Real-Time Radiography
Automated X-Ray Inspection Strategies

Nicolet Imaging Systems

by: Frank Silva 1998
Presented by: Fred Schlieper

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Introduction

The electronics industry is marked by constant change. Continued miniaturization and the constant drive to increase I/O, decrease PCB size and fully populate both sides of the PCBA assembly creates a challenging production environment to say the least. It is noteworthy to state that the success of PCBA assembly, in the face of these challenges, has not been the result of chance nor will it be in the future.

The rate at which change takes place in the electronics industry is also at a fast pace. New designs, package types, and the latest equipment are constantly implemented to meet new product requirements and this places serious pressure on the PCBA manufacturer to achieve high first pass yields in a cost-effective manner. There is no doubt about it, this pace will continue and it is certain to become even more aggressive.

To keep pace, manufacturers must continue to exploit the very products they are creating by using them to work smarter. To quickly adapt to the changes which PCBA manufacturers face on the production floor, greater adoption of automated process monitoring must take place. The use of computerized data collection, data display, and the ability to quickly distribute the information to the correct resources is key to successful SMT manufacturing in the future.

But what about product reliability? Product reliability may not be keeping pace with the current product development rate. Electrical interconnect reliability, although improving, may not be doing so at the same rate. Have we reached the limit in our ability to examine connections? We are witnessing a package change revolution as never seen before. With fine pitch and more quality-demanding package types, the task of increasing both performance and reliability at the same time becomes more difficult. And since manufacturers are pursuing ever more aggressive designs, can both performance and reliability goals be combined into a unified production strategy in a cost-effective manner?

This is the question that has prompted so many electronics manufacturers to implement zero-defect or six-sigma quality improvement programs. The goal of six-sigma is to achieve a manufacturing process that produces fewer than 3.4 defects per one million opportunities (3.4 DPM). Combined with a Total Quality Management (TQM) ideology, these programs have shown significant advance in accomplishing the tasks of improving performance and reliability. In some instances, improvements of several orders of magnitude have been accomplished.

With all these manufacturing ideologies and advancements, where are the restrictions that currently slow or prevent further improvement? It is becoming clear that the ability to control the soldering process hinges directly on the ability to make proper process measurements. A key solution to assure the continued success of SMT assembly and the achievement of high product quality will lie in technologies that offer a path toward total process control. One of these technologies is automated X-ray inspection in either its 2-D transmission or 3-D digital tomosynthesis form.

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Factors to Quantify: Product Reliability and Process Capability

With the advent of advanced and smaller packaging geometrys, direct process control has now become mandatory for competitive PCBA manufacturing. Even so, most manufacturers maintain the mistaken belief that controlling the process is the most difficult task in achieving the necessary product reliability. In actuality, making the proper process measurements is where the difficulty arises.

Here are some no-nonsense definitions of two terms commonly used in the electronics industry:

- **Quality** That physical state necessary to have a reliable product
- **Reliability** Performs to specification without failure

By these definitions, in order to predict product reliability, regardless of its physical complexity, we must know it's physical state. But how can we know the physical state of solder interconnects, the most error-prone feature on completed SMT board assemblies? Right now the two methods predominantly used to accomplish this task are human visual inspection and in-circuit electrical testing (ICT). But these two techniques do not reveal the critical features that indicate the physical state of solder connections. In addition, these inspection technologies do not offer variable data that is sufficiently accurate and repeatable so as to enable adequate process control.

We know already that ICT works well in locating errors related to electrically malfunctioning devices. ICT also does a fair job of characterizing solder connections as either open or closed. However, electrical testing does not reveal information associated with product reliability such as solder quantity and distribution, which may have significant impact upon board performance over time. Likewise, ICT does not provide process control data, nor does it add value to the process. We can see that electrical testing will always remain a necessity so long as components are suspect for failure. However, because of today's PCBA environment, test access is becoming even more limited. The long-term viability of both human visual inspectors and ICT is uncertain.

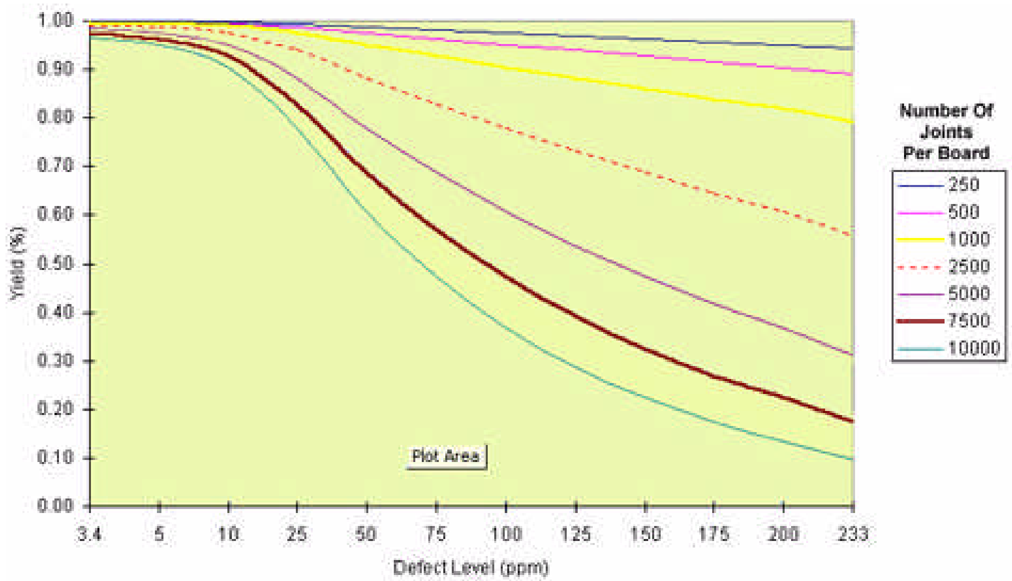
Working with the outmoded methodology of using human inspectors to guarantee product quality will never help achieve world class product reliability or manufacturing practices. The human inspector just cannot provide the necessary data collection capabilities to accommodate process control in today's manufacturing environment.

Process verification with process control is a necessary step to achieving world class quality goals. Machine vision has now become a mandatory element to control those processes that pose the most significant roadblocks to manufacturing a reliable product. By applying measurement and control mechanisms to "direct" the process in the correct way, lower defect opportunities can be realized.

