technical viewpoint

LEADING EDGE AOI:

Comparing Statistical Appearance Modeling™ (SAM) to Traditional Automated Optical Inspection (AOI)

by Bob Ries

Director of Marketing, SMT Systems

INTRODUCTION

AOI has become the inspection method of choice for today's SMT lines. A wide range of systems are available in the SMT equipment marketplace, ranging from traditional, algorithm-based machine vision inspection to advanced adaptive knowledge-based technology. This paper highlights applications for AOI on the PCB assembly line, describes the image analysis methods used by traditional AOI systems and compares them to CyberOptics' proprietary Statistical Appearance Modeling™ (SAM) software, which employs recently-developed mathematical techniques to simplify programming and substantially reduce the amount of expertise required to operate a high-performance inspection system.

The paper concludes with a summary of the results from a real-world case study performed by a major telecom manufacturer to evaluate AOI system performance, specifically CyberOptics' SAM-driven KS 100™ post-placement inspection system.

WHY AOI?

As components and board features grew smaller and smaller, it became obvious to PCB manufacturers that manual inspection was inadequate for the task. Human visual inspection is labor intensive and inherently unreliable — repeatability is low, particularly between operators. Even with an experienced inspector, visual fatigue inevitably leads to missed defects. AOI has developed into the logical alternative.

AOI is also gaining in popularity as a supplement to traditional in-circuit testing (ICT) and functional test, because the density and complexity of today's PCBs and components make it increasingly difficult to use a test-probe or bed-of-nails fixture to physically access connections for ICT or functional test.

Having satisfied themselves that AOI does offer economic advantages, many PCB manufacturers now regard AOI systems as an integral part of their SMT line. In-line systems like CyberOptics KS 100 are being used successfully as cost-effective process monitoring tools, supplementing traditional test strategies. Identifying defects early in the process, while there is still time to correct the problem and repair the board, is inexpensive in comparison to the cost of reworking finished boards after ICT, functional testing and final inspection.

Typical AOI applications include:

- Post-placement monitoring to detect unfavorable trends such as placement drift or incorrect reel mounting, which can then be fixed before the flaw is repeated on numerous boards.
- Post-placement inspection to identify missing, skewed, misplaced or reversed (incorrect polarity) components for repair before reflow.
- Post-reflow screening to locate solder bridges, broken joints, dry joints and other solder defects before ICT and functional test.

TRADITIONAL, ALGORITHM-BASED AOI

Conventional vision systems rely on mathematical algorithms to detect defects. These algorithms, which can be described as numerical "recipes," use a rigid set of rules to provide a basis for accepting or rejecting a PCB at some point in the assembly process. In a real-world SMT environment, algorithm-based vision systems are very complex and require the expertise of vision scientists or engineers to set up, operate, maintain and modify.

Adding to the complexity, a traditional vision system usually employs between 200 to 300 different algorithms which can be combined to form composite recipes for various components; this is a task that usually requires extensive programming time by an expert vision engineer. When a vendor modifies a standard component, the associated algorithm may need to be revised, either by the AOI supplier or the user – all of which requires additional programming time and adds to the overhead of an already complex system. Finally, the appearance of components of the same type can vary significantly from example to example, thus making it difficult for algorithm-based systems to encompass all these variations.

There are many popular image-analysis algorithm methods, including template or pattern matching, edge detection, feature extraction, gray scale modeling, Fourier analysis, optical character recognition (OCR) and many more. Template matching is the most commonly-used method.

HOW TEMPLATE MATCHING WORKS

Template matching tries to determine what a specific object, such as chip capacitor, looks like on average and then uses that information to create a fixed, pixel-based template. Templates are created for each type of component to be inspected, and an inspection program for an entire board is constructed using the specified templates in the appropriate positions to find the designated components. To create functional templates, users of algorithm-based systems need to be reasonably knowledgeable in the field of image analysis.

But rarely will the system locate an exact match for the defined pattern, so the template must be constructed broadly enough to identify and accept similar matches that are fairly close to the template. The appearance of even a simple component – such as a 0805 chip capacitor – can vary widely within a single production run. (See Figure 1.) This kind of variability may cause a conventional inspection system to make a "false call," a potentially costly error. False calls include both false accepts, where the system passes a PCB that actually has a defect, and false rejects, where a good board is rejected by mistake.

