An Outlier Detection Based Approach for PCB Testing with Principal Component Analysis

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Contribution

- Identifying outlier board/connector measurements
  - Novel approach for board measurements analysis
  - Test window for finer analysis
  - Performance evaluation

- Detect and compensate for systematic variation of measurement data
  - Compensation with regression lines and difference values
  - Compensation and detection with PCs
Outline

- Board Test
  - Capacitive Lead Frame Testing
- PCA Based Outlier Detection
- Global Analysis
- Localized Analysis
- Comparison with Traditional Outlier Detection method
- Mechanical Variation Compensation
- Summary and Future Work
Board Test Categories

- Loaded Board Inspection
- Structural Test
- Functional Test
- System Test

**Structural Test:**

- In-Circuit-Test (ICT)
  - Powered Test: Digital, Mix-signal...
  - Unpowered Test: Short test, TestJet...
Capacitive Lead Frame Testing

- Capacitance formed between tested pin and sense plate
- Open defect on tested pin affects the normal signal level

Ref: Parker, Hird ITC 2007
Capacitive Lead Frame Testing

(a) Non-defective pin
(b) Opened Tested pin
(c) opened neighbor pin
Principal Component Analysis (PCA)

- The 1\textsuperscript{st} Principal Component contains largest variance from the data projection.
- The 2\textsuperscript{nd} Principal Component is orthogonal to the 1\textsuperscript{st} one, contains second largest projected variance.
- Is good at analyzing multi-dimensional interrelated data.
Measurement Analysis  (Data_j24)

- Total 83 board measurements (Boardruns)
- Clear outliers: 17, 18, 19, 20, 21, 22
- Potential outlier: 4, 5, 14, 15……
Single Connector Analysis

18, 19, 20, 21, 22
Let $M$ be $(m \times n)$ matrix of Capacitive Lead Frame Testing measurements
- $m$ is the number of boards
- $n$ is the number of tested pins per board

\[
\begin{pmatrix}
  x_{11} & \cdots & x_{1n} \\
  \vdots & \ddots & \vdots \\
  x_{m1} & \cdots & x_{mn}
\end{pmatrix}
\rightarrow
\begin{pmatrix}
  \frac{\sum_{k=1}^{n} x_{k1}}{n} & \cdots & x_{1n} \\
  \vdots & \ddots & \vdots \\
  \frac{\sum_{k=1}^{n} x_{k1}}{n} & \cdots & x_{mn}
\end{pmatrix}
\]

Centering

1st PC
Using the Singular Value Decomposition \( M_c = USV^T \)
where

\[ U_{mxn} \quad \text{Scaled version of PC scores} \]
\[ S_{nxn} \quad \text{Diagonal matrix with square roots of Eigen values in descending order} \]
\[ V^T_{nxn} \quad \text{Eigen vectors (PCs).} \ V \text{ is the transformation matrix} \]

Matrix \( Z = M_c V \) gives the z-score value of boards

Z-score value of a board is a linear combination of all the corresponding measurement values for that board
PCA for PCB Outlier Detection

\[ Z = M^c V \]

Variance of columns in the Z score matrix are automatically ordered by the algorithm from high to low.
Test Statistics

\[ d_{1i}^2 = \sum_{k=p-q+1}^{q} z_{ik}^2 \quad p : \text{the sequence number of the last PC used} \]
\[ d_{2i}^2 = \sum_{k=p-q+1}^{p} \frac{z_{ik}^2}{l_k} \quad \iff \quad d_0^2 = \sqrt{\sum_{k=1}^{p} \frac{z_{ik}^2}{l_k}} \]
\[ d_{3i}^2 = \sum_{k=1}^{p} l_k z_{ik}^2 \]
\[ d_{4i} = \max_{p-q+1 \leq k \leq p} \left| \frac{z_{ik}}{\sqrt{l_k}} \right| \quad \iff \quad X_i = \log_{10}(\max_{p-q+1 \leq k \leq p} \left| \frac{z_{ik}}{\sqrt{l_k}} \right|) \]
Measurement Outlier Analysis with Test statistic

- Test statistics calculation with Principal Components from data set.
- Board measurements are sorted according to the respective $d$ value.
- The outlier boards should stand out at the high-end of the Cumulative Distribution Function curve in $d$ scale.
Board run numbers on CDF plot from left to right:

52, 51, 50, 53, 49, 32, 73, 24, 48, 25, 74, 72, 83, 71, 57, 47, 1, 42, 56, 70, 6, 68, 38, 37, 58, 43, 59, 41, 39, 55, 40, 2, 23, 78, 33, 35, 44, 69, 79, 54, 75, 36, 64, 80, 76, 31, 77, 65, 60, 29, 81, 63, 61, 62, 3, 67, 66, 82, 27, 45, 28, 46, 26, 30, 34, 12, 8, 7, 10, 9, 16, 11, 13, 14, 15, 4, 5, 17, 22, 19, 18, 20, 21
Test Statistic for Outlier Detection

\[ d_{1i} = \sqrt{\sum_{k \in E} Z_{ik}^2} \]

- \( Z_{ik} \): Value of the \( k \)-th PC for \( i \)-th board
- \( E \): a subset of PCs - most significant PCs are used here

- Sort the boards with respect to \( d_1 \)
- Plot cumulative distribution function (CDF) of \( d_1 \)
- Outliers are clearly identifiable on right side of plot, and typically are separated from other devices by a clear margin
PCA vs. Standard Deviation (STDev)

\[ \text{Average} + \alpha \times \text{STDev} \]

\[ \text{Average} \]

\[ \text{Average} - \alpha \times \text{STDev} \]
# PCA vs. Standard Deviation (STDev)