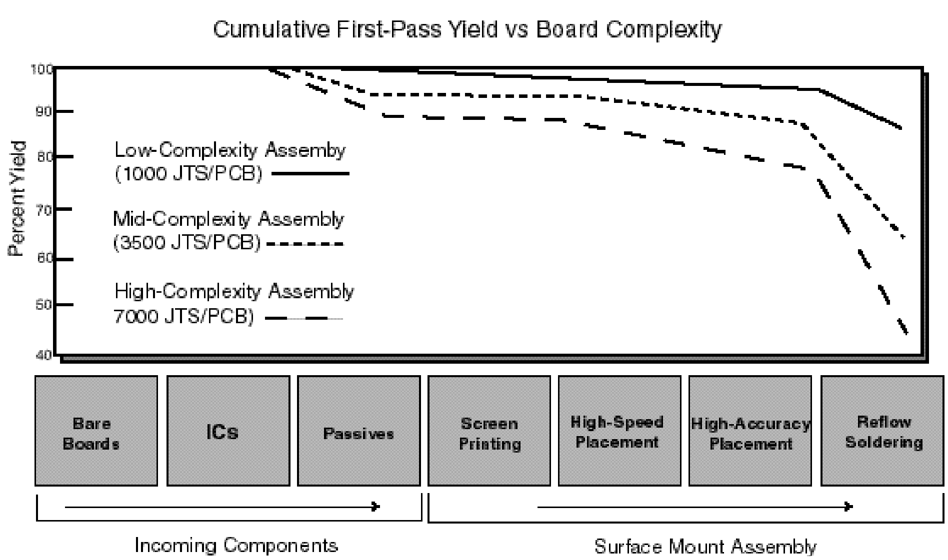
Yield (Board Yield vs. Defect Level)

Prior to considering a manufacturing inspection or test strategy, two topics are important to review. Critical to time-to-market and competitive manufacturing is the achievement of high yields with a low defect rate. Additionally, the opportunity to induce defects in any one stage of the process and the capability to measure features and properly identify defects should be areas of great concern to PBCA manufacturers. Both of these issues, yield and defects, directly relate to the ability to manufacture at cost competitive rates.

Figure 1 (below) shows the relationship between the number of solder joints on a PCB and the theoretical yields versus defect rates. Certainly today as electronic packages and products continue to shrink at an ever increasing rate, achieving higher yields while more and more joints are added to a board is becoming increasingly difficult, not to mention more costly.



Defects are introduced from a wide variety of sources. Figure 2 (below) provides insight as to how yield is affected by the various process stages. Each stage in the SMT process will introduce different, and in some cases more difficult, challenges in which to control yield and the potential opportunity to introduce solder connection defects. The influences and factors leading to the formation of defects and the impact on yield reduction must be well understood and characterized to avoid the production of defects and improve yield.



To achieve low DPM rates, rigid controls must be in place at every stage of the production process. The point is to understand the process conditions that may lead to the production of a given defect and eventually prevent this defect from being produced altogether through process intervention. Easier said than done.

The key to high yield in the shortest possible time is to:

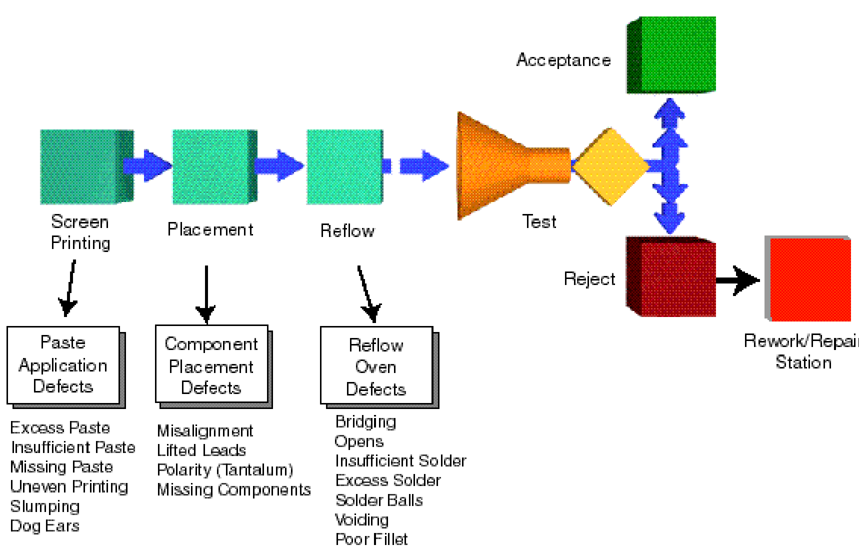
- Identify those variables that have the most impact on the reliability of the soldered connection.
- Concentrate on reducing and controlling the parameters that cause the variation in the first place.

Defects that propagate to the field must be avoided if a company is to be successful. Defect reduction will lower costs and ultimately improve product quality. Again, the yield chart illustrates the probability of introducing defects into the assembled board and reveals that successful SMT manufacturing must be driven by process knowledge and strict controls. This is made possible today with the adoption of automated test and inspection equipment that is capable of providing process monitoring and real-time data collection and display capabilities.

Stages Where SMT Solder Joint Defects are Introduced

Even in a well characterized and qualified process, defects will be produced. The introduction of new lines and designs will always produce a much higher defect rate until the process is characterized and changes are implemented to control the new production process. Higher lead counts and tighter process tolerances imposed by fine pitch and ultra fine pitch devices are combining to increase the potential for defects.

Defects can be introduced beginning with incoming material, but more frequently they are introduced during the assembly process itself. Figure 3 (below) illustrates the most common types of process related defects. Each stage of the assembly process contains opportunities for both random and systematic errors. Since the SMT process is a complex series of stages, the control of variation is quite demanding. Defects can be produced in any one stage of the assembly process and defects can be formed by interacting variables from each of these stages with the final effects exhibited after the reflow process. It is the marginal production of screen printing, component placement, and solder reflow that interactively lead to the formation of defects.



For World Class manufacturers, field data indicates DPM rates on the order of 150-300 for 25-20 mil pitch QFP's and below 100 DPM for 50 mil pitch and discrete devices. Even at these rates, the cost of rework and field returns can be quite substantial.

