

**A Comparison of
Automatic Optical
Inspection and
Automatic X-ray
Inspection of Surface
Mount Assemblies**

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Approved on behalf of Managing Director, NPL, by Dr C Lea,
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A Comparison of Automatic Optical Inspection and Automatic X-ray Inspection of Surface Mount Assemblies

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ABSTRACT

A comparison of automatic optical inspection (AOI) and automatic X-ray inspection (AXI) was undertaken using a number of reflow soldered printed circuit assemblies with known defects. Six AOI systems and one AXI system were compared. All the AOI systems and the AXI equipment benchmarked exhibited acceptable capabilities in locating missing components, misalignment of passive components (0603 size), tantalum capacitors, SOICs and coarser pitch QFPs, bridging of SOICs and tantalum component polarities.

The AXI system and some AOI systems performed better than other AOI systems at locating misalignment of PLCCs and finer pitch QFPs, insufficient solder joints on PLCCs, tantalum capacitors, QFP toe fillets, SOIC toe fillets, 0603 passive components and SOIC heel fillets, excessive solder joints and bridges on PLCCs and QFPs.

No equipment was 100% successful at locating insufficient solder joints on QFP heel fillets or through-hole hole joints. The AXI system was more successful at locating poor quality heel fillets on QFPs than any of the AOI systems.

The AXI system was not capable of locating wrong value components or wrong polarity components other than tantalum capacitors.

INTRODUCTION

Many electronics manufacturers are contemplating the replacement of manual inspectors using microscopes with automatic inspection systems. Such systems have been made widely available in the last year or so and the National Physical Laboratory (NPL) carried out an evaluation of six automatic optical inspection (AOI) systems earlier this year. This work was reported in the publication “Benchmarking Assisted and Automatic Inspection of Electronic Assemblies” (Ref. 1). Some of these systems were found to be suitable for a wide range of component types in locating a number of defects such as missing components, misalignment, bridges, component polarities and wrong value components.

However, no equipment was 100% successful at locating insufficient solder joints on QFP heel fillets. This is because of the difficulty in gaining visual access to the heel fillets. Indeed this is also a major problem in manual visual inspection, with only the heel fillets of corner leads easily visible on most finer pitch devices. However, most International and National visual inspection standards call for heel fillets on gullwing joints to be present for a solder joint to be acceptable.

A possible solution to this problem is to use Xray inspection. By using a transmission Xray image, heel fillets should be more visible and thus it should be possible achieve a greater coverage of this type of solder joint. Coupled with the interest in using Xrays to inspect ball grid array (BGA) and flip chip components, where the solder joints are hidden beneath the package, it was decided to extend the NPL’s earlier study of AOI systems to include an automatic Xray inspection (AXI) system.

The benchmarking assessed the following equipment criteria :

- machine cost
- ease/cost of programming
- ability to locate assembly defects
- amount of false detects created
- speed of inspection

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TEST ASSEMBLY

The same test assemblies as those that were used in the earlier evaluation (Ref 1.) were utilised for this project. The information on these assemblies from the previous report is repeated here.

The test assembly was a multilayer PCB containing 94 surface mount (SM) components and 1 through hole (TH) component, as shown in Figure 1 and detailed in Table 1. Component pitches varied between 0.020" (0.5 mm) and 0.050" (1.27mm) for SM components. The TH component was 0.1" (2.54mm) pitch. Seven different component styles were incorporated.

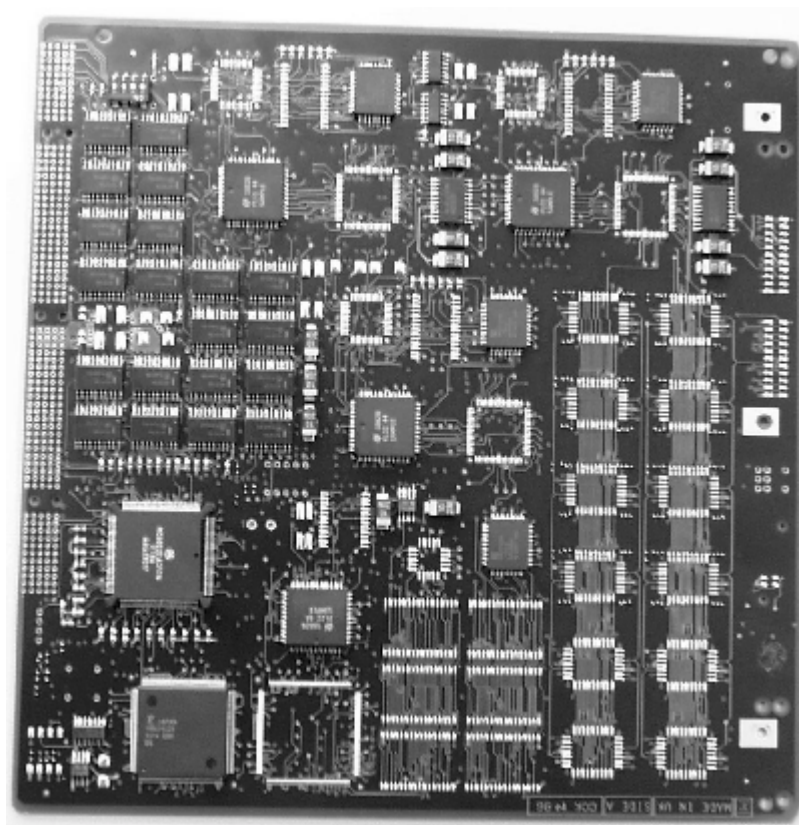


Figure 1 : Test assembly

Table 1 : Test assembly content

Component	Pitch (inches)	Pitch (mm)	No. of components	No. of joints
QFP176	0.020"	0.5	1	176
QFP132	0.030"	0.75	1	132
PLCC44	0.050"	1.27	4	176
PLCC32	0.050"	1.27	4	128
SOIC20W	0.050"	1.27	20	400
SOIC20W(PdNi)	0.050"	1.27	2	40
SOIC14	0.050"	1.27	3	42
SOIC8	0.050"	1.27	2	16
Tantalum Capacitor	Case D		13	26
Chip caps and res.	0603		48	96
TH DIP switch	0.1"	2.54	1	8
Total Joints				1240

In total, thirty five test assemblies were produced by Fujitsu Telecommunications using their normal production process. This comprised solder paste printing with a DEK 265 printer utilising a 0.006" (150µm) laser cut stainless steel stencil with metal squeegee blades. The solder paste used was a no-clean RMA based product utilising 62Sn37Pb2Ag solder alloy. SM components were placed using FUJI CP4-3 and FUJI IP2 placement machines. Reflow was conducted in a Conceptronic HV102 with nitrogen. The ten assemblies used for the benchmarking were all reflowed in the later oven. No touch-up of solder joints was undertaken. The DIL switch was added by hand soldering.

All assemblies were visually inspected using a 5x-30x binocular zoom microscope with ring illumination and defects noted. The guidelines used to assess the quality of assembly were IPC-A-610 rev B (ref. 2). The more stringent class 3 criteria for high performance electronic products was used. These guidelines have been incorporated into IEC 61191-2 (ref. 3) and IEC 61191-3 (ref. 4). Level 3 applies in the case of these standards.

Up to twenty five, largely defect-free assemblies were made available to equipment suppliers for debugging. A further five defect free assemblies were tested to assess false detection rates. Defects were incorporated into the remaining five assemblies. Where possible these defects were incorporated prior to solder reflow so that the joint characteristics were not unduly effected. However, some defects could only be incorporated after reflow using rework techniques.

The range of defects incorporated in the assemblies included the following :

- missing components
- misaligned components (x and y directions)
- wrong components (correct size but different value)
- poor quality solder joints (insufficient or excess solder)
- wrong polarity components
- solder bridges (shorts)
- poor lead or component planarity including tombstones (component on end) and crocodiles (one end of the component slightly lifted causing a unsoldered joint at that end)

Some joints were created which, whilst not poor quality joints outside permitted limits, were intended to see if the machines flagged them good or bad.

A number of changes where made to the defect assemblies which were not defects but which were intended to assess if the equipments were capable of detecting the changes. These included :

- different manufacturers (correct component types)
- different lead finish (correct component type)
- slight misalignments (within permitted limits)
- acceptable but not perfect solder joints
- abnormal levels of flux residues

TEST SYSTEMS

Six different automatic optical inspection systems were evaluated in the initial project report. These systems were all based on analysis of images generated from black and white CCD camera systems utilising a variety of lighting sources and lighting angles. Three of the systems (machines A, B & C) used only vertical cameras, viewing the test assemblies in plan view. The remaining three AOI systems also utilised vertical cameras but augmented these with angled cameras. The viewing angles of these systems were typically 60° from the horizontal. A summary of the equipment including approximate costs, is shown in Table 2.

