Principal Component Analysis-Based Compensation for Measurement Errors Due to Mechanical Misalignments in PCB Testing

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Abstract

Capacitive Leadframe Testing is capable of detecting open solder defects in Printed Circuit Boards (PCB). Principal Component Analysis (PCA)-based approach has been shown to be effective in identifying outlier devices using Capacitive Leadframe Testing measurements. In practice, when a sense plate orientation is shifted or tilted, the resulting measurement variation makes detecting outliers harder. Approaches are introduced to compensate for the 'abnormal' measurements due to sense-plate variations. A PCA based technique is developed to estimate the relative amount of tilt and shift in sense plates. Such estimates can be used to compensate for mechanical misalignments. It can also isolate the misalignment related information from the defect related information in the data. The effectiveness of this technique in the presence of the two common forms of mechanical variations is illustrated using experimental measurements from a laboratory setting. The approach is not sensitive to the order of pins, and as such, shows promise for detection of complex but systematic errors introduced by sense plate misalignments.

Keywords: Board testing, Capacitive open testing

1 Introduction

Testing for defects in printed circuit boards has to address challenges such as parameter variations and increased circuit densities. Capacitive Leadframe Testing (also called TestJet[®] in industry) is very effective in detecting open solder defects in PCB testing [1]-[3]. Outlier detection technique based on Principal Component Analysis (PCA) was demonstrated in a recent study to be capable of further enhancing fault detection [4]. The PCA-based approach treats multi-variable measurements from connectors in a holistic manner to overcome the measurement and component parameter variations inherent in test data. Sensitivity of the approach can be enhanced by selecting windows of physically adjacent pins.

When good boards are tested under different fixtures which are subject to mechanical alignment variations of the sense plate, the measured values may vary depending on the degree of misalignment. This paper considers approaches to compensate for the measurement differences of different fixtures to enhance accuracy of detection of

outliers. We analyze the impact due to variation of the tilt and the vertical shift of sense plate using measurements conducted in a laboratory setting. A PCA based technique is presented for data sets containing different modes of misalignment illustrating its ability to identify the degree of misalignment. A technique for compensating for tilt and shift based misalignments of the sense plate in testing PCBs is presented and evaluated. The proposed technique shows significant promise of being able to handle complex but systematic error patterns such as those introduced by fixture-to-fixture variations.

Section 2 describes Capacitive Leadframe testing and illustrates the problem of mechanical variations of fixtures. Section 3 outlines the PCA based outlier detection algorithm. Section 4 investigates the impact of sensor plate tilt and shift variations on measurement data. Section 5 contains the major contributions of this paper: PC based approaches for extracting tilt and shift information from measurements, and compensating for such variations in testing PCBs. The approaches are evaluated using datasets that include the impact of two potential types of mechanical misalignment during the Capacitive Leadframe Testing. The major observations and future research are identified in the final section.

2 Capacitive LeadFrame Testing

Figure 1 The Capacitive Leadframe test mechanical structure

Capacitive Leadframe testing measures the capacitance between the test pins and a sense plate, as shown in Figure 1, to identify open solder defects. When an AC signal

stimulates the tested pin, the sense plate suspended over the connector will transfer a capacitively coupled signal into a buffer and then to the tester, where the signal is converted to a measure of capacitance. The measured capacitance may be fairly small, often under 100 femtofarads (fF). If there is an open solder defect existing between the board and the connector pin, the capacitance detected by the tester often decreases significantly, to perhaps 10 fF or even less. Variations in these measurements must be accounted for to avoid false pass/fail indications.

Mechanical variations in the connector or the sense plate cause changes in the measurement values although the connector itself and its connections are not defective. Such situations may occur when there is variation in connector height with respect to pin height within the connector, or coplanarity of the connector ball connections is lopsided causing the sense plate to be tilted or vertically shifted.

Figure 2 Simulation of mechanical 'tilt' on the sense plate

Figure 2 shows one normal connector under test with mechanical variation on a sense plate, where the sense plate has a variation in its planarity relative to the connector – that is, it is tilted with the left side slightly higher than the right. (This can be caused by the connector itself having a planarity problem relative to the board itself, due to irregular soldering.) We refer to this as a right-tilted sense plate. This in turn opens a gap between the left side of the sense plate and the connector. In Figure 2 the angle of the tilted sense plate angle is exaggerated for illustration. The practical angles in our experiments are smaller than 0.26 degree, simulating very small mechanical variations that are hard to control. In our tilt experiments we simulated small increments of tilt by inserting spacers on one side and later, on the other side.

