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Comparative Evaluation of AOI Systems

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Abstract
The electronic industry trend of smaller component packages and tighter spacing has put greater demands on manufacturing for process control and product verification. Defects must be caught earlier in the process to provide feedback to the process. Large quantities of manual rework on components that can barely be seen or handled put too much strain on rework operators. Manual inspection as a means of process control has become less effective by these factors causing fatigue, missing defects, and reduced thru-put. In-circuit test as a means of product verification also has issues because it requires space on the printed circuit board for test pads. Automated Optical Inspection (AOI) is an increasing popular method to address process control and product verification. Faster processors with higher density memory devices have enabled image capture and processing to become a viable alternative. This paper will detail the methodology used to select and evaluate AOI systems as an alternative process control and product verification tool.

Introduction
Four AOI systems were identified and tested for performance and capability. The systems were selected based on installed base, reputation, number of years in the market and technology. Each system was evaluated for:
1. Defect coverage
2. False defect rate
3. Speed
4. Repeatability

The systems were tested in a production facility. The test vehicles used to evaluate the systems had a variety of parts ranging from 0603 passives, 160-pin quad flat packs, and thru-hole connectors (processed with pin-thru-paste). In order to control the experimental noise, the same assemblies were used as test vehicles on each system. Each system vendor was given identical programming aids and was required to program their system to meet the pre-defined fault coverage. Workmanship standards (based on IPC 610) were used as a reference for deciding true or false defects.

Even though all the AOI systems evaluated were intent on inspecting and pointing out defects, they all had differences in their approach. These differences included: number and type of cameras, type of lighting, computer operating system, image processing method, moving boards or camera, statistical tools, repair workstation setup, and programming method. To maintain the confidentiality of the AOI vendors the systems used for the evaluation have been named A, B, C and D.

Evaluation Setup
The evaluation was done using two double sided assemblies that require paste and reflow processing for both sides. For reference purposes the test vehicles are identified as:
1. Assembly 1 side 1
2. Assembly 1 side 2
3. Assembly 2 side 1
4. Assembly 2 side 2

Figure 1 and Figure 2 show the layout of the selected assemblies. Maximum height of the components under inspection was 1/2 inch. The panels had a variety of parts ranging from 160-pin fine pitch QFPs, thru-hole connectors (processed with pin-thru-paste), SMT passives, and odd shaped mechanical parts. A total of 30 panels of each type were serialized and used for the evaluation.

The point in the process the evaluation was done is shown in Figure 3.

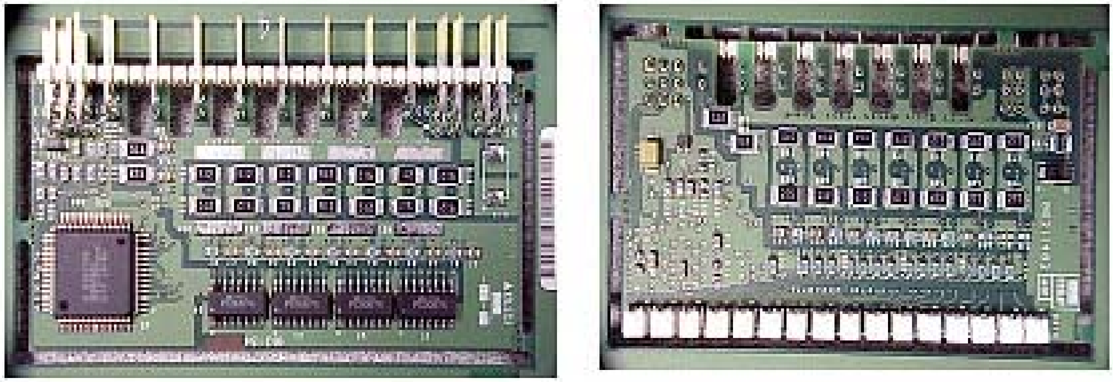

Figure 1 - Assembly 1 - Sides 1 and 2

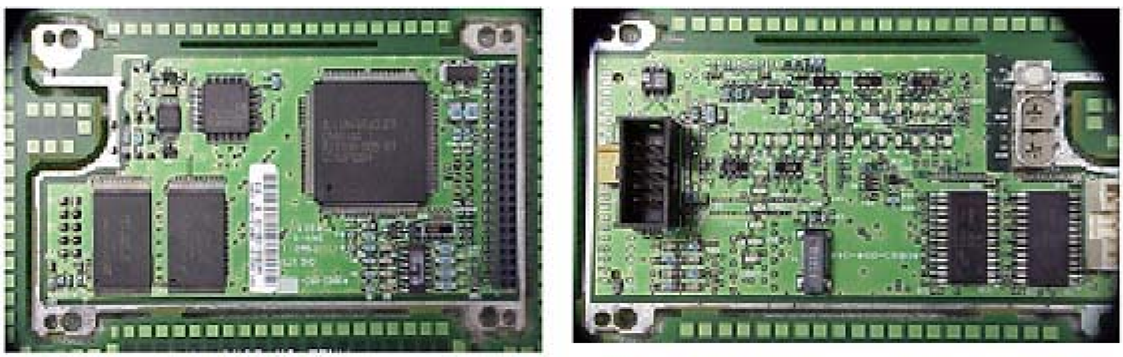

Figure 2 - Assembly 2 – Sides 1 and 2

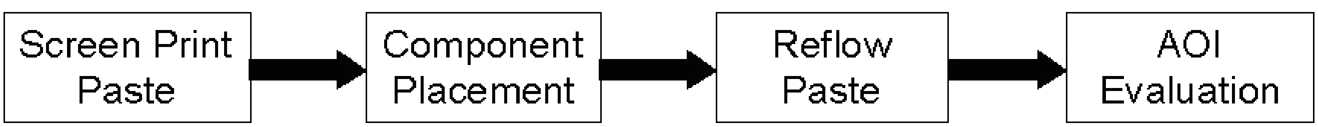

Figure 3 - Process the Evaluation Flow

Each vendor was required to program their system to meet the pre-defined fault coverage. The vendors were required to be present and provide technical assistance during the evaluation. To facilitate the programming, each vendor was given:
1. Five randomly selected panels of each assembly
2. One "golden board" for each assembly
3. CAD data for each assembly
4. Printed and re-flowed PCB with no parts for each assembly
5. One bare PCB of each assembly

Each vendor was allowed 2 to 3 weeks for initial set up and programming. The inspection evaluation with the AOI system was only started when the program was declared "production ready." Once the program was declared ready no changes were allowed during the evaluation.

Data Collection

The following procedure was followed for data collection:
1. Inspected all boards manually and documented defects found.
2. Inspected all boards with AOI system and documented defects, false calls, cycle time, and repeatability.
3. Verified all defects along with the representative of the AOI system vendor.

The following definitions were used to document the results:

Defect coverage: $\frac{\text{Number of actual physical defects detected by the AOI system}}{\text{Total number of defects present on the inspected panels}}$

False defect rate: $\frac{\text{Number of false defects x 1 million}}{\text{Total number of opportunities}}$

Cycle time: The time from entry into the system until the inspection is complete

Repeatability: Run one board with known defects through the system 50 times and compare the mean and standard deviation of the number of defects identified each time.

Table 1 shows the number of opportunities on each side of the assemblies used for the evaluation

Table 1 -Total Number of Opportunities for Each Test Board

Product	Item	Qty/Board	Qty/panel
Assembly 1 – side 1	Components	51	612
	Solder joints	218	2616
	Total	**269**	**3228**
Assembly 1 – side 2	Components	73	876
	Solder joints	184	2208
	Total	**257**	**3084**
Assembly 2 – side 1	Components	56	336
	Solder joints	517	3102
	Total	**573**	**3438**
Assembly 2 – side 2	Components	88	528
	Solder joints	262	1572
	Total	**350**	**2100**

Defect Coverage Results
Table 2 shows the % of defects that each system caught from each assembly.