All these automatic systems use a varying number of algorithms to compare captured images of the test assembly with known good (“golden”) images captured during programming and debugging. Some latitude is allowable in the difference between the test image and the golden image. The degree of allowable difference is user definable and forms part of the programming and debugging procedures. The number and types of algorithms used may also be user definable. Some systems are also capable of using images of known defects to assist in locating defects on the test assembly.

The AXI system evaluated was a transmission Xray system with a vertically orientated source and detector and a pass through conveyor to carry the assembly to be inspected into position. The image produced show different contrasts due to the density of the material placed between the Xray detector and the source. Part of a typical image is shown in figure 2, showing small outline IC (SOIC) joints, chip resistor (R0603) joints and chip capacitor (C0603) joints.

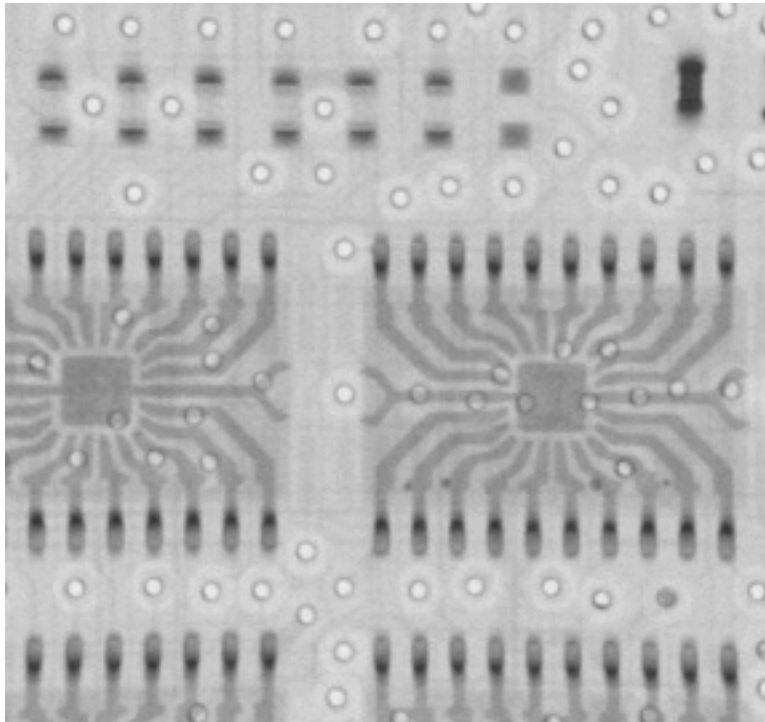


Figure 2 : Typical Xray transmission image of test assembly

The image captured shows darker areas which correspond to solder joints, leadframes, plated through holes and internal plates of capacitors. The image is analysed in a similar manner to that used in the AOI systems.

CAD data for the assemblies, a 'golden' assembly and a bareboard were made available to those participating partners who wished to receive them, prior to the benchmarking. Up to twenty further 'golden' assemblies were made available for up to 8 hours for debugging. The benchmark was carried out on an additional ten assemblies (five 'golden' and five with defects). These latter ten assemblies were not previously seen by participating partners prior to the benchmark. Specific details are given in Table 2.

Table 2 : Equipment Summary

Machine Identifier	A	B	C	D	E	F	AXI
Number of vertical cameras	3	2	2	3	2	6	1 X-ray detector
Number of angled cameras	0	0	0	4	8	4	0
Camera movement	Stationary	Stationary	Moving	Stationary	Stationary	Stationary	Stationary
Camera magnification	different	same	different	same	different	same	various
Lighting	Incandescent lamps	Red LEDs	White illumination	High freq. fluorescent	Xenon flashes	Red LED Flashes	X-ray
Diffuse lighting	yes	yes		yes	yes	yes	N/A
Vertical lighting			yes		yes	yes	N/A
Side lighting			yes		yes	yes	N/A
Angled lighting					yes		N/A
Operating system	Windows	Unix	Windows	Windows	OS2	Windows NT	OS9
Approx. cost (£)	85K*	85K*	45K*	120K*	140K*	100K*	200K*

*based on information given by the equipment supplier

RESULTS

Each of the inspection machines were used after programming and debugging to inspect the five "golden" assemblies and five "defect" assemblies. The results are based on detection of errors from the initial run of these assemblies through the systems. As only a very limited number of component defects were available during programming and debugging, those machines which use statistical algorithms to aid their identification of defects may exhibit a lower detect rate than would be possible after more extensive debugging using further examples of component and solder joint defects for the software to learn from.

The programming and test times for each equipment trial are given in Table 3. The programming time does vary considerably, but this data cannot be verified in all cases and was supplied by the equipment suppliers where marked with an *. The debug times are very similar. Test times varied from 20 to 160 seconds, with the AXI system comparing favourably with the AOI systems. Test times could be shortened by increasing computer processing power.

Table 3 : Programming and Test Time Summary

Machine Identifier	A	B	C	D	E	F	AXI
CAD sent before visit	yes	yes	no	yes	yes	yes	yes
Sample assembly sent before visit	yes	yes	no	yes	yes	yes	yes
Programming time (hours)	4*	16*	12	20*	12*	6*	15*
No. of assemblies used for debugging	20	20	10	4	20	10	10*
Debug time (hours)	3	5	2	3	5	3	5
Test time (secs) per assembly	45	20	114	160	30	60	25

*based on information given by the equipment supplier

The false detect rates for all test assemblies are summarised in Table 4. There is no particular trend apparent from this summary other than that false detect rate for the AXI system was lower than the AOI systems for comparable programming and debug times. The results are presented in more detail in Tables 5 to 9 for the known defects on assemblies 31 to 35. These tables list the component ID, component type and the defect and it's severity. The AXI results are highlighted for easier comparison. There is also a joint classification (good/bad/marginal) based on IPC-A-610 with each instruments performance for that defect listed.

Table 4 : False Detects Summary

Equipment Identifier	A	B	C	D	E	F	AXI
Assembly number							
26	1	4	4 (14)	17	N/A	0 (0)	0 (0)
27	2	3	6 (7)	18	1 (1)	0 (0)	0 (0)
28	1	N/A	3 (6)	23	2 (3)	4 (5)	1 (3)
29	3	2	9 (10)	17	2 (2)	5 (12)	0 (0)
30	3	2	4 (4)	27	2(2)	2 (4)	0 (0)
31	3	4	18 (42)	14	3 (12)	1 (1)	3 (6)
32	1	15	15 (31)	17	2 (2)	6 (6)	1 (1)
33	2	N/A	9 (13)	18	1 (1)	0 (0)	0 (0)
34	4	4	3 (9)	28	1 (1)	7 (21)	0 (0)
35	8	N/A	7 (8)	22	0 (0)	2 (2)	3 (11)
Total	22	49*	78 (144)	201	12 (25)*	27 (51)	8(21)

number outside brackets equals number of component false detects

number inside brackets equals number of lead false detects (where available)

