AUTOMATIC SOLDER PASTE PRINTER POSTIONAL FEEDBACK CONTROL

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ABSTRACT

Stencil printing is a critical first step in surface mount assembly. It is often cited that the solder paste printing operation causes about 50%-80% of the defects found in the assembly of PCBs. Printing is widely recognized as a complex process whose optimal performance depends on the adjustment of a substantial number of parameters. It is not uncommon to hear that stencil printing is more of an "art" than "science". In fact, the process is so complex that sub-optimal print parameters usually end up being used. In addition, stencil printing produce relatively noisy data, which makes the print process extremely difficult to control. Ideally, minimizing the variance of the deposited location and volumes will improve the quality of the process and produce more reliable solder joints.

In general, there are two critical aspects to a printing process. The goal of solder paste printing is to put down the right "volume" of paste on the right "spot". In another words, we not only have to monitor the amount of paste volume we also need to monitor X, Y and Θ registration of the board. This issue is compounded when dealing with miniature components such as 0201, 01005, 0.4mm and 0.3mm CSP and lead free paste. Lead-free paste is known to have less spread, or wet-ability, and adds to the challenge.
In this paper we present the results of tests that show registration control, using a closed loop control scheme, is viable. Using registration feedback from a solder paste inspection system to the solder paste screen printer, the solder paste can be repeatedly put in the right "spot" board after board. We will also discuss best practices regarding how to set up the closed loop between the solder paste inspection system and the screen printer. To develop a robust feedback mechanism, the control process must work over a wide range of board layouts and configurations. To this end, there are best practices to follow when setting up the control loop that optimize the feedback process. To define these best practices, we will discuss the sensitivity the feedback loop parameters such as the board layout, paste location, and the solder paste inspection setup.

Key words: Closed loop process control, solder paste inspection, print registration, miniature components, process yield, feedback loop..

INTRODUCTION

Inspections systems for SMT lines have been mainly used for defect detection and process characterization. Although these are important functions for an inspection machines, it is usually better to control a process thus improving the yield and throughput of an SMT lines than it is to detect defects after the defect has been generated. Closed-loop process controls are starting to appear in SMT manufacturing lines, as board assemblers are demanding higher first pass yields with higher quality.

Closed loop process control can be defined as a system that continually monitors and adjusts a process to maintain a particular target value of an output or outputs. For a closed-loop process control system to function we must identify the output or outputs factors and what input factors influence the variation of those outputs. For solder paste printing you may, for example, consider paste deposit height, volume, shape, etc. as the outputs for a solder paste printing process and print process parameters, paste type, tooling etc. as the inputs. Once these factors are identified, you must then quantify these factors through the use of formal statistical tools such as Design of Experiments (DOE) to fully realize the benefits.

Presently, closed loop process control is primarily seen in the component placement and reflow processes. As the boards are getting denser and components are getting smaller, most assemblers are looking for ways to prevent defects before they impact yields. One area where process control can be implemented with significant impact to the entire assembly process is the solder paste printing process. We are starting to see genuine interest in a defect prevention capability rather than defect detection capability. It is well understood that the volume of paste deposit is a direct function of the stencil thickness, but is influenced by other process parameters outside the control of the printer making volume control a challenge. However, positional accuracy control, X, Y and θ can be directly controlled by the printer.

Controlling positional accuracy is the first step in controlling the overall print process. It is a first step in realizing the full potential of solder paste inspection systems. In the following sections, we discuss a solder paste printing feedback method that improves the alignment capability of the printing process

POSITIONAL ACCURACY CONTROL

Positional or registration control is possibly the most straight forward closed-loop control system that can be applied to a solder paste printer. Although most printers have automated systems that perform the alignment of the stencil to the PCB, it is not uncommon to see solder paste deposits end up at locations that are not ideal. Figure 1a, b and c demonstrates such scenarios. It is clear for the figures below, condition 'c', even though delivering correct amount of paste, will be detrimental to a board assembly process. Solder paste alignment errors can be produced either by board-to-board variations, stencil stretch, inaccuracies in the alignment system or from other sources.