Figure 3 shows a connector tested with a vertically shifted sense plate. The sense plate is raised a bit higher with respect to the internal connector pins being sensed. A simple variation in the height of the plastic connector housing can cause this. Indeed, typical specifications on connector housing height are given in 'max' form with no tolerance. The actual tolerance is probably in the +/- 0.004 inch (0.1 millimeter) range, but is unspecified. Another source of variation comes from using connectors from more than one connector vendor. Again, the height specification may vary significantly between vendors. In

our shift experiments, we simulated shift variations by inserting equal-height spacers on both sides of the connector.

Figure 3 Simulation of mechanical "shift" on the sense plate

In a laboratory setting, we injected specific mechanical variations of both "shift" and "tilt" types, and then collected data for a variety of connectors on a small set of boards. Figure 2 and Figure 3 show the experimental setups for the experiments. The amounts of shift or tilt injected were relatively small offsets from a "zero" reference. They were 8, 16 and 24 thousandths of an inch (mils) or, 0.20, 0.41 and 0.61 millimeters. The respective setups (see Table 1) will be named as Tilt_1, Tilt_2, Tilt_3 and Shift_1, Shift_2, and Shift_3 in the following text. The shift and tilt experiments were independent; we did not combine their effects. Tilt_0 and Shift_0 both refer to the reference case, which does not contain any variation. Since a single board may be tested more than once, a data record is termed as *boardrun* for each test of the devices.

Setup	Left or right End Tilt Height (mils)	Setup	Vertical Shift Height (mils)
Tilt_0	0	Shift_0	0
Tilt_1	8	Shift_1	8
Tilt_2	16	Shift_2	16
Tilt_3	24	Shift_3	24

Table 1. Experimental data sets

3 PCA Based Outlier Detection

In this section, we provide a general description of the PCA based outlier detection method. Let $M_{m \times n}$ be the matrix of capacitance measurements, where m is the number of boards and n is the number of pins tested on each board [4]. Let M_c be the centered matrix where mean value of its column is subtracted from each element. Singular Value Decomposition (SVD) decomposes the matrix into the form $M_c = USV$. The Principle Component score or Z-score matrix $Z_{m \times n}$ is given by, $Z = MV$ [5]-[11]. Each principle component (PC) is statistically independent, and they are arranged such that an earlier PC is more significant than a later one.

With Z , each board is now characterized by the Z -scores, given by the corresponding row of Z . The method proposed in [4] selects a subset of the Z -scores for each board, and compresses it into one value d_{li} [11], which characterizes the board i for outlier detection, where E is

$$d_{li} = \sqrt{\sum_{k \in E} z_{ik}^2} \quad (1)$$

a subset of PCs, which are more significant than the remaining subset of the PCs. The cardinality of the subset for our experiment was set to be 5. The devices with higher d_{li} values are the potential outliers.

For illustration, let us consider the outlier detection scheme with a set of measurements, referred to as Data_j31, corresponding to a J31 standard connector on a set of 22 boardruns. Visual inspection of Figure 4 which shows the row measurement values in Data_j31, identifies the boardruns 1, 3, 4 and 22 as clear outliers.

Figure 4 Raw measurement plot for Data_j31

Figure 5 CDF plot of d_1 for Data_j31

Next we use the first 5 Principal Components (PCs) to calculate the d_l value. Figure 5 shows the cumulative distributive function (CDF) plot for d_l for all of the boardruns in Data_j31. Boardruns 6, 4, 22, 1 and 3 all clearly stand out at the high end of CDF curve where they indicate much larger d_l values than the other boardruns. Remaining 17 boardruns are clustered together on the left side of the plot. The five boardruns show a clear break from others which means that they are far different from

others based on the holistic PCA analysis. This technique can effectively filter the abnormal boardruns.

4 Fixture Misalignments

In a real test environment, DUTs tested under abnormal sense plate positions, such as tilted or vertically shifted sense plates, may result in measurements significantly different from those tested with normal sense plates. Consequently, even a non-defective board tested with a different fixture containing mechanical variations will have measurement values different from those from the reference fixture. We may draw incorrect conclusions when comparing the test results from the two fixtures.

