Large Format Digital Color AOI

By Joseph L. Vilella and Robert M. Kane

The advances inherent in these automated optical inspection (AOI) systems include environmental and imaging advantages together with the development of collection and processing strategies.

The need for AOI equipment capable of performing 100 percent verification of populated printed circuit boards (PCB) at different stages of the assembly process began to be recognized in 1996. This recognition was more prevalent in the telecom sector and was motivated by the inception of the 0402-sized components. The small size and quantities of these chips on an average cell phone board presented a critical placement and visual inspection challenge. Accordingly, high-volume telecom manufacturers employed state-of-the-art grayscale AOI systems to identify placement errors. While they had their detractors, the machines provided a reasonable solution as long as board complexities were not extreme and inspection cycle times were relatively slow. The problem, however, was that board complexities began escalating. Additionally, the demand for higher production rates compressed cycle times. This situation prompted the need for better and faster AOI technologies.

A Different Approach to the Problem

From conversations with clients and prospective users, it was clear for one company* that a radically different AOI technology was needed. There were misconceptions, lack of performance and disappointments attached to AOI that had to be overcome. The response was to make the technology forward-looking and realistic in what it could do. It was slated to provide "patentable" intellectual property, and with carefully programmed strategies, remain technically ahead of the pack as camera and computer technologies evolve. What follows is an outline of this company's strategy.

The first step was to identify clearly and accurately the strengths and weaknesses in existing AOI systems. Once those were understood, enough information was available to perform what is referred to as a "Punch/Counter Punch" approach to developing new technology, i.e., a specific technical challenge is a punch that must be countered effectively to win the ultimate technology battle. For example, a punch can be a positive feature that must be outmaneuvered (as with a competitor having a better mouse trap), or a negative feature that must be overcome with a better process. The table illustrates the punches confronted relative to existing AOI technologies and the ways in which they were countered by the new system.**

By using a large format image, the negative mechanical features (of small images) inherent in inspections were prevented. With the larger image, either in the 3.6 in2 or the 3.6 x 5.6" formats, the camera requires fewer movements, thus achieving specified inspection cycle times. In effect, one image captures all the information previously acquired through the use of hundreds of 0.25" images. Further, the slow camera motion produces no damaging vibrations, thus eliminating the need for heavy granite stages and actually permitting critical AOI inspection operations on the processor's casters. Lastly, due to its sensor size, the image is taken with the camera positioned several inches away from the target. This provides the necessary clearance to inspect any board regardless of component height while preserving inspection depth of field.

Image Collection Technology

The new AOI imaging design technology selection centered around an ability to inspect without an extreme view count, which intuitively required a large image. Board programming process simplification was a factor as was the need to meet the process requirements by assessing product quality as well as by generating the parametric information required for process control. With these considerations in mind, the design problems in Figure 1 were defined, and the selection process began.

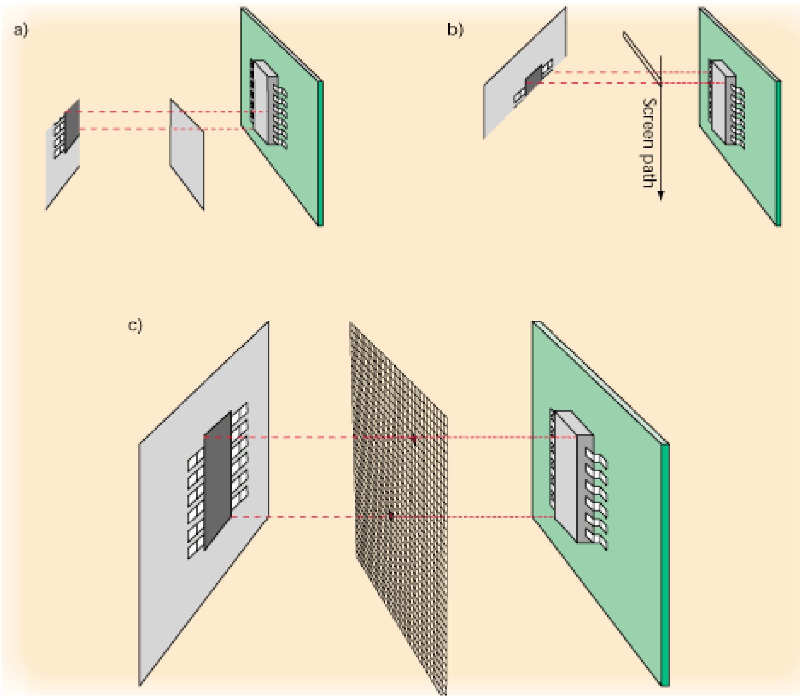


Figure 1. New system design problems are defined by three options: streaming video 2-D frame grabber (a), 1-D scanning array (b) and a large fixed 2-D array (c).