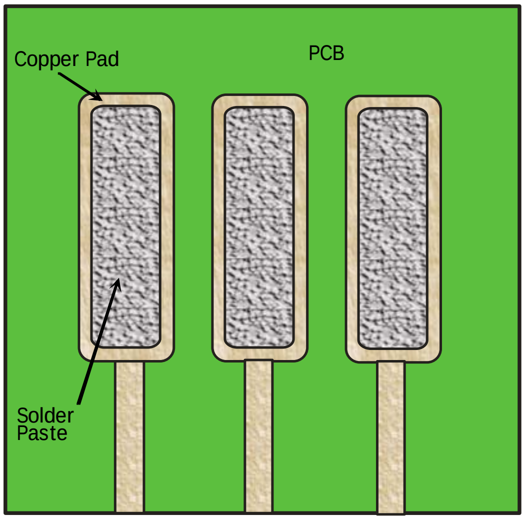

Figure 1a. Perfectly aligned solder paste

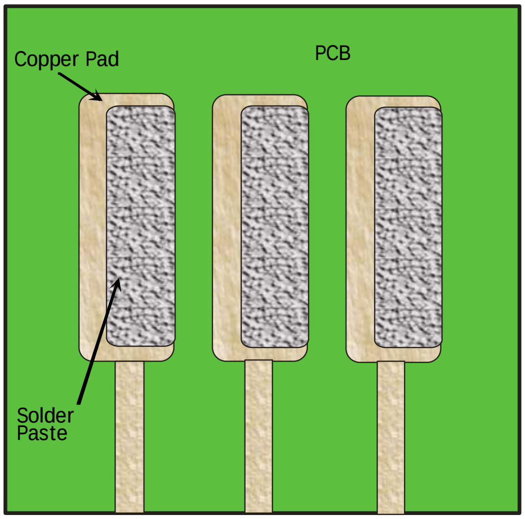

Figure 1b. Partially mis-aligned solder paste that may be acceptable in many SMT line

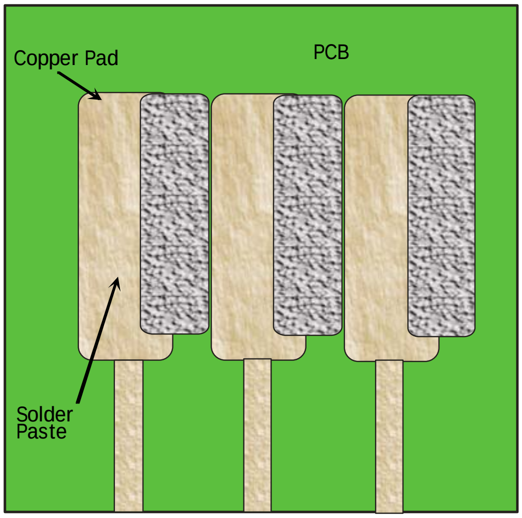

Figure 1c. Clearly mis-aligned solder paste that would most likely cause assembly errors.

In general, the position of the deposits relative to the pads can be measured within the printer. However, since the inspection is typically carried out while the board is still inside the printer, this operation can considerably slow down the primary function of the printer, resulting in lower throughput. In addition, if there is a mis-alignment or calibration issue with the vision system within the printer, the error is likely not detected since the same vision system is used to align the stencil as it is used to measure the solder paste position. Both these issues are addressed by using an external solder paste inspection system. Subsequently, the inspection result can be fed back to the printer to make required offset adjustment to keep the process in control.

To improve the performance of the positional accuracy we tested a closed loop system using a CyberOptics SE300 SPI system to measure X, Y and θ print offset of solder paste on a PCB. This information was then passed on back to the printer which made appropriate corrections to the print offset as necessary. Figure 2 shows the closed loop concept and figure 3 details the actual data flow through the feedback loop.

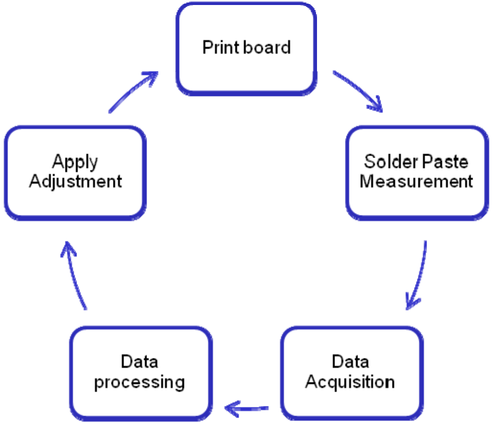

Figure 2 Closed loop print control concept

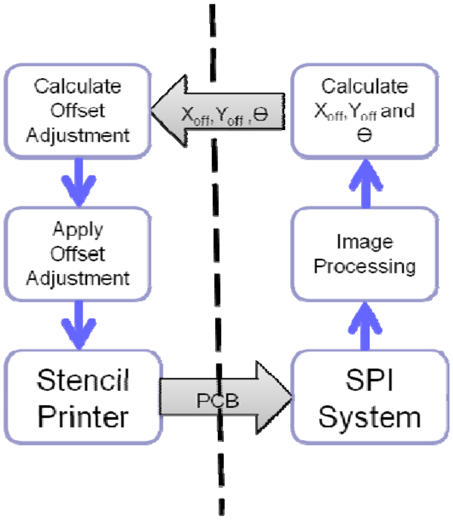

Figure3. Details of the closed loop feed back loop used to correct and maintain solder paste alignment.