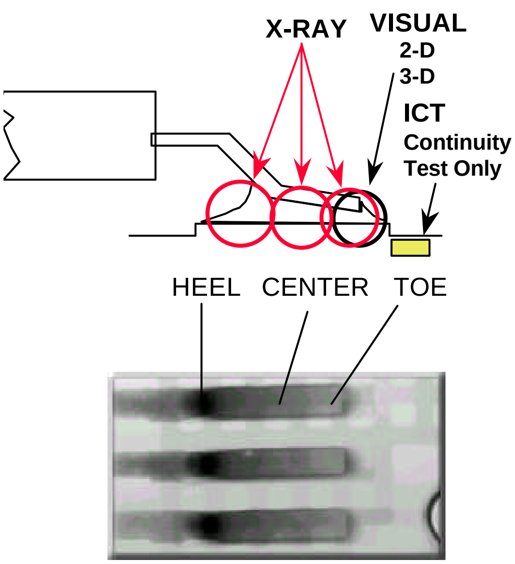
It is well understood that the cost per defect rises dramatically at the end of the production line. The logical conclusion is that a defect should be detected as early as possible to ensure a cost-effective operation. Further, the types of defects that can escape visual, optical, and electrical test techniques will likely be causes of field failures. Field and warranty repairs can cost manufacturers a tremendous amount of money as a result of service costs, replacement costs, and lost revenue due to customer dissatisfaction.

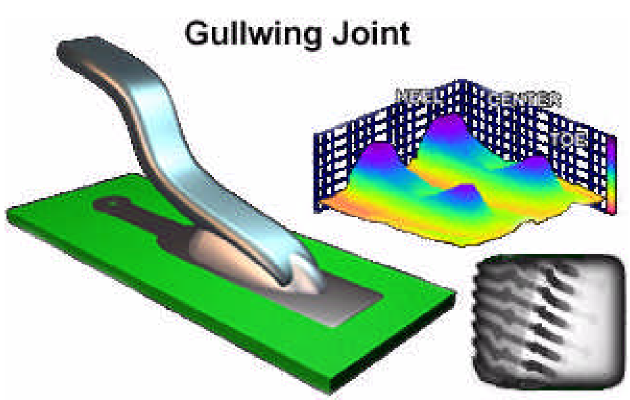
Common Process Inspection and Test Methods

On virtually every SMT manufacturing line today there are some type of process inspection and test methods employed. Many of these methods do not have the "access" or the data collection capabilities to keep pace with the changes occurring in SMT manufacturing. A review of the common inspection and test methods will be discussed with specific reference to inspection and test "access" and their respective data collection capabilities.

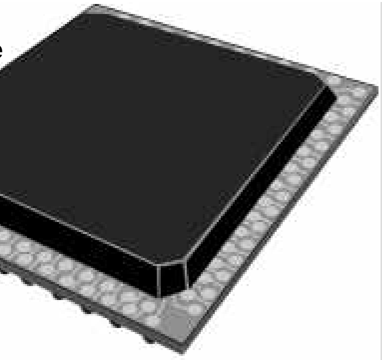
To effectively produce high yielding and reliable connections the use of automated process inspection and test equipment must be employed. This includes inspection / imaging test and electrical process testers. The key issue to consider is how effective the equipment is to help ensure product reliability and provide relevant information for use in process control. In the end the most effective solution will be a system which provides critical measurement data which can be monitored to help prevent the formation of a given defect.

Figure 4 (below) illustrates a gullwing connection and the ability of the various methods to access the heel, center, and toe regions of a leaded soldered connection. Today, with increased implementation of area array packages (Figure 5, below) access is reduced all together.

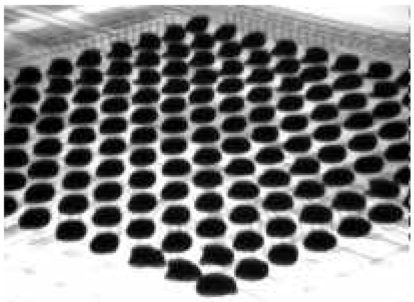




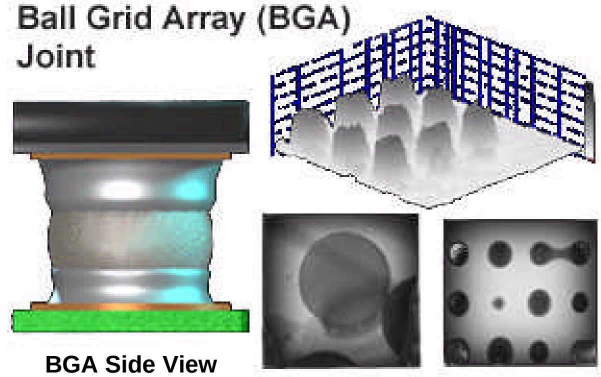
BGA Package



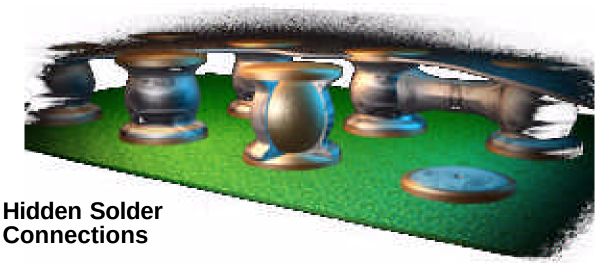
BGA X-Ray



Ball Grid Array (BGA) Joint



BGA Side View



Hidden Solder Connections

A Question of Access

Visual

The use of human visual inspection is the most commonly used PCBA diagnostic tool, as it is considered to be the most adaptable and cost effective. However, today, visual criteria for solder joint quality assessment becomes less practical in many cases, due to the extended use of hidden connections and fine pitch devices. Visual inspection can also be very misleading. Problems with solder joint reliability have little to do with outward cosmetic appearance or adherence to workmanship standards (Ref. 2). The overall effectiveness of this inspection methodology to access the soldered connection properly is quite limited and subjective. In addition, the ability to make meaningful measurements and collect data is limited at best. Yet, this approach is the most widely used method employed worldwide.

Even with the best microscopes available, the human visual approach will forever be limited by:

- Fatigue
- Line of sight
- Ability to make reliable and repeatable measurements
- Technology

Traditional approaches to ensuring quality standards in the manufacturing environment have always relied upon visual inspection. Although data from visual inspection has been used for process control, this data cannot provide real-time feedback, nor is it sensitive enough to provide fine-tuning enhancements necessary for rigid quality goals. Several industry studies have already shown that human inspectors catch fewer than 50% of all soldering defects. Every major manufacturer will agree that visual inspection also contributes to additional scrap cost, unnecessary rework and repair, and allows a high percentage of escapes. These escapes are the number one profit reducer for the manufacturer and manifest themselves in the form of warranty repairs in the field.