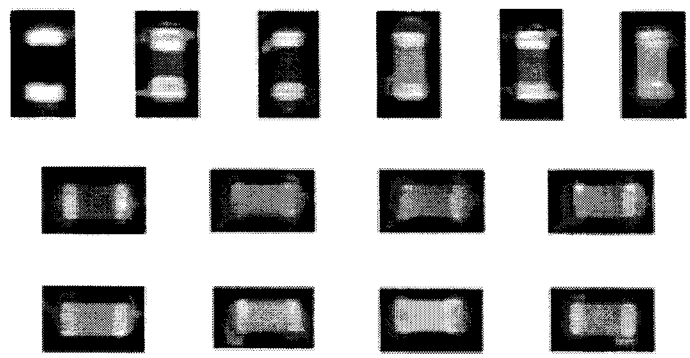

Figure 1. Appearance Variations in 0805 Chip Capacitors

Template-matching inspection methods are often too rigid to accommodate legitimate variations in component appearance including contrast, size, shape and shade. Even the simplest components can be difficult to locate consistently. False rejects occur when a component is present but the AOI system cannot detect it. Ultimately, if false rejects occur often enough to interfere with production, frustrated operators may switch the inspection machine to pass-through mode, thus nullifying all the benefits of AOI.

If the template is expanded to include a wider range of possibilities, the system may have difficulty differentiating between acceptable and unacceptable images because the differences between a passing image and a failing image are often very subtle. This confusion may cause a false accept when a defective board passes inspection and continues down the line, only to fail during in-circuit testing or functional testing. At that point, the board needs costly rework or it must be scrapped.

To overcome these limitations, conventional AOI systems require extensive re-programming by highly-skilled engineers, who attempt to fine-tune their inspection methodology to accommodate all the legitimate variations. Reprogramming can take between one or two days for minor tweaking and may require several weeks when creating and optimizing an inspection program for a new board.

COMPARING SAM TO TRADITIONAL AOI

CyberOptics' KS 100 and KS 50 systems use an entirely different approach to AOI, developed by engineers at CyberOptics Ltd in the UK, called Statistical Appearance Modeling or SAM. This adaptive, knowledge-based software uses proven mathematical techniques to automatically teach itself to recognize legitimate variations in a series of visual images. The fundamental technology behind SAM is transparent to the programmer or operator, so no specialized training or image-analysis experience is required to set-up and run a KS system. SAM requires considerably less programming time than algorithm-based machines, and everyday fine-tuning is virtually eliminated.

How Statistical Appearance Modeling Works

Using SAM is simple and straightforward. Working from an inspection program created from any ASCII CAD data or placement data, the operator views the board layout on-screen and uses the cursor to draw a box around all of the components to be inspected. Then the operator shows the KS system a series of good boards, allowing the SAM software to collect data on different examples of acceptable component images. Each new example provides more information about the range of possibilities for that component and location. SAM then uses the collected data to build an adaptable mathematical model encompassing the range of allowable variations for each component type.

Unlike algorithm-based approaches, which require customized programming based on users' perceptions of how components may vary, SAM's empirical approach demands no inherent understanding by the user or inspection system of what it's deciding. SAM uses its own objective mathematical observations to create a detailed model of what to look for in an acceptable object or component. SAM allows the AOI machine to determine for itself which aspects of a component's appearance can vary and by how much, with no direct input from the user.

During production, SAM continues to collect measurement data which the operator can use periodically to update the model and improve machine performance. As more data is incorporated into the model, the system gradually refines and improves its estimate of what the object should look like and how its appearance can legitimately change due to natural variations is size, shape, color and surface patterns. As a result, machine performance improves over time and the false call rate goes down; typically the production false call rate stabilizes below 100 ppm, which is five to ten times better than most AOI systems.

ADVANCED KS TECHNOLOGY INCREASES REPEATABILITY

As described earlier, many traditional AOI systems rely on detecting the edges of components to achieve accurate and repeatable measurements. But these edges are not easy to find using standard vision technology. Because component edges aren't perfectly straight, attempts to fit a straight line to such an edge can be difficult. Also, edges tend to be dark regions sitting on dark backgrounds, and identifying these accurately is especially prone to pixel noise variations.

Using edge-based recipe methods, a traditional vision system yields a repeatability where one standard deviation corresponds to around 1/10th of a pixel. SAM software, however, offers repeatability where one standard deviation corresponds to 1/20th of a pixel. Plus, SAM's ability to produce accurate and repeatable measurement data is particularly important in more advanced applications where these measurements are used in statistical process control (SPC).