* averaged O/D = operator dependent

Table 5 : Defect Results for Assembly 31

Comp Ident.	Type	Defect & Degree	Classification (IPC-A-610 etc.)	A	B	C	D	E	F	AXI
		Capacitors								
C2	Tantalum	Exc. misalign Y	bad	yes	no	yes	yes	yes	yes	yes
C14	Tantalum	Flux residue	good	U	U	U	A	U	U	U
C17	Tantalum	Max. misalign. Y	marginal	bad	bad	good	bad	bad	bad	yes
C148	C0603	Missing	bad	yes	yes	yes	yes	yes	yes	yes
C176	Tantalum	Exc. joint	bad	no (1)	no (2)	no	yes	yes	no	yes
C177	Tantalum	Exc. misalign X	bad	yes	yes	yes	yes	yes	yes	yes
C180	Tantalum	Insufficient (0%)	bad	no (3)	yes	no	yes	no (2)	yes	yes
C181	Tantalum	Misalign X (50%)	bad	yes	yes	no	yes	yes	yes	yes
C182	Tantalum	Polarity (180deg)	bad	yes	yes	yes	yes	yes	yes	yes
C183	Tantalum	Different value	bad	yes	yes	yes	yes	no (2)	yes	NC
		Semiconductors								
IC1	QFP	Insufficient (toe & fillet 50% rise)	bad	no (2)	M	no	no (4)	no	no	no (5)
IC1	QFP	Exc. Misalign. X	bad	yes	no (2)	yes	yes	yes	yes	yes
IC3	SOIC	Bridge	bad	yes	yes	yes	yes	yes	yes	yes
IC5	QFP	Missing	bad	yes	yes	yes	yes	yes	yes	yes
IC15	PLCC	Insufficient (10%)	bad	no	yes	yes	yes		yes	yes
IC15	PLCC	Exc. Misalign. X	bad	no	yes	no	yes	yes	yes	yes
IC31	PLCC	Polarity (90deg)	bad	yes	NP	yes	yes	no (2)	no	NC
IC36	SOIC	Exc. Misalign. X	bad	yes	yes	yes	yes	no (2)	yes	yes
IC511	SOIC	Bridge	bad	yes	yes	yes	yes	yes	yes	yes
IC505	SOIC	Flux residue	good	U	U	A	A	U	U	U
IC519	SOIC	Polarity (180deg)	bad	yes	no (2)	yes	yes	no (2)	yes	NC
		Resistors								
R276	R0603	Crocodile	bad	yes	yes	no	yes	yes	yes	yes
R277	R0603	Insufficient (0%)	bad	yes	yes	yes	yes	yes	yes	yes
R278	R0603	Exc. joint	bad	no (1)	yes	yes	yes	yes	yes	yes
R283	R0603	Acc. joint (50% rise)	marg./good	bad	bad	good	bad	good	bad	good
R284	R0603	Poor joint (cold)	bad	yes	yes	no	yes	no	yes	yes
R285	R0603	Crocodile	bad	no	yes	no	yes	yes	yes	yes
R285	R0603	Diff. manufacturer	good	bad	good	good	good	good	good	good
R288	R0603	Max. misalign. Y	marginal	good	good	good	good	good	good	good
R319	R0603	Max. misalign X	marginal	bad	good	good	bad	good	good	good
		Through-hole								
RL1	TH	Diff. component	bad	yes	NP	NP	yes	NP (2)	NP	NP

NV = Not viewed, NP = Not programmed, NC = Not capable, U = Unaffected, A = Affected, M = Masked by another defect
yes = defect located, no = defect not located
bad = flagged bad, good = flagged good

Notes :

- (1) Difficult to set up machine to locate both insufficient and excess joints
- (2) Located after reprogramming. Effect on false detect rate unknown.
- (3) Located as slew.
- (4) May be possible with reprogramming. Effect on false detect rate unknown.
- (5) This joint could not be found because of the number of other poor joints on this device. If it were the only poor joint or one of a small number, then the system may have been able to locate it.

Table 6 : Defect Results for Assembly 32

Comp Ident.	Type	Defect & Degree	Classification (IPC-A-610 etc.)	A	B	C	D	E	F	AXI
Capacitors										
C17	Tantalum	Misalign. X (15%)	marginal/good	bad	good	good	bad	good	bad	bad
C148	C0603	Acc. joint (50%rise)	marginal/good	good	bad	good	bad	good	good	good
C180	Tantalum	Acc. joint (50%rise)	marginal/good	good	good	good	bad	good	good	good
C176	Tantalum	Misalign X (10%)	marginal/good	bad	good	good	bad	bad	bad	bad
C177	Tantalum	Planarity	good	bad	good	good	bad(6)	bad	good	bad
C178	Tantalum	Insufficient (0%)	bad	no (3)	no	no	yes	yes	yes	yes
C527	C0603	Exc. joint	bad	no (1)	no (2)	no	yes	yes	M	no (7)
C527	C0603	Insufficient (0%)	bad	no	no	no	yes	yes	yes	no (7)
C533	C0603	Acc. joint (50% rise)	marginal/good	good	good	good	bad	bad	good	good
Semiconductors										
IC1	QFP	Bridge	bad	yes	no (2)	yes	yes	no (2)	yes	yes
IC1	QFP	Planarity	bad	no	no (2)	no	yes	no (2)	no	no (7)
IC1	QFP	Misalign (10%)	good	good	good	good	good	good	bad	good
IC1	QFP	Excess joint	bad	no (1)	no (2)	no	no	yes	yes	yes
IC1	QFP	Acc. joint (200% rise)	marginal/good	good	good	good	good	good	good	good
IC5	QFP	Polarity (90deg)	bad	yes	NP	yes	yes	NP (2)	yes	NC
IC15	PLCC	Polarity (180deg)	bad	yes	yes	yes	yes	NP (2)	yes	NC
IC36	SOIC	Exc. misalign Y	bad	yes	yes	yes	yes	yes	yes	yes
IC37	PLCC	Bridge	bad	no (5)	no (2)	no	yes	yes	no	yes
IC37	PLCC	Acc. joint (large vol.)	marginal/good	good	good	good	bad	good	good	bad
IC44	SOIC	Insufficient (toe & heel fillet 0%)	bad	no	yes	no	yes	no	yes	yes
IC92	SOIC	Insufficient (toe & heel fillet 0%)	bad	no (4)	yes	yes	yes	no (2)	no	yes
IC96	SOIC	Planarity	bad	no (4)	no (2)	no	yes	no (2)	no	yes
IC101	SOIC	Excess joint	bad	no (1)	yes	no	yes	no (2)	no	yes
IC121	PLCC	Excess joint	bad	no (1)	no (2)	NP	no	yes	yes	yes
IC504	SOIC	Acc. joint (50% rise)	marginal/bad	good	good	good	good	good	good	bad
IC511	SOIC	Misalign. X (10%)	marginal/good	good	good	good	bad	good	good	bad
IC511	SOIC	Planarity	bad	no	no (2)	no	yes	no (2)	yes	yes
IC517	SOIC	PdNi lead finish	good	bad	bad	bad	bad	good	good	good
Resistors										
R275	R0603	Insufficient (0%)	bad	yes	no (2)	no	yes	yes	yes	yes
R277	R0603	Insufficient (0%)	bad	no	no (2)	no	yes	yes	yes	yes
R285	R0603	Wrong value 100K Ω	bad	yes	NP	NP	yes	no	NP	NC
Through-hole										
RL1	TH	Bent pin	bad	yes	NP	NP	no (2)	no (2)	NP	NP

NV = Not viewed, NP = Not programmed, NC = Not capable, M = Masked by another defect

yes = defect located, no = defect not located

bad = flagged bad, good = flagged good

Notes :

- (1) Difficult to set up machine to locate both insufficient and excess joints
- (2) Located after reprogramming. Effect on false detect rate unknown.
- (3) Located as slew
- (4) May be possible with reprogramming. Effect on false detect rate unknown.
- (5) Found on retest.
- (6) Failed as poor joint
- (7) Located after reprogramming. No effect on false detect rate.

Table 7 : Defect Results for Assembly 33

Comp. Ident.	Type	Defect & Degree	Classification (IPC-A-610 etc.)	A	B	C	D	E	F	AXI
		Capacitors								
C148	C0603	Insufficient (10%)	bad	no	yes	no	yes	yes	yes	yes
C177	Tantalum	Diff. manufacturer	good	bad	bad	bad	bad	bad	bad	good
C527	C0603	Max. misalign X	marginal	bad	bad	bad	bad	bad	good	good
C533	C0603	Insufficient (10%)	bad	no	yes	no	yes	no (2)	no?	no
		Semiconductors								
IC1	QFP	Exc.misalign (50%)	bad	yes	yes	yes	yes	yes	yes	yes
IC5	QFP	Bridge	bad	yes	no (2)	no	no	yes	yes	yes
IC5	QFP	Max. misalign	marginal	good	bad	bad	bad	good	good	good
IC5	QFP	Polarity (180deg)	bad	yes	NP	yes	yes	no (2)	yes	NC
IC15	PLCC	Insufficient (0%)	bad	no	yes	NP	yes	yes	no?	yes
IC36	SOIC	Max.misalign. Y	marginal	good	M	bad	bad	good	good	bad
IC44	SOIC	Insufficient (toe & heel fillet 0%)	bad	no	yes	yes	yes	no	no?	yes
IC92	SOIC	Flux residue	good	bad	NP	bad	good	good	NP	good
IC512	SOIC	Wrong component	bad	yes	yes	yes	yes	no	NP	NC
IC512	SOIC	Misalign. X (10%)	marginal/good	M	good	bad	bad	good	good	good
		Resistors								
R281	R0603	Diff. manufacturer	good	bad	NP	bad	good	good	good	good
R285	R0603	Acc. joint (low vol.)	good	bad	bad	good	bad	good	good?	bad
		Through-hole								
RL1	TH	Planarity	bad	yes	NP	NP	yes	NP	NP	NP

NV = Not viewed, NP = Not programmed, NC = Not capable, M = Masked by another defect

yes = defect located, no = defect not located

bad = flagged bad, good = flagged good

Notes :

(2) Located after reprogramming. Effect on false detect rate unknown.