While there are some slight differences they are not significant as shown by the following analysis of variance.

Table 2 – Defect Coverage Results

% of Defects Caught				
Test Vehicle	**System A**	**System B**	**System C**	**System D**
Assembly 1 Side 1	57%	57%	57%	71%
Assembly 1 Side 2	56%	100%	44%	78%
Assembly 2 Side 1	78%	87%	75%	87%
Assembly 2 Side 2	73%	81%	83%	81%
Total	**72%**	**84%**	**74%**	**83%**

One-way Analysis of Variance of Defect Coverage

```
Source DF SS MS F P
System 3 0.0896 0.0299 1.49 0.267
Error 12 0.2408 0.0201
Total 15 0.3304
 Individual 95% CIs For Mean
 Based on Pooled StDev
Level N Mean StDev --------+---------+--------+--------
A 4 0.6600 0.1117 (---------*---------)
B 4 0.8125 0.1801 (---------*---------)
C 4 0.6475 0.1759 (---------*---------)
D 4 0.7925 0.0665 (---------*---------)
 --------+---------+---------+--------
Pooled StDev = 0.1417 0.60 0.75 0.90
```

False Defect Rate Results
Table 3 shows the rate of false defect calls per million of opportunities that each system had for each assembly.

The difference in false call rates between the systems is not significant as shown by the following analysis of variance.

Table 3 - Rate of False Defect Calls per Million

False Call Rate PPM				
Test Vehicle	**System A**	**System B**	**System C**	**System D**
Assembly 1 Side 1	207	93	351	527
Assembly 1 Side 2	994	530	465	216
Assembly 2 Side 1	1057	2094	1483	1057
Assembly 2 Side 2	984	476	762	889
Total	**796**	**855**	**782**	**664**

One-way Analysis of Variance of False Call Rate

```
Source DF SS MS F P
System 3 46925 15642 0.05 0.986
Error 12 4042101 336842
Total 15 4089026
 Individual 95% CIs For Mean
 Based on Pooled StDev
Level N Mean StDev ----------+---------+--------+------
A 4 810.5 403.6 (---------------*---------------)
B 4 798.2 885.5 (---------------*---------------)
C 4 765.2 508.9 (---------------*---------------)
D 4 672.2 376.1 (---------------*---------------)
 ----------+---------+--------+------
Pooled StDev = 580.4 400 800 1200
```

Speed Results
Table 4 shows the mean cycle time in seconds that each system took to inspect each assembly.

The difference in the time to inspect the assemblies between the systems was significant as shown by the following analysis of variance. Systems B and D were significantly faster.

Table 4 - Mean Cycle Time in Seconds

Mean Cycle Time				
Test Vehicle	**System A**	**System B**	**System C**	**System D**
Assembly 1 Side 1	119	32	72	38
Assembly 1 Side 2	124	32	81	41
Assembly 2 Side 1	46	39	65	38
Assembly 2 Side 2	48	21	49	38
Mean	**84**	**31**	**67**	**39**

One-way Analysis of Variance for Cycle Time

```
Source DF SS MS F P
System 3 7334 2445 4.67 0.022
Error 12 6286 524
Total 15 13620
 Individual 95% CIs For Mean
 Based on Pooled StDev
Level N Mean StDev --------+---------+--------+--------
A 4 84.25 43.07 (-------*-------)
B 4 31.00 7.44 (-------*--------)
C 4 66.75 13.52 (-------*--------)
D 4 38.75 1.50 (-------*-------)
 --------+---------+---------+--------
Pooled StDev = 22.89 30 60 90
```

Repeatability Results
Table 5 shows the variation in number of defect callouts identified by each system on a single panel assembly run through each AOI system 50 times.

System A showed no variation in this test calling out the same 5 defects each time. System B and C had about the same amount of variation and system D had the most variation.

Table 5 - Descriptive Statistics of Repeatability Test

Statistics for "number of callouts" from inspecting same assembly 50 times				
Statistic	**System A**	**System B**	**System C**	**System D**
Mean	5	20	9	15
Standard deviation	0.00	1.05	1.50	3.23

Summary of Results
All systems performed well in the evaluation. The only significant differences were in cycle time and repeatability. Table 6 shows the summarized results. Blank entries in the table identify no significant difference in results for those criteria.

Table 6 – Significant Results

Summary Of Significant Results				
Criteria	**System A**	**System B**	**System C**	**System D**
Defect Coverage				
False Defect Rate				
Speed		Best		Best
Repeatability	Best			Worst

Defect Discussion
One of the key pieces of learning from this evaluation is what types of defects the systems could catch. This could help determine where the system is placed in the process or what type of complementary test or inspection is still needed. For the most part this was the same for all the systems. Figure 4 shows the type of known defects on the test vehicles used for the evaluation**.**

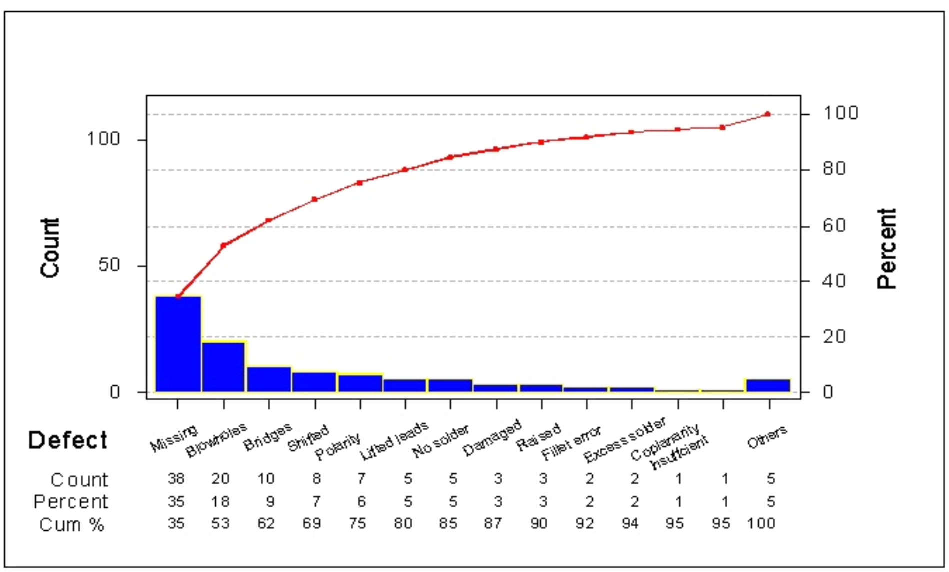

Figure 4 - Defect Pareto of Test Panels used for Evaluation

The types of defects that all the systems were very capable of catching are shown in Figure 5.