Here is an example taken from the experimental data. For pin 20 of connector J10, we see Shift_0 measurement average of 80.2 fF. The Shift_1 average was 75.3, the Shift_2 value was 68.3 and the Shift_3 average was 62.7 fF. This gives a spread of almost 18 fF across the test cases. However, the standard deviations of these measurements were, in all specific setups, less than 0.5 fF. Thus, if we set test limits based on, for example, 12 standard deviations, that would be ± 6 fF. But, since we typically have only a small sample of known-good boards available to derive the basis of the test value and test limits, we can build a test that will later fail falsely because a mechanical variation has now appeared. In setting test limits based only on a given pin's measurements, we can encounter false fails if the limits are set too tightly, or, we could get false passes if the limits are set too loosely. Here we are interested in judging pass/fails based on data across a collection of pins in any given test and applying corrections based on perceived variations that are mechanically induced rather than the effects of defects.¹

In this section, we present analytical expressions representing such variations and discuss regression-based methods to compensate for the effects caused by DUT and fixture mechanical misalignments. Later in Section 5 we present a PCA based scheme which can avoid having to use regression separately to identify the compensation equation coefficients for an individual device, that can be used to estimate the tilt or shift, and thereby generate coefficients for the compensation equations.

The goal of this section therefore is to identify and compensate for the measurement variation caused by abnormal sense plate positions so that it alone does not cause a DUT to be flagged as an outlier.

¹ The apparent sensitivity of the measurement to mechanical variation should also give pause to vendors who build test fixtures with sense plates in them. It may not have been appreciated in the past that some relatively small mechanical variations can lead to larger measurement variability.

4.1 Effects on Measurements due to a Tilted Sense Plate

The capacitance between sense plate and the connector pin is given by:

$$C = \frac{\epsilon \times A}{d} \quad (1)$$

where d is the distance between connector and sense plate, and A is some effective area between pin and the sensor plate. Note that this relationship holds most accurately for a square area and $A \gg d^2$, conditions that are stretched a bit in this case. However this relationship is a good first approximation for understanding what is happening due to sense plate misalignments.

When a sense plate is tilted, as shown in Figure 6, the Δd value, which is the difference from original distance d , would change from minimum to maximum value linearly depending on the pin position. Here we consider only the variation along the length, although the analysis may be extended when such variation exists both along the length and width. The ratio CR of the capacitance values with and without tilt is approximately linear along the length as given below:

$$CR = \left(\frac{\epsilon * A}{d} \right) / \left(\frac{\epsilon * A}{d + \Delta d} \right) = \frac{d + \Delta d}{d} = 1 + \frac{\Delta d}{d} \quad (2)$$

With distance along the normal sense plate, Δd changes linearly with pin physical position on connector from left to right (see Figure 6). Equation (2) results in Equation (3) below where x is the normalized position along the connector:

Figure 6 Fixture with (a) normal sense plate (b) left tilted sense plate

$$CR(x) = A + Bx \quad (3)$$

For measurements with left tilted sense plate, where the right side of plate, near pins 120 and 240 corresponding to the two rows as shown in Figures 7 and 8) is lifted, the ratio, relative to the normally positioned measurement, theoretically should be a straight line with intercept at A (≈ 1) at y-axis. For the right tilted measurement, the ratios would decrease from left to right.

The datasets used in this section includes measurement for boards with connector named *J3* and *J10*. Four boards of each type were involved, they were termed boards B1, B2, B3 and B5. (There was a board B4 not included here as it is seeded with defects.) Besides the normal Tilt 0 test (identified as reference), each board was also tested under sense plate for 3 different right tilt angles, three different left tilt angles, and 3 different vertical shift heights. Thus there is a total of 10 different measurements for one

connector on a single board. We discuss below in detail the data and the analysis for the left tilt setups, and also some of the shift setups. We analyze below in detail the left tilt cases, and present some shift cases.

Figure 7 Raw measurements for B2 with one normal and three left tilted sense plates

(a)

(b)

Figure 8 Capacitance ratio (CR) for J3 connector in B2 with (a) left tilted sense plates, and (b) right tilted sense plates

Figure 7 shows one example of J3 measurements, corresponding to board B2. The reference measurement is Tilt_0, with Tilt_1, Tilt_2 and Tilt_3 with the tilted sense plates as specified in Table 1. Capacitance Ratio CR

obtained by dividing the normal measurement by its respective tilted one, is shown in Figure 8, for both left and right tilt cases. All the plots in Figure 8 follow the linear Equation (3) fairly closely, although we observe a slight nonlinearity. The abnormal readings identified by the red ovals are caused by the paper spacers used in the experiment, which has a different dielectric constant from that of air. Therefore to make it more representative, our analysis excludes such pins, which are indicated by a red oval in subsequent figures as well.