MEASUREMENT OF SOLDER PASTE OFFSET

To correctly apply a solder paste alignment feedback loop, the positional error of the print must first be defined. The goal of a positional feed back loop is to correct for any misplacement of solder paste. In any classical feed back mechanism, the difference in the measured control value and the goal for that control value – the error signal- is what is typically used as feedback. To that end, we will need a common definition of the "error signal" that is shared between the solder paste inspection system and the printer.

The first step in specifying a common interface between SPI and the printer is defining a common positional frame of reference between the two systems. The most obvious frame of reference that can be shared between the SPI system and the printer is the position frame defined by the fiducials found on the PCB. Fiducials are ubiquitous on all PCBs and are required feature on the PCB's copper planes to provide a common frame of reference used by all automated machines in a circuit board assembly line. Using the fiducial frame of reference, a common set of axes (X and Y) can be defined to form a basis for communicating the mis-alignment of the solder paste.

The second step is measuring the "error signal". Figure 4a shows a CAD defined aperture aligned with a copper pad. Since the fiducials are usually located on the copper layer, the alignment of the CAD aperture to the pads is usually pretty good. Figure 4b shows a solder deposit that has been perfectly placed on the pad. Both the center of the CAD aperture and the center of the solder paste deposit can be calculate using a weighted center-of-gravity algorithm that determines the center coordinates of either the CAD aperture or solder paste deposit based on the feature's shape. Figure 5a shows a registration of a solder deposit to the CAD aperture position. Figure 5b shows a similar deposit that is offset from the CAD aperture. In this case, the "error signal" would be the resulting difference in the position of the CAD center and the solder paste center given by X offset and Y offset in the figure.

However, the position of single deposit does not adequately reflect the actual alignment of the printer. The actual position of a single solder paste deposit is affected by the shape of the deposit, local stretch in the stencil, overprint, stray solder balls, and slump etc. Because of these affects, it is not possible to adequately determine the registration of printer from a single deposit. Also, for single deposits with rotationally symmetric shape, the notion of rotational (θ) position error is not defined. Even non-symmetric deposit shapes such as rectangles, small shape changes such as overprint and slump will cause more apparent rotation than reality causing noise in the feedback loop

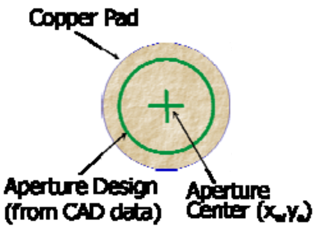

Figure 4a

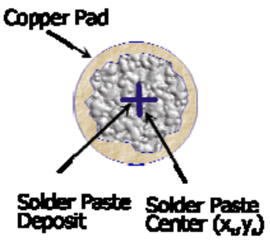

Figure 4b

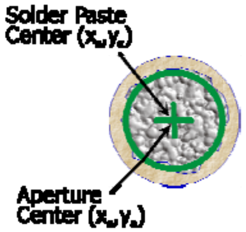

Figure 5a

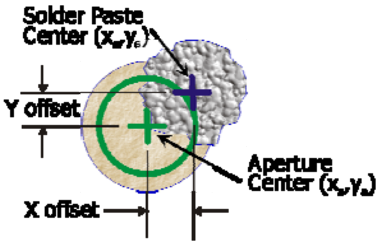

Figure 5b

To provide reliable and stable feedback to the printer, the combined position of a large number of pads is required. Printers typically have three degrees of freedom for alignment - X, Y and rotation, θ. Figure 6shows an array of deposits that show good alignment to the CAD aperture positions. Figure 6b shows an example of position offset (both in x and y direction), Figure 6c shows and example rotational offset and figure 6d shows both positional and rotational offset. To effectively align a printer, all three positional variables must be determined simultaneously and be fed back to printer as parts of the "error signal".