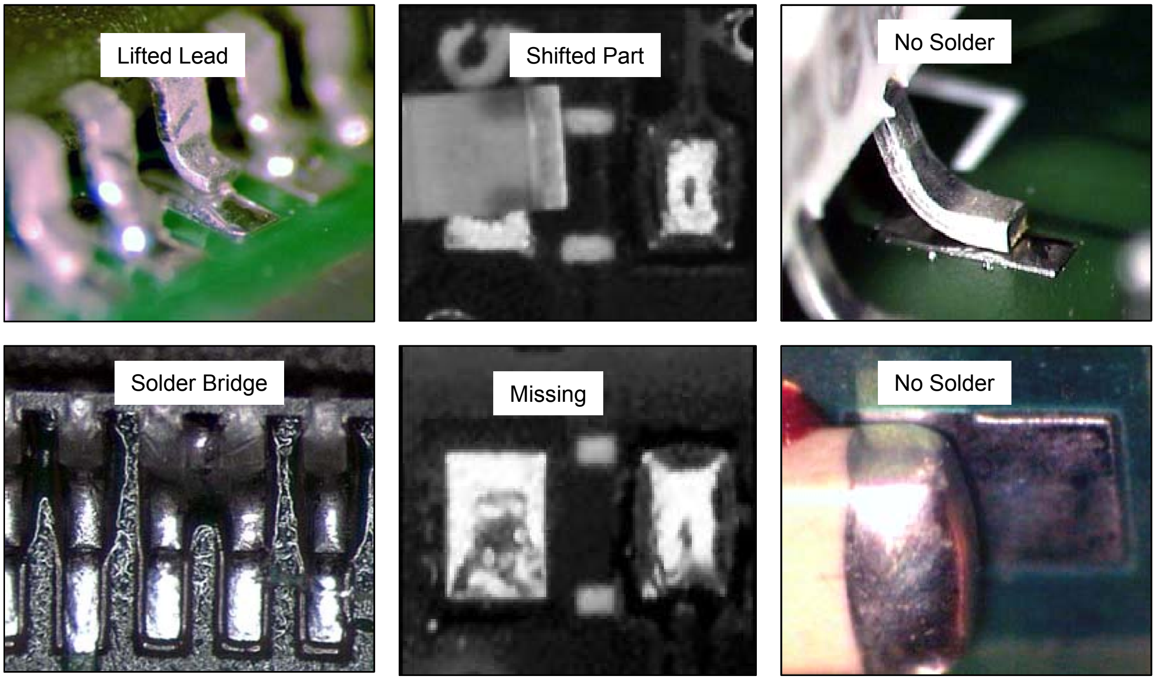

Figure 5 – Defects AOI Systems Detected Very Well

Variation was the enemy of the AOI systems. Images were compared to "good" library parts to determine pass or fail. Anything that caused variation to those images would increase the probability of the AOI system to reject it. There were many sources of this variation. They included:

1. Variation in PCB finish or marking (silkscreen legend can looks like solder bridge)
2. Variation in solder amount (excess solder and insufficient solder)
3. Variation in component marking (polarity marks shift, fade, or color/shade change)
4. Variation in component placement (lead partially off pad)

The majority of time programming the AOI systems was in "tuning" them to call out variations as bad when they really were bad and to ignore the variations when they really were good. Figure 6 shows the defect spectrum where there was "high agreement" between the AOI systems and the human inspector:

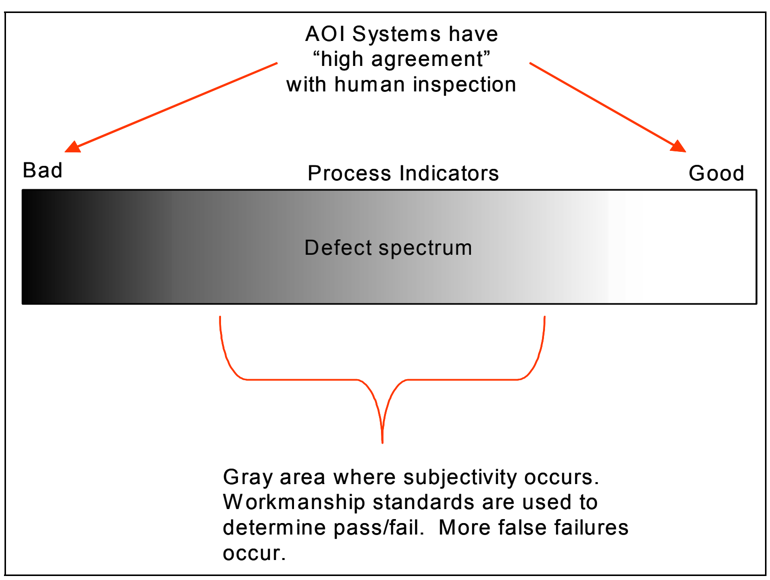

Figure 6 – Defect Spectrum

Part of the "learning" in using these AOI systems is how to use the information that indicates a process shift (process indicator) but isn't quite a defect per workmanship standards. This could be quite beneficial in defect prevention.

Conclusion

There was a significant amount of learning that occurred on how AOI systems operate. There really are no such things as "false calls". The AOI system is identifying the variation of an image to an earlier created library image. This variation then has to be interpreted and defined by the AOI system as good or bad based on its programming and then reconciled by a human operator. The importance of this human interface will result in further work to evaluate ease of programming and ease of operation between the AOI systems.

Acknowledgements: Special thanks to the companies participated in the evaluation process.

Comparative Evaluation of Automated Optical Inspection Systems

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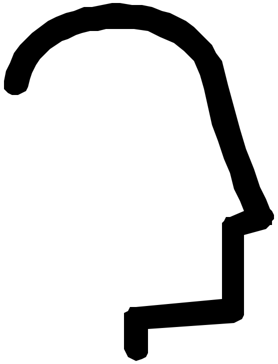
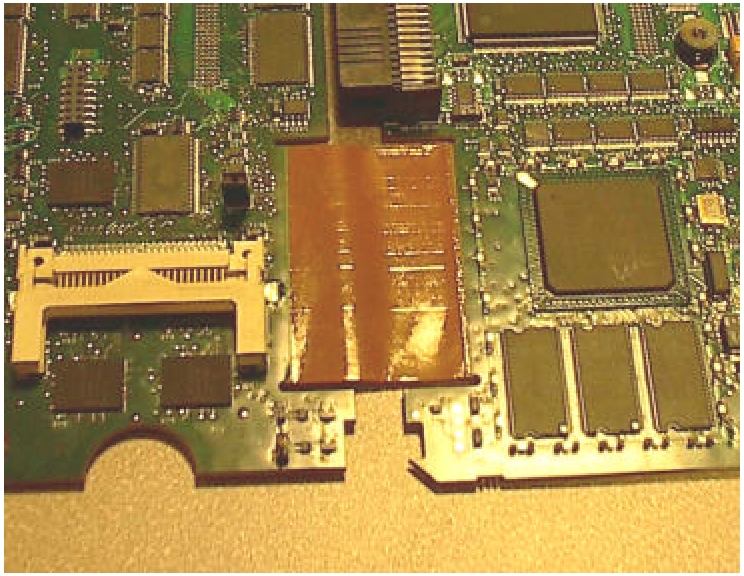
Presentation Outline

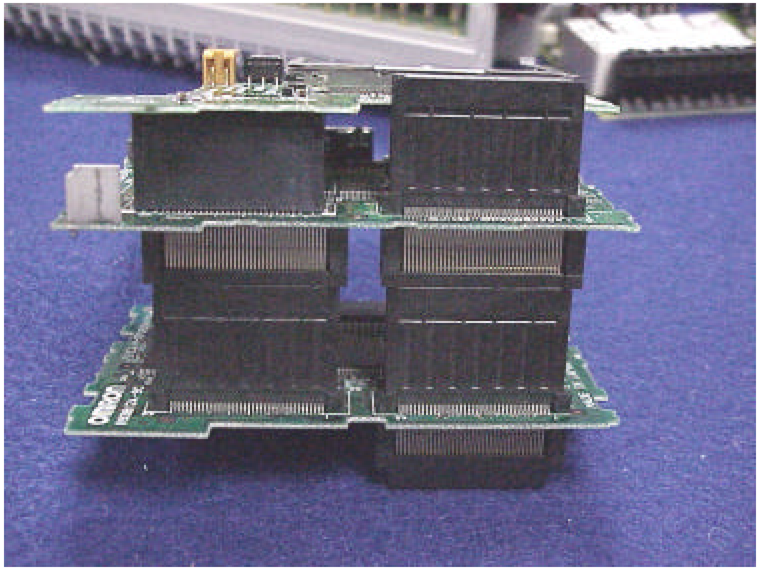


- Introduction
- Evaluation Setup
- Data Collection
- Results
- Conclusions
- Follow-up

