Comparing Digital and Analogue X-ray Inspection for BGA, Flip Chip and CSP Analysis

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Abstract
Non-destructive testing during the manufacture of printed wiring boards (PWBs) has become ever more important for checking product quality without compromising productivity. Using x-ray inspection, not only provides a non-destructive test but also allows investigation within optically hidden areas, such as the quality of post solder reflow of area array devices (e.g. BGAs, CSPs and flip chips). As the size of components continues to diminish, today's x-ray inspection systems must provide increased magnification, as well as better quality x-ray images to provide the necessary analytical information. This has led to a number of x-ray manufacturers offering digital x-ray inspection systems, either as standard or as an option, to satisfy these needs. This paper will review the capabilities that these digital x-ray systems offer compared to their analogue counterparts. There is also a discussion of the various types of digital x-ray systems that are available and how the use of different digital detectors influences the operational capabilities that such systems provide.

Introduction
The telecom boom of recent years, and in particular in mobile telephony, has reinvigorated the need and use of x-ray inspection within the manufacture of printed wiring boards (printed circuit boards – PCBs). This has been mainly due to the use of BGAs and chip scale packages within products, providing ever-increasing functionality at the same or, indeed smaller, overall product size. Now that the use of these package types is so well established, they are being adopted into more and more products and using only optical inspection techniques no longer suffices. The critical opportunity that x-ray inspection provides during manufacture and test is the ability to see the joint quality underneath these packages without the need to destroy the device to make the examination. Optical examination is not possible, as the joints are hidden from sight. Furthermore, as the legislative and commercial requirements for lead-free PCB manufacture get stronger, the need to be able to inspect production quality dramatically increases because the historical benchmarks for good solder joints created with tin/lead solders are no longer the same for lead-free products[1].

Dramatic increases in the use of packages that cannot be quality-checked with traditional test equipment, or at least until very latest stages of manufacture, together with shrinking package size and pitch, has demanded that x-ray system manufacturers have had to improve the quality and the functionality of what they provide to satisfy the industry demands. Initially, this concentrated in moving from a closed x-ray tube to an open, or demountable, x-ray tube to provide the x-rays within their x-ray inspection systems[2]. This results in the x-ray systems of today providing dramatically higher magnification and substantially improved resolution compared with earlier products[2]. The next major development in x-ray inspection system design and functionality has been the ability to examine the solder joints at oblique angle views without compromising the available magnification[3]. Oblique views are critical for BGA/CSP analysis. If these features are only inspected from directly above, the shape of the solder ball will obscure the interfaces that need to be investigated. Traditional x-ray systems tilted the board/device to achieve angled views whilst the x-ray tube and detector remained fixed. In contrast, the recent developments in x-ray systems keep the board/device horizontal at all times and move the detector to achieve the oblique view. In this arrangement, the sample does not need to be moved away from the x-ray tube to prevent potential in-system collisions when an oblique view was needed, as used to be the case. Instead the sample can always be kept as close as possible to the x-ray tube, which by virtue of the geometric magnification that a system offers, guarantees the highest magnification is always available to the operator, whatever oblique view is selected[3].

The most recent development in x-ray inspection systems has been by manufacturers turning their attention to the detection part of the x-ray system so as to improve the quality and resolution capabilities of the analytical images their systems produce, and is the subject of the rest of this paper.

Analogue and Digital X-ray Detectors
Originally, all x-ray inspection images were produced on film; requiring wet chemistry to develop and fix the images, which could not provide the analytical information in real time. This approach could not be called either analogue or digital! Thereafter, the requirements for medical x-ray examinations resulted in the development of image intensifiers (IIs) as the x-ray detector, which can produce the x-ray image in real time and have been readily adopted by x-ray system manufacturers

for PCB and semiconductor applications. The image intensifier (II) works, in simple terms, by having an x-ray sensitive phosphor, such as cesium iodide (CsI), facing the x-ray tube. Any x-rays from the tube that have sufficient penetrating power to pass through a sample, placed between the x-ray tube and the detector, impinge upon the phosphor which converts the incoming x-ray photons into visible photons. These visible photons can then be seen and captured by an optical camera. A charge-coupled device (CCD) camera is the optical camera usually selected for this purpose. The output of the CCD camera can then be presented, real-time, on-screen for analysis. The only difference in the final image for PCB applications compared to medical x-rays is that the dark areas of the image show locations of more dense material, such as solder, and the lighter areas as less dense materials in the sample, such as the board material itself (see figure 1).