The latter included selecting image-capture and image-processing methodologies influenced also by functional objectives. With image capture, a set of three mature imaging technologies, applicable without extensive development, was considered. The most common technology uses a motion capture video camera with a frame grabber that transforms one frame from a stream into a still image. Because the camera is optimized for motion capture for the human eye, image size and quality are secondary concerns. Although this was and continues to be the dominant technology applied to AOI, it was rejected owing to undesirable limitations and its inability to address an important design objective, i.e., achieving fewer and larger images.

A second alternative considered was the line-scan, still-image camera, which provides a larger image based on successive horizontal image lines. However, since continuous camera sweeping captures the image, mechanical subsystem imperfections translate into image distortions. The introduction of such distortions (that vary with wear) means that precise positional measurement data cannot be derived, and hence, process-control parametric measurement is impossible. Additionally, the camera typically rides close to the target and requires considerable lighting. Therefore, even though line-scan camera technology seemed economically attractive and produced a reasonable image size, its drawbacks forced a rejection.

TABLE

System Design Chart

Function	Punch	Detractors	Counter-punch
Mechanical	Complicated system	Many moving parts	Large format image
Mechanical	Excessive down time	Due to fast motion	Large format image
Mechanical	Heavy machine	Difficult relocation	Large format image
Mechanical	Camera/target proximity	Clearance issues	Large format image
Mechanical	Slow cycle times	Small pictures	Large format image
Image collection	Grayscale images	Low color contrast	Digital color (DC) image
Image collection	Small view field	No fiducial reference	Large format image
Image collection	Analog video streaming	Noise-sensitive image	Still-image capture
Image processing	Camera/target proximity	Depth-of-field lack	Large format image
Image processing	Borderline resolution	Insufficient pixels per feature	Large format image
Image processing	PCB programming limits	Variations intolerance	Parametric method w/DC
Image processing	No first-article inspection capability	Insufficient inspection images	Parametric method
Image processing	Large inspection libraries	Many images required per site	Parametric method
Image processing	False-call prone*	Variations intolerance	Parametric method w/DC
Image processing	Excess misdetections**	Variations intolerance	Parametric method w/DC
Image processing	Intermachine program variations	Image system variation intolerance	Parametric method
Image processing	Systems clog computer network	Many images required per site	Parametric method
Image processing	Lack of parametric data	Parts-placement inaccuracy	Parametric method w/DC
Operational	Awkward user interface	Can slow operator	Touch Screen I/F
Support strategy	Slow service, support	High machine downtime	Digital color/Internet

*When tolerances are tightened or relaxed (**)

A less common option offered special-purpose cameras designed for military, space and other technical applications. This class includes extremely large, fixed two-dimensional (2-D) charge-coupled device (CCD) arrays to collect high-resolution, high-precision still images. Because the camera is not designed to maintain a stream of motion video, the image may be handled and processed in the same digital format as its collection. And because precision was a primary consideration in camera selection criteria (and the fact that the unit offered full digital color to provide the critical contrast per feature for performing proper target analysis), this technology became the ultimate choice.

The image was the largest attainable within state-of-the-art CCD technology. Approaching 4" while maintaining a resolution of 0.002" per pixel, it was the largest for any pixel-level resolution while providing a very high likelihood of encountering a fiducial reference within a circuit board image. Thus, because of the high degree of stability in the pixel-to-pixel position in the solid-state CCD substrate, the absolute positional accuracy of every pixel in the image is assured when a fiducial mark could be imaged and located (Figure 2).

