What is really inside your AOI?

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Introduction

Installed for the first time 20 years ago, Automated Optical Inspection (AOI) more recently has become an essential part of our SMT environment. Today, most process engineers are turning to machines as an inspection strategy for addressing quality and productivity issues. As the number of AOI machine manufacturers has grown, so has the array of choices, creating the difficult and confusing task of choosing one AOI machine that meets process and quality requirements.

The objective of this paper is to provide potential AOI users with guidance and better understanding of this array of choices by examining the technologies within them and shedding light upon the costs involved; including purchase, equipment operation and long-term ownership.

The first part of this article is dedicated to the "Fundamentals of AOI", best understood by examining current inspection solutions from the perspective of the two prevailing, but different, technologies: Image Based AOI and Algorithm Based AOI. Each technology contributes a value to the inspection process that can be shown to be different. This value difference is highlighted by "key factors" (explained in more detail below), which have a clear impact on the end user's process. These key factors also are the main considerations when calculating Return on Investment (ROI). Simplified ROI calculations are shown in this article as examples of the differences between Image and Algorithm Based AOI.

Key Terms

Algorithm Based AOI, Image Based AOI

Fundamentals of AOI

Every AOI process starts with a digital image from an acquisition chain (camera, lighting, lens). The resulting picture represents a scene (objects, shapes, background). This scene actually is a matrix of pixels, with a single pixel being the smallest unit of the entire image. The matrix contains the following information on each pixel: location by row & column; light intensity level measured in grey scale for Black & White (B&W) images or in Red, Green or Blue (RGB) values for color.

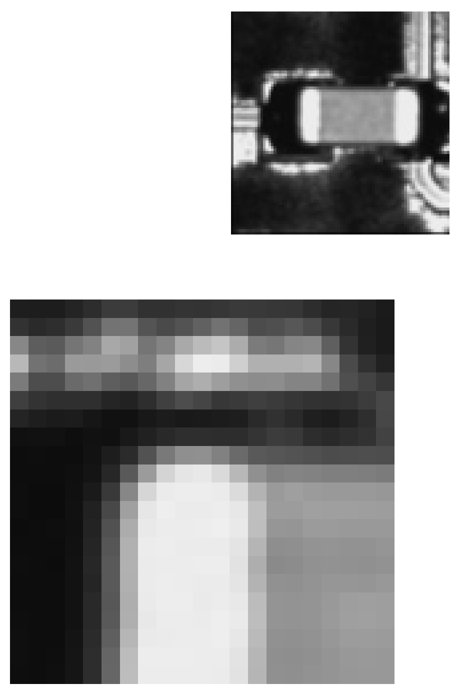
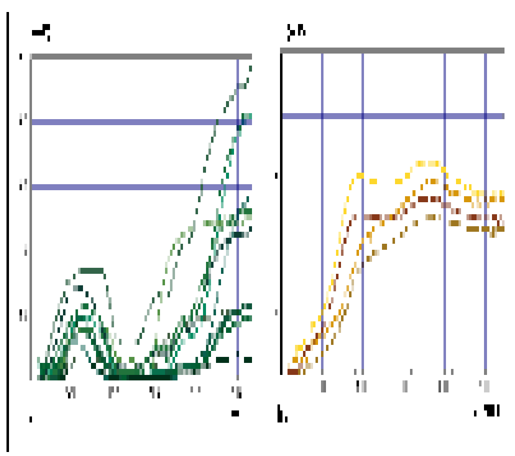


Image with illustration of pixel

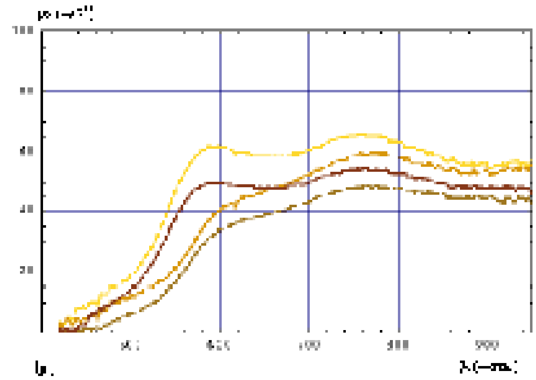
When comparing AOI solutions, people judge the quality of an image by pixel size (usually expressed in microns). A quick calculation of pixel size is achieved by dividing the Field of View (size of the inspected area) by the size of CCD or CMOS.