To find a method to compensate for tilt variation, measurements with highest added tilt (and hence the highest CR), given by Tilt_3 in Figure 8(a), were selected for analysis. The measurement ratios for the two rows of the connector are slightly different, which may be caused by the specific physical layout in the two rows. Thus, we need to plot the measurement ratios for two rows, row with pin 1 to pin 120 and row with pin 121 to pin 240, separately.

Figure 9 Measurement ratio curves fitted with 1st order trend lines for connector J3 in dataset B2.

Figure 10 Capacitance ratio (CR) curves fitted with 3rd order trend lines for connector J3 of board B2, Tilt_3

Figure 9 and 10 give the CR plots for connector J3 in board B2 where the x-axis now gives the pin position. Note that the horizontal axis in Figures 9 and 10 correspond to pin position. We have also eliminated pins affected by the spacers. In Figure 9, the data points are fitted using regression to the expression in Equation (3)

above. The fit appears reasonable, not quite as well as expected. In reality, the complex distribution of the electromagnetic field makes determination of the actual capacitance value a bit more complicated than the simple plate capacitance model assumed. Note that the fit can be significantly improved if a third order polynomial is used for regression as shown in Figure 10. Data for the other boards also indicate similar results, i.e., the first order model is reasonably accurate, but third order model may be used when higher accuracy is needed.

Next we illustrate procedure for regression based compensation for the tilt and its effectiveness. We start with a data set consisting of J3 connector on boards B2, B3 and B5, as well as Tilt_3 version of B2, as shown in Figure 11(a). The measurement at each pin of the abnormal measurement is multiplied by the inverse of the ratio obtained using regression analysis Equations (4) and (5). The results for the three boards after compensation are shown in Figure 11(b).

(a)

(b)

Figure 11 Regression based compensation illustrated using Data J3 B3 (a) Measured values for boards B2, B3, B5 and Tilt_3 B2; and (b) Plot with Tilt_3 B2 value corrected via regression curve. Pins affected by the spacer are removed

Figure 12 illustrates the results of PCA based outlier detection with and without regression-based compensation for tilt.

Figure 12 CDF plot for B2 (1), B3(2), B5(3) and Tilt_3 B2 (4) before and after compensation

Comparing the two CDF plots in Figure 12 we can clearly see the compensation effect to the measurement. Labels 1, 2, 3 and 4 in Figure 12 correspond to B2, B3, B5 and Tilt_3 of B2 respectively. The d_1 value of B2 Tilt_3 is decreased from 170 to less than 30 implying that it is no longer an outlier. This indicates that the approach works. But we need to be able to estimate the tilt in order to be able to compensate for it without having to run regression analysis for each device.

Our measurements also indicate that the regression curves obtained for B2 are accurate for other boards of the same type (B1-B5) for the corresponding amount of tilt. Thus the regression analysis needs to be carried out only for one board with a particular tilt to be able to obtain the CR.

Thus if the tilt for a board is known, we can apply the appropriate correction. For regression-based or theoretical model based correction to be more practical, methods need to be developed to estimate tilts automatically, as well as to obtain regression coefficients for such different tilts. A regression analysis based approach has another complication in that it is very dependent on the ordering of the pins in the data set. We want to remove the dependence on ordering so that we do not need to know the physical layout of pins in order to perform compensation. Estimation of tilt from measurements is addressed further in Section 5.

4.2 Effects on Measurements due to a Shifted Sense Plate

Figure 13 Connector with (a) normal positioned sense plate (b) vertical shifted sense plate

Normal and vertically shifted sense plate diagrams are shown in Figure 13(a) and (b). The vertical mechanical variation of sense plate as shown in Figure 3 is caused by variability in the height of the plate above the pin tips in

the connector. In this case, CR can be shown to be a constant value independent of the pin position.

Figure 14 shows the measurements for board B5 for connector J3 with 4 different sense plate heights, 0, 8, 16 and 24 mils respectively as described in Table 1.