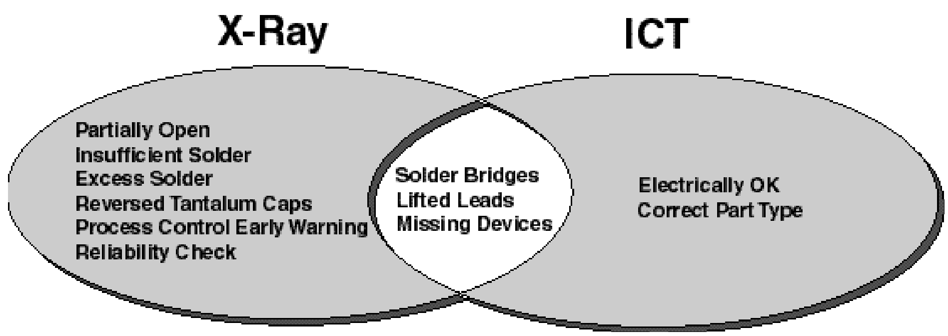
Many SMT manufacturers still consider inspection and test to be non-value added, nor strategic to the manufacturing operation, yet they employ a large number of human resources to identify cosmetic defects unecessarily causing good products to be re-worked and faulty components to pass inspection.

Optical and Laser Imaging

When a camera or laser is substituted for the human eye, and a computer is substituted for the human decision-maker, many uncertainty factors are removed from the inspection process. Yet these methods are still line-of-sight driven. Therefore, if you cannot see a feature with the naked eye, then you will not be able to see it with an optical or laser imaging system. Access to the complete solder joint is limited with these methods.

ICT

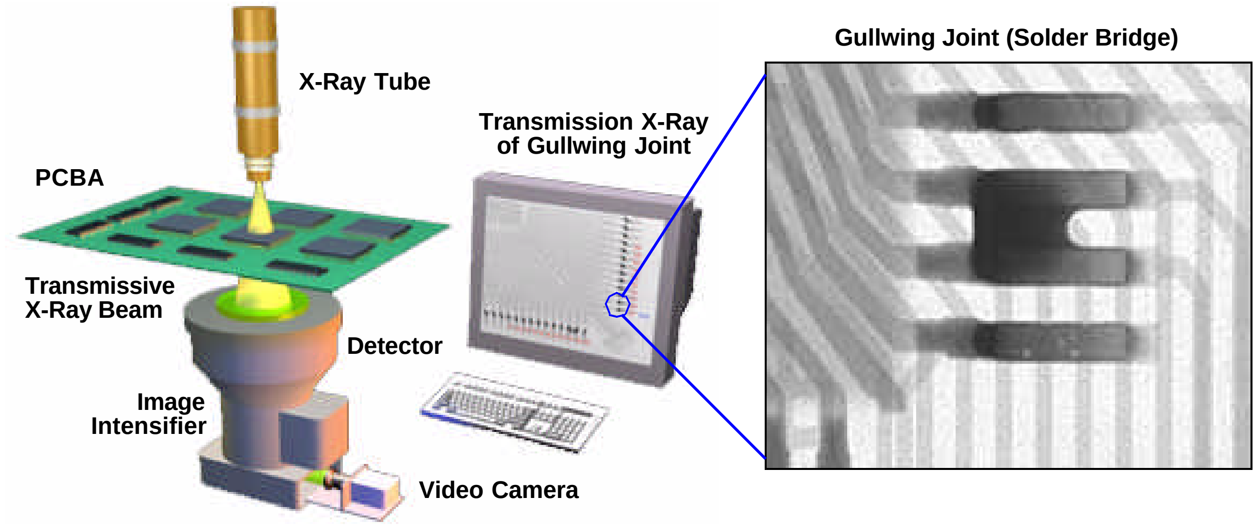
The use of ICT is mainstream and it is good at finding opens, shorts, defective and wrong components (Figure 6, below). However, ICT is essentially a contact test method. Access to the feature or test point must be designed into the PCB. Without these points ICT is rendered useless. Additionally, like the human inspector, ICT can also be misleading. By the very nature of the contact process, the test probe or nail can induce an electrical connection on a partially lifted lead. With the trend toward high-density, double-sided assemblies, which especially evident in the telecommunications industry, there is a transition from full test access



X-Ray Imaging

X-ray is a unique inspection method that offers the most complete information regarding a soldered connection, whether that connection is a J-Lead, Gullwing, or completely hidden (BGA, FCA). The X-ray image provides heel fillet data directly behind and under the lead. Other X-ray information from this area reveals possible partial lifted conditions, as well as errors that occur in optically hidden portions of the assembly, such as solder balls that may exist under components.

X-ray images provide information about solder mass and solder distribution of SMT connections. Figure 7 (below) illustrates a 2-D Transmission X-ray imaging train useful for inspection of single-sided PCBAs. The “access” to the soldered connection that 2-D X-ray imaging provides is along the entire pad connection, contact length (Figure 8 below). Because the X-ray beam is transmitted through the circuit board, such imaging allows for the entire solder joint to be imaged, inside and out, optically hidden or not. X-ray images contain three dimensions of information. Two of the dimensions are represented spatially in (X) and (Y), and the third dimension is represented by a gray level intensity value. The gray level within the image is directly indicative of the solder density and thickness (mass). By utilizing these three dimensions of information, defects can be found and identified. But more importantly, such solder mass-distribution data, being a quantitative measurement, is ideally suited for process control.



Further 3-D X-ray imaging Figure 9 (below) provides additional access since it accommodates the inspection of the top and bottom side of PCBAs both in a single inspection sequence. Additionally, e-D X-ray allows the solder joint to be analyzed along any horizontal height plane or the package plane interface. This access capability is illustrated in Figure 10 (below) which shows a PBGA solder connection and the associated images at various height planes synthesized from several angled X-ray images.