For example, if the AOI uses a 4M Camera (4 million pixels, 2000 x 2000) with a Field of View (FOV) of 38mm x 38mm, the pixel size is 19 microns. By limiting the quality of an image (from the Machine Vision point of view) to pixel size, it is easy to underestimate the value of the lighting system and lens. The lighting system can be characterized by wavelength and by direction (diffused, top-down or angled) and homogeneity.

Exposing objects to different colored light can provide a large variety of images. An object, due to its absorption/reflectivity, reacts differently to the wavelength of colored light as shown in the graphs below. The key is to create contrast between the inspected object and its background, the printed circuit board (PCB).



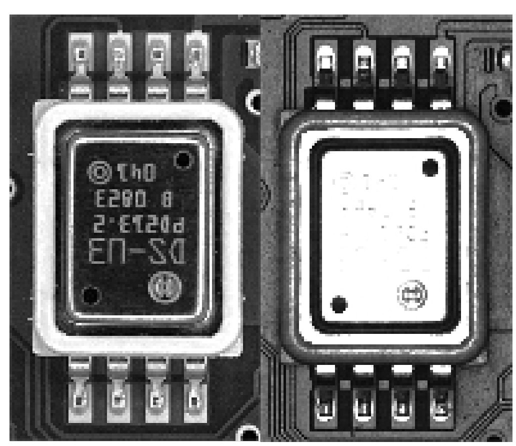
green pcb spectral albedo measurement



Tantalum capacitor spectral albedo measurement

Some AOI systems have selected colors and sources in order to get the best responses from all materials involved in PCB assembly [1].

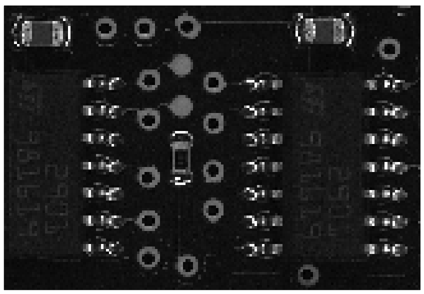
Lighting directions and sources are features to consider when comparing AOI machines. Lighting direction and source are other ways to enhance contrast and improve image quality and stability. Having a directional or diffused source also makes a difference. Today, most AOI machines use axial and angled light sources. This is a key element of solder joint inspection, especially when combined with colored light. The most advanced AOI machines use directional, axial and angled light, with 3 different colors. The illustrations below show contrast differences obtained with axial and angled sources.



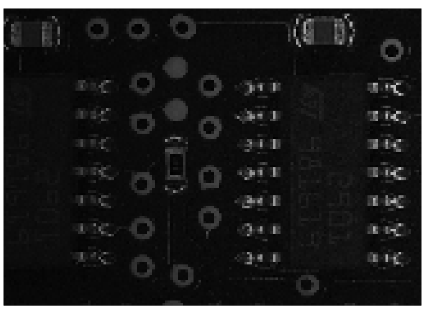
Component under axial and pyramidal lighting

When creating an image, an AOI machine's Field of View (FOV) will contain multiple components placed on a PCB. Some of these components are identical (same part number), and we expect the

AOI to recognize these as the same by testing and providing results showing that these truly are identical parts. Unfortunately, the *rendering* of these same parts in the image could be different due to lighting homogeneity problems in the FOV or a parallax issue induced by a non-telecentric lens. Either case has a direct impact on the false call level that you can expect with your AOI. Indeed, if the image is affected by some optical distortion (e.g., near the edge of FOV) or if the lighting is brighter in the center of the FOV, identical components at different locations in the FOV will not appear the same. The only fix for a system with these limitations is for the AOI programmer to open tolerances to accept more variation, thus compromising test reliability.



Components in the center of the FOV



Components in the corner of FOV

If acquiring an image with homogeneous lighting, no parallax effect and enough contrast is achievable, AOI manufacturers then must balance the need for inspection speed (cycle time) with resolution of the image (size of the FOV) or pixel size. For most AOI suppliers, this is a direct and simple function; if you decrease your pixel size by a factor, n, you increase cycle time by $(1/n)^2$ when using the same camera.

Having said this, the need to inspect smaller and smaller components could affect either the quality of the inspection or cycle time.

Some AOI manufacturers have responded to this issue by offering a variety of cameras or heads (camera + lens + lighting) to inspect both small and large component geometries. A single machine with multiple cameras or heads still must resolve the issue of accuracy and cycle time.

