**COOP-CT-2003-508613**

**MICROSCAN**

# Development of Comprehensive In-Line Quality Control System for Printed Circuit Board Assemblies

**Horizontal Research Activities Involving SME's**

**Co-operative Research (CRAFT)**

## Publishable Final Activity Report

| | | |
|---|---|---|
| Period covered: | Nov 2004 to Feb 2007 | Date of preparation: July 2007 |
| Start date of project: | 1 November 2004 | Duration: 28 Months |
| Project co-ordinator: | P Wallace | Revision No: 1 |

Project co-ordinator organisation: TWI Ltd

PR/TWI/PW/July 07/1

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# 1 Project Execution

## 1.1 Executive summary

The aim of the Microscan project was to produce a powerful tool in the total quality control of Printed Circuit Board (PCB) assemblies. This was to be achieved by combining inspection techniques not normally used in an in-line environment.

Through the development of four prototypes, the principle of using Advance automated imaging (AOI), X-ray, thermography and acoustic inspection, together and in-line, has been developed and a successful proof in principle has been demonstrated.

From the start of the project it was expected that the space and cost savings obtained by combining all of the technologies in one comprehensive machine, could be outweighed by the compromises the combination would bring to the performance of each separate inspection technology. For example when all the inspection prototypes are used together a compromise may have to be made with inspection throughput as X-ray inspection is slower then AOI. In addition using a combined system may not always be convenient and depending on the manufacturing process some stages in the PCB manufacturing line may only necessitate a specific inspection process. These compromising factors depend to an extent on the given PCB configuration that is to be inspected and may or may not pose an issue to the PCB manufacturer.

By good cooperation between the partners developing the prototypes, each of the prototypes has been designed around a common electrical, mechanical and software communications infrastructure. This allows the inspection modules to be used separately, together, interchanged or in different stages of the PCB manufacturing process to give the best results in terms of inspection coverage and inspection throughput. In this way a highly flexible system has been developed.

## 1.2 Project objectives

The strategic objectives of this project were:

1. To overcome current problems encountered in PCB inspection by developing four Non-Destructive Testing (NDT) inspection systems.

2. Combine the developed systems within a PCB assembly system to produce new innovative in-line inspection techniques, which will provide full quality control of the PCB assembly process.

These were realised by the achievement of the following technical objectives:

- Development of an X-ray system for the real-time identification and quantification of defects in PCBs.
- Development of acoustic systems for potential in-line inspection of PCBs.
- Improvement of Automated Optical Inspection (AOI) systems and data recognition.
- Development of thermal/infrared systems for potential in-line inspection of PCBs.
- Provision of feedback mechanisms for the real-time control of the PCB assembly process.
- Development of features which allow the NDT systems to be complimentarily integrated.
- Development of the above systems for use on the new lead-free solder alloys.

## 1.3 List of contractors

TWI Limited (UK)
X-Tek Systems Limited (UK)
LOT Oriel GmbH & Co KG (Germany)
Machine Vision Products Ltd (UK)
Microtel Technologie Elettroniche SpA (Italy)
Beta Electronics Ltd (Ireland)
Ultrasonic Sciences Ltd (UK)

Goodrich Control Systems Ltd (UK)
Fraunhofer Gesellschaft zur Foerderung der Angewandten (Germany)
Kaunas University of Technology (Lithuania)

## 1.4 Work performed

The project was divided into several work packages as follows:

- WP-A: System specifications and sample procurement
- WP-B: Development of radiographic techniques
- WP-C: Development of acoustic techniques including hardware and automated defect recognition algorithms
- WP-D: Development of Automated Optical Imaging NDT technique and system
- WP-E: Development of Thermal Imaging NDT Technique and system
- WP-F: System integration and production trials
- WP-G: Project management

### 1.4.1 Defect catalogue

A "top twenty-four" defect list was agreed between the partners in order to define the scope of the inspection techniques. In addition, a defects catalogue was produced that described the defects in detail.

**Table 1:** Microscan Defect Catalogue

| No. | Description | Selected Inspection Technology(s) | Priority | Defect Class |
|---|---|---|---|---|
| 1 | Dry joints | AOI / THERM? | high | Soldering |
| 2 | Lead less CC solder short | AOI / X-Ray | high | Soldering |
| 3 | Lead less CC poor wetting | AOI / X-Ray/ THERM | high | Soldering |
| 4 | BGA voiding | X-Ray | high | Soldering |
| 5 | BGA bridging | X-Ray | high | Soldering |
| 6 | BGA tilted | X-Ray | high | Soldering |
| 7 | BGA missing balls | X-Ray | high | Soldering |
| 8 | BGA poor wetting | X-Ray | high | Soldering |
| 9 | BGA poor reflow | X-Ray | high | Soldering |
| 10 | Leaded CC poor heel joint | X-Ray / THERM | high | Soldering |
| 11 | Flip chip joints | X-Ray / THERM | high | Soldering |
| 12 | Flip chip under fill | X-Ray / THERM / SAM | high | Soldering |
| 13 | Leaded CC lifted leads | AOI / THERM | high | Soldering |
| 14 | SOT SOIC lead lift | AOI / THERM / X-Ray | high | Soldering |
| 15 | solder balls | AOI | high | Soldering |
| 16 | PTH solder poor fill | AOI / X-Ray | Medium | Soldering |
| 17 | PTH poor lead wetting | AOI / X-Ray | Medium | Soldering |
| 18 | Heat plane delamination | SAM/THERM | Medium | Board |
| 19 | Plastic Encapsulated delamination | SAM | Medium | Components |
| 20 | chip capacitor crack | SAM/X-Ray | Medium | Components |
| 21 | Missing component | AOI/X-ray | Medium | Components |
| 22 | Tombstone component | AOI/X-ray | Medium | Components |
| 23 | Mis-oriented components | AOI- | Medium | Components |
| 24 | Tilted component | AOI | Medium | Components |

### 1.4.2 PCB samples

PCB samples were manufactured in two phases. In the first phase, 30 sample PCBs were provided with deliberate defects suited to a particular inspection technique in order to help develop the prototypes. These defects were inspected with existing systems and the results compared with the results from the prototypes being developed.

In the second phase a total of 100 PCBs were manufactured to aid with the prototype trials. Some PCBs included deliberate flaws and others were manufactured as golden reference PCBs and contained no flaws. In addition, in the second phase the PCBs contained a real working circuit which dissipated heat when power was applied. This was necessary in order to test the passive thermography inspection module.

Considerable effort was spent to make reproducible de-lamination defects in Integrated Circuits (IC) packages. Various parameters were experimented with during the PCB manufacture including the use of lead and lead free solder, different temperature profiles used in the surface mount solder reflow ovens and application of multiple thermal shocks.

Figures 1 and 2 show the top layer PCB artwork and an actual PCB populated with components for the phase 2 samples developed for the project.