Table 8 : Defect Results for Assembly 34

Comp. Ident.	Type	Defect & Degree	Classification (IPC-A-610 etc.)	A	B	C*	D	E	F	AXI
C2	Tantalum	Polarity	bad	yes	yes	yes	yes	yes	yes	yes
C17	Tantalum	Diff. manufacturer	good	bad	yes	bad	bad	bad	bad	good
C19	Tantalum	Add. Component	bad	yes	yes	NP	yes	yes	yes	NP
C177	Tantalum	Polarity	bad	yes	yes	yes	yes	yes	yes	yes
C180	Tantalum	Polarity	bad	yes	yes	yes	yes	yes	yes	yes
C181	Tantalum	Polarity	bad	yes	yes	yes	yes	yes	yes?	yes
C183	Tantalum	Polarity	bad	yes	yes	yes	yes	yes	yes	yes
C527	C0603	Wrong value	bad	yes	no	no	yes	no	no	NC
IC1	QFP	Misalign (25%)	marginal	good	bad	good	good	good	bad	good
IC1	QFP	Insufficient (heel fillet 50%)	bad	no	no	no	no	no	no	no (7)
IC5	QFP	Insufficient (toe and heel 0%)	bad	no	no	no	yes	no (2)	yes	yes
IC18	PLCC	Max. misalign. X	marginal	M	good	good	bad	good	good	good
IC18	PLCC	Wrong component	bad	yes	NP	yes	yes	NP	NP	NC
IC30	PLCC	Misalign. X (10%)	marginal/good	good	good	good	good	good	good	good
IC44	SOIC	Max. misalign. X	marginal	bad	bad	bad	bad	good	bad	good
IC65	PLCC	Polarity	bad	yes	no	yes	yes	no (2)	yes	NC
IC110	SOIC	Diff. manufacturer	good	bad	good	bad	bad	good	bad	good
R49	R0603	Exc. misalign. X	bad	yes	yes	yes	yes	yes	yes	yes
R65	R0603	Max. misalign X	marginal	bad	bad	good	bad	good	bad	good
R84	R0603	Misalign. X (10%)	marginal/good	good	bad	good	good	good	good	good
R656	R0603	Inverted	bad	yes	yes	yes	NP	yes	yes	NC
R275	R0603	Tombstone	bad	yes	yes	yes	yes	yes	yes	yes
R284	R0603	Insufficient (0% rise)	bad	no	yes	no (2)	yes	no	yes	yes
R285	R0603	Insufficient (10% rise)	bad	no (3)	yes	no	yes	no (2)	yes	yes
R289	R0603	Insufficient (0% rise)	bad	no	yes	yes	yes	yes	yes	yes
R530	R0603	Misalign. (50%)	bad	yes	yes	yes	yes	no	no	no (7)
R532	R0603	Missing	bad	yes	yes	yes	yes	yes	yes	yes
RL1	TH	Poor joint (hole fill)	bad	NP	NP	NP	NP	NP	NP	NP
RL1	TH	Poor joint (hole fill)	good	NP	NP	NP	NP	NP	NP	NP

* not confirmed as defect report unavailable

NV = Not viewed, NP = Not programmed, NC = Not capable, M = Masked by another defect

yes = defect located, no = defect not located

bad = flagged bad, good = flagged good

Notes :

(2) Located after reprogramming. Effect on false detect rate unknown.

(3) Located as slew

(7) Located after reprogramming. No effect on false detect rate.

Table 9 : Defect Results for Assembly 35

Comp. Ident.	Type	Defect & Degree	Classification (IPC-A-610 etc.)	A	B	C*	D	E	F	AXI
C10	Tant	Missing	bad	yes	yes	yes	NP	yes	yes	yes
C17	Tant	Misalign. X (10%)	good	good	good	good	good	good	good	good
C533	C0603	Diff. manufacturer	good	bad	good	good	bad	good	good	good
IC1	QFP	Missing	bad	yes	yes	yes	yes	yes	yes	yes
IC5	QFP	Bridge	bad	yes	yes	yes	no (4)	yes	yes	yes
IC5	QFP	Misalign. X (50%)	bad	no	yes	yes	yes	no	no	no
IC30	PLCC	Missing	bad	yes	yes	yes	yes	yes	yes	yes
IC92	SOIC	Misalign Y Exc.	bad	yes	yes	yes	yes	no (2)	yes	yes
IC127	SOIC	Missing	bad	yes	yes	yes	yes	yes	yes	yes
IC515	SOIC	Missing	bad	yes	yes	yes	yes	yes	yes	yes
IC516	SOIC	Misalign. X (50%)	bad	no (5)	yes	yes	yes	no (2)	no	yes
RL1	TH	Orientation	bad	yes	NP	NP	yes	NP (2)	NP	NP

*not confirmed as defect report unavailable

NV = Not viewed, NP = Not programmed, NC = Not capable

yes = defect located, no = defect not located

bad = flagged bad, good = flagged good

Notes :

- (2) Located after reprogramming. Effect on false detect rate unknown.
- (4) May be possible with reprogramming. Effect on false detect rate unknown.
- (5) Found on retest.

DISCUSSION OF RESULTS

Defects from similar components across all the assemblies have been collected together and summarised to form a series of “confidence” charts. Where a system found all occurrences of the component defect type, it was given a high confidence rating. It should be noted that this may be based on location of a single defect. Where a system found some but not all occurrences of defect type, it was given a medium confidence rating. Where a system did not find any occurrences of defect type, it was given a low confidence rating. Again, it should be noted that this rating may be based on the detection of a defect at only one possible location. We now deal with specific component types, looking at the possible defects and the detection efficiency of the respective instruments.

Chip Capacitors and Resistors :

Table 10 : Chip capacitor and resistor confidence chart

R0603/C0603	A	B	C	D	E	F	AXI
Missing	H	H	H	H	H	H	H
Misalign	H	H	H	H	M	M	M
Insufficient	M	M	M	H	M	M	M
Excess	L	M	M	H	H	H	M
Tombstone	H	H	H	H	H	H	H
Inverted	H	H	H	H	H	H	NC
Crocodile	M	H	L	H	H	H	H
Different Value Capacitor	H*	L	L	H*	L	L	NC
Different Value Resistor	H	?	?	H	L	?	NC

? = claimed capability but insufficient data to confirm

* = all occurrences found but this may have been due to external component differences which may not always be present

NC = not capable

Generally the AOI systems and the AXI system handled inspection of chip resistor and capacitor defects well. All systems achieved a high rating for missing components, and tombstoning (figure 3), and a medium or high rating for misaligned components and insufficient joints figure 4). All the machines except one of the AOI machines scored medium or high for excess solder joints (figure 4).