There are techniques for avoiding any trade-off between cycle time and inspection quality. One of these techniques is to use “sub-pixel” technology. Developed more than a decade ago, sub-pixel resolution can be obtained in digital images containing well defined lines, points or edges that can be processed by an algorithm to reliably measure position of the aforementioned line, point or edge within the image. The algorithm achieves this with an accuracy exceeding the nominal pixel resolution of that image.

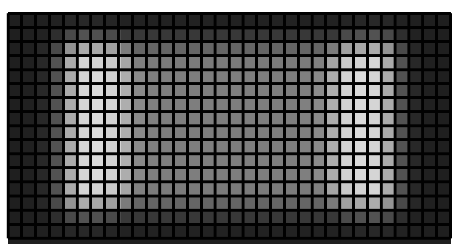
The different AOI categories

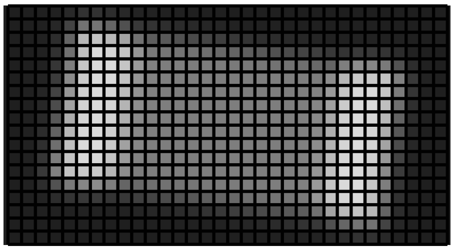
The optics, camera and lighting play a key role in all AOI machines, but the real differentiator resides in the vision software tools that can be applied to captured images.

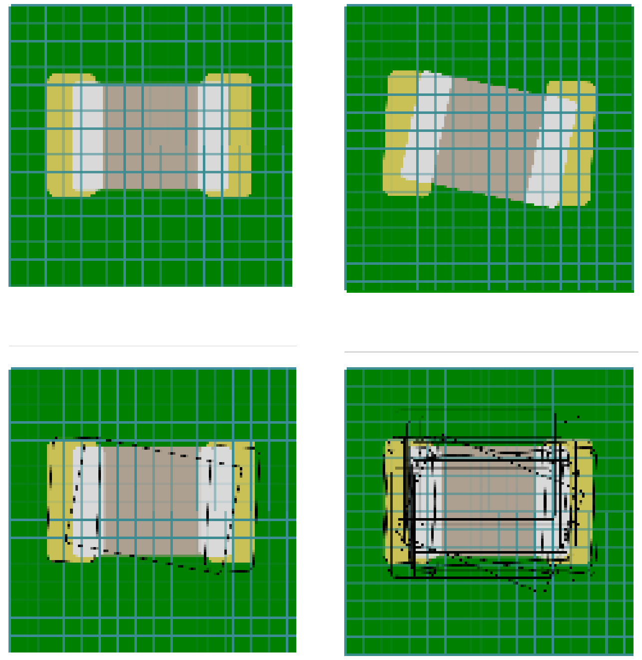
To avoid an endless list of categories by detailing each and every tool available, a common way to categorize machines is by comparing “image based” AOI to “algorithm based” AOI.

Image Based AOI

Also known as Image Comparison AOI, image based machines are designed to use the raw information or pixel grid contained in the image. Early systems used “grey scale” techniques to compare pixel to pixel within a region of interest.







In the two images above, the same component appears in the same region of interest but with a slightly different angle. Using pixel-by-pixel “grey scale” comparison, the second image should fail [3], due to lack of information at certain pixel locations within the region of interest. As you can see, this methodology has very poor accuracy when a component is skewed.

With today’s new image treatment methodologies, along with increased computing capabilities, image based technologies have improved. Most systems now employ a bank of images or image library. This allowing it to reference images of known good components as well as known defective components, in order to test the circuit board (and highlight defective components). Test results depend upon quality of the image database or image library, which is created from a populated board or boards. (Note: This point will be explored in more detail in the ROI portion of this article)

Image based technologies are designed to qualify a component by comparing its image to a collection of known good and bad images. The variety of comparison techniques range from the basic to neuronal networks, but the core question asked by an image based AOI is the same: “Does my current image look like one stored in my image bank?“

After making its comparison, the image-based machine will either respond with: “Yes, it is a good component,” or “No, I must compare to the next image in the bank.” The comparison process continues until the component is failed or a suitable match is made.