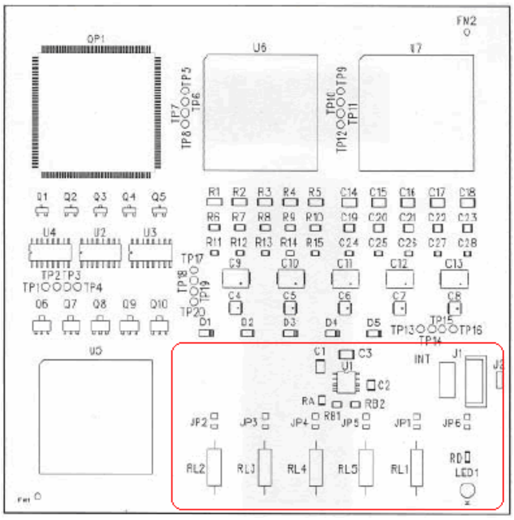


**Figure 1:** Top layer of a phase 2 PCB showing PCB silk screen artwork. Red rectangle indicates the functional test circuit for the thermography tests.

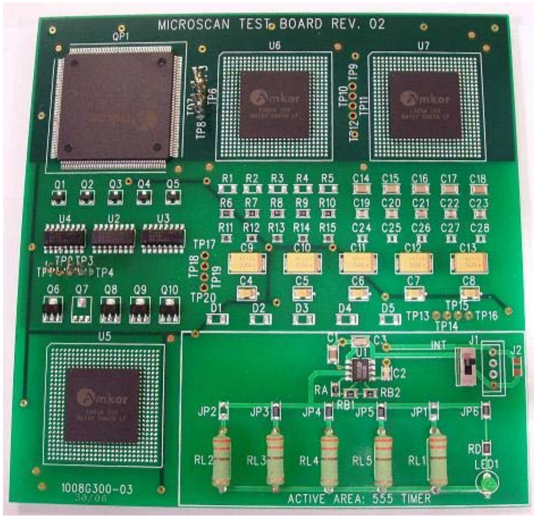



**Figure 2:** Photograph of the phase 2 PCB populated with components.

### 1.4.3 Radiographic technique development

An X-ray system to image PCB defects was initially developed for static components, and many images of defects were taken. In addition the X-ray cabinet was modified to accept and interface a custom made PCB conveyor system. Particular attention had to be paid to X-ray safety, as the prototype was designed in such a way (to increase inspection throughput) that the lead box housing the conveyor entrance and exit was always open, giving the potential to expose X-rays outside of the prototype cabinet. After simulation and empirical calculation, lead tunnels were developed to keep radiation exposure to a recognised safe limit. In addition a collimator was developed to limit the radiation fan angle of the X-ray source.

A 5 axis manipulator system housed in the X-ray chamber was developed to enable the inspected PCB to be lifted from the conveyor, moved at different positions with respect to the X-ray source and detector, and then returned to the conveyor. A gripper attached to the manipulator for PCB holding was developed to allow for fast manipulator motion. Software algorithms were developed in order to detect poor Ball Grid Array (BGA) wetting and re-flow. Tilting the PCB allows for angled X-ray images of BGAs which can be more revealing for certain defects such as poor BGA wetting. However, testing of the system revealed that obtaining angled X-ray images suitable for the defect detection algorithms is not always possible. A compromise has to be made between tilt angle and magnification, since tilting the PCB necessitates increasing the distance between the PCB and source to avoid sample collision with either the source or conveyor. Control software was developed to automate the inspection process and provide communication with earlier and later stages of the PCB manufacturing/inspection line.

Figure 3 shows the X-ray inspection module prototype with labels indicating some important aspects of the design. Figure 4 shows the PCB handling scheme used in the X-ray chamber. Figure 5 shows typical X-ray images obtained for BGAs when imaging the inspected PCB at different heights from directly above. Figure 6 shows that with the manipulator the angle of the PCB as it is presented to the X-ray source and detector can be changed. Tilting the PCB allows for oblique X-ray images of the BGA component which can be more revealing for certain defects such as poor BGA ball wetting.


**Figure 3:** X-ray inspection module prototype.

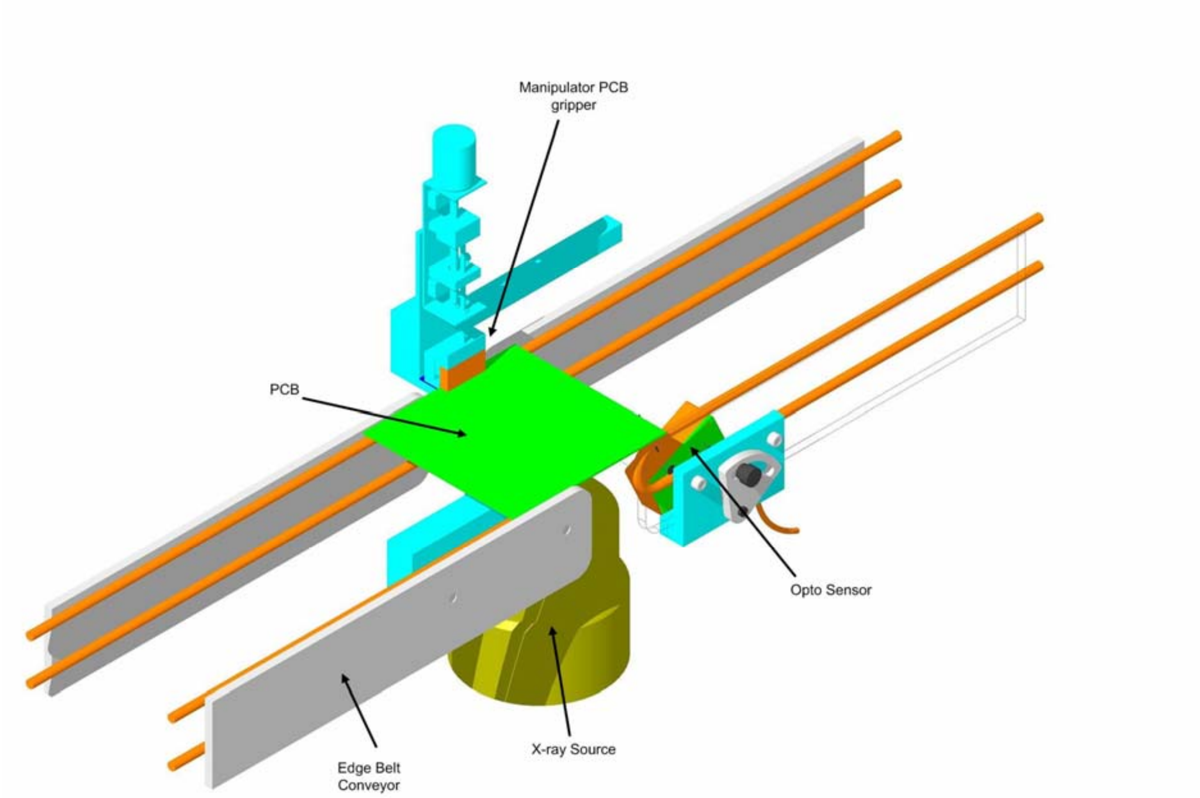
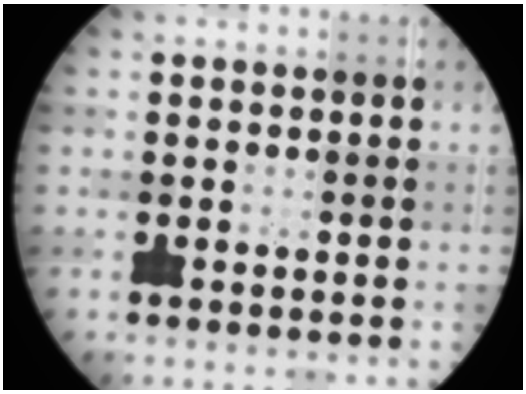
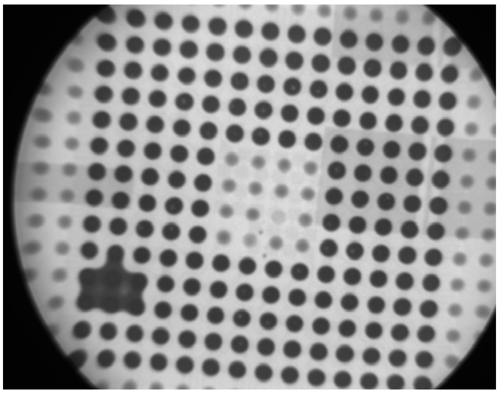
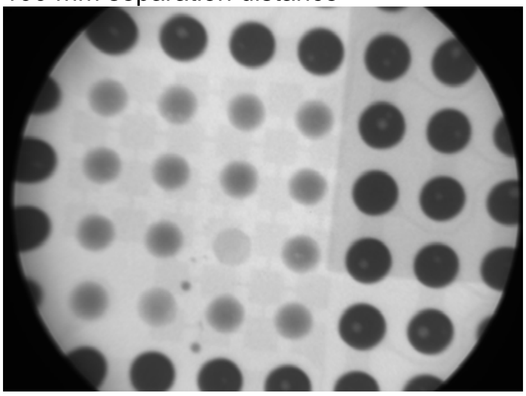