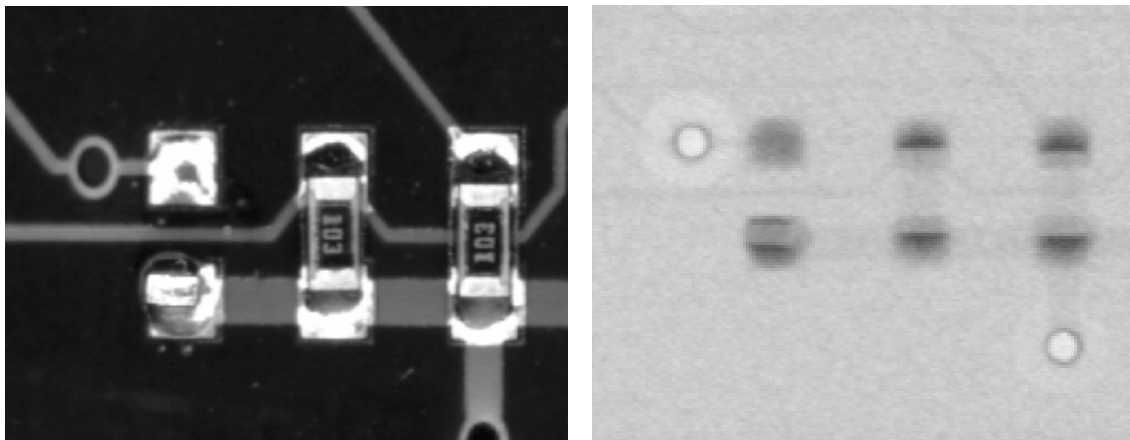


Figure 3 : Comparison of AOI and AXI images for tombstoned component

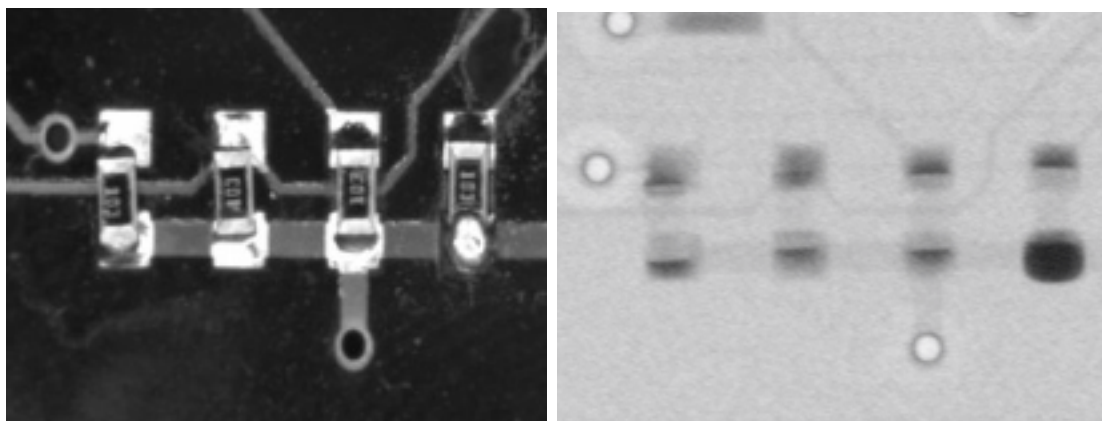


Figure 4 : Comparison of AOI and AXI images for insufficient and excess solder joints

The AXI system cannot identify inverted components nor locate different value capacitors. This was also extremely difficult for AOI systems, as it would be for a manual operator. Several AOI machines did achieve a high rating for this category although it should be noted that the body colour of the replacement component was slightly different from the original and this may have aided their location of the defects.

Location of wrong resistor values requires optical character recognition (OCR) algorithms used on the component marking to be successful. Not all the AOI systems have OCR. The component marking is transparent to Xray and therefore the AXI had no capability in locating this type of defect.

Tantalum Capacitors :

Table 11 : Tantalum capacitor confidence chart

Tantalum case D	A	B	C	D	E	F	AXI
Missing	H	H	H	?	H	H	H
Misalign	H	M	M	H	H	H	H
Insufficient	M	M	L	H	M	H	M
Excess	L	M	L	H	H	L	H
Polarity	H	H	H	H	H	H	H
Different Value Capacitor	H	H	H	H	M	H	NC

? = claimed capability but insufficient data to confirm

NC = not capable

Missing components were found by all systems including the AXI system, as were wrong polarity components (figure 6). The AOI systems achieved recognition of this defect by detecting polarisation marks. The AXI system utilised the internal differences within the component. All systems including the AXI system scored high for misaligned components except for two vertical camera based AOI systems (B & C) which scored medium. Two of the AOI systems (both with angled cameras) outperformed the AXI system at locating insufficients (figure 5). One of the remaining AOI systems only scored low. Three systems (including the AXI) achieved a high confidence at locating excess solder joints (figure 7), with three of the remaining AOI systems only achieving low confidence ratings. Generally all the AOI systems performed well for different value tantalum capacitor although it should be noted that the wrong components were of a different body colour (yellow rather than black) than

on the “golden” assemblies. The AXI system is not capable of locating this type of defect.

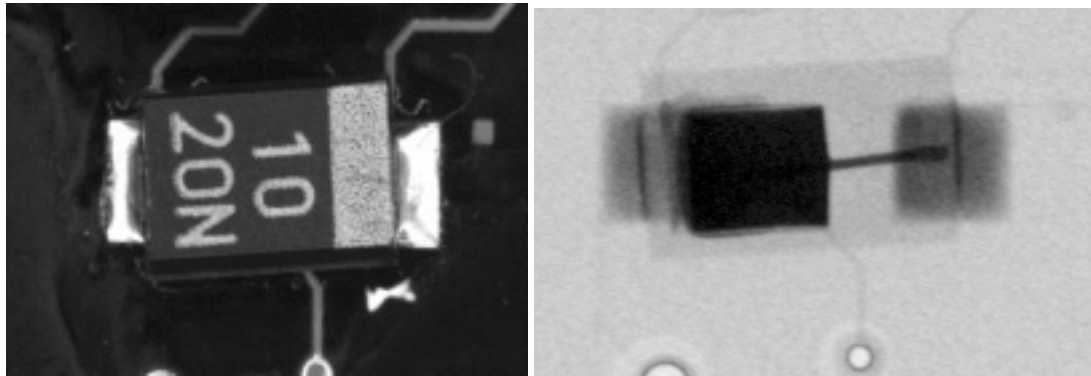


Figure 5 : AOI and AXI images of tantalum capacitor insufficient joint

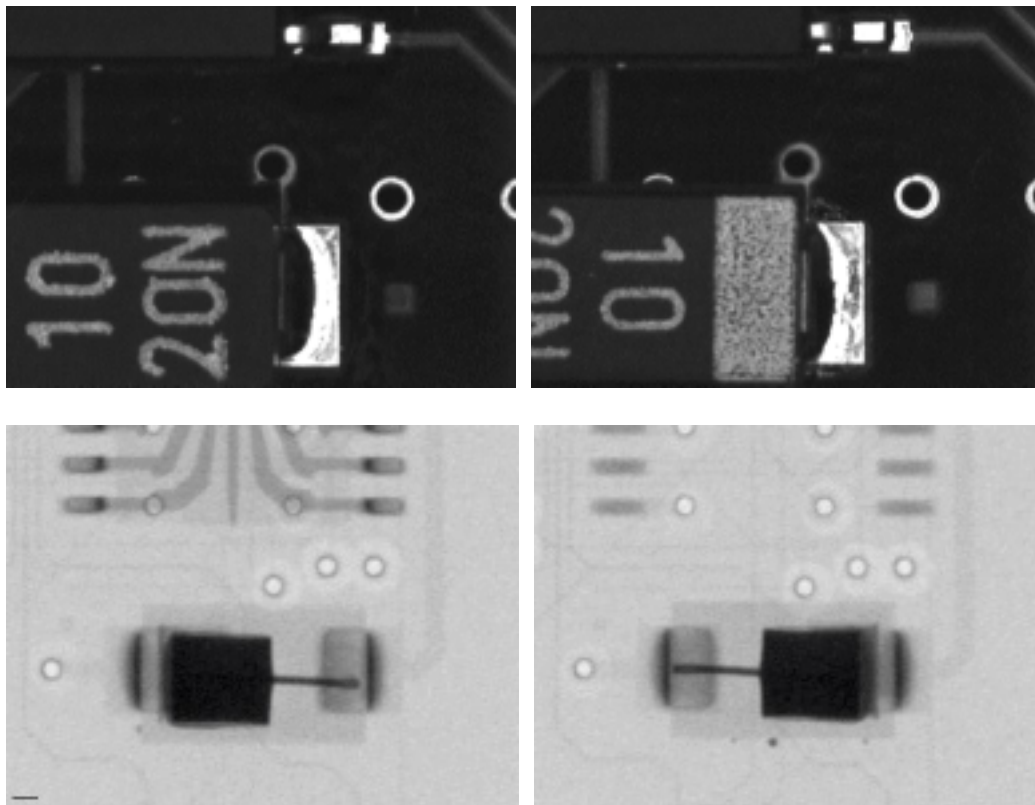


Figure 6 : AOI and AXI images of wrong polarity tantalum capacitors

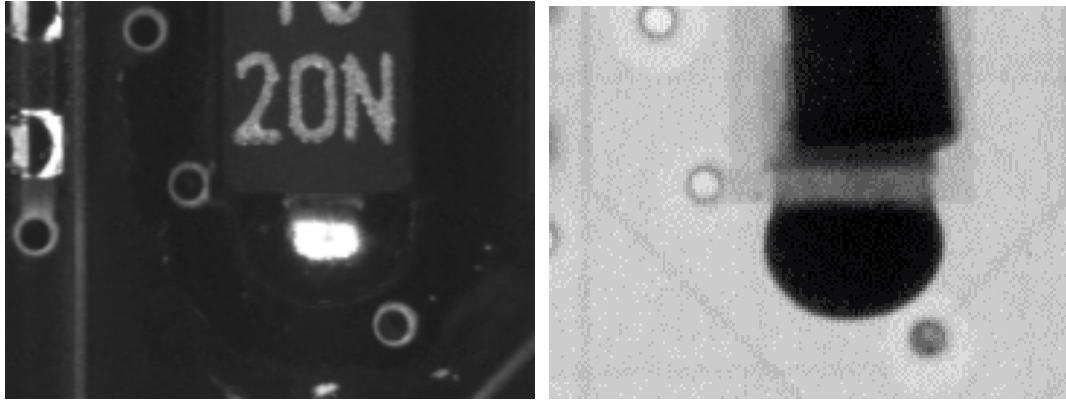


Figure 7 : AOI and AXI images of excess joint on tantalum capacitors

Small Outline ICs :

Table 12 : SOIC confidence chart

SOIC	A	B	C	D	E	F	AXI
Missing	H	H	H	H	H	H	H
Misalign	M	H	H	H	M	M	H
Insufficient (toe & heel fillet)	L	M	M	H	L	M	H
Excess	L	H	L	H	L	L	H
Bridge	H	H	H	H	H	H	H
Polarity	H	M	H	H	M	H	NC
Wrong Component	H	H	H	H	L	L	NC

NC = not capable

Location of defects on SOIC was generally achieved successfully for most systems with the AXI system and one of the AOI systems (D) achieving high confidence for missing, misaligned, insufficient joints, excess joints and bridges.