Due to process variability, image based systems must consult a large, and oftentimes growing, image database, which can have an adverse impact on cycle time. Some image based systems try to compensate for this cycle time impact by creating models of process variability using a statistical approach with high-speed image acquisition. With this method, the huge image bank is simplified by calculating for each pixel the average and standard deviation of grey level value. During the inspection process, the “distance” between each model and each real component image is used to pronounce a verdict -- good or bad. As this AOI captures images of more components and adds them to the image bank, the “statistical” image becomes fuzzier, and the AOI becomes incapable of separating the “good” component from the “bad” one.

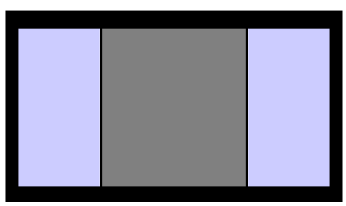
Algorithm Based AOI

Using mathematics and geometry, algorithm based AOI systems employ pattern recognition techniques to locate a component within an image. Instead of comparing one image to another, this technology uses a defined pattern (geometry or skeleton of the object) to find it in the picture.

This is very powerful technology because the component is defined only by its shape, regardless of grey scale or pixel information. Algorithm technology also offers better accuracy because there is no need for pixel matching, and changes in the process environment have no adverse effect. Slight color changes of the component or circuit board do not impact the algorithm based AOI's ability to identify the component with accuracy. The following pictures illustrate how pattern-matching technology works to find an object within changing environments and different lighting conditions.

In our industry, this technology is applied by defining a pattern linked to a component. The first step is to define the pattern that characterizes the component. For example, the following patterns could be use to define a capacitor 0201 or 01005:

(a)



(b)

The definition could be made using "synthetic images" (a) or simply by defining the shape of the component (b).

Once this information is saved in the inspection program, the vision system analyses real-time images to find the pattern in the right location (defined by the component's Reference Designator and X, Y, & theta). There are several techniques for doing this, but the most accurate is called Vectoral Imaging. As illustrated below, the vision system highlights the boundaries of the component by a series of vectors (green fragmented lines).

Using mathematical interpolation and sub-pixel resolution, the vectors more closely match the exact shape of the component than the pixel grid. This provides much greater accuracy when matching the component to the machine's component library.

When inspecting solder joints, lifted leads or bridges, location of the component (body of the component) is critical and this level of accuracy is required.

The key factors to understanding the differences

How do we translate the differences between image and algorithm based technologies in metrics that matter to our industry?

Given that the first objective of AOI use is to reduce PCB defects, the system must be effective in detecting all defective components at the stage of production where the machine is used. Experience shows, in some circumstances, AOI could miss some defects. This is usually measured by the metric called false accept rate (FAR), expressed in ppm (parts per million) and calculated by the ratio of the number of false accepts to quantity of tested components.

Often FAR is associated with another metric called false calls rate (FCR), which measures in ppm the number of good components found as defective. The FCR has a direct impact on the process flow and the quality of your process. If the false call rate is too high, the probability of letting real defects escape the system is much higher. Have you ever witnessed an operator performing PCB review, accepting false calls while overlooking a real defect? With a high rate of false calls, this operator is prone to miss the real defect by being lulled by the large number of false calls. The real defect becomes a false accept because the operator was not diligently looking for a defect.

Cycle time (CT) also is crucial to the SMT process and AOI should not be the bottleneck while performing 100% inspection. In some cases, certain AOI machines are required to deactivate some tests in order to achieve cycle time.

Most potential AOI buyers use AOI programming time (PT) as a key factor in choosing a machine. The PT factor includes transforming data from CAD to a working inspection program, then fine-tuning the program to compensate for variability in the manufacturing process.

Other key factors include Program Portability (PP) and Process Control (PC). The first, PP, is of great importance for users who will run multiple PCB assembly lines. When a need arises to move production from say, “Line 1” to “Line 2”, running the same AOI program, without time consuming modifications, is essential. The second key factor, PC, is critical to customers who not only want to catch defects, but improve the manufacturing process by finding the cause of the defects then correcting; AOI capabilities such as accuracy and repeatability are essential to both of these key factors.

Programming Time on Image Based AOI

Usually, people are introduced to AOI at the programming stage. A great opportunity exists at this stage for discovering the power and capability of the equipment and learning techniques for finding defects and achieving 100% PCB inspection. It is here that the two AOI categories, image based and algorithm based, diverge and become two distinct programming methods. The image based AOI first acquires a bank of images for a program, and programming seems very smooth as the first boards are learned by the machine. But in simply teaching images, the question arises, “What did the programmer achieve so far?” By capturing images from the first few boards, the machine learns only from a sampling of the lot being tested. When these same boards are inspected a second and third time, the program appears stable and ready for mass production. This teaching process is repeated on other PCB’s of different designs and components, and additional programs are created using the small sampling method. To someone unfamiliar with different AOI machines, this programming appears amazingly fast and efficient. When programming a quantity of different products (shown as N), overall programming time appears to be N multiplied by the amount of basic programming time.