Introduction

Identified "**Need**" – Alternative to In-Circuit Test



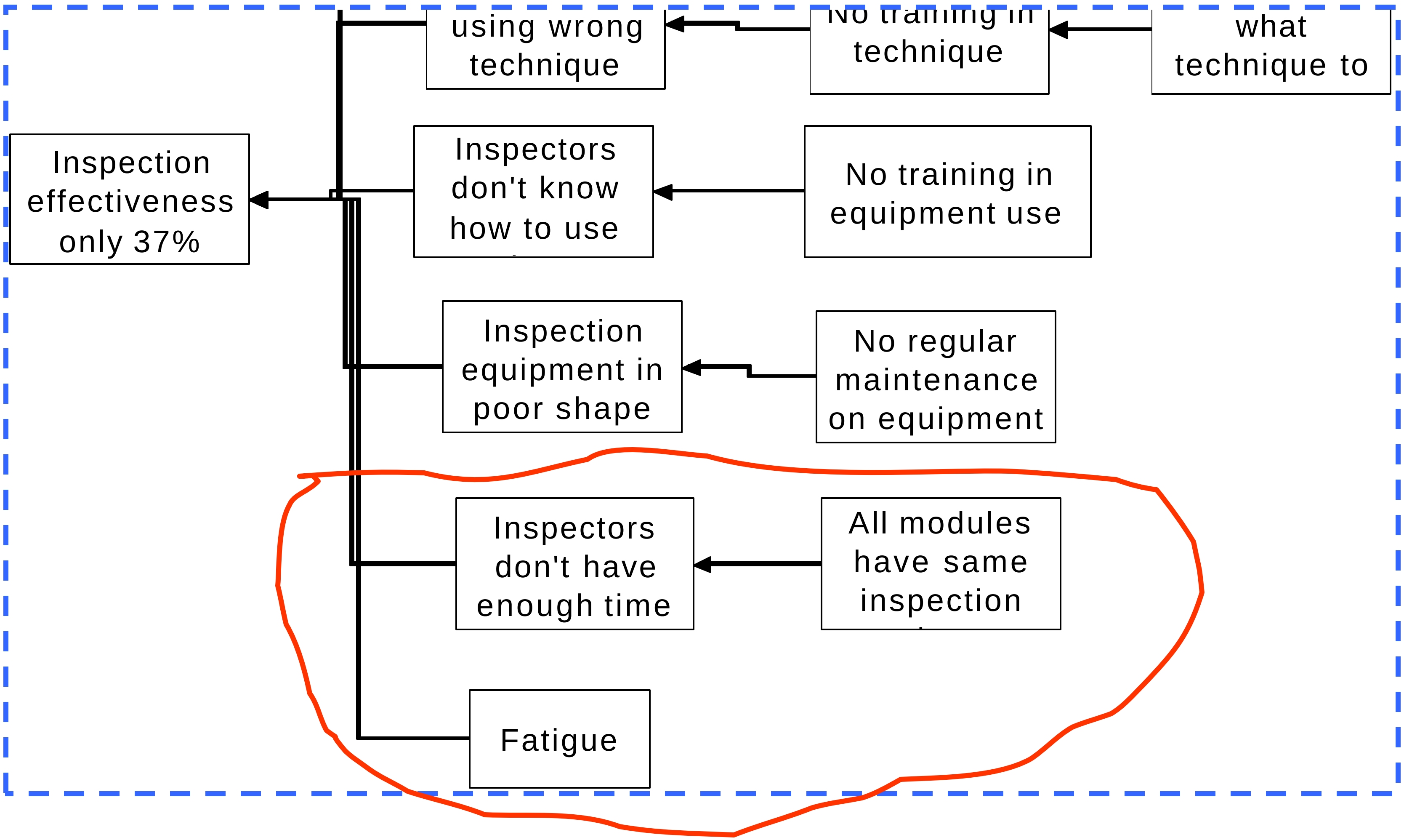


High density designs no longer have the luxury of space for test pads

Introduction

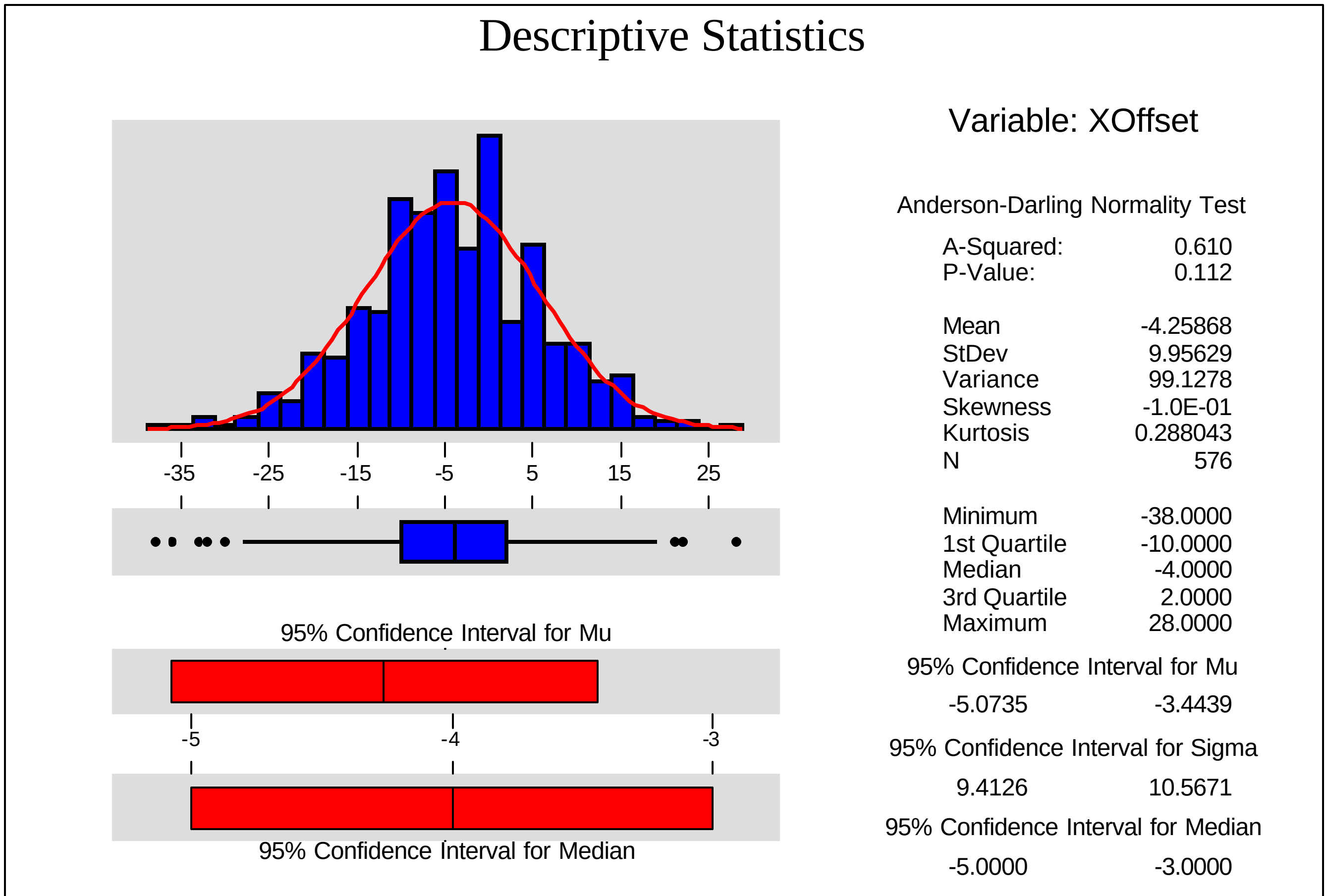
Identified "**Want**" – Improved Inspection Effectiveness

Causal Map



Introduction

Identified "**Want**" – Feedback On Process



Is process "normal"

Is process changing?