All systems including the AXI were rated high for missing components and bridges (figure 10). High or medium rating were achieved for all machines for misaligned components (figure 8). All machines except the AXI system achieved high or medium confidence rating for wrong polarity detection. The AXI would be capable of detecting wrong polarity SOICs if a polarity marking were present in the leadframe of the device. Four of the six AOI systems (A, B, C & D) were also rated high for location of the wrong component. The other two systems were only rated low. The AXI system is not normally capable of location wrong components.

Poor solder joints were located less successfully with only one AOI system (D) and the AXI system finding all occurrences of insufficient joints (figure 9). Indeed, the AXI system found several insufficient heel fillets that were not noticed by during manual optical inspection or located by any of the AOI systems. Two AOI systems (B & D) and the AXI system found all occurrences of excessive solder joints.

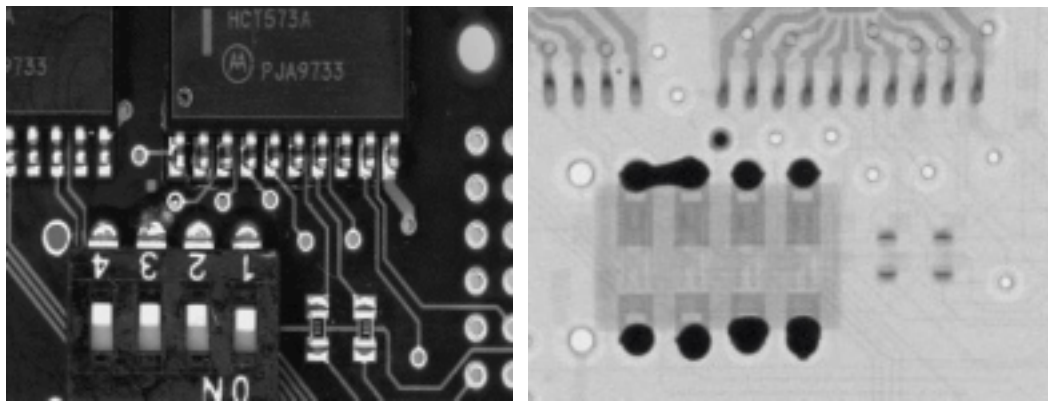


Figure 8 : AOI and AXI images of misaligned SOIC (at top of image), with bridge on the underside of through hole switch, not visible on AOI top side view.

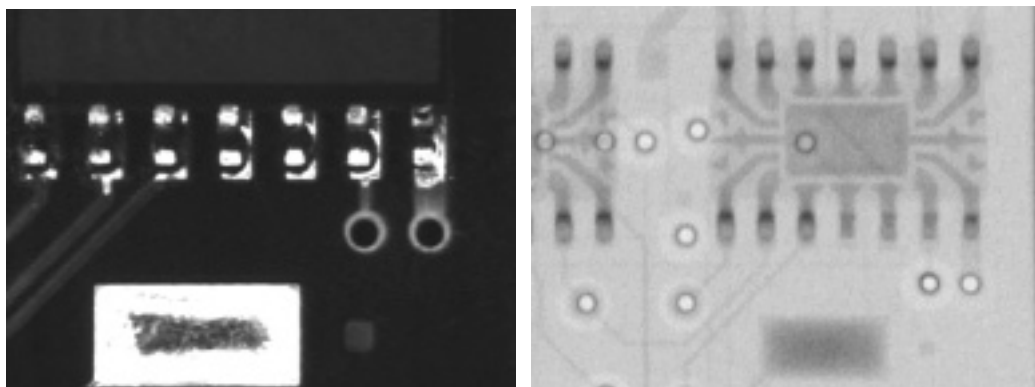


Figure 9 : AOI and AXI images of insufficient SOIC joints

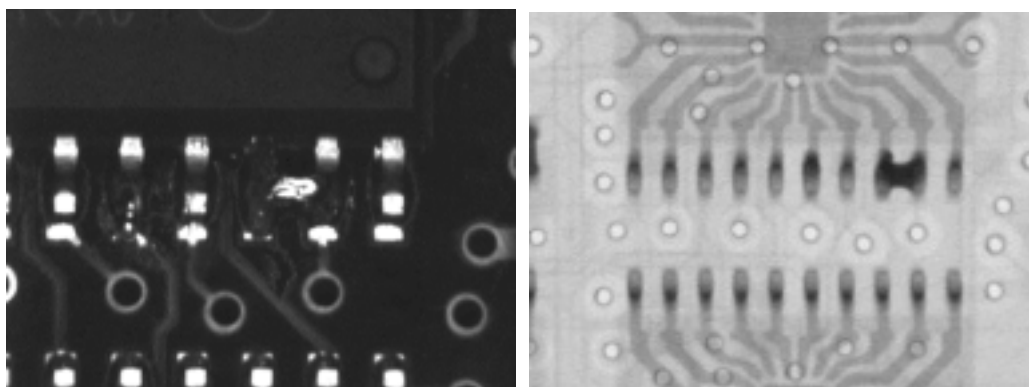


Figure 10 : AOI and AXI images of SOIC bridge

Plastic Leaded Chip Carriers :

Table 13 : PLCC confidence chart

PLCC	A	B	C	D	E	F	AXI
Missing	H	H	H	H	H	H	H
Misalign	L	H	L	H	H	H	H
Insufficient	L	H	H	H	H	M	H
Excess	L	M	?	L	H	H	H
Bridge	M	M	L	H	H	L	H
Polarity	H	M	H	H	M	M	NC
Different Component	H	?	H	H	?	?	NC

? = claimed capability but insufficient data to confirm

NC = not capable

The results for PLCCs are similar to those for SOICs as the AXI system and one of the AOI systems (this time system E) achieved high confidence ratings for missing, misalign, insufficient, excess and bridges.

All systems including the AXI located missing components but of the vertical camera systems only one AOI and the AXI system were rated high for misaligned components (figure 14). All three AOI systems with angled cameras were rated high. This may be because the alignment is difficult to judge when viewed directly from above because the top of the PLCC leads being wider than the bottom of the leads, mask the alignment of the lead on the pad. A comparison between vertical and angled AOI views of a PLCC are shown in figure 11.

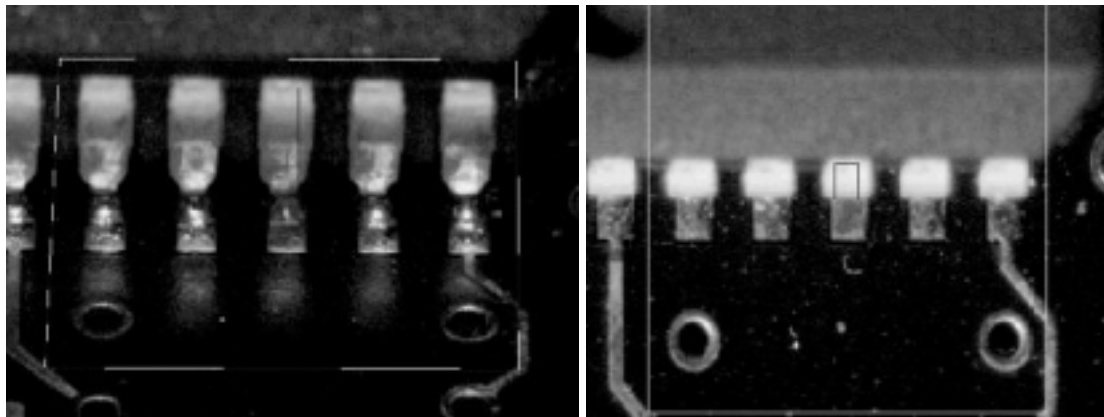


Figure 11 : Vertical and angled images of PLCC (source : Orbotech)

Bridging (figure 12) was generally located better by those systems incorporating angled cameras, possible for the same reason as noted above, although one angled system was rated as low. The AXI system achieved a high confidence rating. It should be noted that some systems do not routinely check for bridges on PLCCs as it is felt that this is a very low level defect for PLCCs and it is not worth slowing the inspection time by including additional checks for bridges.