Algorithm Based AOI Programming Time

Programming an Algorithm Based AOI greatly differs from machines that first learn images. (In fact, on an algorithm machine, a user can program offline from data while a PCB still is in the design stage.) Based on mathematical and geometric data for each component and the circuit board upon which the component will be placed, the machine applies algorithms to test each part when board assembly begins. Most of this information is contained in a library, which is linked to the current program and tuned by incorporating current process variation (clear variability affected by the PCB and process). This tuning process often is seen as more time-consuming than teaching images on an image based system, but when programming subsequent products, the same library is used and time spent fine-tuning is recaptured.

When comparing PT from the first product to the last (Graph below), you can see that when time remains “constant” for an Image Based AOI, it decreases substantially decreases for the Algorithm Based AOI.

False Calls and False Accepts Rates

As previously mentioned regarding programming, Image Based AOI machines appear fast and show impressive results on short production runs while Algorithm machines require more time to program. However, as production grows from a few PCB’s to just 30 or 40 boards, it is worthwhile to compare these systems further.

False Calls and False Accepts are the most critical factors when considering AOI machines. Again, catching a defect is the primary function of any AOI. The Image Based system, using its bank of images to segregate defective components from good ones, must quickly grow the quantity of images in the bank to allow for process variability. At the same time, the image-based system is very dependent upon the operator who captures these images and feeds the database. This person’s judgment of each flagged component (false call or real defect) is key to growing the image database to allow for variability, and any mistake leads to confusion. In other words, when an operator classifies an image to use it as a reference, he or she mistakenly could reference a defective component as good and vice versa. To be effective, an AOI must eliminate operator error and accurately segregate clearly defective components from good ones. If we graph the criteria for good and defective components with two Gaussian curves, the more detailed and efficient testing methodology of an Algorithm Based AOI shows clear discrimination and separation between the two curves, representing stable and reliable results (see graphs below).

Using an Image Based AOI associated with an image array or databank, the risk for unclear criteria is higher because images from good and defective components often appear very similar in appearance to an operator. Moreover, as the operator populates the database, any misjudgment will lead to more confusion. In this case, both Gaussian curves become closer and overlapping. The area between the curves represents confusion and generation of false calls and false accepts.

With an Algorithm Based AOI, criteria are established using geometric measurements and thresholds, which produce a clear divide between good and defective components whatever the process variation. This insures a stable and reliable inspection process for the life of the product.

For the Imaged Based AOI to maintain the very impressive performance it achieved on a few boards (<50), the core element (the image database or criteria) must grow with more and more images as process variation occurs. This blurs the criteria due to the operator judgment factor and leads to poor results on longer production runs (High False Call Rate and High False Accept Rate).

On the other hand, Algorithm Based AOI with “hard data” programming (based on measurements and threshold) offers a very stable and reliable long-term solution.

Cycle Time (CT)

AOI CT--the time to load, inspect and unload a board--is driven mainly by the CT of all equipment in the line required to produce a specific product of given specifications. In the AOI segment of the line, mathematically reducing pixel size will increase cycle time and most AOI systems must trade away detection of very small component features and defects to gain speed. To overcome this issue, some systems are equipped with multiple cameras. There are two camera systems, for example, featuring a low and high-resolution capability and correspondingly different FOV. Multiple camera machines selectively inspect very small parts with the higher resolution camera. But implementing a multiple camera machine in production adds cycle time and limits flexibility.

Another approach is to address the CT issue with algorithm technologies to improve resolution without decreasing FOV, which slows the inspection process. One such technology is known as “sub-pixel”. Algorithm based AOI’s improve resolution by a significant factor by processing images with this method. There is no time penalty when inspecting small features or components with sub-pixel algorithms.

Additionally, when an assembly process has a lot of variation, CT can be a problem for image based AOI because the machine must check against a growing number of images in the database. The image bank grows in order to maintain an acceptable number of false calls. It takes more time to process multiple image references for each component. This is one of the most prevalent complaints from users of image based AOI.