Figure 14 Plot of measurements with normal and vertical shifted sense plate for board B5 for connector J3

Figure 15 illustrates the CR plots of connector J3 in dataset for B5. Although the difference of measurement ratios between the two rows is clear, the ratios still have an important role to play in the compensation. Furthermore, the figure illustrates that the CR deviates from a constant value independent of pin position to some degree.

Figure 15 CR curves fitted with 3rd order trend lines for connector J3 of B5

Figure 16 CDF plots for B2(1), B3(2), B5(3), and Shift_3 of B2(4) before and after compensation

Figure 16 gives the CDF plot before and after the compensation using regression based values. As is shown, the d_i value of original outlier B2 shift_3 (the number 4 in Figure 17) is decreased significantly, which means it is not flagged as an outlier any longer.

Here also, if there is a way of identifying the shift by an independent means, then it is possible to generate parameters for the compensation curve and then apply it to compensate for the shifted plate. We address this in the next section.

5 PCA Based Tilt and Shift Evaluation

The objective of this section is to investigate how to identify the amount of tilt in a sense plate so that parameters for the compensation curves can be derived.

5.1 Evaluation of Tilt and Shift of Sense Plates

For this discussion, consider four different sense plates, each with a different tilt. By measuring the same board using these different sense plates, we show that we can identify the degree of tilt of different plates.

Figure 17 shows plots corresponding to B1 including reference case (Tilt_0) and for three values of tilt.

Figure 17 Plot of raw measurement of data B1 with three left tilted plated measurements

Figure 18 Plot to principal component values to data B1 for tilted plates

The corresponding PC plots in Figure 18 shows the values of different PCs for the four cases. Only 4 of them are visible as the remaining PCs have values close to zero in this case. Note that the value of 1st PC is almost linearly proportional to the tilt corresponding to the board.

The same phenomenon is observed on measurements with vertical shifted sense plate. Figure 19 is the plot of data B2 with vertical shifted sense plates. Based on the PC plot of Figure 20, it is clear that the first PC is able to identify the amount of shift in the sense plate as well. Note that the PC coefficients are different in the case of tilt from those for shift, as the PC coefficients are data dependent.

Above results indicate that PC based analysis can extract the information associated with tilts and shifts. For example, if a board is sent through multiple fixtures each of which is different from others only in its tilt, the tilt can be identified, and possibly compensated for. In practice fixtures may differ in both tilt and shift and may exhibit even more complex variations. However, the two basic cases are of interest in developing a theoretical basis for compensation. A very important factor to note is that PC calculation ignores the order of the pins, yet is able to identify the amount of shift or tilt. Human observations, on the other hand, depend on the order of the pins to recognize whether shift or tilt is present.

Figure 19 Raw measurement of data B2 with three vertical shifted plated measurements

Figure 20 Plot of principal component values to data B2

For example, if pin numbers are shuffled randomly for data shown in Figure 19, a human observer will be unable to detect the pattern corresponding to a shift or tilt. This shows the potential of PC based analysis to detect complex, yet systematic variations introduced alignment variations from fixture to fixture.

5.2 Overcoming Effects due to Misalignment

As first PC contains information about the tilt or shift of the sense plate, a number of options become available for tackling the problem of compensating for shift or tilt. First option is to use (constant) scale factors that convert the Y-axis of Figures 18 and 20 to corresponding tilt angle and shift respectively. Once such scale factors are derived, the CR value can be analytically evaluated, for example, using Equation (2) for the case involving tilts. Below, we look at a second option, in which we remove shift and tilt related information from measurement data, and attempt to detect the faults based on remaining value.

The relationship between the set of measurements M and the PCs (i.e., the Z scores) Z is given by $Z = MV$. The i^{th} column of M corresponds to the measured capacitance values of i^{th} pin for the different boards. Similarly, the i^{th} column of Z correspond to the i^{th} PC for the different board measurements. Thus if we replace the i^{th} column of Z with zeros (say Z'), and obtain the corresponding $M' = Z'V^{-1}$, M' corresponds to capacitance values with the i^{th} PC removed. We call such values, adjusted capacitances.