X, Y and θ can be determined for the whole PCB by comparing the center positions (X_s and Y_s) of the solder paste deposits with the center positions of the CAD apertures (X_c and Y_c). Using a least squares optimization technique, a X, Y and θ offset can be determined that defines a best fit alignment between the solder paste features and the CAD features. In terms of the frame of reference defined by the fiducials, the best fit rotation of the CAD frame of reference to describe the solder paste position can be defined with the following equation:

$$\begin{bmatrix} X_s \\ Y_s \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} X_c \\ Y_c \end{bmatrix} + \begin{bmatrix} X_{off} \\ Y_{off} \end{bmatrix} \qquad (1)$$

where X_{off}, Y_{off} and θ are the data that is passed to the printer by the solder paste inspection system for each board. Finding a best fit alignment based on a large population of solder paste deposits allows the feedback error signal to directly reflect the capabilities of the printer (i.e. adjusting for X, Y and θ over the whole stencil). In addition, using many solder paste deposits reduces the noise in the error signal returned to the printer.

In addition to the X_{off}, Y_{off} and θ, the center of rotation must be mutually defined between the solder paste inspection equipment and the printer. Since rotation is applied before X and Y offset in the equation above, the values of X_{off} and Y_{off} are a function of the center of rotation X_{center} and Y_{center}. For our implementation of positional feedback, we chose to define the center of rotation as the average center of the solder paste deposits given by

$$X_{center} = \frac{1}{n}\sum_{1}^{n} X_s^n \quad and \quad Y_{center} = \frac{1}{n}\sum_{1}^{n} Y_s^n \qquad (2)$$

where X_{center} and Y_{center} define the average center of all the solder paste deposits. Another possible center of rotation could be the origin of the board or fiducial frame. However, choosing center of rotation other than X_{center} and Y_{center} will cause the resulting X_{off} and Y_{off} to be large to compensate any rotation.

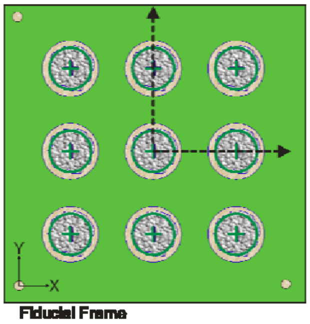

Figure 6a. Perfect alignment

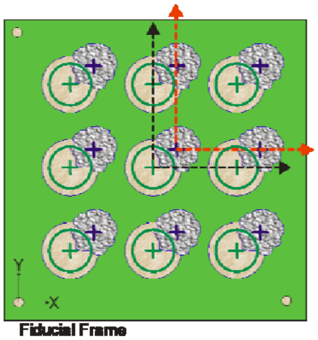

Figure 6b. X and Y offset

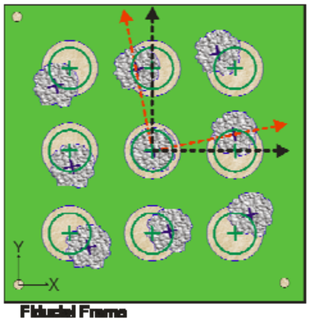

Figure 6c. Rotation offset

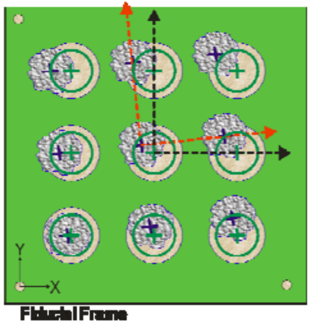

Figure 6d. X, Y and θ offset

In summary, to implement the feedback loop, the offset, (X_{off} and Y_{off}), the center of rotation (X_{center} and Y_{center}), and rotation θ are passed from the solder paste measurement system to the printer.

EXPERIMENTAL PROCEDURE

To evaluate the performance of the closed loop control, three tests were conducted. First a gage test was conducted to determine the capability of the SPI system. Second, a proof of concept test was run to demonstrate feasibility of the positional feedback control and to determine the affect of feedback parameter. Finally, using a production representative board, we tested the alignment of the printer with and without feedback control to determine if there is any improvement in the printer's process capability when using feedback control. The following sections detail the tests and the results.

Gage Testing and Results

Using the board shown in figure 8, a gage study was conducted to determine the repeatability of the SPI machine. For the gage study one board was inspected 15 times and the result is presented in figure 7. The range for the 15 boards was measured to be less than 5µm for X-Y offset and 0.002^0 for Θ. This was considered to be acceptable. Based on this results, the X, Y offset specification was set to be ± 0.05mm.