Program Portability (PP)

This is critical, not only for large manufacturers with several SMT lines, but also for smaller shops having only 2 lines. An inability to use the same inspection program on both lines is a huge problem in terms of resources and costs. Image Based AOI users face this issue more often than algorithm based users simply because of this need for images. The camera and lighting in Line 1’s AOI, for example, would have to be a duplicate of those in Line 2’s machine in order to have program transportability with like images. In other words, a programmer would be required to match images from line to line using two very similar, but slightly different vision systems.

Algorithm Based AOI programs exclude real images and base inspection on component and circuit board measurement. When these machines are properly calibrated, programs are completely transportable and exchangeable from one AOI to another. This clearly impacts the cost of ownership by reducing programming and eliminating the need to collect more images.

Process Control (PC):

More and more users wish to use AOI to control their process. But to guarantee successful PC, the AOI must be accurate and repeatable to provide the best data. Using a bank of images to inspect components cannot provide best results as this method is based only upon what has been inspected previously. It makes no allowances for process variability and excludes precise, detailed definition of what is to be inspected. Moreover, image based machines learn “on the fly” with operator input and often require loose tolerances at the inspection stage to lower the false call rate. Process Control becomes difficult, if not impossible, to implement with such data.

On the other hand, algorithm based AOIs measure the component with reference to the CAD data and criteria that are not based on any learned characteristics. These systems rely on the real component’s geometric shape as defined in CAD. This method provides accurate and repeatable data to supply to the Process Control software. Algorithm based AOI machines have been used since 2002 for process and closed loop control. They remain the system of choice for manufacturers who require rigorous process control parameters for their assembly lines.

The table below summarizes pros and cons of both AOI categories:

	Imaged based AOI	Algorithm based AOI
Programming Time	✓	
False Accepts Rate		✓
False Calls Rate		✓
Cycle Time	✓	✓
Program Portability		✓
Process Control		✓

With fast programming and cycle time, image based AOIs are very impressive during demonstration or the first few days of use. Soon thereafter users begin to suffer from high false call rates, poor defect detection and lack of portability. This clearly impacts quality and adds cost.

The Facts

The value of any AOI is in improving and maintaining quality in the manufacturing process by reducing the overall number of defects. In order to measure the amount of value an AOI can provide, we calculate ROI, including all costs directly linked to the system and all savings that can be achieved at test and rework, plus reduction of field returns occurring after AOI installation.

ROI calculations often are complex, so for purposes of this article we offer a simplified methodology, which does not include all possible savings (e.g., ICT coverage reduction). This simplified
ROI should provide a fair comparison of both categories of AOI technology.

The method used is called Net Present Value (NPV), which sums all the cash flows linked to the investment, costs and savings for a period of 5 years (a common depreciation period). Furthermore, this method makes a simple comparison using the following AOI assumptions:

- Average sale price of Image Based AOI is significantly lower than Algorithm Based AOI (50% lower in that case)
- No engineering required for Image Based AOI
- Engineering required for Algorithm Based AOI (20% of full time engineer (for 5 years)
- 1 full-time operator for Image Based AOI (for 5 years)
- With Algorithm Based AOI full-time attention is not needed (20% of full time operator for 5 years). Most of the time, line operator acts as AOI operator as well.
- Yield improvement on algorithm based system is 20% higher than an image based machine--process dependent

NPV results will have the following trend:

Given these conditions and despite a heavier upfront investment, the Algorithm Based AOI is able to generate up to $140,000 in savings over 5 years compared with only $35,000 in savings on an Image Based AOI over the same period.

Moreover, running the same calculation and assuming that quality improvement will be the same for both types of AOI machines, the algorithm based system remains a better investment than the image based AOI because it reduces defects and shows a lower cost of ownership. Reviewing overall costs and savings shows that the reduced upfront investment is not in the best interest for the customer from either a savings or quality standpoint.

Conclusion

Because there are many AOI choices from multiple manufacturers in today's market, any company looking to add or replace AOI technology would be well-served to come back to these basics:

- Technology
- Quality Improvement
- Return On Investment

These basic elements represent the real *added value* of an AOI system to a user's process. This paper explains the important features of AOI machines and highlights their impact on successful AOI implementation. It provides future AOI users the tools for selecting the right equipment.

Too often, a quick demonstration showing fast programming and implementation does not reveal the true cost of long-term AOI ownership, leaving the user to continue to invest great effort into inspection process improvement.

References

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