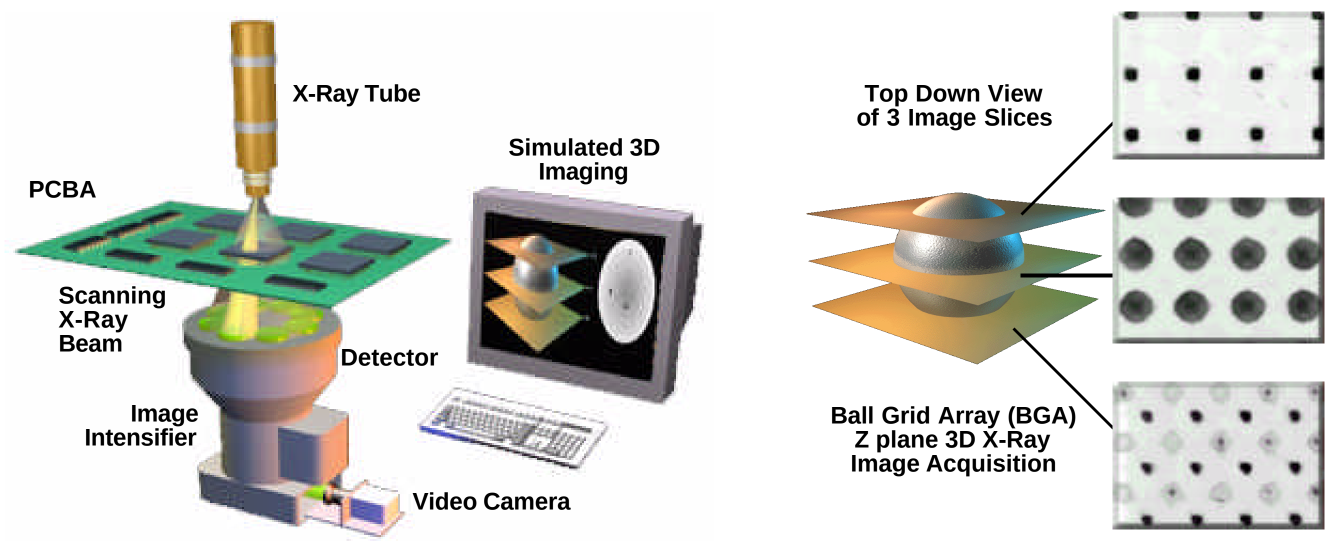
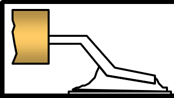
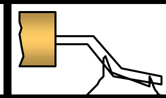
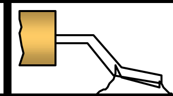
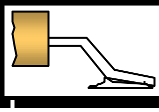


Figure 11 indicates the “access” which each inspection/test method provides and their respective capabilities to correctly evaluate a soldered connection. Again, unless a proper inspection or test solution is adopted information relative to product quality may be misleading to the SMT manufacturer.

	Gullwing Leads	X-Ray	Vision	3D-Laser	ICT
Example A Heel and Toe Fillets Structure Good		Accept	Accept	Accept	Accept
Example B Heel Fillets Only Structure Good		Accept	Reject (False Call)	Reject (False Call)	Accept
Example C Toe Fillets Only Structure Bad		Reject	Accept (False Call)	Accept (False Call)	Accept (False Call)
Example D No Fillets Structure Bad		Reject	Reject	Reject	Accept (False Call)

Process Information Capabilities

The ability to generate meaningful data is another important attribute for inspection and test equipment. While it is valuable to identify whether a board, a component, or a soldered connection is acceptable or defective (Go/No Go), it is strategic to generate and collect variable data.

Visual

Visual inspection methods provide one of the least opportunities to collect data which is relevant to process variation and the long-term reliability of the soldered connections. At best, visual methods can detect gross problems if they can be seen at all. An additional problem with this technique is there exists a significant delay from the time a defect is detected to the time corrective action can be taken. This delay time between available information and action, combined with the lack of process variation sensitivity, is not sufficient to control a process within six-sigma limits.

Optical and Laser Imaging

Optical and laser imaging allow for external features of the solder connection to be automatically measured. Such measurements include toe fillet presence (for gull wing), pin/pad offset, lifted leads, and solder bridging. Only in those cases when gross variations exist can such measurements provide insight as to the “survivability” of that connection in the environment to which it has been designed. Such optical means of examination, however, do not provide the necessary sensitivity for the most important measurement necessary to verify the integrity of the solder connection. This important measurement is of the area associated with the component lead-to-lead contact, also referred to as the pad contact length.

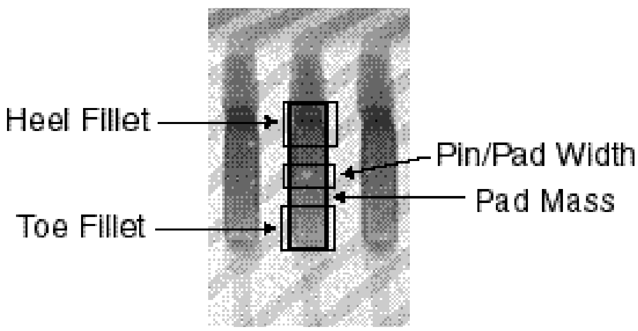
ICT

Similar to the human visual inspector, ICT has limited data collection capability. On an IC package soldered connection ICT basically provides Go/No Go data on whether electrical contact is made. Data regarding insufficient, excess solder, misalignment, in other words, useful process information cannot be generated using ICT equipment. While the several types of defects can be found and later classified there is no opportunity to collect variable or reliability data on the solder connection, just electrical function at the time of the test.

X-Ray Imaging

X-ray technology provides the most complete insight into the soldered connection from heel to toe and the associated fillet regions. Only an analysis technology providing an inherent transmissive imaging capability will reveal the pad contact and heel area to provide a measurement of these critical hidden features. Such technologies include ultrasound, thermal imaging, and X-ray. However, only X-ray provides the speed, accuracy, and repeatability necessary for a production environment. X-ray Inspection works at the solder joint level, and can see and measure features inside the solder joint including solder fillet shape analysis.

A significant quantity of data can be obtained from the X-ray measurement of SMT solder connection features. Many key SMT interconnect areas can be monitored through use of automated X-ray including: Toe Fillet Solder Mass and Location, Heel Fillet Solder Mass and location, Heel Fillet Solder Mass and Location, Pad/Lead Width, Total Solder Mass of the Pad, as well as fillet shape measurements. These are graphically illustrated in Figures 12 & 13 (below).



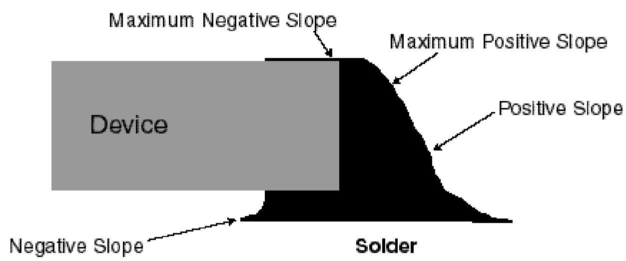
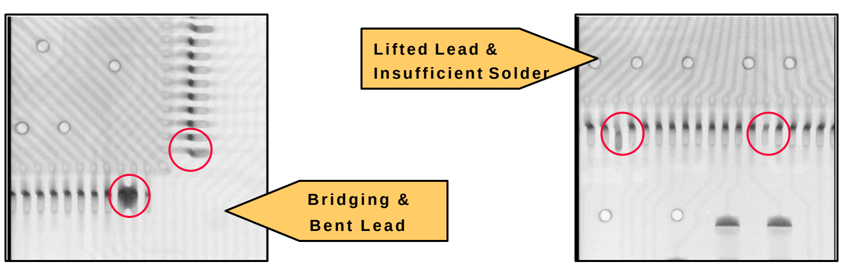


Figure 14 (below) shows several features of a soldered joint measured with X-ray, and the associated defect detection of fault cause directly at the solder pin level. By utilizing information form these solder distribution measurements, defects can be accurately found. Most important, the data may be effectively applied for process control in support of defect reduction programs of the factory floor.