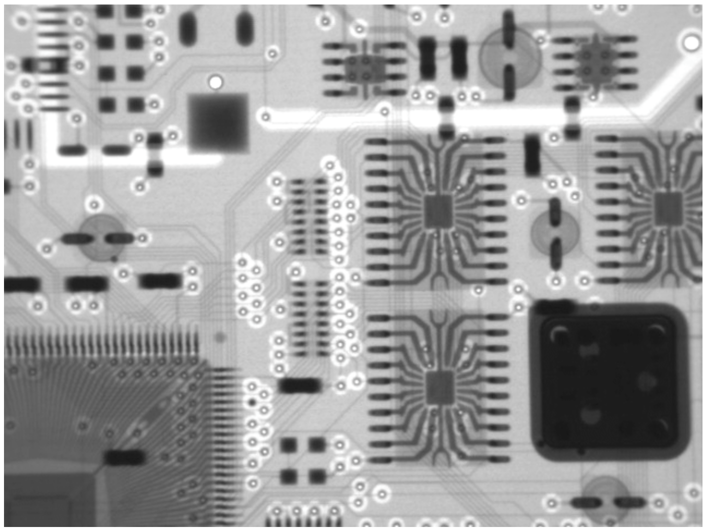

Figure 1 - 0.3 Mpixel Analogue Intensifier X-ray Image of a PCB

The cameras that have been historically used can acquire data at 25 frames per second (fps), hence the 'real-time' terminology, at 8-bit gray-scale. They have had around 640 x 480 pixels, or 0.3 Mpixels, per frame image, capturing visible photons from over the entire intensifier phosphor surface, typically a circular area of either 4" (100 mm) or 6" (150 mm) in diameter. The larger the diameter of the phosphor, the lower the resolution of the captured image with the same size camera. As an example, a 4" diameter image intensifier can have a resolution of up to 50 line pairs per centimeter (50 lp/cm). This is the standard available from most x-ray equipment manufacturers and is often termed an 'analogue' detector as the image information coming out from the CCD camera is in analogue format.