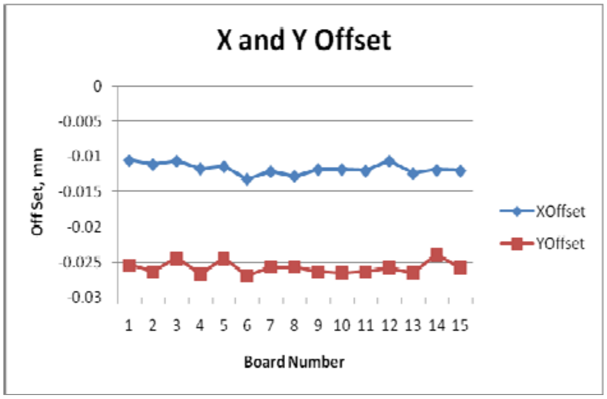

Figure 7a. Gage repeatability tests for X and Y offset measurements

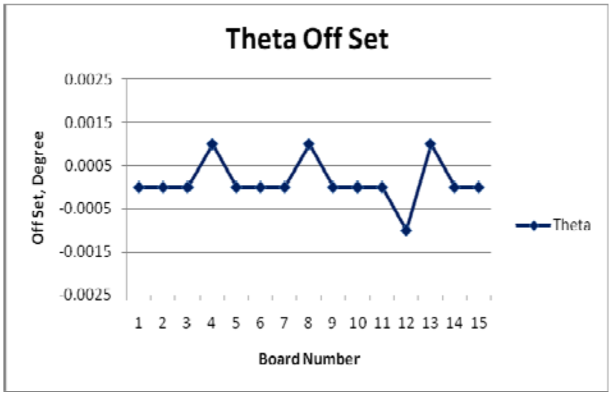

Figure 7b. Gage repeatability tests for Θ offset measurements.

Proof of Concept Test Procedure

The objective of this test was to evaluate the performance of the closed loop controller interface and acceptable range of correction factor application. The correction factor is defined as the percentage of SPI measured offset error value applied to the next board in the printer as a correction. The correction factor can be considered the proportional gain of the feedback loop. For example, a 50% correction factor multiplies the SPI measured alignment offset error by 0.5 to determine the offset correction that is applied to the next print. As in any feedback system, optimizing the feedback loop gain is a compromise between the speed and stability of the feedback system. For the purposes of this test, correction factors of 50% and 25% were chosen.

This test was conducted using a standard Speedline test board which is a 254mm x 203mm x 1.575mm, four layer FR-4 board with ENIG surface finish. The layout of the board is shown in figure 8. The test board incorporated a wide range of commercially available components and packages such as QFPs, BGAs, PLCCs, QFNs, 0402s, and 0201s. The print test was run on 40 boards to get statistical confidence in the results.

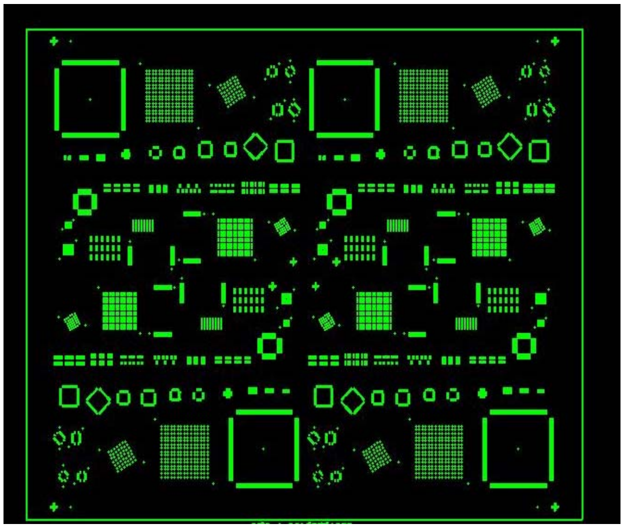

Figure 8. Layout of test board used to measure the capability of the SPI system

Proof of Concept Test Results

Figure 9 and 10 shows the results from the proof of concepts tests. Results from the rear to front (R2F) squeegee direction are shown here with two different correction factors. There results for the front to rear squeegee direction were similar. The graph shows that for 50% correction factor it takes 4 boards to reach the target registration. On the other hand, for 25% correction factor it takes about 8 boards to reach the target registration. As you would predict, a smaller correction factor is slower to react but is less sensitive to noise in the system thus holding the offset value to a much tighter range.

