB technologies.

Thus, if we compare Table 1 and Table 2, we see that the previous efforts, summarized in Table 1, were more towards changing one of the modules, the Image Capture Module, Image Analysis Module or Programming Paradigm to meet evolving needs of PCB inspection over the last ten years. Table 2 suggests that we are going to see a tightly coupled evolution of the three modules and their surrounding system architecture to deal with new PCB technologies. Additionally, we are going to see significant changes in AOI usage and also sharing of data across AOI platforms. We may also see that X-ray and AOI will play an important role together in the future to inspect new PCB substrates, packages, and attachment materials.

6. What should I look for in an AOI system now that will allow me to address these new technologies?

The most important attribute of an AOI system is a flexible or object oriented system architecture that allows the AOI designers to plug in new image capture devices, image processing algorithms, and programming paradigms. The system architectures should be designed so that they can output data in a standard format to be used for analysis and process control. A properly architected system can "plug" in new modules and output new types of data without disruption of the whole system. This type of system can adapt and grow to meet new challenges and is a better investment than one that needs to be overhauled for every change.

With that said, it is impossible to evaluate the system architecture and its modules without a full engineering review. But a review of the products offered by AOI vendors in the past and the technology roadmap ought to be reviewed. Customers can review the programming interface and the quality of the results during evaluations and demos. We suggest however, that a customer focus on accuracy and repeatability of results, the ease of use, and data analysis over time rather than just looking at the hardware or, as we like to call it, "curb appeal". A supplier ought to be able to demonstrate their programming process and results rapidly. They should allow the customer to put their hands on the machine. They also ought to be able to leverage current part library data and input data formats of customers' current installed systems. Another critical point to examine is the level of knowledge required for program generation. Any programmer ought to get identical inspection coverage and the same level of diagnostic repeatability, regardless of experience.

Finally, customers need to change their mind set from using AOI as an end of line defect screening device and think more of it as a continuous process improvement tool. This change in mind set is required by the new technologies that are coming. However, it can also significantly improve yields with the existing technologies.

7. What is the role of AXI in the future?

More hidden joints and new interconnect technologies have and will continue to drive the need for AXI and other image capture techniques for examining hidden joints. The high cost of AXI as a separate inspection platform is still a deterrent to adoption. Cycle time requirements do not currently match line rates for complete inspection and many defects cannot be visualized by X-ray. System costs are high compared to AOI. Currently, AXI tends to be used as a process development and process monitoring tool. In the future, AXI is more likely to be combined with AOI in a single platform. If techniques for examination of hidden joints can be incorporated into a combined optical inspection system, and can be applied only where needed it is more likely that customers will consider them. Ideally, a well architected AOI system should be able to plug in AXI image capture methodologies and image processing techniques as well as those traditionally associated with AOI to facilitate the creation and evolution this type of combination machine.

8. Summary

For the past 20 years we have seen a number of changes in PCB technology. While these changes were dramatic, they had a relatively small impact on AOI technology. However, the adoption of new PCB technologies such as PoP, flexible circuits, and conductive adhesives may drive major changes in AOI technology. In addition, the new materials and manufacturing processes allow for little error. As a result, they may drive major changes in how customers use AOI, such as relying more on pre-reflow inspection. Finally, analysis of defect and measurement data, feedback of data to the process, and sharing of data will be required to build more boards correctly the first time.