Evaluation Setup

AOI System Participants Selected For Evaluation

- 4 In-line AOI systems were selected for evaluation
- For confidentiality purpose the systems named as A, B, C, D

Evaluation Setup

Criteria Used For Selecting Participants

- Installed base
- Vendor reputation (confidence factor)
  e.g. responsiveness, available when needed etc.
- Number of years in the market
- Technology

Evaluation Setup

Criteria Used To Compare Systems

- Defect coverage
- False defect rate
- Inspection speed
- Repeatability

Evaluation Setup

Definitions

• Defect coverage:

Number of actual defects detected by the AOI

Total number of known defects on the panels

• False defect rate:

Number of false flag **x** 1 million

Total opportunities

• Inspection speed

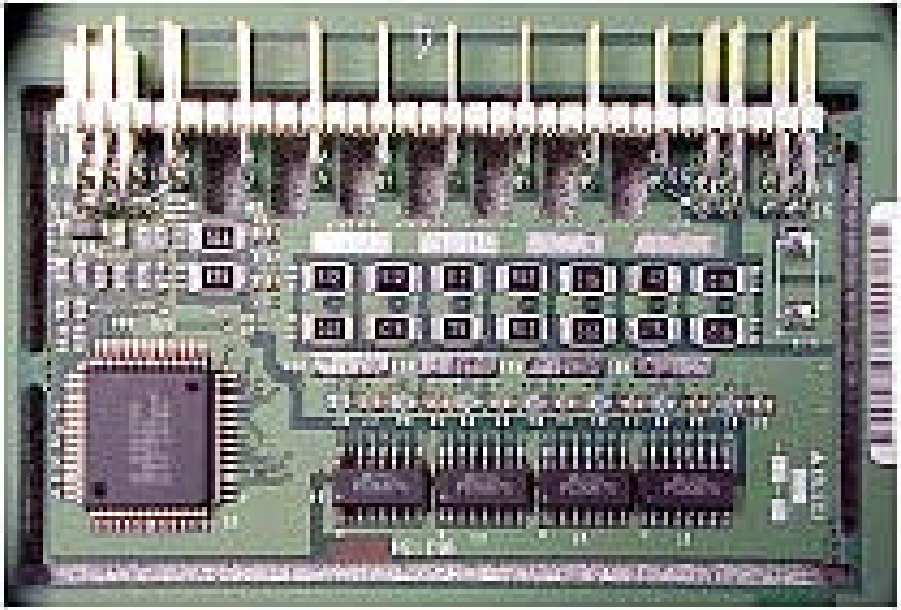
Time from board enter to board exit

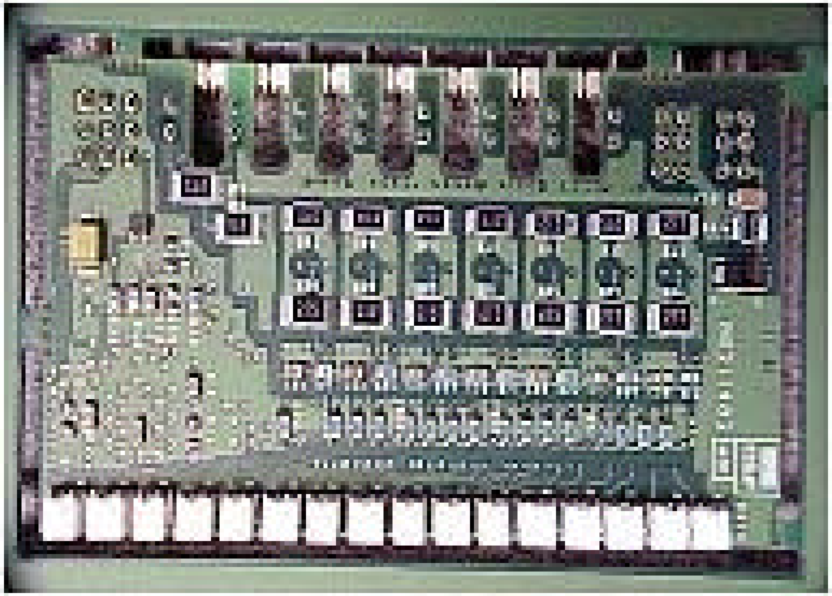
• Repeatability:

Run one board with known defects 50 times and compare results

Evaluation Setup

Test Vehicles Used

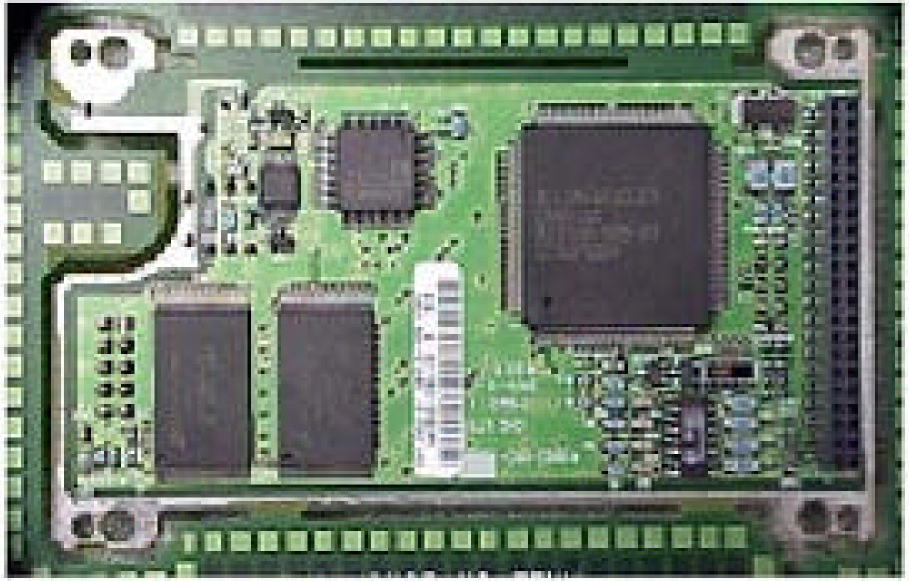
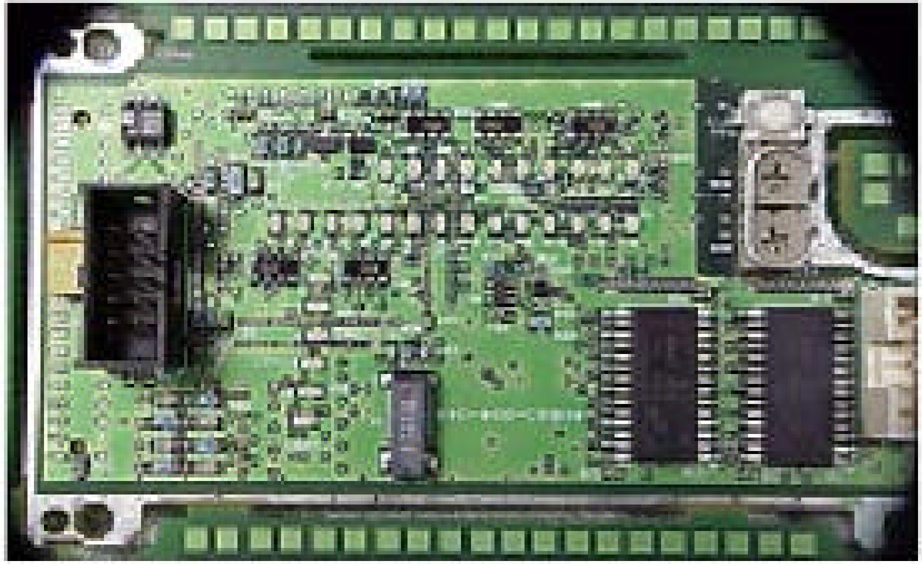