Pin #	Condition	Length	Width	Off Position	Heel Solder	Toe Solder	Pad
1	Bent	35	1,833	22	15,496	1,803	13,343
2	Good	39	1,585	18	19,043	2,025	10,092
130	Lifted	36	1,517	18	12,777	2,194	14,848
140	Good	39	1,629	17	18,541	2,373	9,965
141	Insufficient	36	1,493	15	12,179	844	6,796
158	Bridge	42	2201	17	72,450	3418	5,879
159	Bridge	45	2185	16	21,269	3823	5,523

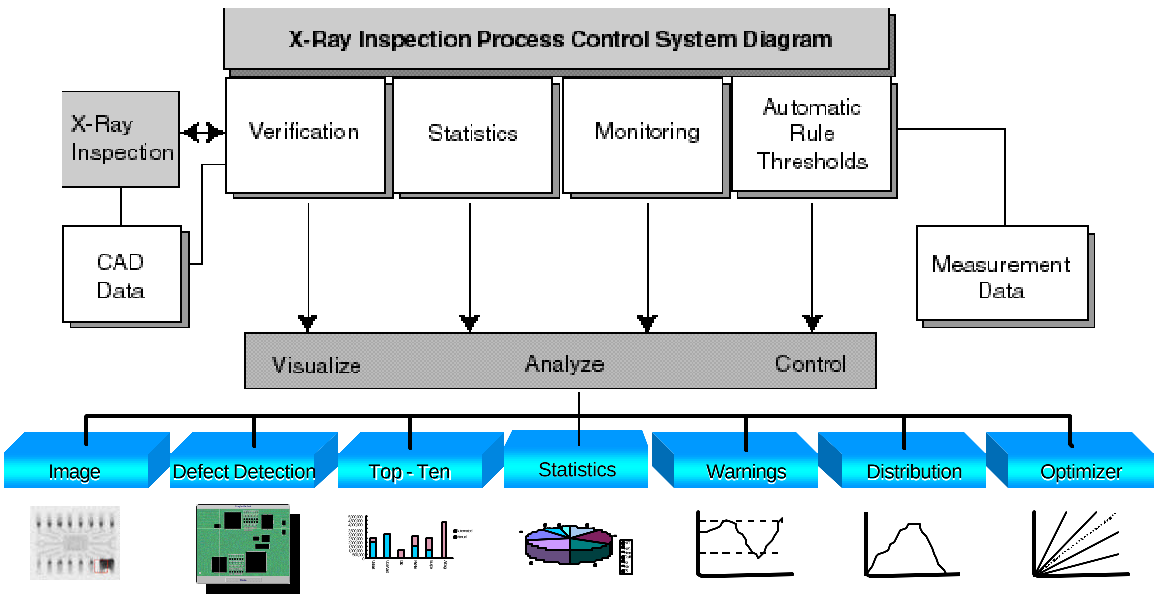
Proper process control demands that problems arising on the production line be controlled at the earliest time possible. Correcting the problem before boards are produced is not only desirable; it is necessary to support a six-sigma manufacturing environment. In addition, gradual trends that cause process deviation away from what is considered to be a "perfect" solder connection requires corrective action. X-ray offers superior sensitivity required for such measurements.

Using the data collection abilities of automated X-ray inspection allows for a knowledge-based approach to process measurements and control necessary for today's electronics manufacturing environment. Ultimately, by understanding the variations in the SMT process stages and later their control will lead to a highly competitive SMT operation.

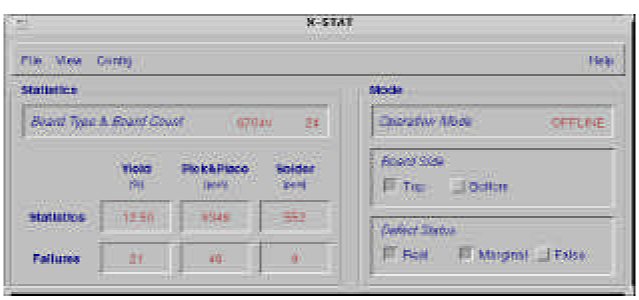
Strategies

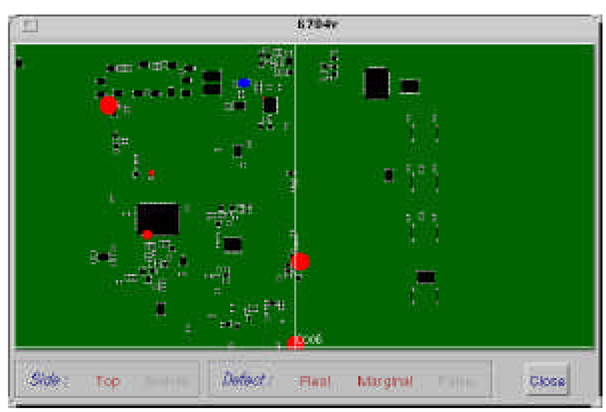
Process Control

Implementation of a computerized information system that provide visualization, analysis and control feedback on critical process parameters will support defect management. The block diagram in Figure 15 (below) provides the framework to piece together all the necessary inspection data to perform real-time process monitoring and control feedback. Such control schemes are commercially available and have been in use at highly competitive manufacturing facilities for the past few years.

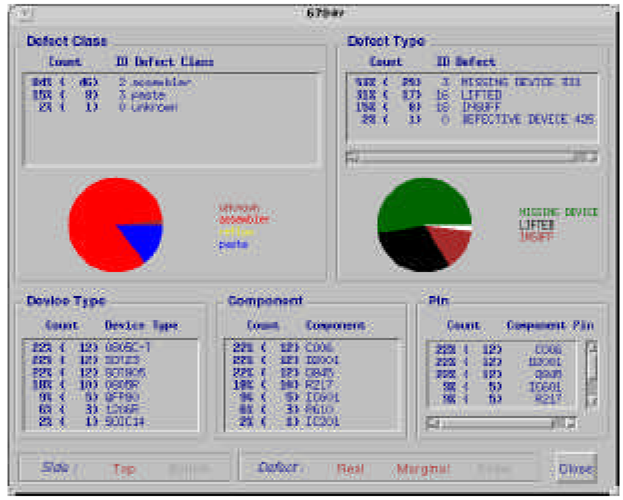


In today's electronics environment, process monitoring is a prerequisite to improve production efficiency, reduce costs and create a competitive and productive assembly. It is through the inspection and test process that data collection and the ability to provide defect detection, defect classification, and data measurement trends that knowledge of the variables which adversely affect the assembly process can be understood.