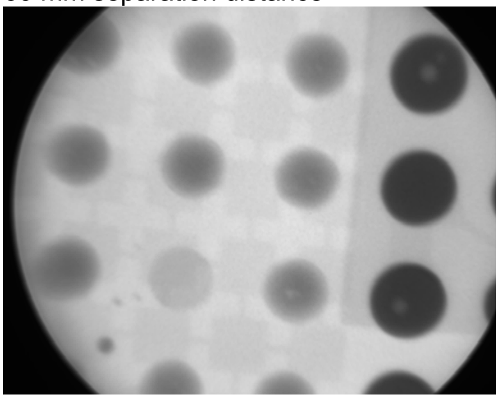

**Figure 4:** PCB handling scheme used in the X-ray chamber.





100 mm separation distance | 60 mm separation distance





20 mm separation distance | 10 mm separation distance

**Figure 5:** X-ray images of 180 ball BGA with different separation distance between PCB and X-ray source (95kV, 60.0μA). Artificially introduced solder bridging and solder ball voids are clearly visible.

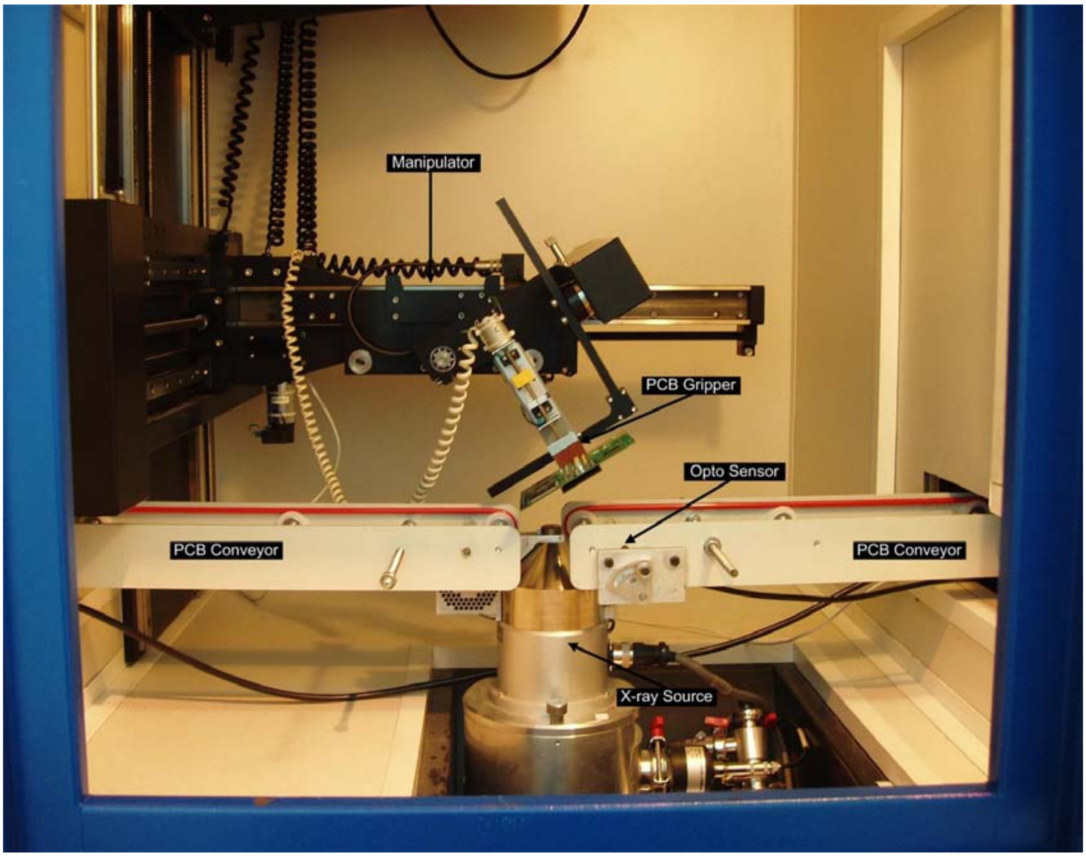



**Figure 6:** Tilting the PCB allows for angled X-ray images of BGAs which can be more revealing for certain defects such as poor BGA ball wetting.