INHERENT FLEXIBILITY WITH KS AOI

Most conventional vision systems rely on a x-and-y table to move to a specific location on a PCB. In an attempt to fit a legitimate component of significantly differing appearance, for example, a rigid traditional method tends to slip and slide about in x-and-y axis to achieve an optimal fit by adjusting the only variable parameter that's available – the position. In contrast, the CyberOptics KS AOI system with SAM software is inherently flexible when examining a specific type of component. By fitting an appropriate SAM model to the component – whose variability is controlled to allow only those appearances that can really occur – the appearance is adjusted to the best position without compromising the x-and-y location.

Additionally, certain types of allowable component color variations – such as the overshadowing or the overexposing caused by adjacent larger components – are practically impossible to accommodate with algorithm-based methods. SAM, however, works out what visual-image permutations are allowed. Users don't have to rely on algorithms that require extensive programming. New reels and components from new vendors don't require extensive re-tuning of inspection programs. And, SAM recognizes logo and text variations on components and boards. Traditional OCR-based techniques can't cope with variations in printing quality or appearance. The SAM method, however, simply recognizes such differences as just another form of valid variation.

ADVANCED KS 100 STEREO VISION

Traditional, high-end AOI systems cannot fully accommodate three-dimensional variations in PCB appearance caused by localized warp and stretch. Even physically clamping a board doesn't guarantee absolute flatness. Telecentric lenses eliminate errors caused by optical parallax effects, but they also eliminates perspective. Measurements between one point and another that should follow the curve of a board's surface are instead made by measuring straight lines across the chord of the surface. This causes significant measurement inaccuracy and automatically removes valuable information about the shape of a board's surface.

The high-performance KS 100 uses stereo vision to create a height map and then mathematically flatten the PCB image to compensate for localized warp and stretch, thereby increasing measurement accuracy. This synthetic board-flattening capability produces measurement results at an accuracy level usual found only with high-end, off-line coordinate measurement machines.

How the KS 100 Machine Works

The KS 100 machine uses a standard board conveyor to move the PCB under the cameras. Lighting is supplied by simple high-frequency fluorescents. As the board is indexed on the conveyor and passed under the camera array, a photo-mosaic image of the entire PCB surface is construct by joining together rows of stereo pairs of images (as show in Figure 2). This photo-mosaic image is then synthetically flattened, and analyzed in real time.

KS 50 APPLICATION ADVANTAGES

KS 50 is an affordable entry-level AOI system designed for PCB assembly screening and verification. This system installs in-line – either pre-reflow or post-reflow – to provide 100% loaded board inspection at production-line speed. The KS 50 AOI system helps eliminate labor-intensive, visual end-of-line inspection, thus ensuring 100 percent inspection of components as small as 0402 capacitors. Plus, the KS 50 augments ICT and functional testing and reduces ICT workload by catching board defects prior to final test. KS 50 uses the same sophisticated SAM software as the KS 100 system Inspection programs are created from any ASCII CAD or placement data.

KS 50 is the most affordable AOI system on the market today and typically returns the initial investment in less than one year. Plus, since the KS 50 shares a common machine platform with KS 100, it is easily upgraded.

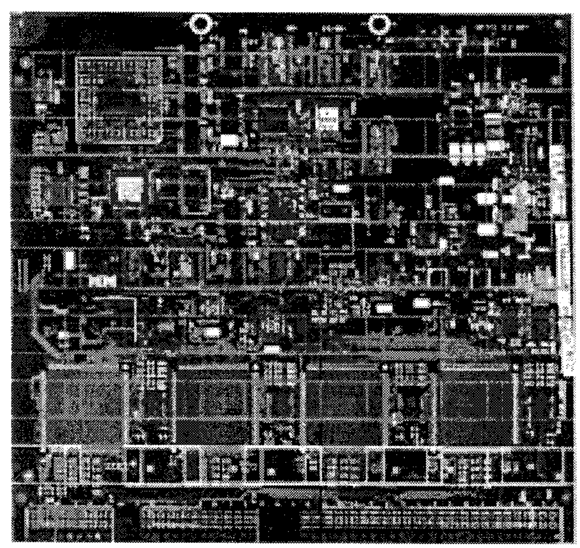

Figure 2. Photo-Mosaic Image of PCB Surface

KS 100 APPLICATION ADVANTAGES

The KS 100 is the most robust system in the KS family of AOI products. It is specifically designed for the most demanding applications, where 100% post-placement inspection is required for closely monitoring the placement process.