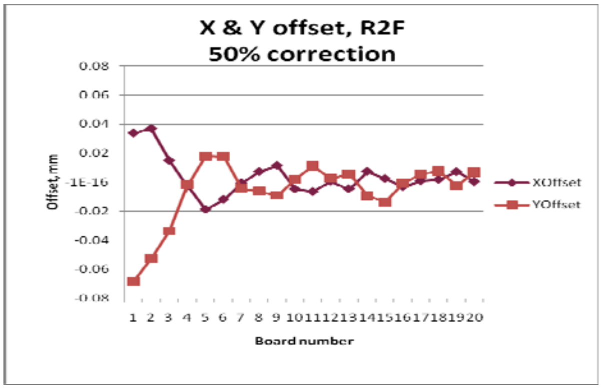

Figure 9a. X and Y offset feedback correction with a 50% correction factor applied to the feedback loop

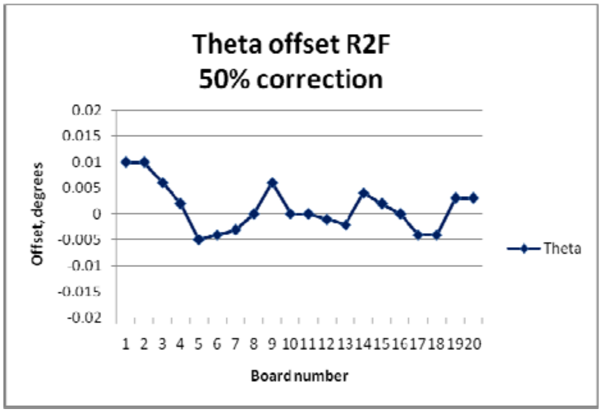

Figure 9b. Θ offset feedback correction with a 50% correction factor applied to the feedback loop

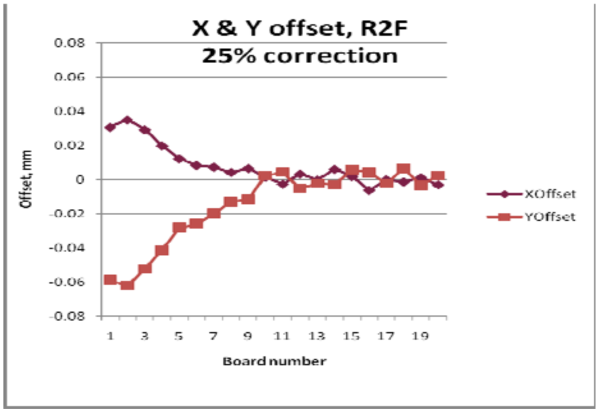

Figure 10a. X and Y offset feedback correction with a 25% correction factor applied to the feedback loop

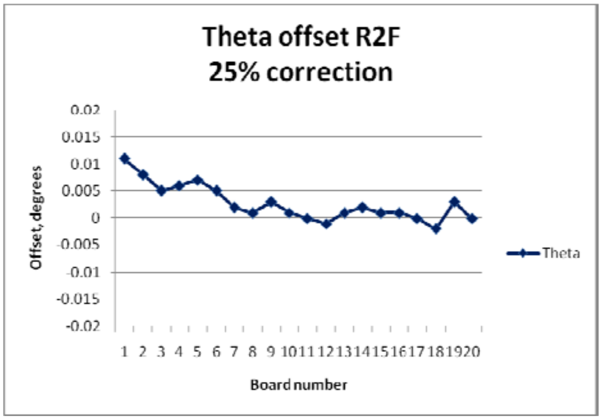

Figure 10b. Θ offset feedback correction with a 25% correction factor applied to the feedback loop

Comparison Test Procedure

The objective of this test was to compare the print process performance of a printer without the presence of closed loop control with a printer using position feedback control. An additional objective of this test was to evaluate the stability of the controller for long manufacturing periods (i.e., to simulate a production condition) by determining the ability of the controller to maintain the print process close to the target registration value.

The test was performed for 100 boards using a commercially available type 4, lead free paste. The board used for this test was a commercial cell phone board, with four phones to a panel. Due to the proprietary nature of the product, the actual image of the board is not shown here. The board was 191mm X 117mm X I17 mm with OSP pad finish. Four areas on the board were chosen to be monitored for X, Y and Θ convergence. The four areas of the board were chosen to provide adequate coverage of the board. As a baseline at the beginning of the test, the board was aligned to the stencil by the operator using visual methods. Once the optimum alignment was achieved, the process was run for 100 boards without any positional feedback.

After the 100 board lot of boards was printed without positional feedback, the feedback loop was turned on with a correction factor of 50% .

Comparison Test Results

Figures 11a and 11b shows results from the baseline test (no feedback employed) for F2R stroke direction only. R2F stroke direction showed similar behavior. It is clear from the plots, both X and Y offset fluctuate around a fixed offset which is not zero.