Figure 21 plots the adjusted capacitances in which all but the 1st PC are set to 0. As expected, it shows the different trends corresponding to different degrees of tilts. The plots show divergences corresponding to tilt for each row as shown in Equation (2). The difference is due to the fact that the first PC also capture much of the common variation among the different boards. Thus removing the first PC will not result in an exact correction to the measurement values to explicitly compensate for tilts, but it will also remove some of the variation that is common to all the boards in the measurement set. This also accounts for the negative values. In Figure 22, we show the adjusted capacitance values reconstructed by removing the first PC, but leaving the others intact, which compensates for systematic tilt variation among sense plate. To evaluate whether the adjusted capacitances, by removing component due to the 1st PC, can isolate the tilt related information, we use two synthetic measurement traces in addition to data used before. The new data set, shown in Figure 23 contains two simulated defective boards, indicated by Def_1, Def_2, in which the Tilt 2 capacitance measurements of pins 124 and 165 have been changed to 7fF corresponding to typical open faults.

Figure 21 Adjusted capacitances by setting all but 1st PC equal to 0 for data B1 of Figure 18

Figure 22 Adjusted capacitances by setting only 1st PCs equal to 0 for data B1 of Figure 17

Figure 23 Data set including two synthetic traces, Def_1 and Def_2 simulating open faults on pins 121 and 165

Figure 24 Adjusted capacitance by setting all but 1st PC to zero for data in Figure 23

Figure 25 Adjusted capacitances by setting only 1st PCs to 0 for data in Figure 24

Figure 24 shows the corresponding curves by retaining only the contribution due to the first PC. Note that the Tilt_2, Def_1 and Def_2 curves are almost overlapping, which indicates that the PC1 successfully captures the tilt information even though the last two contains low capacitances corresponding to injected faults.

Next we generate the adjusted capacitances by removing the tilt information by setting the first PC to zero, while retaining all the other PCs. Figure 25 shows the resulting traces, where the two defects stand out. This is a clear indication that the PC based method can compensate for tilt related information while retaining defect information.

Next we repeat the procedure for shift based misalignments. In Figure 26, we introduce two traces in which defects are injected in the Shift_2 data at pins 75 (Def_1) and 165 (Def_2) respectively, by setting the corresponding capacitances to 7fF. Figure 27, which contains adjusted capacitances corresponding to 1st PC again indicates that it is capable of extracting the shift. Note that the Shift_2 curve overlaps with Def_1 and Def_2, which correspond to Shift_2 injected with faults. Figure 28 contains the adjusted capacitance traces by removing the first PC contribution to compensate for the shift. The injected defects can be clearly seen in the adjusted capacitance curve.

The above results make a convincing case that the PC based analysis can extract systematic changes to measurements that are introduced due to shift and tilt based misalignments. However, given the fact that the PC based analysis is agnostic to the pin configuration, there is a high likelihood that the approach will work for other misalignment patterns.

Figure 26 Data set including two synthetic traces, Def_1 and Def_2 simulating open faults on pins 75 and 165

Figure 27 Adjusted capacitance by setting all but 1st PC to zero for data in Figure 26.

Figure 28 New raw matrix based on setting only 1st PC to 0

6 Summary

The misalignment of the sense plate can diminish the accuracy of outlier identification using PCA for TestJet-based board testing. Approaches for compensating for the misalignment are examined in this study. Test data was presented to indicate the impact of tilt and shift type misalignments. We simulated these in a laboratory setting not relying on production data which is poorly controlled. A simple parallel plate capacitance model was used to obtain the influence of tilts and shifts on measurements. Regression analysis was used to evaluate the model. Given the amount of shift or tilt, or the corresponding parameters for regression curves, it is possible to compensate for misalignments. However, obtaining such information is not trivial.

We have demonstrated a PCA based method that could be used to identify the degree of tilt (or shift) present in a sense plate. It yields values that are linearly proportional to the shift or the tilt. With proper calibration, this method can be used to obtain the exact shift or tilt, which may then be used to correct the measurement errors caused by misalignments. Further research is needed to extract the absolute values of the tilt/shift from the PCA analysis and to use it in a model for correction. In addition, we demonstrated a PC based technique to directly remove misalignment related component in the data, while retaining defect related information. The techniques developed have been evaluated using a limited set of test data, and only for sensor plate misalignments corresponding to shifts or tilts. Further evaluation is necessary to generalize the strategy for more complex misalignment errors.

A PCA based approach does not need to identify the physical positions of specific pins. Therefore, the approach presented in this paper shows promise for detection of complex but systematic errors introduced by sense plate misalignments, beyond visually identifiable patterns corresponding to shifts and tilts. The matrices needed for the calculation can be evaluated based on data obtained by testing the same board using sense plates with different tilts. We plan to develop this scheme further, and evaluate using additional test data.

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