Real-time software solutions arm the SMT process engineer to realize and implement a process control strategy. Figures 16-18 (below) illustrate how the measured data generating during automated X-ray inspection can be complied and formatted to provide real-time on-line statistical display at the device, component and pin levels. Additionally, the problem areas on the PCB can be graphically represented to quickly pinpoint areas where frequent defects or faults are produced. Using information in this manner enables the fastest possible path to corrective action. Since this information is collected and displayed during machine run-time it offers immediate feedback regarding the performance of the line.



Point of Implementation

Automated X-ray is best utilized and implemented directly after the reflow operation. While, good control of the printing operation will help minimize the potential for defect production at later assembly stages, it is the reflow operation that finally forms the soldered connection. Definitely, there are still many variables that can later influence even a tightly controlled printing operation and ultimately produce defective soldered connections. So what about the double sided assemblies? Inspection and test strategies need to be implemented upstream. But for the double-sided assembly only 3-D X-ray imaging can separate top s from bottom side joints. Therefore, this inspection method is practical to implement after the second reflow or wave solder operations either in an in-line or off-line configuration. Definitely today, the use of a combination of inspection technique to collect data after critical process stages can be an effective SMT manufacturing strategy.

Frequency of Test

Just how frequent should one inspect or test the PCBA? If the process is not well characterized and the assembly is complex, then the key again to achieve high first pass yields and product quality will be through 100% process monitoring. After careful process characterization and product reliability testing, if a understanding of the critical process variables are developed, a high frequency sampling approach may still provide enough information for process control purposes. Depending on board complexity, many manufacturers are opted for the following test strategy frequency:

- High frequency sampling
- Sampling of known hot spots
- Monitor only SMT interconnections
- Monitor only top side active SMT components
- Monitor only fine pitch devices

However, it is worth mentioning that systematic changes in the process can be monitored through sampling approaches and SPC, if the sampling frequency is shorter than the time it takes the process to drift. Additionally, sampling methods cannot cover the random defects that tend to contribute the majority of defects when the process is “in-control”. Random defects can occur anywhere on a board and can only be reliably detected through high-frequency sampling or 100% inspection. For high liability assemblies such as those found in many automotive electronics applications and high performance high cost telecommunications boards sampling techniques will not provide the path to competitive and quality manufacturing.

Six sigma process planning and the achievement to produce high yielding and reliable assemblies requires a commitment to use newer process technologies that anticipate, measure, control and define soldering issues, solderability problems, and minimize process variability. (Ref. 2) The key isn't just to find a defect immediately or just after the defect is produced but to prevent the likelihood of even forming a defect.

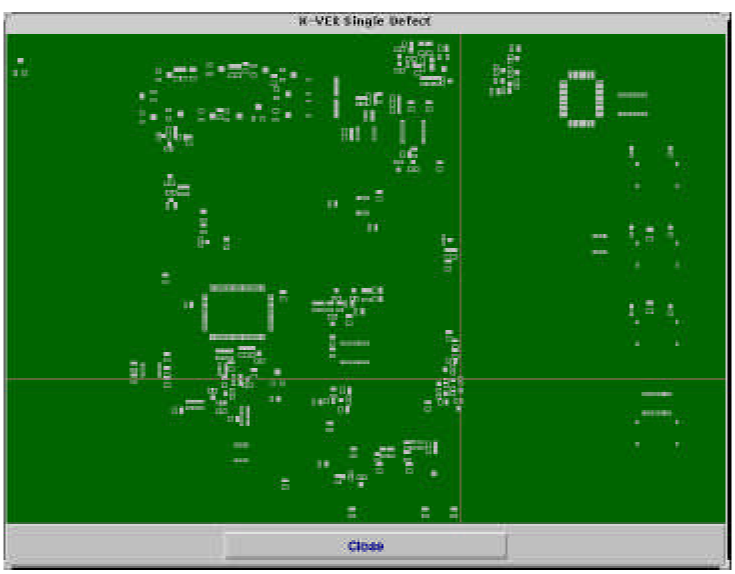
Integrated Strategies

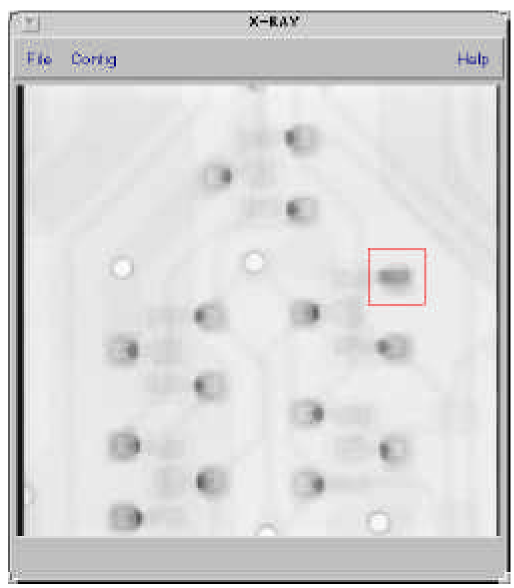
Today the widespread availability of networked solutions will allow integrated manufacturing strategies to become more mainstream. Such solutions will pave the way toward directed closed looped process control in the future. But today, manufactures can at least realize benefits to help in repair verification and the sharing of critical information gathered across single or multiple manufacturing lines.

Repair Verification

Defect detection information generated at the time of X-ray inspection can be immediately networked to a repair verification station prior to any touch up or repair operations. At this operation, personnel can verify the defect using operation, personnel can verify the defect using the visual aid of an X-ray image and graphical representation of the PCB board Figures 19 - 21.