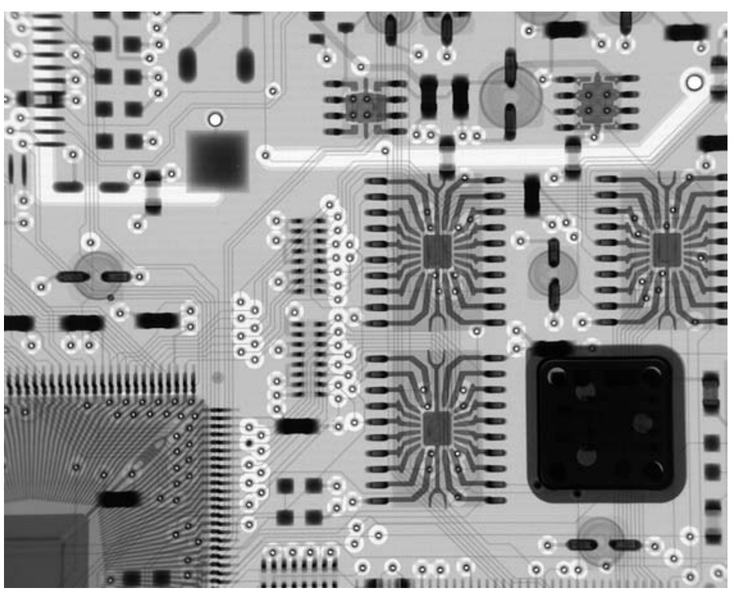

Figure 2 - 1.3 Mpixel Digital Intensifier X-ray Image of PCB in Figure 1

To improve the image resolution, image size and image gray-scale sensitivity still further, a variety of other detectors have been made available for some years from certain manufacturers, as alternatives to the analogue image intensifier. In addition to better overall image clarity over the standard analogue systems (see figure 2) allowing the opportunity for better analysis, the improvements these detectors bring to x-ray inspection can be particularly important at higher magnifications and for samples with little inherent x-ray contrast difference. Here, the much greater gray-scale sensitivity of these detectors allows better visual separation of features within applications such as non-conductive die-attach, voids in packages, voids in molding compounds and glob-tops, microvia inspection, etc. These different types of detector are all called under the same generic term of 'digital detectors'. However, there are a number of different technologies that can be used. The similarity between them is that the image data output is in digital instead of analogue format. Traditionally, these digital detectors have been available as expensive options to x-ray systems. But recently, some manufacturers have been able to provide certain digital detectors as standard within their systems without adding to the costs compared to analogue systems.

Digital vs. Analogue

Both analogue and digital detectors have the same basic parts. An x-ray sensor, of whatever type, converting the incoming x-rays into some other medium that can be measured or imaged, usually including some type of amplification. This is followed by an analogue to digital (a-d) converter, making the image signal into an easy format for the image-processing computer to handle. The major difference between analogue and digital is where the a-d conversion takes place, as seen in figures 2 and 3. In the analogue system, an analogue signal exits the detector and has to be converted within the image-processing computer. With digital detectors, the a-d conversion takes place within the detector itself and only a digital signal comes out of the unit.

With the above in mind, the difference between analogue and digital detectors would seem to be very trivial. However, the real differences for x-ray inspection of BGAs and CSPs comes from the nature of the x-ray sensor used together with its resolution, speed of operation and gray-scale sensitivity.