The results of turning on the feedback loop are shown in figures 12 and 13. We see from these results the closed loop control algorithm is capable of reaching the target value rather quickly. Additionally, it is observed that the average registration value can be maintained close to the target for the entire duration of the test.

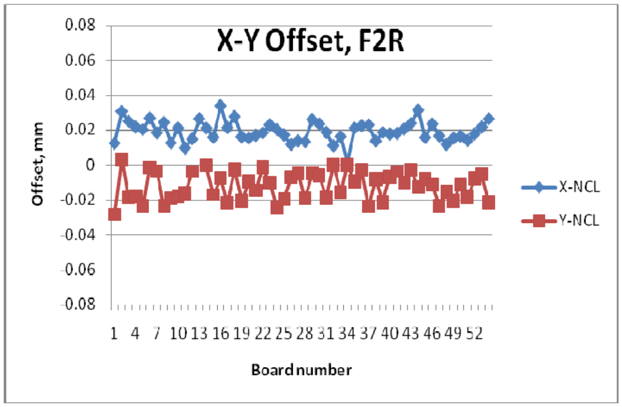

Figure 11a. X and Y offset for a printing process without feedback showing consistent non-zero offset print-to-print

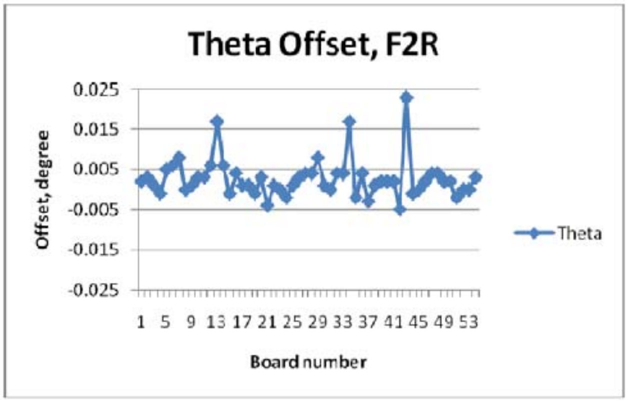

Figure 11b. Θ offset for a printing process without feedback showing consistent non-zero offset print-to-print

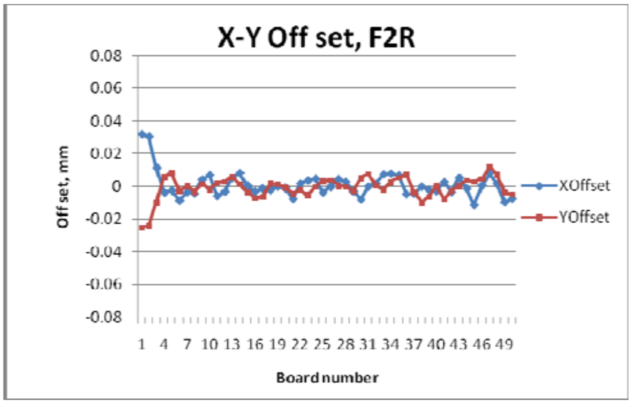

Figure 12a. X and Y offset for the front-to-rear squeege direction using feedback control showing consistent near zero offset print-to-print

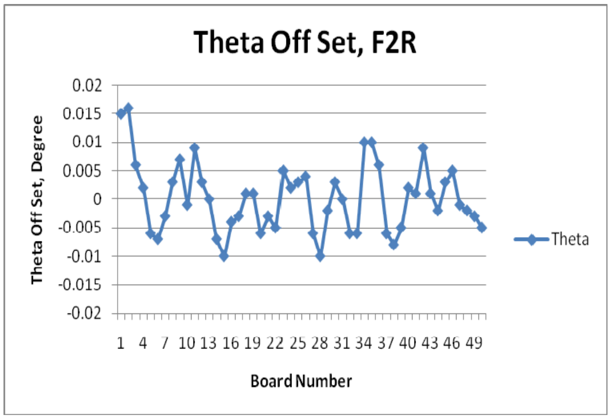

Figure 12b. ϴ offset for the front-to-rear squeegee direction using feedback control showing consistent near zero rotational offset print-to-print

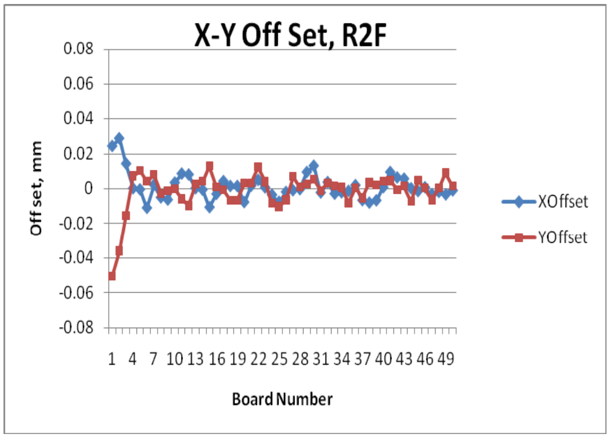

Figure 13a. X and Y offset for the rear-to-front squeegee direction using feedback control showing consistent near zero offset print-to-print