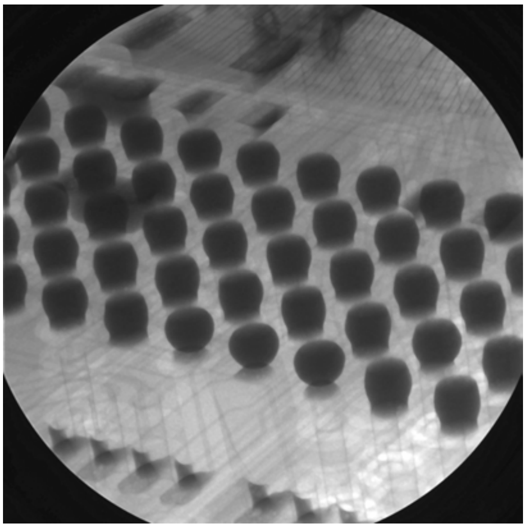


**Figure 7a:** X-ray image of BGA.

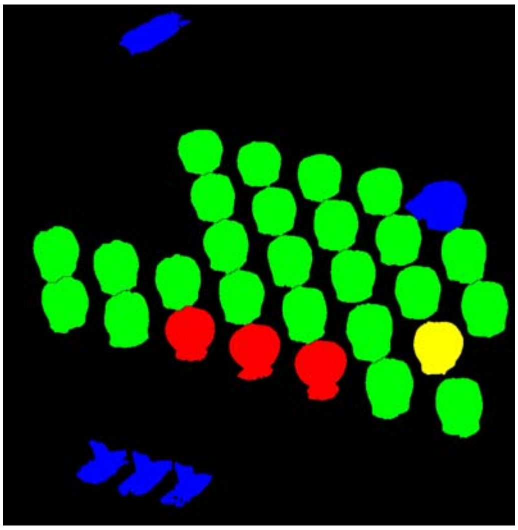
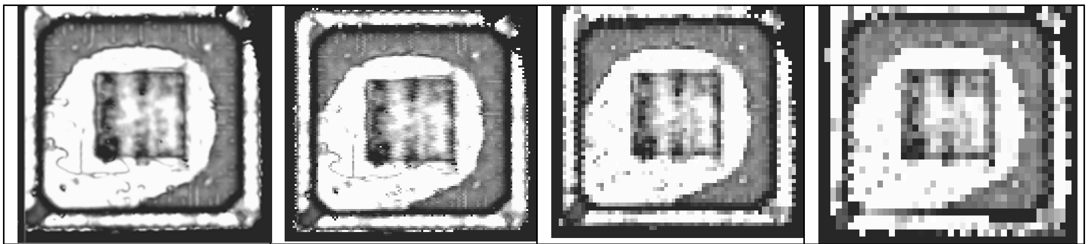


**Figure 7b:** Classification of good balls - (green), bad balls (red).

### 1.4.4 Acoustic technique development

A scanning acoustic microscope (SAM) was developed to inspect primarily for planar defects in IC packages on PCBs. Initially, experiments were conducted to establish optimal ultrasonic transducer inspection frequencies together with experiments testing different scan steps for determining the minimum image acquisition time with the minimal acceptable image quality (see Figure 8 for a typical result). One of the goals for the development of the SAM was to incorporate a water irrigation nozzle to avoid the necessity of immersing the inspected PCB totally in water (see Figure 9). This also made it easier to mechanically incorporate the conveyor into the system, with the minimum of modifications as the belts carrying the PCB did not have to be submerged in water (see Figure 10). Many experiments were carried out to establish the effect of the “water column” between the ultrasonic transducer and the component under test. Finally, two methods incorporating defect detection algorithms were developed for automatically sentencing a good and a bad component. A signal processing algorithm was developed to enable reliable detection of the defect from the Radio Frequency (RF) waveform data acquired, using relatively big steps of scanning (see Figure 11). However, because of the time involved to collect and process the RF data, a simpler approach was developed whereby the collected data from the SAM is immediately stored as simple intensity values. Using the same technique as for the Automated Optical Imaging (AOI) prototype, inspected PCB images are subtracted from a golden reference image and any resulting differences according to a threshold value are used as an indication of a component failure. Control software was developed to automate the inspection process and provide communication with earlier and later stages of the PCB manufacturing/inspection line. A special user interface was created to enable the SAM to be programmed with the positions of the components to be inspected (see Figure 12).



| | | | |
|---|---|---|---|
| Original high resolution image<br><br>Scan time = 5 mins | Resolution 0.15, Bidirectional<br>2700mm$^2$/sec<br>Scan time = 25 s | Resolution 0.3, Bidirectional<br>5700mm$^2$/sec<br>Scan time = 9 s | Resolution 0.5, Bidirectional<br>5700mm$^2$/sec<br>Scan time = 6 s |

**Figure 8:** Effect of reducing scan resolution on image detail – image degradation is minimal for larger step sizes.

**Figure 9:** Irrigation nozzle on 25MHz ultrasonic transducer.

**Figure 10:** SAM Scanner incorporating PCB conveyor system.

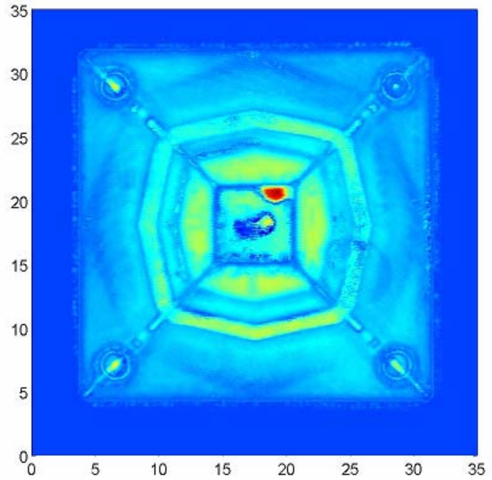


**Figure 11a:** Delamination visible in an IC using 0.035mm scanning step.

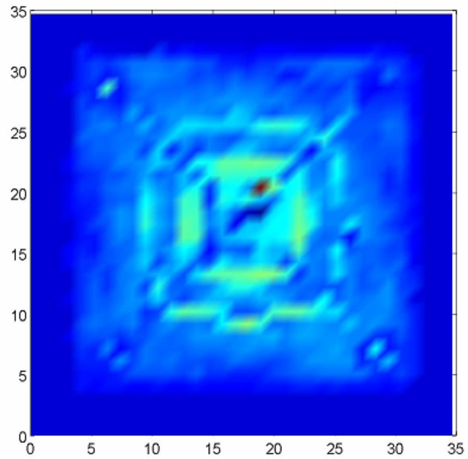


**Figure 11b:** Delamination visible in the same IC as imaged in 12a, using 1 mm scanning step.

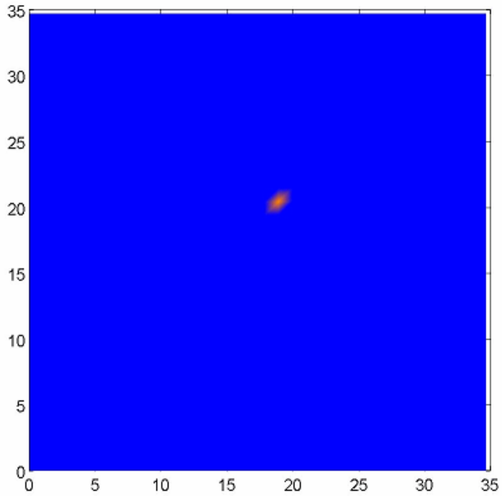


**Figure 11c:** Resulting image after signal processing of the 1 mm scanned step RF data clearly indicating the delamination.