KS 100 inspects everything on the PC board, including components and connectors. It detects identifying marks, including labels, logos and polarity indicators, and provides instant 10% gage R&R. As described earlier, KS 100 uses stereo vision to mathematically flatten circuit boards rather than clamping or supporting the PCB.

KS 100 inspection programs are created from any ASCII CAD or placement data file. Plus, because programming the KS 100 doesn't require skilled engineers or vision scientists, simple and intuitive programming can be accomplished in less than 20 minutes. Among high-end AOI systems, the KS 100 provides the quickest payback, typically less than one year. When compared in head-to-head evaluations with other AOI systems, the combination of SAM modeling and KS 100's stereo-vision imaging technology has demonstrated accuracy and repeatability far superior to any existing, high-end AOI system on the market today.

A REAL-WORLD EVALUATION OF KS 100

A prominent SMT manufacturer recently evaluated the CyberOptics KS 100 AOI system and compared its performance and cost-saving advantages to competitive AOI systems. Their objective was to realize some or all of the following benefits by including an AOI system in their SMT manufacturing line for post-placement/pre-reflow inspection:

- Continual process improvement
- Lower test and repair costs
- Increased test capacity
- Complementary testing
- Increased throughput
- Reduced labor expenses for inspection and repair
- Reduced time to market for new product

ESTABLISHING A BENCHMARK

The SMT manufacturer performed in-circuit tests (ICT) and functional tests on PCBs as preliminary benchmarks for subsequent evaluation and testing of the AOI systems. The defects that would be detected earlier in the process (post-placement/pre-reflow inspection) if the AOI system were deployed included: missing part, damaged part, misplaced part, wrong part and reversed polarity. As highlighted in Figure 3, the actual total percentage of placement-related defects that would be detected and eliminated earlier in the process by a KS 100 added up to 59 percent of the total defects identified.

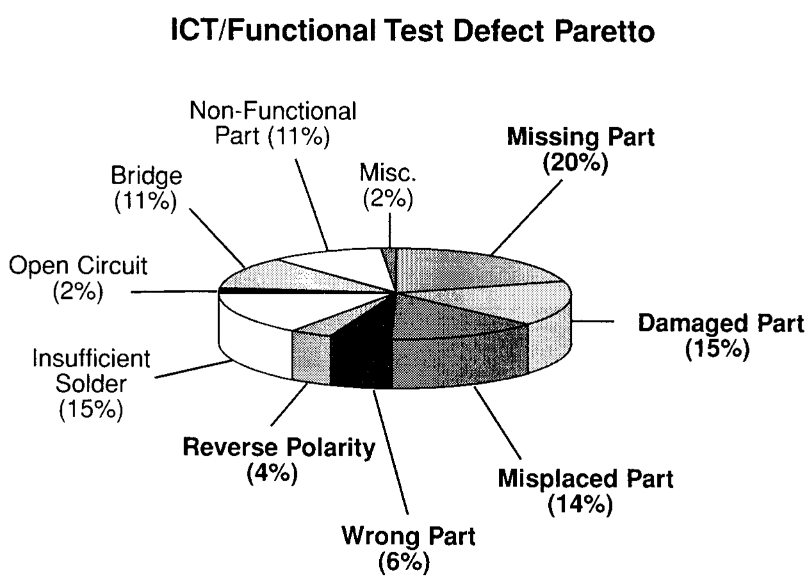

Figure 3. Sources of PCB Defects

REALIZING PAYBACK AND ROI GOALS

By taking data from a defect Pareto chart (see Figure 3) and determining how many defects could be reduced or eliminated using the KS 100 AOI system, it was possible to calculate the resulting savings and payback period.

Figure 4 presents an example of input data used to calculate payback and ROI. Cost savings achieved by reducing testing, minimizing rework and eliminating scrap were typically sufficient to pay for the KS 100 AOI system in less than one year, as highlighted in Figure 5.