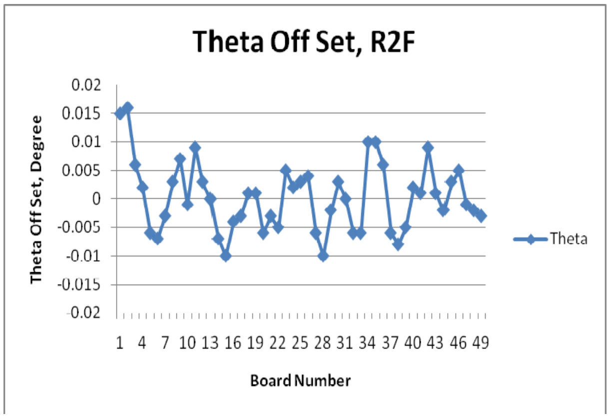

Figure 13b. ϴ offset for the rear-to-front squeegee direction using feedback control showing consistent near zero rotational offset print-to-print

Finally, comparing print performance between with/without closed loop control shows process improvements produced by the closed-loop control system. Comparison of the process capability index, Cpk, for X and Y offset measurements for the cell phone board is shown in Table 1. The increase in the Cpk for both X and Y offset with control is due to the centering and tightening of the print process. Additional statistical analysis confirms the improvement of print performance by employing the closed loop process control. This analysis is presented in figure 14. Figure 14 shows the individual moving chart for X offset with both with and without feedback control. It is clear from this analysis that both mean and control limit improve for process with the closed loop control.

Table 1. Cpk for the printing process alignment for without and with positional feedback.

	Cpk	
Test Condition	*X offset*	*Y offset*
Without Feedback	1.6	1.5
With Feedback	2.0	2.3

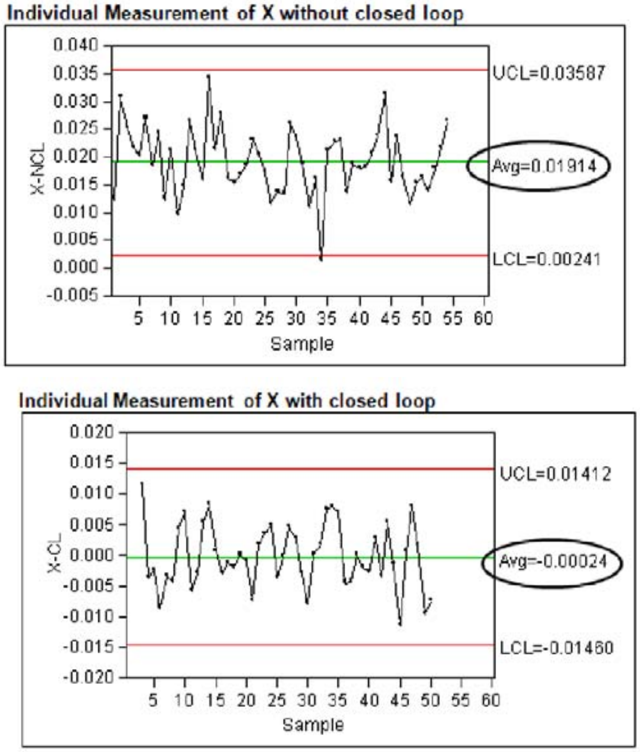

Figure 14. Control Charts of a printing process without and with feedback control

CONCLUSIONS AND RECOMMENDATIONS

Closed-loop controls have been implemented at many stages along circuit board manufacturing lines. They have successfully been implemented within reflow ovens and at the components placement stage. As the push towards product miniaturization becomes inevitable, it is clear that closed loop-process controls for printing process will slowly but surely required to maintain quality and yield of the board assembly process. Closed-loop controllers, when implemented correctly, present the advantages of keeping complex processes within control limits even when small external perturbations affect the product line. In addition, closed loop control minimizes operator intervention and has self-tuning properties.

From our limited laboratory environment, controlled experiments, we have shown an improvement in the print process capability using closed loop control. The full extent of the benefit can only be accessed by employing such a system in a true high volume production environment.