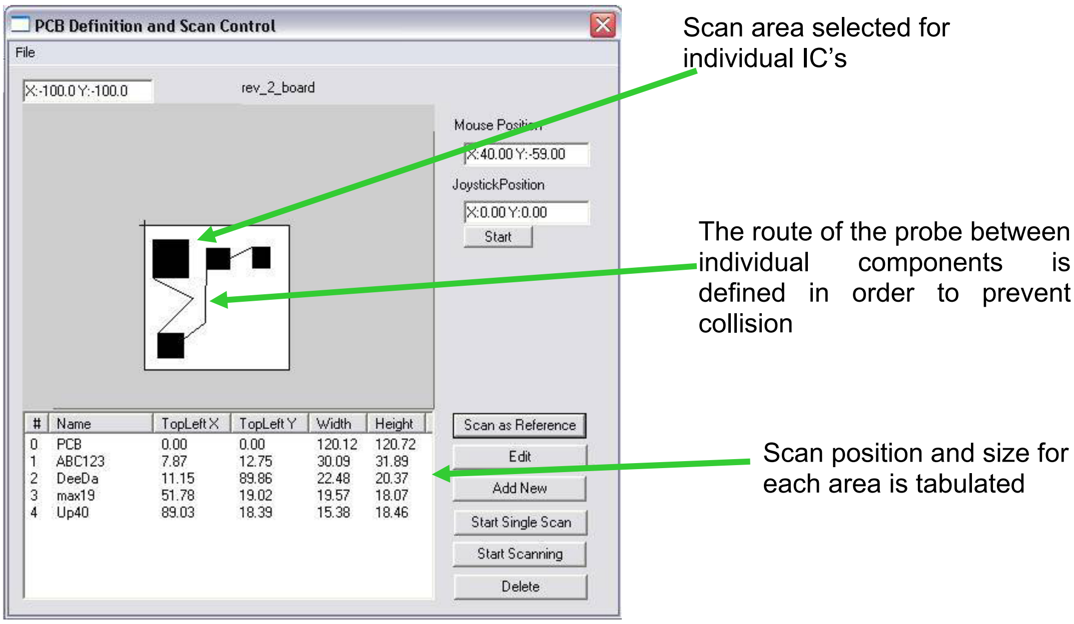



**Figure 12:** SAM dialogue window for set-up of PCB scanning. Part of the software developed in the Microscan project.

### 1.4.5 Automated optical imaging technique

Initially an off-the-shelf table top inspection system was used as the test bed for the AOI algorithm development. Algorithms were developed to immediately sentence a PCB fail without the usual requirement for a user to set up threshold values for each component. However, the system acquired its images by taking multiple camera images and stitching the images together. Unfortunately, the quality of the stitching was not optimal for the algorithms, and caused many false alarms. At this stage, attention was given to developing a prototype from scratch using a fixed position high resolution camera and employing enhanced algorithms via a generic software framework. This also enabled a custom built conveyor to be integrated. Algorithms have been developed to compensate for any slight variance in PCB position when it is presented to the camera and to correct for intensity variation from luminance changes due to light reflection. Control software was developed to automate the inspection process and provide communication with earlier and later stages of the PCB manufacturing/inspection line. Algorithms were developed to automatically sentence defects including missing, titled and mis-oriented components. Figure 13 shows a typical result after application of the algorithm. In addition an AOI image processing software framework was developed allowing application of the algorithms developed (see Figure 14).

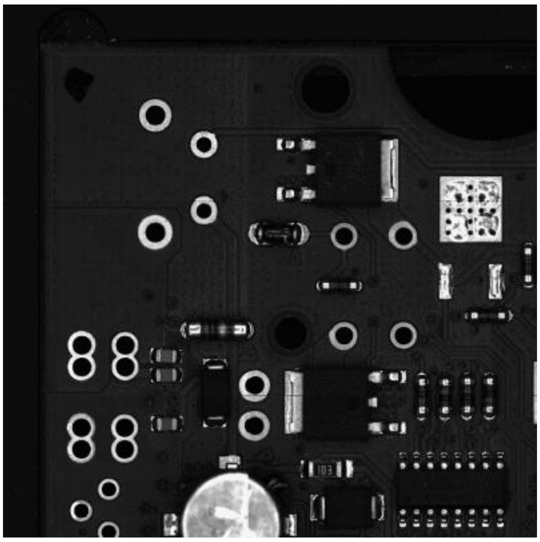


**Figure 13a:** Golden reference image.

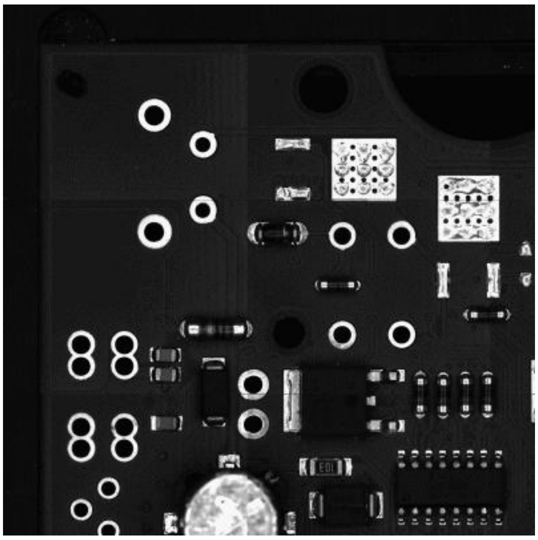


**Figure 13b:** Inspected image.

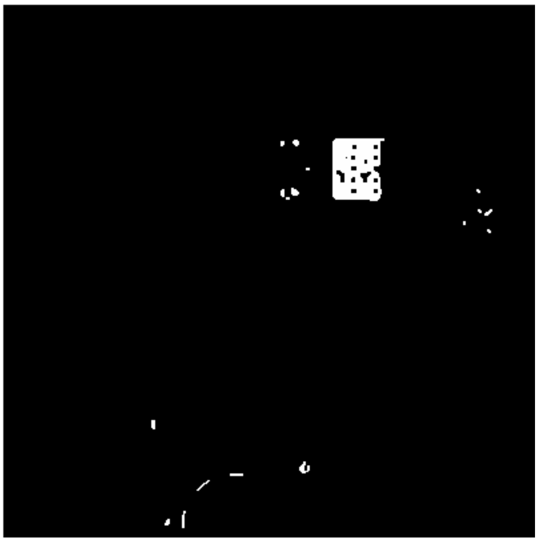


**Figure 13c:** Final residual image after subtracting image (b) from (a).

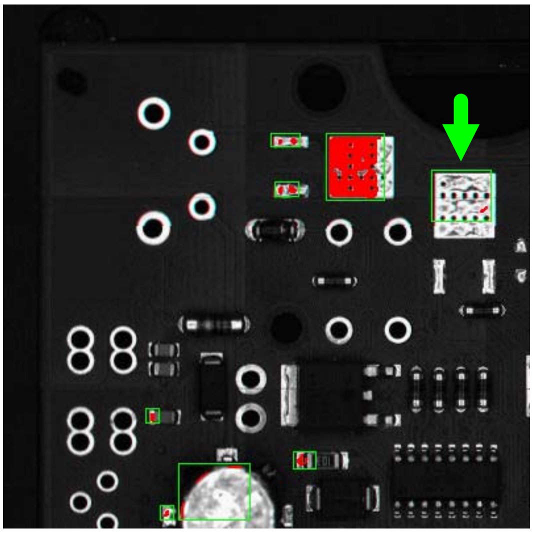


**Figure 13d:** Identification of potential defects indicted by software via green boxes. Big arrow indicates false alarm due

to shining of the solder surface, this is highlighted for illustration purposes only.