Some systems experienced difficulty in locating insufficient and excessive solder joints (figure 13), but again perhaps the systems with angled cameras were slightly more

successful. The AXI system achieved a high confidence in locating both types of defects, as well as locating some inner lead fillets not found by manual optical inspection or AOI. Those systems which were programmed to locate a different component were all successful in achieving this, although it should be noted that the AXI system is not capable of locating this type of defect, nor in locating polarity problems without a marker in the leadframe as discussed in SOIC results above.

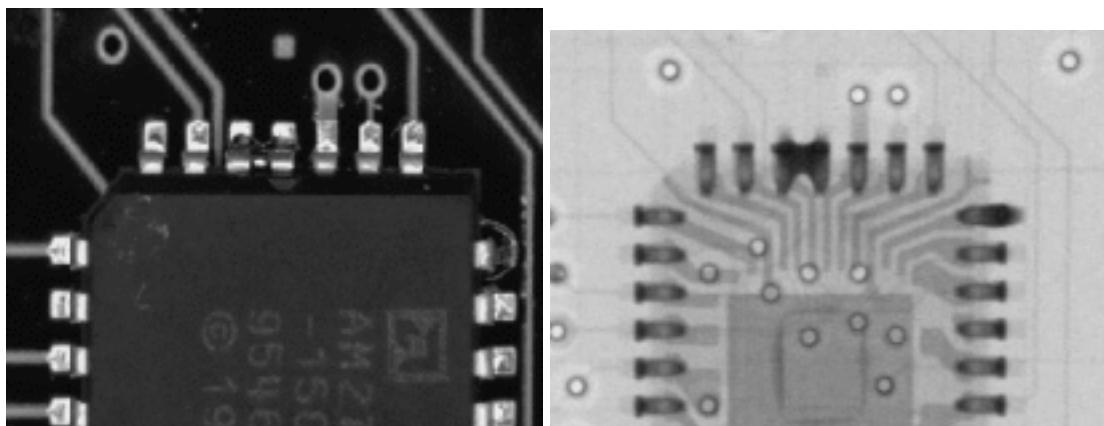


Figure 12 : AOI and AXI images of PLCC bridge

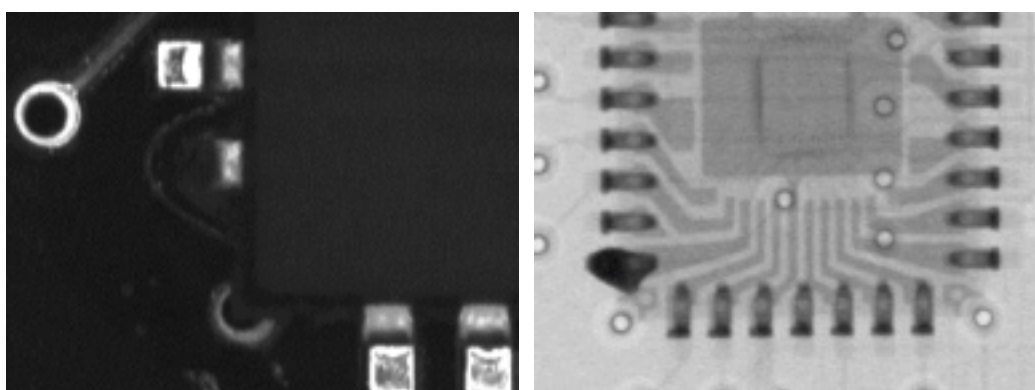


Figure 13 : AOI and AXI images of excess PLCC joint

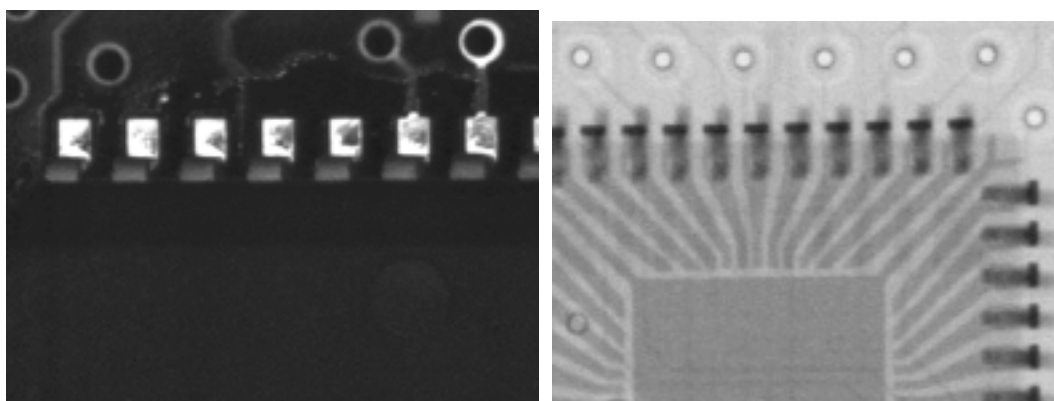


Figure 14 : AOI and AXI images of PLCC misalignment

Quad Flat Packs :

Table 14 : QFP confidence chart

QFP	A	B	C	D	E	F	AXI
Missing	H	H	H	H	H	H	H
Misalign	M	M	H	H	M	M	M
Insufficient - toe fillet	M	M	L	M	M	M	M
Insufficient - heel fillet	L	L	L	L	L	L	M
Excess	L	M	L	L	H	H	H
Bridge	H	M	M	M	M	H	H
Polarity	H	?	H	H	M	H	NC

? = claimed capability but insufficient data to confirm

NC = not capable

The systems generally performed less well when moving to the finer pitches of the QFPs (0.5 and 0.65 mm pitches) compared to the SOICs (1.27mm pitch). All systems still performed well in locating missing components and were rated medium or high for misalignment (figure 16). However no system was rated high for insufficient solder joints (figure 14). The AXI system performed best in location of heel fillets, achieving a medium confidence rating, as well as locating some toe fillets not located with manual optical inspection or AOI. Only two of the AOI systems and the AXI system achieved a high rating for excess solder joints. Similarly only two AOI systems (A & F) and the AXI systems achieved high rating for bridges (figure 15) compared to all systems for the 1.27mm pitch SOICs. It should be noted that the AXI system has no capability to locate polarity defects unless there is a suitable marker in the device leadframe.

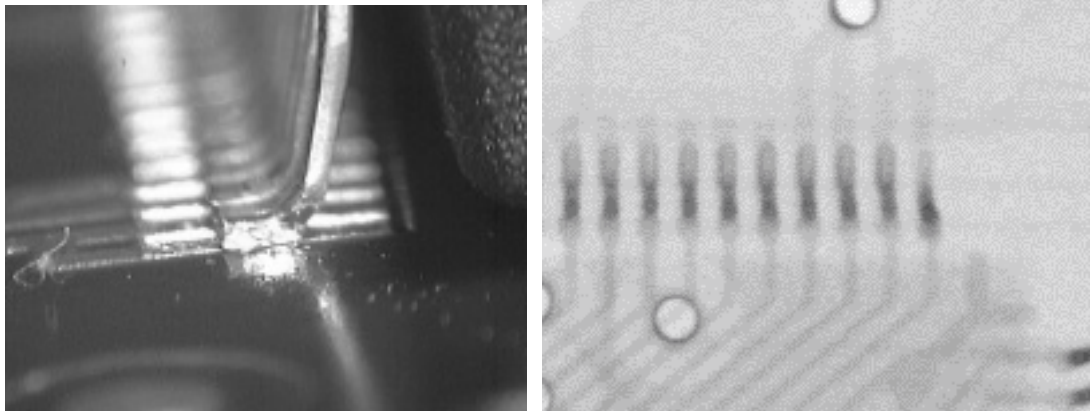


Figure 14 : Optical microscope and AXI image of insufficient toe and heel fillet on QFP