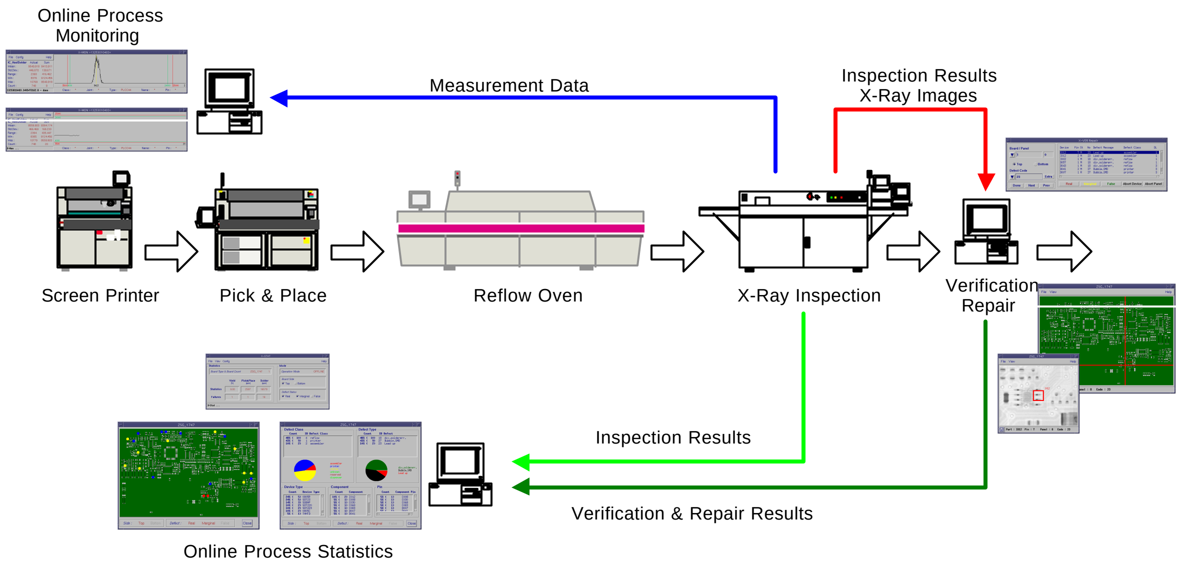
Additionally, at this stage, assignment of the equipment producing the defect can be input. If a connection is detected to be off-position then the likely cause of the defect can be attributed to the placement machine. Insufficient and excess solder would be attributed to the screen printing operation. In future SMT lines, the information generated from X-ray inspection and defect detection will help to automatically drive the repair and rework functions.

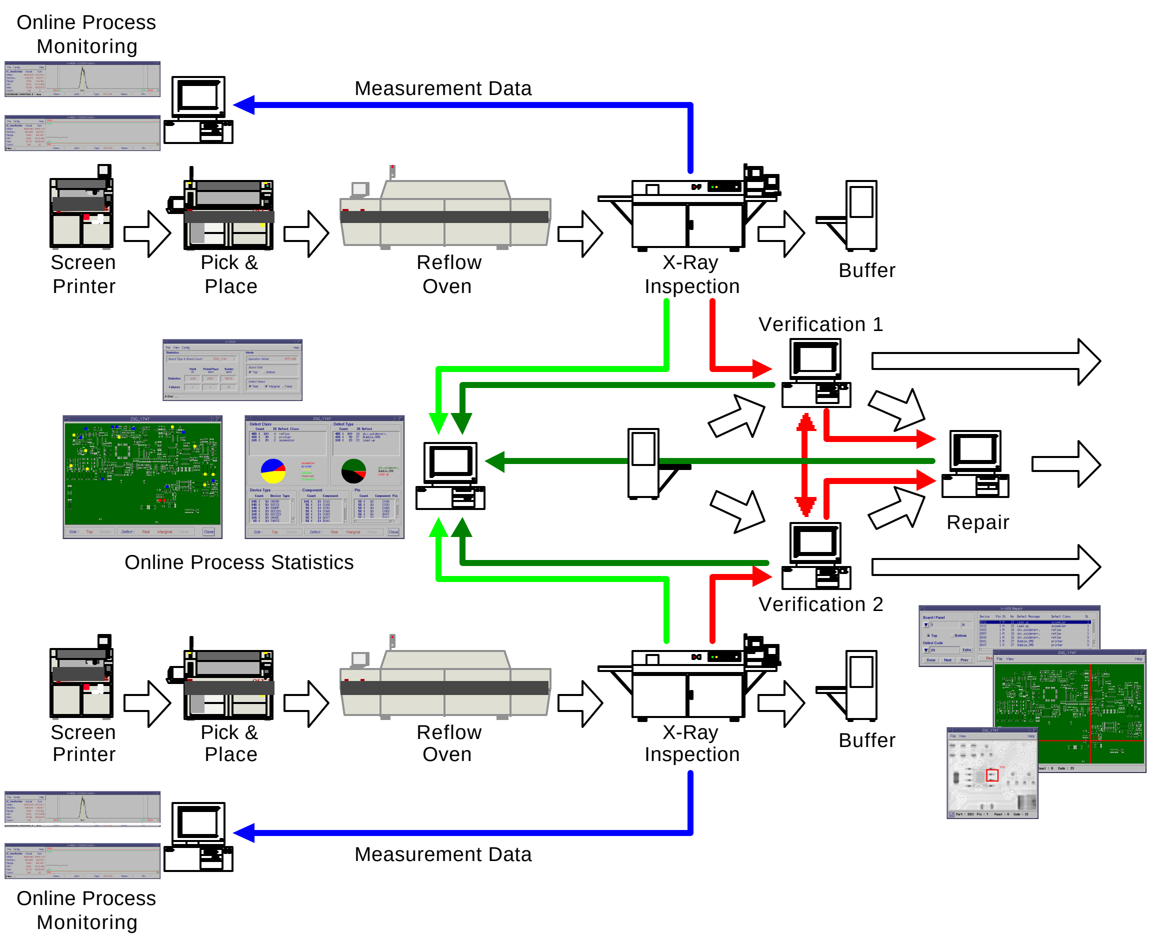




Collection & Display of Data from Single and Multiple Lines

The integrated strategy utilizes advanced networking capabilities enable the latest software combine data measurement and defect detection capabilities to provide and share process information with other SMT equipment and the factory network to create a process knowledge database. For example, display monitors can be stationed at various stages of the SMT process to present the critical process measurements that indicate how that stage of the SMT process is operating. Figures 22 and 23 (below) illustrate integrated strategies for both single and multiple line manufacturing assembly process.





Conclusions

Product quality can keep pace with the ever-changing world of SMT board design and manufacturing. But to keep pace, manufacturers must look to adopting solutions that utilize process data to limit and perhaps prevent defects, even on complex PCBA's with high joint count toward six sigma defect levels. Automated control offers the most effective solution to enable process and defect management. With recent advances in real-time software solutions, on-line data collection, and display can help manufacturers keep pace with their demanding environment.

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