Assembly 1 – Sides 1 & 2

Evaluation Setup

Test Vehicles Used

Assembly 2 – Sides 1 & 2

Evaluation Setup

Inspection Opportunities

Product	Item	Qty/Board	Qty/panel
Assembly 1 – side 1	Components	51	612
	Solder joints	218	2616
	Total	**269**	**3228**
Assembly 1 – side 2	Components	73	876
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Assembly 2 – side 1	Components	56	336
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Assembly 2 – side 2	Components	88	528
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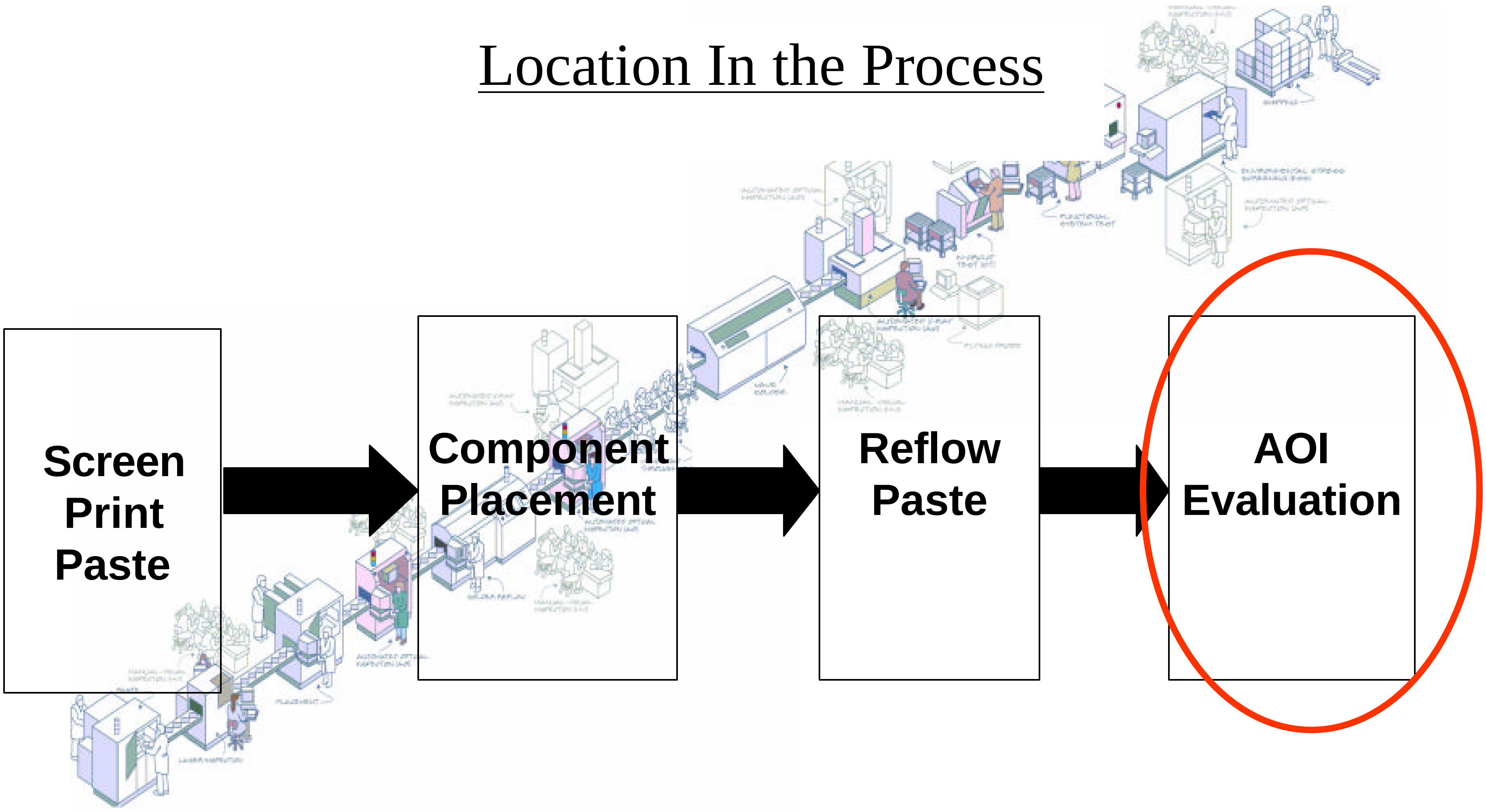
	Total	**350**	**2100**

Evaluation Setup

Location In the Process



Data Collection

Process Used

1) Inspected all boards manually and documented defects found

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Results

Defect Coverage Results

% of Defects Caught				
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Total	**72%**	**84%**	**74%**	**83%**

Differences not significant

Results

False Call Rate Results

False Call Rate PPM				
Test Vehicle	**System A**	**System B**	**System C**	**System D**
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Differences not significant

Results

Inspection Speed Results

Mean Cycle Time				
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Assembly 2 Side 2	48	21	49	38
Mean	**84**	**31**	**67**	**39**

Significantly faster

Results

Repeatability Results

Statistics for "number of callouts" from inspecting same assembly 50 times				
Statistic	**System A**	**System B**	**System C**	**System D**
Mean	5	20	9	15
Standard deviation	0.00	1.05	1.50	3.23