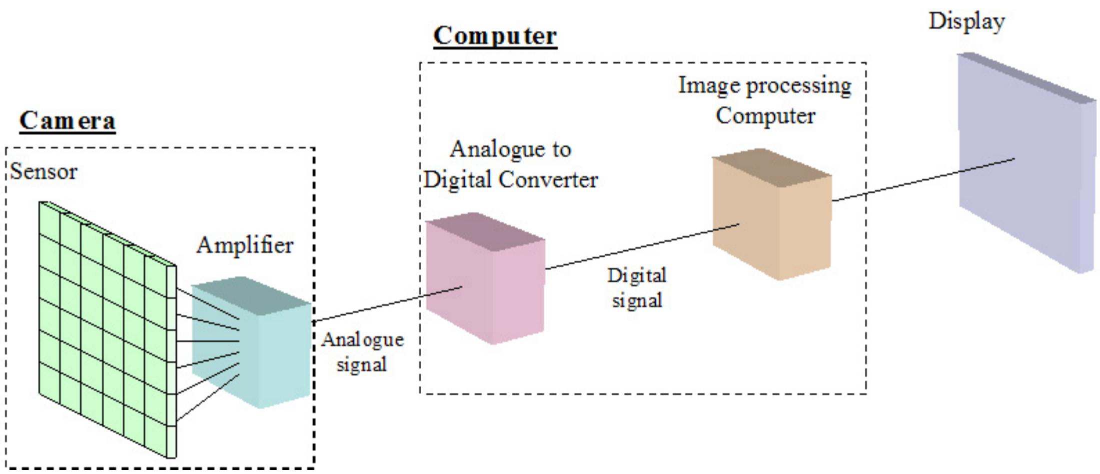

Figure 2 – Analogue detector based x-ray system schematic

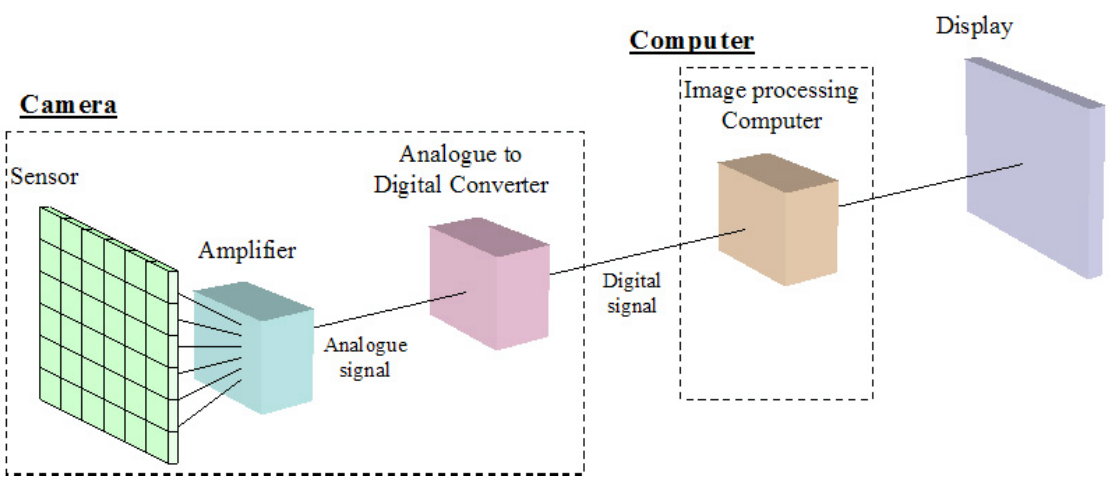

Figure 3 – Digital detector based x-ray system schematic

Possible sensors for digital detectors for x-ray inspection include:

- Image intensifier using a digital CCD camera – a digital image intensifier
- CMOS flat panel detector
- Amorphous silicon imaging panel
- Amorphous carbon with scintillator panel
- Fibre-optic plate with x-ray scintillator (FOS)
- FOS coupled to a CCD camera

Of the above choices, the two that are most commonly available for x-ray inspection of BGAs and CSPs are the digital image intensifier, using a digital CCD camera, and the CMOS flat panel detector. These will be discussed in greater depth as to advantages and disadvantages that they provide for PCB and semiconductor inspection. The rest of the possible sensor choices, using different x-ray sensitive materials, were all developed for the medical market as ways of replacing traditional medical x-ray films. As such, they are typically large in size, which means they cannot provide any magnification, they do not provide a live x-ray image that is so vital for quick inspection around a PCB and finally, they are very expensive. The FOS coupled to a CCD camera is smaller than the others are, but its performance is poor compared to either a digital image intensifier or a CMOS flat panel, and it is still very expensive.

Digital Image Intensifier vs. CMOS Flat Panel

The digital image intensifier uses the same x-ray sensitive phosphor in the analogue intensifier but a digital CCD camera of higher pixel count, gray-scale sensitivity and improved resolution replaces the analogue CCD camera. The CMOS flat panel detector also uses a CsI phosphor to convert the incoming x-rays into visible photons but instead of a CCD camera to capture the resulting picture, a two-dimensional silicon photodiode array is used. The optical photons from the phosphor create storage of electric charge at each pixel in the photodiode array according to the light intensity received. The charge is then transferred to corresponding data lines, periodically, from which a digital image can be recovered. A comparison of the features and performance of the two detectors can be seen in table 1 together with the equivalent information for an analogue intensifier as a reference. There are digital intensifiers on the market that offer fewer pixels and there are larger CMOS flat panels that have many more pixels. However, the most commonly available items within commercially available x-ray inspection systems are shown in the table.

Table 1 – Comparison of Features of CMOS Flat Panel Detector with Digital and Analogue Image Intensifiers

Feature	Analogue Intensifier	Digital Intensifier	CMOS Flat Panel
Pixel Size of Detector	640 x 480	1280 x 1024	1000 x 1000
Image Size (Mpixels)	0.3	1.3	1.0
Resolution (line pairs/cm)	50	72	80
Gray-Scale Resolution	8-bit	16-bit	12 or 14-bit
Frame Rate (frames/sec)	25	25	4

As table 1 shows, the performance of both digital detectors is substantially better than the analogue intensifier. Looking at the comparison between the two digital detectors further:

- The digital intensifier has a 30% greater image size compared to the CMOS flat panel (433% more than the analogue)
- The CMOS flat panel resolution is 10% greater than the digital intensifier (266% more than the analogue)
- The digital intensifier has 2X or 4X the gray-scale resolution of the CMOS flat panel (128X more than the analogue)
- The digital intensifier has > 600% faster frame rate acquisition than the CMOS flat panel (analogue has the same as the digital intensifier)

Using lower specification digital intensifiers can be compared separately. Much larger CMOS flat panels are available but have not been used in this comparison because their additional costs as options equate to having to add on a substantial percentage of the total x-ray system price for their purchase and thereby rules them out for typical PCB and semiconductor applications. Part of the reason why larger CMOS flat panels are more expensive than intensifiers is because of their high cost of manufacture through their requirement of large areas of processed silicon. This also results in relatively high levels of manufacturing defects within the CMOS flat panels, compared to CCD chips, that have to be disabled and removed from the data capture system to prevent the presence of failed detector lines within the x-ray image. The electronic removal of these defective sensors is not necessarily perfect, as the electronics puts in a ‘guess’ for the values that these missing elements should be seeing. At high contrast levels, these defects become visible within the final, analytical images.