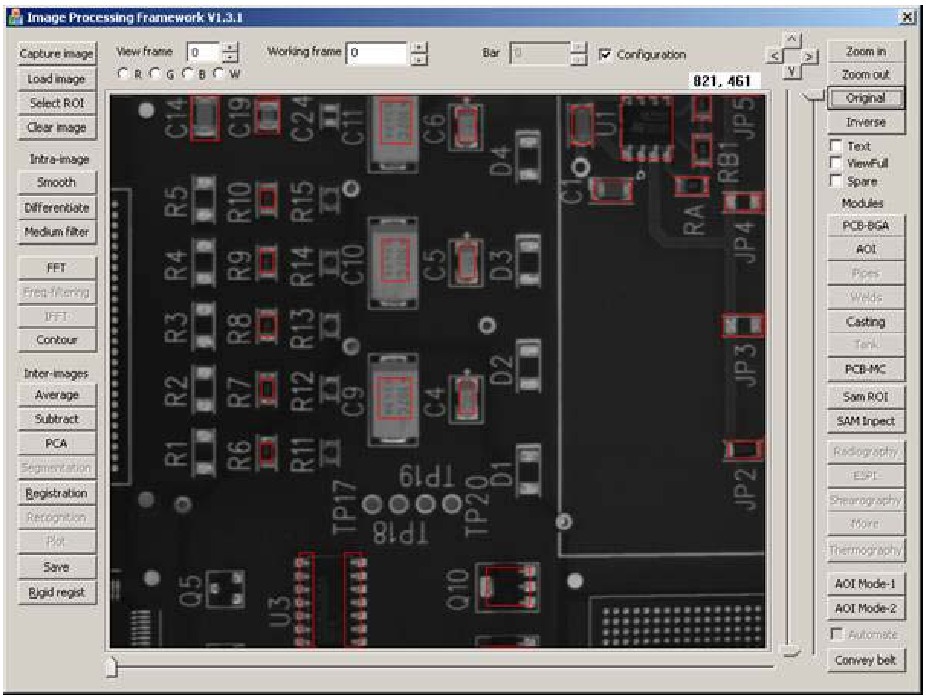



**Figure 14**: AOI image processing software framework applicable.

### 1.4.6 Thermal imaging technique development

Initially experiments were set up and conducted to establish the usefulness of active thermography for PCB inspection. A high resolution Infra-red camera and external heating source comprising flash lamps was developed. Active thermography results showed that this technique could detect de-lamination in PCBs and in the plastic packaging of ICs (see Figures 15 and 16 for typical image results). However, it was concluded that it is easier to interpret and detect these types of defects with the other detection techniques. In a second alternative approach, a passive thermography system was developed. Figures 17 and 18 show typical image results obtained from the passive thermography set up. For the passive thermography set up an infra-red camera was deployed but instead of an external heat source, power was applied to the PCBs via a linear actuator plunger. Figure 19 shows the scheme implemented in the passive thermography prototype and Figure 20 shows an actual photo of the set up. A software application was generated that acquired thermal signatures every time a PCB was presented by the conveyor. Control software was developed to automate the inspection process and provide communication with earlier and later stages of the PCB manufacturing line. A linear actuator with spring loaded power/test probes was incorporated into the system. Thermography system software was developed to activate the linear actuator to power the PCB when detected. Upon detection of a PCB the software instructs the camera to acquire an image and then to compare predefined areas of the image with threshold values to determine if component temperature values have exceeded predefined limits.

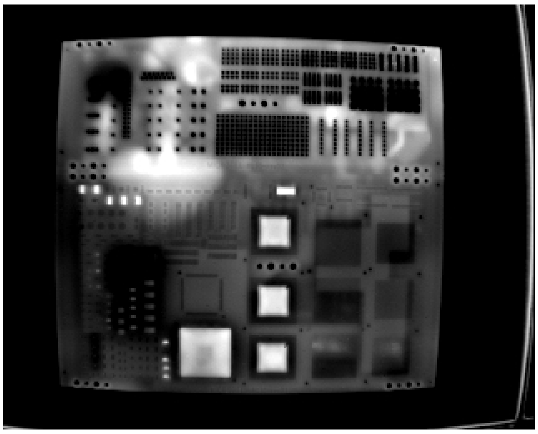


**Figure 15:** Active thermography results showing delamination (visible as milky white areas) in a PCB.

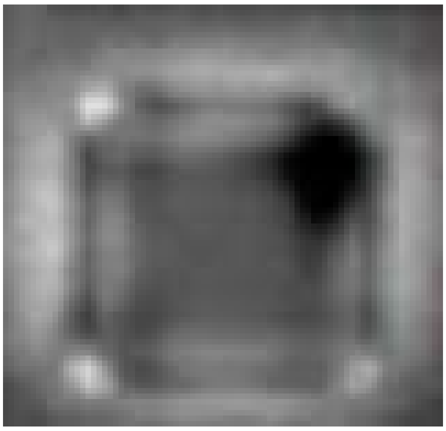


**Figure 16:** Active thermography result showing delamination (top right of package) in a BGA IC package.

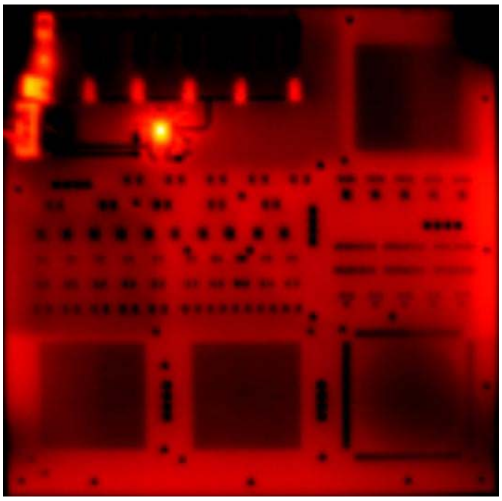


**Figure 17:** Passive thermography result for a PCB that is powered up. The lightest colours indicate the hottest areas on the PCB, and correspond to the IC and LED that are present.