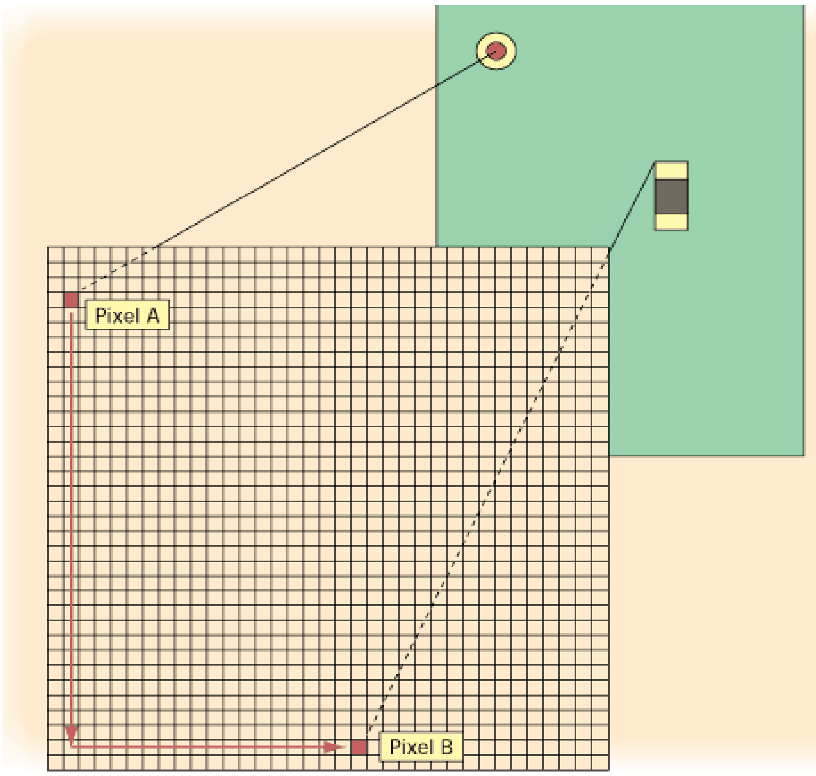
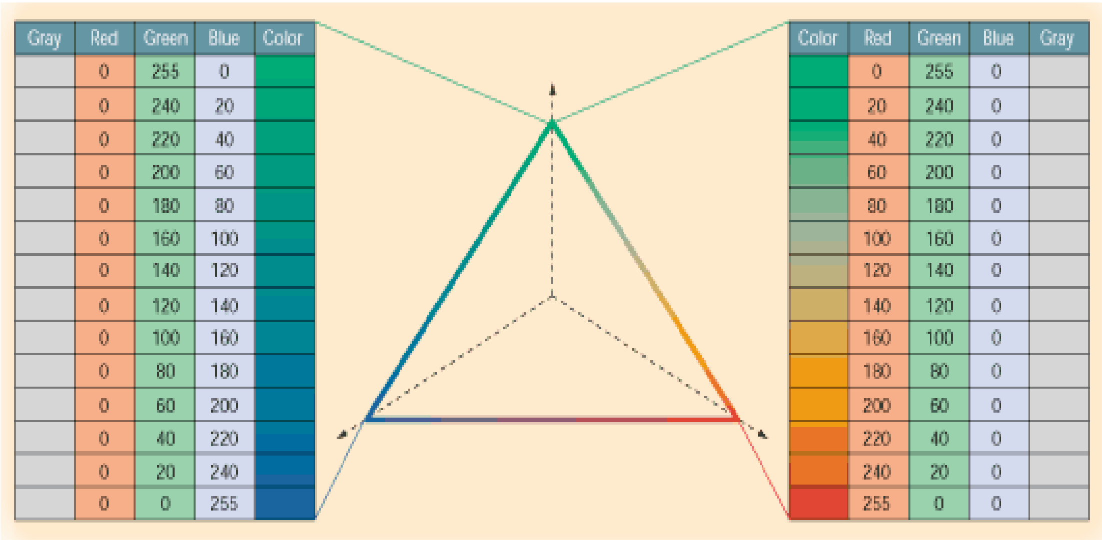


Figure 2. The large high-resolution image includes a board fiducial positional reference.