The greater the number of pixels within the x-ray image, then the more detail there is available for inspection and this can allow operators to inspect BGAs and other PCB joints, for example, at lower magnification without losing the analytical quality. By not having to inspect the same part at additional higher magnification views, as might have been necessary with the analogue systems, then more time and money is saved on the inspection process without having compromised the test integrity. The small difference in resolution between the two digital detectors may be difficult to see when they are part of complete x-ray systems. This is because the final image to the operator will be through an image processing computer and output on either an analogue or digital monitor, which can change the final result from what emerged from the detector. The greater the gray-scale resolution then the more gray level exist to allow separation of subtle, low-contrast difference objects and features within the PCB or semiconductor device.

Binning the CMOS Flat Panel

The largest difference in specification between the digital detectors being considered is that of frame rate. This is the speed at which the detector can acquire images. The analogue and digital intensifiers can both acquire image data in ‘real-time’ at 25 frames per second. The CMOS flat panel is only able to acquire images at 4 frames per second, therefore not in real time. This is caused by the delay in response time of the photodiode array to the, generally low intensity, x-ray signals being acquired during inspection. The photodiodes require some time for sufficient charge build up before sending an acceptable image, something the CCD cameras can do much more quickly. Using the CMOS flat panel within an x-ray inspection system, therefore, means that several seconds of data acquisition must elapse before there is sufficient detail to be seen on the operator screen. It takes the CMOS flat panel 6X as long to acquire the same quantity of frames compared to the digital image intensifier. During x-ray inspection this delay in presenting an adequate image using a CMOS flat panel means that moving around a PCB can be difficult, as there is always the need to wait for the image to see if you are at the correct location. As the digital image intensifier produces the usable images so much faster, it makes finding inspection locations within the sample immediate.

There is a technique that can be used with CMOS flat panels that will raise the frame rate by as much as 4X from that quoted. This is called ‘binning’. Although binning increases the frame rate to 16 frames/sec, which is much closer to the real-time mark, it is achieved by updating the signal captured to only one quarter of the pixels in the array in every cycle – i.e. sending less information at each cycle. So although the speed of acquiring data has increased it will still take the same time as before binning to acquire an adequate image for analysis from all of the pixels. But while binning is being used the resolution of the images produced is being dramatically reduced as only 25% of the image is being updated at any one time. So the trade-off of using a binning technique does not offer additional benefits for x-ray inspection. This is why certain manufacturers use an analogue detector for easier sample movement and location within their system. They then offer a CMOS flat panel detector as an optional extra which can be moved into place once the correct sample location has been found, and there is more time to take a longer exposure with the higher resolution detector. Using a digital image intensifier does not require this approach as the large amounts of data within the image are being captured and presented in real time.

Conclusion

As devices and features requiring x-ray inspection continue to shrink in size, the next step in improving the analytical quality of BGA and CSP x-ray inspection, as well as for investigating other components and devices, is to move towards an x-ray inspection system having a digital detector. The increase in image size, resolution and gray-scale resolution that these detectors provide, enable higher quality inspection, often at lower magnification, allowing for better overall test quality but often at an increased speed of throughput. The two main digital detectors that are available for today’s x-ray inspection systems are the digital image intensifier and the CMOS flat panel. The opportunities that the CMOS flat panel may offer in the future for even better resolution, as patterning on silicon continues to reduce in pitch, suggests that if the inherent defect rates fall and, most importantly, the price falls dramatically then this approach will provide the solution. At present, however, the price/performance comparison to the digital image intensifier, and the difficulties the CMOS flat panel has with frame rate speeds, suggests that digital image intensifiers offer the best solution for BGA and CSP inspection for at least the medium-term future.

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