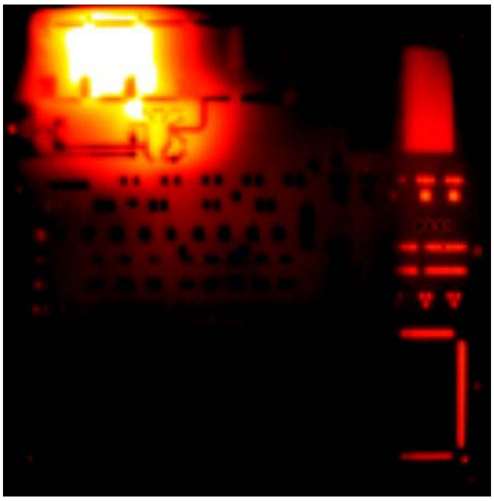


**Figure 18:** Passive thermography result for a PCB with short circuited resistors across output of the IC.

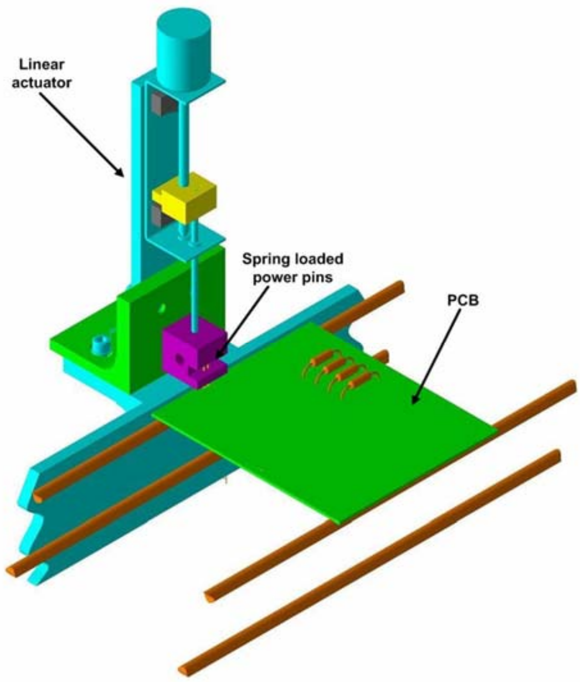



**Figure 19:** Scheme implemented in passive thermography prototype to automatically power PCB.

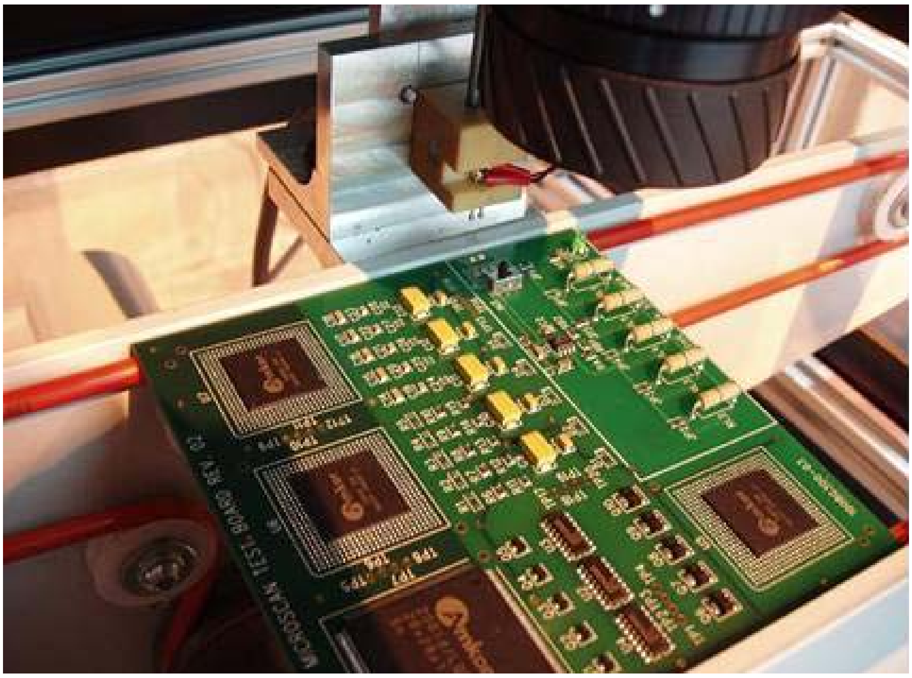


**Figure 20:** Actual photo showing inside the thermography prototype chamber after the PCB has arrived. The IR camera is located in a fixed position above the active area of the PCB.

### 1.4.7 Systems integration

Initially all the prototypes were developed and tested separately. However specifications were agreed between the developing partners from the outset of the project, and a standard industry interface, called SMEMA, was adopted for each prototype. This facilitated the interfacing of the partner's equipment at a mechanical, electrical, and software communications level. A common conveyor design was developed, and a common control circuit was designed and developed to ensure compatibility between the prototypes. The adoption of the SMEMA standard means that, not only can the prototypes operate with each other, they can be incorporated into most PCB surface mount manufacturing lines. Initially in the project, priority was given to the development of the AOI prototype. As well as for algorithm design, the AOI prototype was used as a test bed for the implementation of the SMEMA scheme. Lessons learnt from the AOI implementation enabled easier integration with the other prototypes.

Figure 21 shows the final Microscan prototype PCB in-line inspection system. Figure 22 shows the signal communication scheme implemented for each inspection module. Figure 23 shows a photograph of the conveyor control and SMEMA interface board developed for each inspection module.


**Figure 21:** Microscan Prototype PCB In-line inspection system.

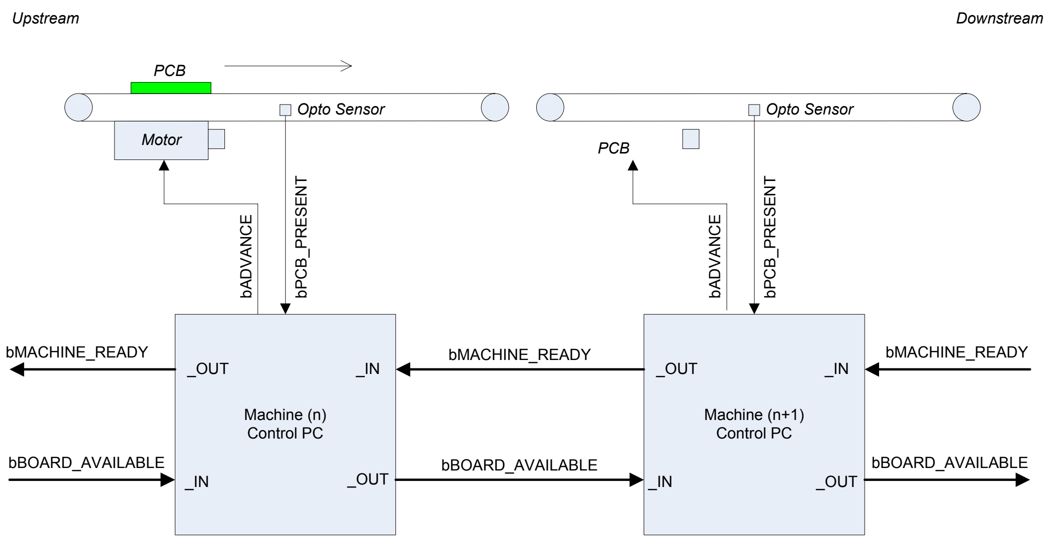



**Figure 22:** Communications signals used to facilitate systems integration.

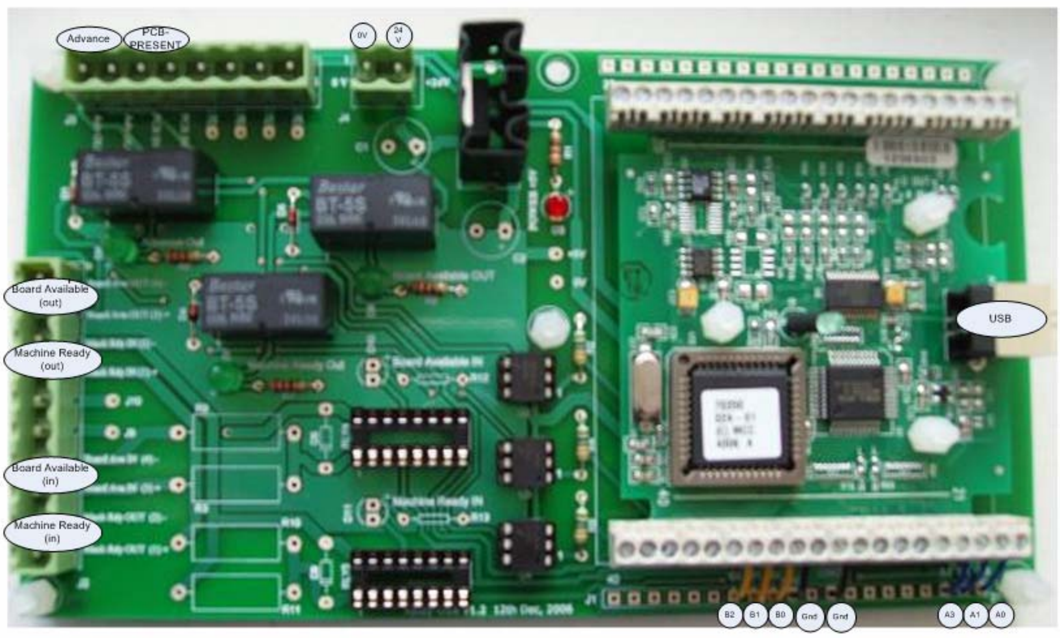



**Figure 23:** Photograph of the conveyor control and SMEMA interface board that was designed and developed for utilisation in all the inspection prototypes.