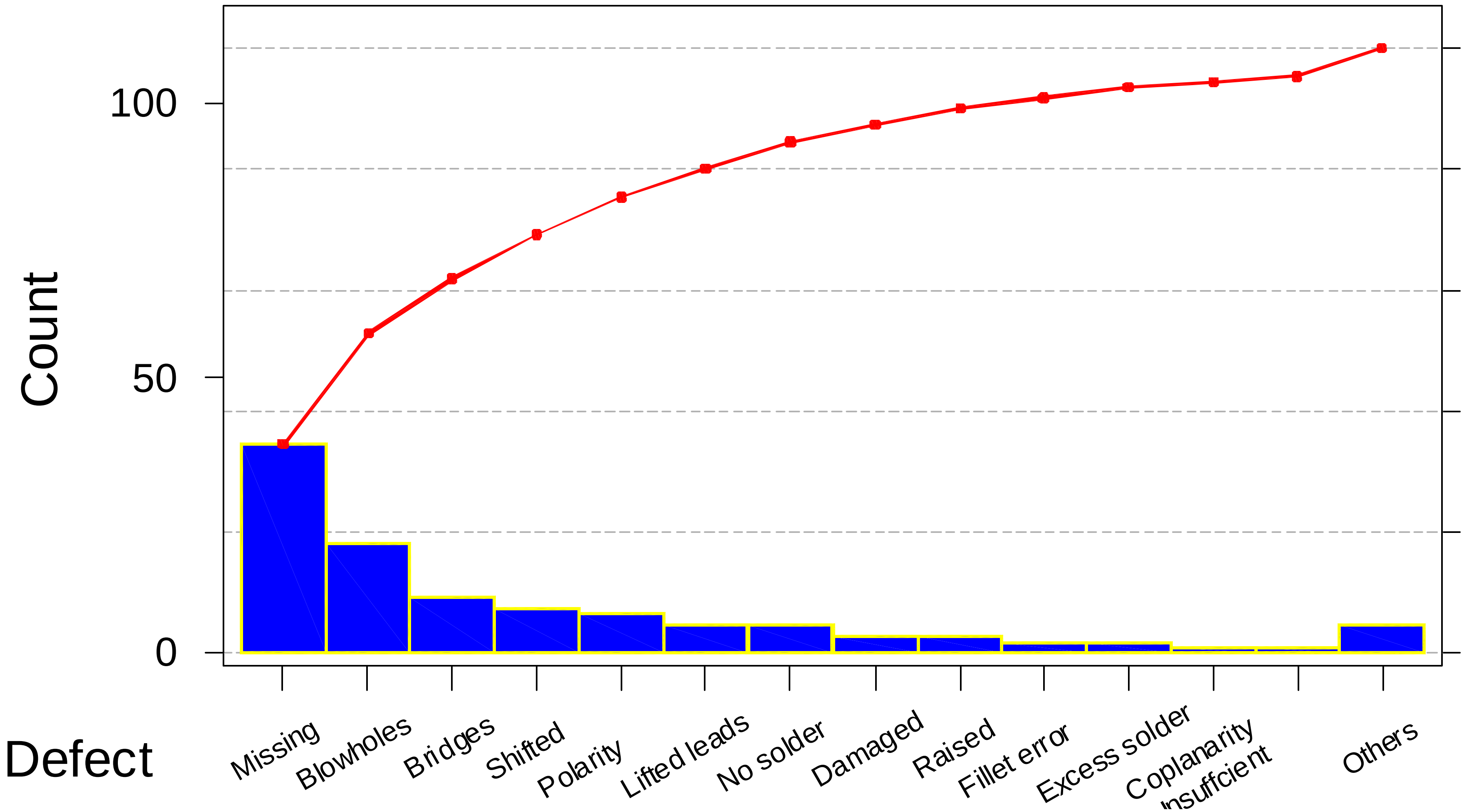
Significantly less variation

Conclusions

Summary Of Significant Results				
Criteria	**System A**	**System B**	**System C**	**System D**
Defect Coverage				
False Defect Rate				
Speed		Best		Best
Repeatability	Best			Worst

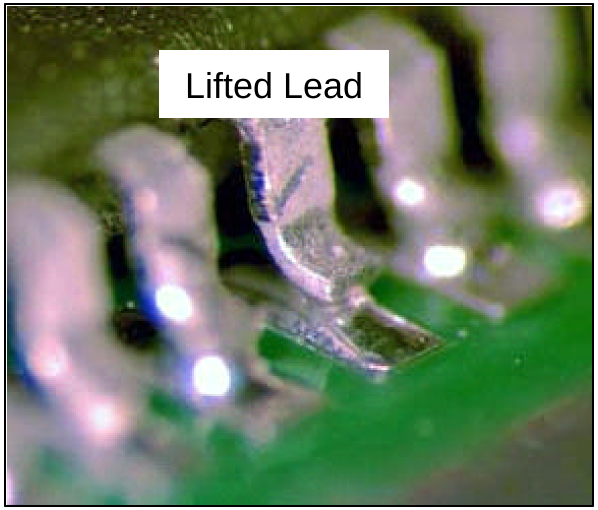
Conclusions

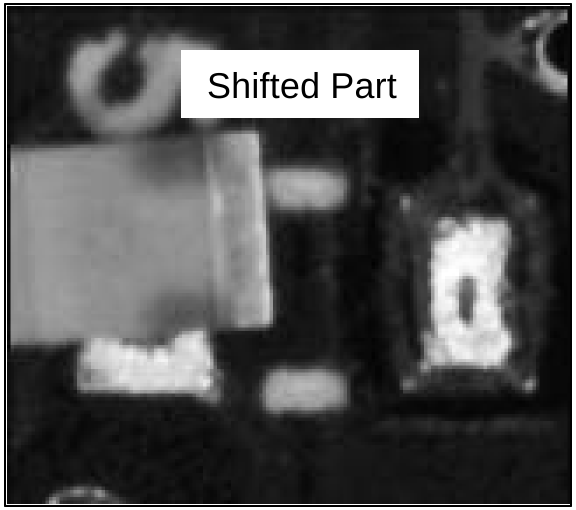
Summary Of Defects Caught By All Systems