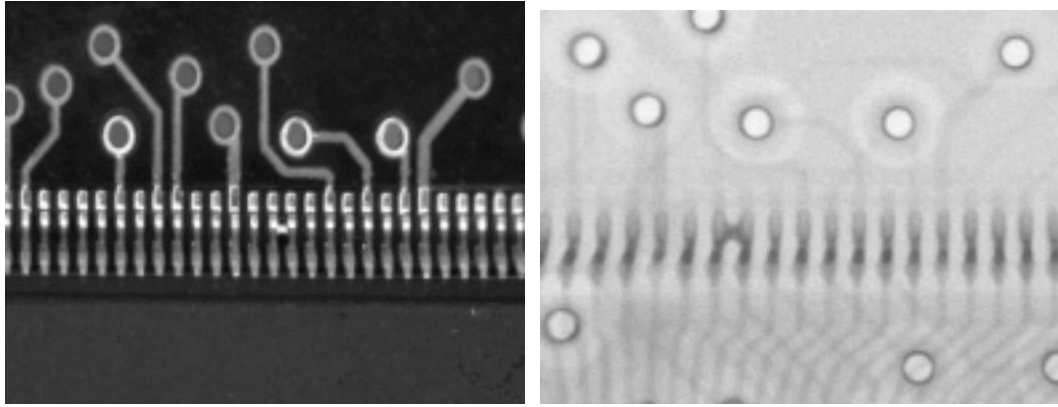


Figure 15 : AOI and AXI images of bridge on QFP

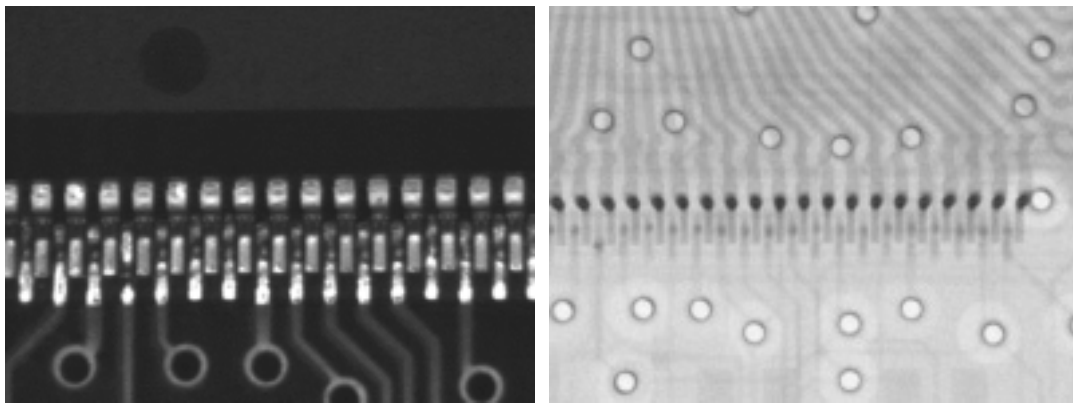


Figure 16 : AOI and AXI images of misaligned QFP

Through Hole Components :

Not all systems were programmed to inspect the single through-hole component on the assembly. Those that were generally performed well at locating bent pins, different components, planarity and component polarity. No system exhibited a capability to inspect varying degrees of TH solder fill during the benchmark.

False Detect Rates :

It should be noted that no equipment scored medium or high in all categories. The equipment which probably came closest to achieving this also had the highest false detect level, as shown in Table 15.

Table 15 : False detect rate averaged over all 10 test assemblies

	A	B	C	D	E	F	AXI
percentage of joints	N/A	N/A	1.2	N/A	0.2	0.4	0.15
percentage of components	2.2	4.9	7.9	20.3	1.2	2.7	1.1

On a per joint basis, false detect rates below 1% were achieved by two AOI systems (E & F) and the AXI system. The AXI system achieved the lowest false detect rate. No system achieved a zero false detect rate. It should be noted that false detect rates may be reduced by further refinement of programme without unduly impacting on

sensitivity, although the effect on detection rates of this refinement was not monitored in this study.

CONCLUSIONS

In summary, all equipment exhibited acceptable capabilities in the following areas :

- missing (all component types)
- misalignment (0603s, tantalum capacitors, SOICs, 0.65mm pitch QFPs)
- bridging (SOICs)
- polarity (PLCCs, SOICs, tantalum capacitors, QFPs)
- wrong component (tantalum capacitors)

In the following areas, some systems performed well whilst other systems were less successful. If defect location is required in these categories then a system would need to be chosen with care and may not be capable of efficiently locating all of these categories :

- misalignment (0.5mm QFPs, PLCCs)
- insufficient (PLCCs, tantalum capacitors, QFP toe fillets, SOIC toe fillets, (only one high confidence), SOIC heel fillets (only one high confidence)
- excessive (all component types)
- bridges (PLCCs, QFPs)
- wrong component (PLCCs, QFPs, 0603s, SOICs)

In the following areas no equipment was 100% successful at locating defects :

- insufficient QFP heel fillets (no equipment found all poor quality QFP joints)
- through-hole hole fill

AXI found some poor joints on the assemblies not previously found by manual or automatic optical inspection. These included inner J-lead joints, SOIC heel fillets and QFP toe fillets. The AXI system did have problems finding some poor joints on components where a significant number of other joints had also failed. This was due to an averaging function in the AXI software but many users may not consider this a problem, as with this number of defects the complete component may need to be reworked anyway.

The AXI system exhibited a lower false detect rate than any of the AOI systems. This may be because Xray images are simpler to process and analyse than AOI images as there is only one view with no lighting alternatives. It should be noted that AXI is not generally suitable for detecting the wrong component, wrong orientation (tantalum capacitors excepted) or inverted resistor location. The AXI system is approximately 50% more expensive than an AOI system with comparable capabilities, but the AXI test times were faster than most (but not all) AOI systems and the AXI system has BGA and flipchip capabilities (which were not assessed here). With AXI systems there may be issues with double-sided assemblies, as solder joints on the under side of the assembly would be 'visible' to the X-rays and could interfere with defect detection (figure 17). This problem could be alleviated by using a tomosynthetic or laminography system which are capable of building an Xray image of one side of a double-sided

assembly at a time. Such systems are significantly more expensive than the AXI evaluated in this project. Alternatively, the assembly could be designed to avoid joints on the top & bottom of the assembly in the same vertical position.

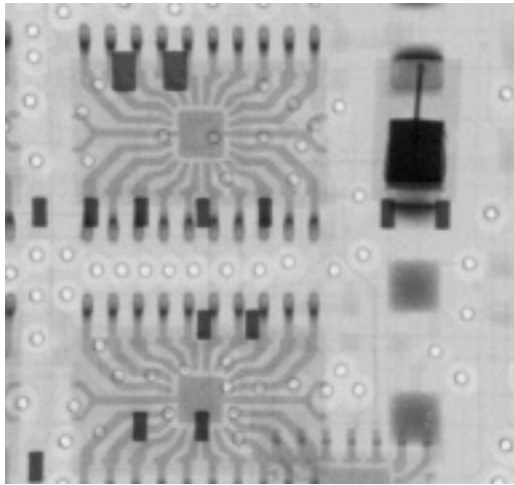


Figure 17 : AXI image of double sided assembly showing bottom side components obscuring top side joints

AOI and AXI are not precise measurement techniques, they will not differentiate between 24% and 26% misalignment. But, if adequately programmed they can be utilised to locate a wide range of common electronics assembly defects. Such systems will not guarantee that the assembly will function and therefore functional electrical test will still be required. But they would give the end user a degree of confidence that the assemblies inspected are fit for their intended purpose and will give some prediction/qualification of reliability, which electrical test systems cannot do.

Automatic optical inspection and automatic Xray inspection after soldering of assemblies will find increasing number of applications in the following areas :

- (i) reducing number of defects (i.e. reject rate) at electrical test
- (ii) reducing number of solder joints to be viewed by inspector
- (iii) increasing inspector efficiency (inspector can concentrate on potential defects flagged by the system)
- (iv) inspection of coarser pitch components in higher volume production

There are a number of areas where systems need to be chosen carefully to give efficient defect location coverage. These include :

- (i) Fine feature inspection : This may be improved with more extensive programme development but similarly on some systems false detect rates may increase.
- (ii) Programming effort and skill level of the programmer : For the setting up a high level of computer literacy is required, the level may vary from system to system. In operation semi-skilled inspectors may be replaced by skilled computer literate machine operators.

(iii) Smaller volume production : High programming overhead per assembly design and the high equipment costs, may restrict system utilisation for low volumes.

REFERENCES

- (1) NPL Report CMMT (A) 173 : Benchmarking Assisted and Automatic Inspection of Electronic Assemblies : M Wickham and C Hunt : June 1999
- (2) IPC-A-610 Revision B December 1994 : Acceptability of Electronic Assemblies
- (3) IEC 61191-2 : Printed board assemblies : Part 2 : Sectional specification - Requirements for surface mount soldered assemblies
- (4) IEC 61191-3 : Printed board assemblies : Part 3 : Sectional specification - Requirements for through-hole mount soldered assemblies

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