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>Abnormal Boardruns Detected</th>
<th>Boardruns No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>5.5</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>4.5</td>
<td>2</td>
<td>14, 17</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>3, 11, 14, 17, 83</td>
</tr>
<tr>
<td>3.5</td>
<td>11</td>
<td>3, 4, 5, 6, 8, 11, 14, 15, 17, 59, 83</td>
</tr>
<tr>
<td>3</td>
<td>18</td>
<td>3, 4, 5, 6, 8, 9, 11, 14, 15, 16, 17, 18, 19, 20, 21, 51, 59, 83</td>
</tr>
<tr>
<td>2.5</td>
<td>35</td>
<td>3, 4, 5, 6, 7, 8, 9, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 34, 36, 47, 48, 51, 53, 57, 58, 59, 60, 63, 68, 73, 80, 81, 83</td>
</tr>
</tbody>
</table>
PCA vs. Standard Deviation (STDev)
Localized Analysis

Pins in white color are VDD/grounded pins.
Test Windows (Data_j24)
Localized Analysis
Test Window Shift

Data3_j24 Local Analysis -- window shift

Data3_j24 Local Analysis -- window shift
Size of Test Window

Window size simulation for Data_j24
Comparison of Global and Localized Methods (Data_ j3)
Measurement matrix $M$
(m boards $\times$ n tested pins)

Sort matrix according to pin location

Divide to $w$ test windows
($w=1$ for Global Analysis)

Center matrix in each group

Derive Z scores for each group

Evaluate $d_i$ values in each group

Compare maximum $d_i$ value in different groups

Sort $d_i$ Value

Pass/ Fail; outlier type/ position

PCA Flow Chart
Capacitive Lead Frame Testing Challenges

Tester AC Source stimulates one pin, all others are grounded

[Courtesy of K. Parker, Agilent Technologies]
Compensation for Mechanical Variation

[Courtesy of K. Parker, Agilent Technologies]

Spacers placed between plate and connector at one end. Again, the spacers have a different dielectric constant from air.

Spacers placed between plate and connector. Most connector pin tips see an air gap to the sense plate, but at the ends, the gap has a different dielectric constant.
Compensation for Mechanical Variation
Compensation for Mechanical Variation

J3 board2 left Tilt3 row by row

\[ y = 0.0045x + 1.0888 \]
\[ y = 0.0053x + 1.1027 \]

- row with pin 1 to 120
- row with pin 121 to 240

J3 board3 left Tilt3 row by row

\[ y = 0.0048x + 1.0885 \]
\[ y = 0.0041x + 1.0626 \]

- row with pin 1 to 120
- row with pin 121 to 240

J3 board2 left Tilt3 row by row

\[ y = 3 \times 10^{-7}x^3 - 5 \times 10^{-5}x^2 + 0.0076x + 1.0488 \]
\[ y = 3 \times 10^{-7}x^3 - 7 \times 10^{-5}x^2 + 0.0091x + 1.0488 \]

- row with pin 1 to 120
- row with pin 121 to 240

J3 board3 left Tilt3 row by row

\[ y = 6 \times 10^{-7}x^3 - 1 \times 10^{-4}x^2 + 0.0095x + 1.0383 \]
\[ y = 3 \times 10^{-7}x^3 - 6 \times 10^{-5}x^2 + 0.0068x + 1.0359 \]

- row with pin 1 to 120
- row with pin 121 to 240
Compensation for Mechanical Variation

J3 3 normal measurements

J3 3 normal measurements -- truncated

J3 3 normal and 1 compensated measurements

J3 3 normal and 1 Tilt_3 measurements
Compensation for Mechanical Variation

cdf curve of the tiltcomp.xls data
Compensation for Mechanical Variation

Difference value plot between tilted-plate measurements and normal measurements

![Difference value plot](image-url)
Compensation for Mechanical Variation

- J10 4 normal and one Tilt3 measurements
- J10 4 normal and one compensated measurements

Measured Capacitance (fF) vs Pin Number
Compensation for Mechanical Variation

cdf curve of the comp1.xls data

cdf function \( F(x) \)
d1 value

20 40 60 80 100 120 140 160
Compensation for Mechanical Variation
Compensation for Mechanical Variation

Difference value plot between tilt-measurement and normal measurement.
Compensation for Mechanical Variation
Compensation for Mechanical Variation

cdf curve of the comp1.xls data
Compensation for Mechanical Variation

- Principal Component Value
- Boardrun Number

- Measured Capacitance (fF)
- Pin Number

- Reference
- Tilt_1
- Tilt_2
- Tilt_3

- Shift_1
- Shift_2
- Shift_3

- Compensation for Mechanical Variation

- 1st PC
- 2nd PC
- 3rd PC
PCA Based Tilt or Shift Evaluation
Summary

- Can effectively identify outlier boards
- Localized analysis can increase test resolution and assist in the location of outliers
- The global and localized analysis can be combined to filter the outliers
- Can be applied to other kinds of PCB test data beside Capacitive Lead frame test data
- Compensation is effective for fixture variation
Future Work

- On-line testing techniques to enhance the detection efficiency
- Investigate data variation caused by measurement errors, mechanical and electrical tolerances
- Technique to compensate for the effects of mechanical variations parameter variations by setting the PC values
Related Publication

- **Conference and Workshop Papers**
  - X. He, Y. K. Malaiya, A. P. Jayasumana, K. P. Parker and S. Hird, "Principal Component Analysis-Based Compensation for Measurement Errors Due to Mechanical Misalignments in PCB Testing" To appear at the 41st International Test Conference (ITC'10), Austin, Texas, November 2010

- **Poster**
Thank you!

Questions