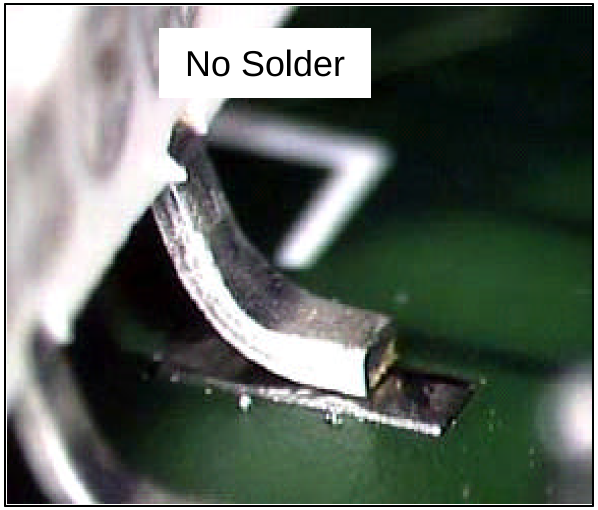


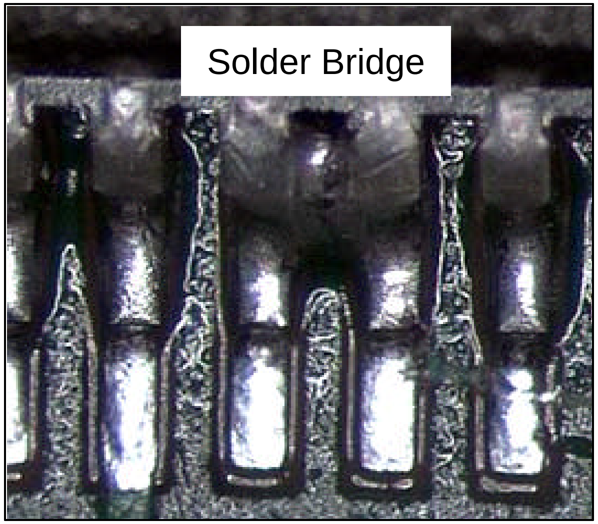
Conclusions

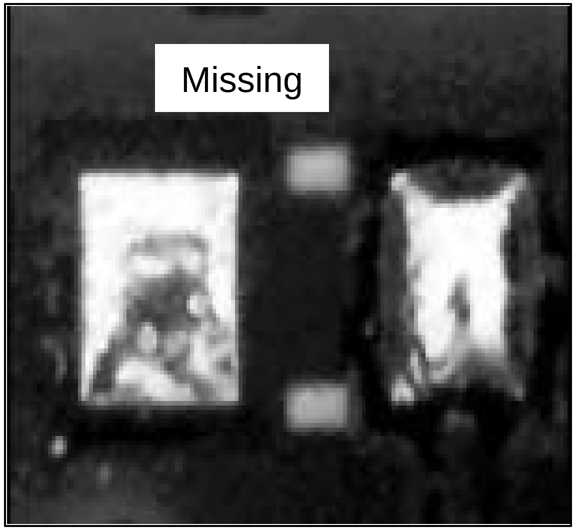
Defects Detected Very Well

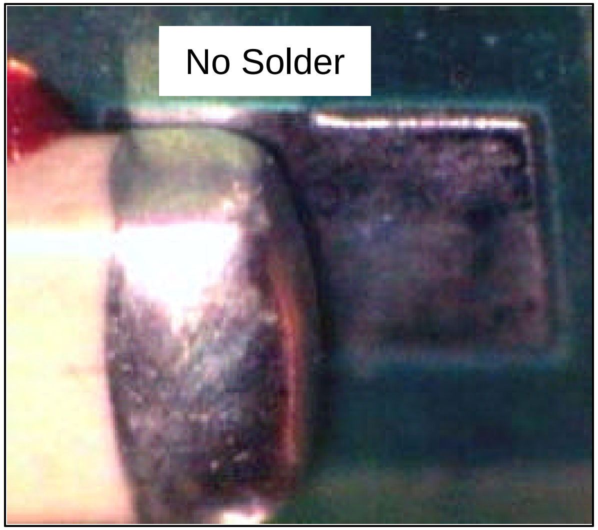






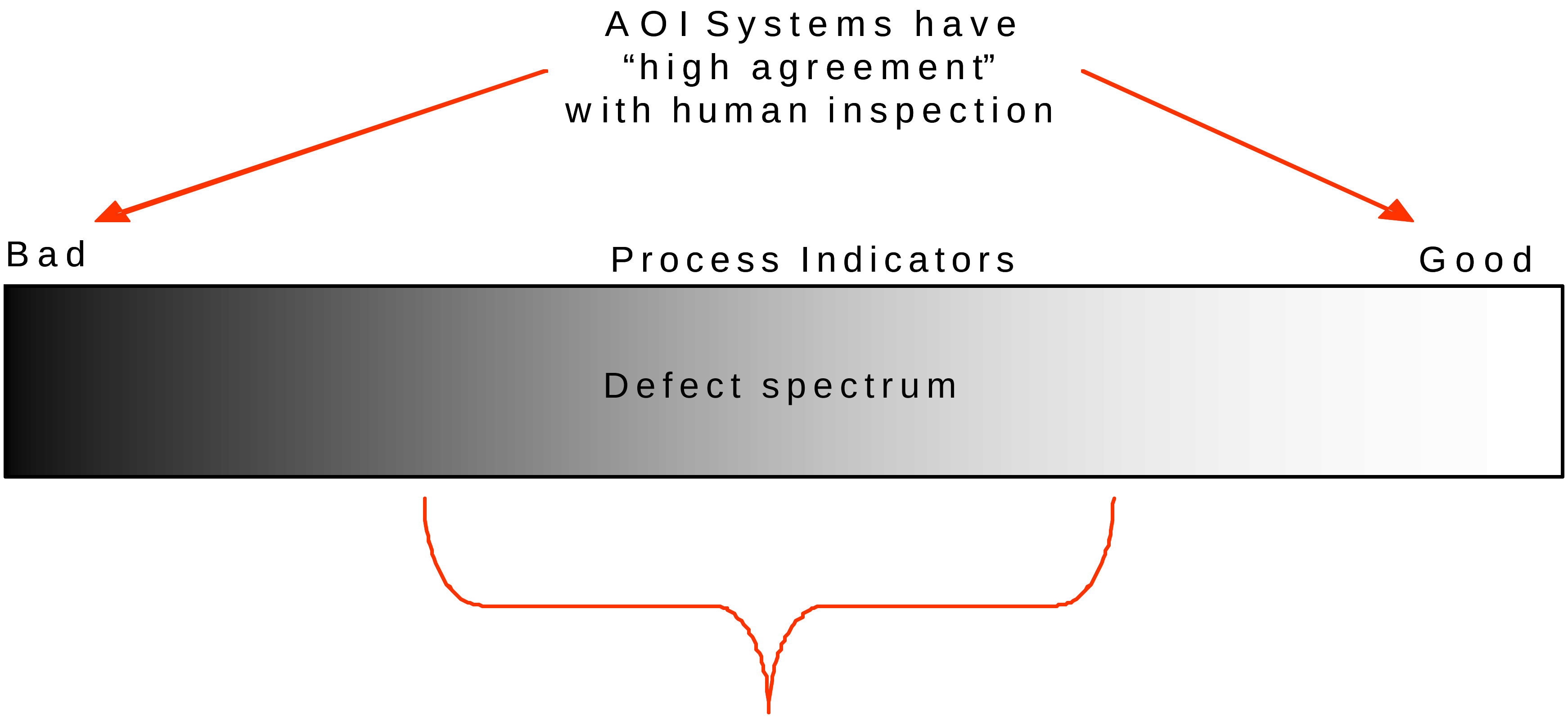






Conclusions

Defects That Cause False Failure Or Misses



Gray area where subjectivity occurs. Workmanship standards are used to determine pass/fail. More false failures occur.

Conclusions

Variation is The Enemy of The AOI System

Variation in..........

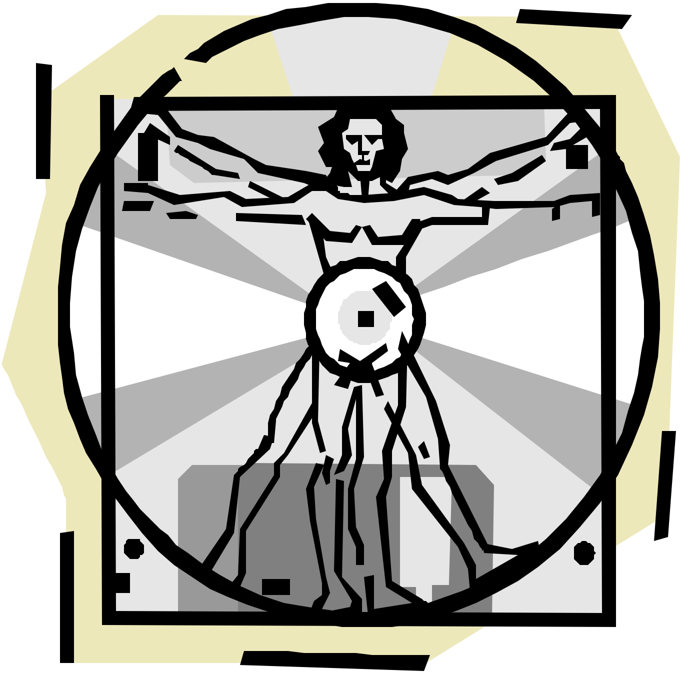
- PCB marking
- Component marking
- Shape or size of solder joint
- Placement

Conclusions

Majority of time with all systems was in **"<u>tuning</u>"** the programs

Conclusions

The importance of the human interface led to follow-up work ....



Follow-up

AOI Evaluation Matrix									
Evaluation Criteria	Criteria Weight 1 - 5 (5 = most important)	Score 1 - 7 (7 = Best)				Weighted Score			
		Unit A	Unit B	Unit C	Unit D	Unit A	Unit B	Unit C	Unit D
Cost $	4								
Test Speed	2								
Ease of Operation	4								
Ease of Programming	4								
Operation/Maint Cost	3								
Overall Support	4								
Board Size Restrictions	2								
Failure Reporting (Defect ID)	4								
Defect Clarity & Identification	4								
False Failures	3								
Defect coverage	5								
OCR Capability	2								
Repeatability	4								
CPk capability	4								
Interface to our Network	2								
Business Analysis	2								
Inspection Flexibility (wave/paste)	2								
					Totals	0	0	0	0

Thank You !

Questions?