Color vs. Grayscale Image Processing

Color in the large digital-imaging camera is available optionally. However, because color data processing carries a computational cost, using color in the inspection process requires resourceful manipulation to derive maximum efficiency. Every image consists of a map of light intensities at pixel locations. In a color imaging system, each pixel is assigned three values corresponding to the intensities within the red, green and blue (RGB) color bands. In the case of a grayscale imaging system, every pixel is assigned a value equal to the average light intensity across the spectrum, which is exactly equivalent to the average of the three color-band intensities. Every grayscale level can occur from an infinite number of unique RGB intensities, resulting in the principle of grayscale camouflage of varying colors (Figure 3).



Gray	Red	Green	Blue	Color
	0	255	0	
	0	240	20	
	0	220	40	
	0	200	60	
	0	180	80	
	0	160	100	
	0	140	120	
	0	120	140	
	0	100	160	
	0	80	180	
	0	60	200	
	0	40	220	
	0	20	240	
	0	0	255	

Color	Red	Green	Blue	Gray
	0	255	0	
	20	240	0	
	40	220	0	
	60	200	0	
	80	180	0	
	100	160	0	
	120	140	0	
	140	120	0	
	160	100	0	
	180	80	0	
	200	60	0	
	220	40	0	
	240	20	0	
	255	0	0	

Figure 3. Grayscale vs. color contrast. Every pixel is assigned a value equal to the average light intensity across red, green and blue spectrums.

The concept of color camouflage also exists in a color image based on the presence of random thermal noise in the measurement process. When the ideal or noiseless coordinates of a color are known, a "truth" vector exists. In the presence of noise, an uncertainty region exists as a spherical volume around the truth-vector end with a radius of one-half the noise figure. Alternatively, when the color vector is transformed to grayscale, the camouflage region becomes a solid triangular section through color space with thickness equal to the noise figure. By taking the ratio of the camouflage volumes, a merit figure of 2,500 results, indicating a dramatic advantage for color over grayscale contrast detection, a critical factor for accurate AOI inspection (Figure 4).

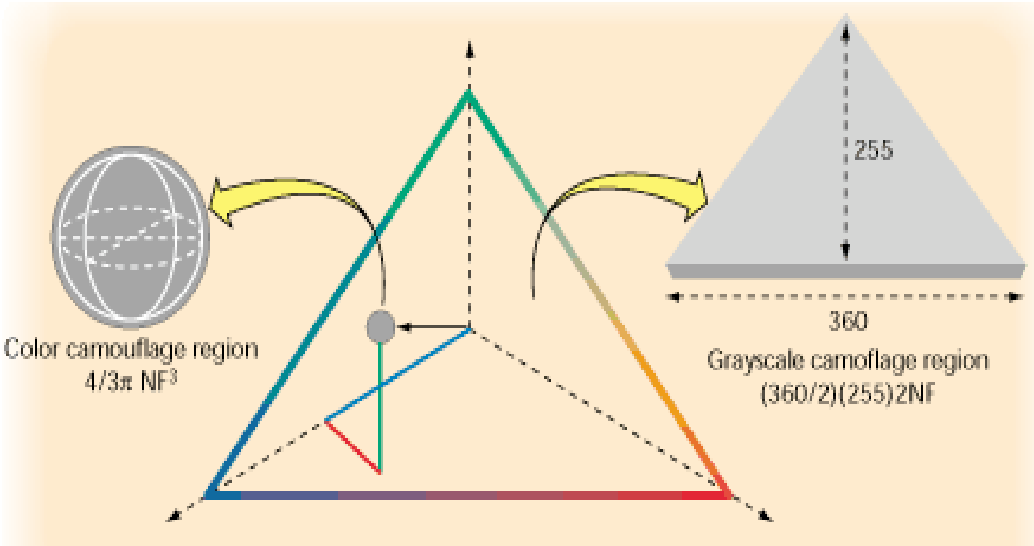


Figure 4. Illustrating quantitative color-contrast advantage. When the color vector is transformed to grayscale, the camouflage region becomes a solid triangular section through color space.