Production Inputs					
Days of Operation Per Week	5	Notes:	Inputs cells in white		
Weeks of Operation Per Year	50		Calcuations in blue		
Number of Shifts Per day	3				
Hours Per Shift	8				
Non Production Hours Per Shift	3				
Typical Cycle Time Per Board (seconds)	90				
Boards Scrapped Per Shift ($ value)	$250				
Run Time Per Year (hours)	3750				
Annual Board Volume per Line	150,000				
Typical Board Length (inches)	10				
Typical Board Width (inches)	12				
Typical Board Area (inches²)	120				
First Pass Yield at Test (pre-inspection)	75%				
Test Cycle Time (seconds)	90				
Test Cost Per Hour	$150				
Placement Related Defects (% of total defects)	53%				
	Defect Rates (% Of Boards)	Rework Time (Minutes)	Total Rework Cost Per Hour	Repair Cost Per Board	Total Cost Per Year
Pre-Reflow Rework Cost Input/Summary					
Placement Related Defects	15%	5	$25.00	$2.08	$46,094
Post-Reflow Rework Cost Input/Summary					
Placement Related Defects	15%	20	$25.00	$8.33	$184,375
	1st Pass	2nd Pass	Total Cost Per Year		
ICT Cost Summary	$562,500	$140,625	$703,125		
	Per Day	Per Year			
Scrap Cost Summary	$750	$187,500			

Figure 4. Production Data Input

Inputs					
List Price	$120,000		Notes: Inputs cells in white		
Options (cal target)	$3,850		Calcuations in blue		
Residual Value After Three Years	$20,000				
Installation and Training	$0				
Maintenance Per Year	$12,000				
Engineer/Operator Cost Per Year	$70,000				
	Defective Boards Per Year	Rework Cost Per Year			
Pre-Reflow Rework Cost Increase					
Placement Related Defects	22,125	$46,094			
	New Yield	Cost/Year			
ICT Cost Decrease With Improved Yield	90%	$82,969			
	Defective Boards Per Year	Cost/Year			
Post-Reflow Rework Cost Decrease					
Placement Related Defects	22,125	$184,375			
Scrap Reduction Per Year	$27,656				
Payback Analysis		Year 0	Year 1	Year 2	Year 3
Equipment, Installation and Training		-$123,850			$20,000
Maintenance and Engineer/Operator			-$82,000	-$82,000	-$82,000
Rework Costs			-$46,094	-$46,094	-$46,094
Scrap Savings			$27,656	$27,656	$27,656
Rework Savings			$184,375	$184,375	$184,375
ICT Savings			$82,969	$82,969	$82,969
Projected Cash Flows		-$123,850	$166,906	$166,906	$186,908
Payback Period (years)		0.74			
Internal Rate of Return		124.65%			
Cost of Capital	20%				
Net Present Value		$199,424			

Figure 5. Payback and ROI Analysis for KS 100

ACHIEVING AOI SYSTEM-PERFORMANCE GOALS

Following is a summary of the system requirements specified by the SMT manufacturer during an trial of competing AOI systems, and the performance results of the KS 100 evaluation:

USER-DEFINED SYSTEM REQUIREMENTS

- Software: UNIX/NT
- Programmed using CAD
- Repeatability: <10mm dynamic test (1 board tested 20 times)
- Accuracy: <15mm dynamic test (1 board tested 20 times)
- Test time: <40 seconds
- Programming time: <30 minutes
- Detect post-placement defects: missing component, wrong orientation, wrong component, damaged component, wrong position
- False calls: <100 ppm
- Record results against barcode

KS 100 AOI RESULTS

- Repeatability: 2.9 μm in x-axis; 3.5 μm in y-axis
- Accuracy: 8.2 μm in x-axis; 6.86 μm in y-axis
- False calls: 42 ppm
- False accepts: 0 ppm
- All faults found on known defective boards
- Average test time: 35 seconds
- Programming time: <20 minutes

CONCLUSION

Various vision systems and a variety of image-analysis techniques have been in use for SMT manufacturing for many years, with some success. The CyberOptics KS family of products represent the next generation of AOI technology – adaptive, knowledge-based systems that free the engineer and the operator from tedious reprogramming.

In actual trials on SMT manufacturing lines, KS systems have proven more repeatable than traditional AOI systems, and with fewer false calls. Because KS systems build a library of component models which are refined over time, the longer a KS system is used, the more effective it becomes.

CyberOptics Corporation
5900 Golden Hills Drive
Minneapolis, MN 55416 USA

For More Information

Tel: USA (800) 746-6315
USA (763) 542-5000
Fax: USA (763) 542-5100

E-mail: info@cyberoptics.com
Website: www.cyberoptics.com

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