### 1.4.8 Trials

The prototypes have been trialled individually and together in the laboratory. Where possible, the prototypes have been trialled in the end user factories. It was not possible to trial the X-ray inspection module prototype outside the laboratory because of its large physical size and weight. Figure 24 shows a photo of the AOI inspection module being trialled at one of the end user partner sites.

**Figure 24:** AOI prototype trialled at the end user factory sites.

## 1.5 Project achievements against state-of-the-art

In the Microscan project an in-line inspection system comprising four different inspection techniques has been developed and a proof in principle has been demonstrated. This is the first time that this has ever been done. There are a number of achievements in this project that can be considered novel against the state of the art:

- The combination of the inspection techniques offers the capability for 100% defect coverage.
- The inspection prototypes have been designed in such a way that they can be used either independently or together.
- A generic software framework has been developed that allows defect detection algorithms to be tested across different inspection techniques including AOI, X-ray and SAM.
- It is the first time that a water irrigation probe, used to minimise water contact with the PCB, has been included in an in-line SAM for PCB inspection.
- Defect detection algorithms for detection of poor wetting of balls have been implemented.
- The use of leaded tunnels enclosing the entry and exit conveyors of the X-ray inspection module, allowing the X-ray source to be continually on and thereby increasing the maximum inspection throughput.

## 1.6 Impact on the PCB manufacturing industry

In recent years the complexity of PCB assemblies has been increasing, leading to ever increasing demands placed on NDT examination for quality assurance.

Currently, with the exception of AOI, most NDT is applied off-line in a batch situation, generally using only one inspection technique. If a serious defect is found, it is possible that the whole batch will be scrapped. Once a fault is found with one technique, it is frequently necessary to confirm this with optical or scanning electron microscopy and metallurgical sectioning. This type of methodology adds greatly to the cost of each PCB batch.

At present when utilising all four inspection prototypes of the Microscan system it is suited for high-return PCBs, particularly PCBs manufactured for products in medical use and aerospace, rather than high throughput production work. Nevertheless, depending on the number and type of components present, the total inspection process for a PCB can take approximately a minute.

Already at the start of the project it was expected that the space and cost savings obtained by combining all of the technologies in one comprehensive machine, could be outweighed by the compromises the combination would bring to the performance of each separate inspection technology. For example when all the inspection prototypes are used together a compromise may have to be made with respect to inspection throughput. In addition depending on a given stage in the manufacturing process it may not be necessary or convenient to apply all inspection techniques. These compromising factors depend to an extent on the given PCB configuration and complexity that is to be inspected and may or may not pose an issue to the PCB manufacturer.

Since each of the prototypes has been designed around a common electrical, mechanical and software communications infrastructure it enables the inspection modules to be used separately, together, interchanged or in different stages of the production process to give the best results in terms of inspection coverage and inspection throughput.

Given the ever increasing complexity of PCB assemblies, and the trend to increase the population density of components driving the move to more complex surface mount assembly technology such as BGA and other small foot print devices, there will be increased demands on NDT examination for quality assurance. It is key that two of the inspection prototypes in the system cater for inspection of BGAs.

# 2 Dissemination and use

## 2.1 Microscan website

TWI host a website, with the domain name www.microscan.eu.com for disseminating information about the Microscan project to the public. Figure 25 shows the Microscan website home page. A contact page on the website provides telephone and form access to TWI's scientists and specific enquiries will be automatically forwarded to appropriate partners involved in the project. There is also a publications page listing the publications that have arisen from the project. Finally, there is a project section giving extensive data on the typical PCB defects that are detectable, and details of the prototype development.


**Figure 25:** Home page of the Microscan website.

## 2.2 In-line scanning acoustic microscopy PCB inspection system

A prototype in-line scanning acoustic microscopy system has been developed. The system is capable of automatically testing for delamination in integrated circuit packages. The system is different to other SAMs that are already commercially available in that the system is fully in-line. Other manufacturers claim that their systems can be modified for in-line inspection, but then it is the component rather than components on the PCB that is inspected in-line. The components are mounted in trays, which are moved to the acoustic microscope by a robot manipulator. The deployment of a water irrigation nozzle as an alternative to total water immersion enables the prototype system to be truly in-line. Unlike other commercial solutions multiple components on the same PCB can also be inspected.

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## 2.3 In-line X-ray PCB inspection system

A prototype in-line X-ray PCB inspection system has been developed. Unlike other X-ray inspection systems the X-ray inspection prototype was developed so that the X-ray source was always switched on, thereby maximising inspection throughput. Other manufactures ensure their systems are radiation safe by incorporating trap doors, the opening and closing of which increases inspection time per PCB. In addition when the trap door is open then the X-ray source has to be switched off. Lead tunnels were developed to enclose the entrance and exit conveyors to the inspection prototype. This ensures a minimum safe amount of X-rays that is permissible to escape from the system whilst at the same time allowing the X-ray source to be always switched on. A programmable manipulator incorporated into the X-ray system and script software to perform automated defect detection for BGAs has also been developed.

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## 2.4 Defect detection software for BGAs

Automated defect detection software has been written to automatically detect defects (“poor wetting”) in X-ray images of BGA balls and PCB pads. Algorithms have been developed for image enhancement / pre-processing, automated separation of balls in X-ray images, blob shape analysis of balls, and identification and classification of ball shapes on normal pads. Financial support and collaboration is sought to allow the software to be optimised for increased reliability of defect detection.

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## 2.5 Ultrasonic RF data analysis software

Software for defect detection and visualisation of RF ultrasonic data obtained from the scanning acoustic microscopy prototype has been developed. It carries out discrimination of indications and provides information about them.

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## 2.6 The Microscan system

A prototype in-line system for detecting PCB defects using automated optical imaging, X-ray, thermography and acoustic microscopy. The four techniques have been developed to operate separately, together or interchanged to give the best results in terms of inspection coverage and inspection throughput. The AOI prototype has been proven to be able to detect missing components, misplaced components, solders shorts and lifted leads. The X-ray prototype has been proven to be able to detect BGA ball bridging, BGA ball voiding, mis-oriented BGAs and poor wetting and reflow in BGA balls. The passive thermography prototype has been proven to detect shorted components in a powered circuit. The scanning acoustic microscopy prototype has been proven to be able to detect de-lamination and so called “pop corn” defects in Integrated Circuit (IC) packages. Parts of the system are available for demonstration at the TWI premises.

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