Image Processing Method Selection

A serious limitation emphasized by practical AOI experience has been the inability to pre-program for normal and acceptable variations within the production process. Variations in substrate and component appearance, as well as minor placement changes cause false calls. A method to resolve this problem and used by many AOI systems during the image selection process keeps a programming-level person at the machine during the earliest phases of production or whenever part changes are occurring. This person has the responsibility of instructing the machine to accept variations as they are encountered.

This process demands the storage of multiple reference images of acceptable variations and declaring them to be acceptable. As a result, an effective board program includes up to 10 images for each component installed on the board, each of which is compared to an inspection target image before the board is declared "good." Based on this undesirable situation, the new AOI system design objective was to avoid image processing that depended on literal images (see sidebar).

Another objective to be addressed by the new image processing methodology is differentiating image parts that are pertinent to inspection and those that are not. Fortunately, all methodology requirements are similar to the normal process applied by the human mind during inspection. Specifically, the inspector has expectations of what will be seen but also is capable of adapting to hue shifts or shadow changes (Figure 5).

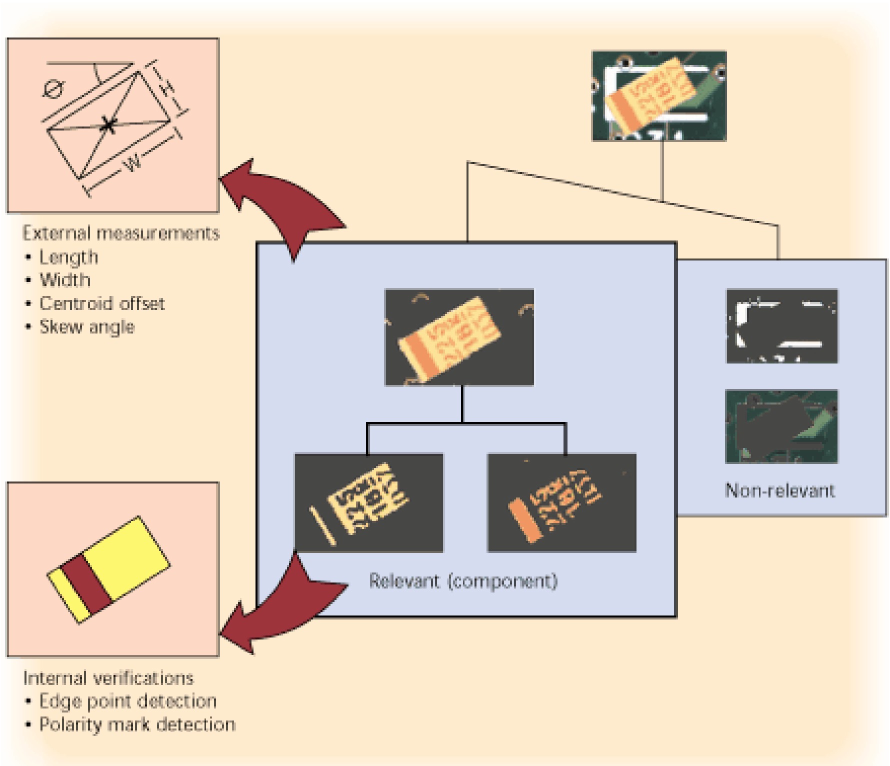


Figure 5. The Parametric Imaging Process: Process of distinguishing between image features that are pertinent to inspection and those that are not.

In parametric image analysis, algorithms serve to segment image pixels into pertinent and nonpertinent subpopulations. Nonpertinent pixels are excluded from consideration and the parametric model expectations are compared to edge and corner features. The result is an open-ended approach that is amenable to variations within tolerance specifications and is based on a very sparse but powerful reference library. However, the approach's success hinges on the ability to detect contrast features in the image. Fortunately, because the analysis indicates a superior color-contrast separation to grayscale, the option to process color data becomes the primary algorithm priority.

Summary

Based on the structured analysis of the design requirements and a careful avoidance of AOI pitfalls, an efficient and effective AOI solution was derived by using large format digital color imaging. The simplicity of the new approach permits a better, faster path toward more advanced generations of a powerful AOI technology that can parallel human vision closely. An ever-increasing CCD array size, combined with active thermal control and faster data transfer techniques, only serve to ensure that there always will be room for AOI improvements for populated PCB inspection.