Printed Circuit Board Inspection Using Image Analysis

Horng-Hai Loh and Ming-Sing Lu

Abstract—Computer vision has been widely used in on-line inspection of electronic components. In this paper, we present a computer vision system using structured lighting, which provides us with an efficient solution for solder joint inspection. Our system uses a novel structured-lighting inspection technology to overcome some difficulties that traditional computer vision systems often experience. We developed a slant map surface shape estimation technique for the solder joint. From this technique, a solder joint can be determined to be a good (concave), bad (convex), bridged solder joint, or solder joint with surplus solder, or lacking solder.

Index Terms—Inspection, printed circuit board, solder joint, structured light, surface mount technology.

I. INTRODUCTION

Surface mount technology (SMT) components have been widely used in the electronics industry recently. One major advantage of using SMT components is that they can increase the component density on a printed circuit board (PCB) substantially. The size of the components to be put on the PCB can also be reduced. This makes SMT component inspection difficult, and various quality control issues of the SMT components have been explored. In this paper, we present a novel SMT components inspection system using a structured-lighting approach, which has been proved to be effective in finding SMT solder joint defects.

From a report of PCB manufacturers [5], the SMT component defects can be classified into the following four categories:

1) component misplacement, which is about 10%;
2) component with wrong polarity, which is about 25%;
3) component absent, which is about 20%;
4) solder joint defect, which is about 55%.

Among the solder joint defects, we can further classify them into bridged solder joint, lacking solder, surplus solder, open, poor solderability, and component shifting [4]. The solder joint defects all come from an inappropriate manufacturing process and, thus, it is critical to find out these solder joint defects and correct the manufacturing process. SMT components rely on the solder joint to provide the electrical connection to the PCB and the mechanical holding strength; therefore, the quality of the solder joint can be critical to the quality of the final product made from SMT components.

II. APPROACH

Inspection technologies for PCB solder joints have been developed using various methods with a certain degree of success [1], [2]. For example, a range sensor can be used to detect miss parts. A charge-coupled device (CCD) camera can be used to find misplaced parts, and run-length coding can also be applied to find the exact part number [6]. However, a large percentage of PCB defects are from solder joints. Therefore, we focus our inspection system on the solder joint defects. The solder joint inspection process can be divided into two phases. The first phase is to find whether there is a bridge between neighboring solder joints. The second phase is to identify and classify the solder joint defects.

Whether we can have a good solder joint depends on the quality of the solder paste. The solder paste can determine the shape of the solder joint. In this paper, we use a slant map to extract the shape information of a solder joint, which is based on the slant angle of the solder joint surface. We use a set of two-dimensional (2-D) images to extract the slant angle of the solder joint surface. There exists a number of factors that can affect the solder joint shape, including the gravity, the solderability of the solder pad, the shape of the lead, and the amount of solder. It is found that, when a solder joint is placed on a flat surface, it usually goes into a cap shape, which is a result of the balance of the surface tension of solder, the solderability of the flat surface, and the weight of the solder itself. The equation for surface tension can be described as [1]

$$\gamma_s - \gamma_{ls} = \gamma_l \cos \theta$$

where

- $\gamma_l$ liquid surface tension;
- $\gamma_s$ base surface tension;
- $\gamma_{ls}$ surface tension between liquid and base;
- $\theta$ degree between liquid and solder pad.

Pressure difference of the surface

$$\Delta P = \gamma_l \left( \frac{1}{R_1} + \frac{1}{R_2} \right)$$


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and static liquid pressure

\[ \Delta P = -\rho g \Delta z \]  

(3)

where

- \( \Delta P \) pressure difference of the surface;
- \( \rho \) solder density;
- \( g \) gravity;
- \( R_{1} \) radius of the \( X-Z \) surface;
- \( R_{2} \) radius of the \( X-Y \) surface.

We can use (2) and (3) to solve \( R_{1} \) and \( R_{2} \), which represent the basic shape of the solder joint. There are three types of solder joints which can represent typical shapes of solder joints. These three solder types are (as shown in Fig. 1):

1) standard cap-shape solder joint;
2) solder joint with a metal pin;
3) solder joint with a metal plate.

We can derive two vectors which can determine the shape of the solder shape, slant and tilt. The tilt and slant vectors of a solder joint are illustrated in Fig. 2.

Fig. 1. Three different types of solder joints. (a) Standard cap-shape solder joint. (b) Solder joint with a metal pin. (c) Solder joint with a metal plate.

The slant vector can determine the basic shape of the solder joint, and the tilt vector is more to do with the third type of the solder joint (i.e., the solder joint with a metal plate.) It is because the first two types of solder joints are symmetrical on the \( X-Y \) surface, and the third type solder joint is connecting with an IC or other SMT component’s lead [3]. To extract the slant vector, we developed a hemispherical lighting system. This lighting system consists of a structured LED array. The LED array is placed on the lighting system to project light source from different position/orientation onto the solder joint surface. The slant vector can be extracted from a set of 2-D images based on the reflection of the structured light from the solder joint surface. From the slant vector, there are three slant angles (as shown in Fig. 3) which represent the solder joint shape and are directly relative to the quality of the solder joint:

1) slant angle between solder joint surface and solder pad: \( \theta_{l} \);
2) slant angle of the solder joint: \( \theta_{e} \) (which is determined by the amount of the solder);
3) slant angle between solder joint surface and SMT component’s lead: \( \theta_{p} \).

Wassink [4] has found that there is a linear relation between \( \theta_{e} \) and the height of the solder joint; therefore, we can classify different solder joints based on \( \theta_{e} \). The slant angle \( \theta_{e} \) has been found to be in the range between 33°–39°. He also found that \( \theta_{l} \) could be related to the solderability of the solder pad. A solder pad with good solderability can have the solder joint appearing in concave shape, therefore, \( \theta_{l} \) can be seen as a feature for the solder joint, and \( \theta_{l} \) is usually in the range between 9°–13°. Lastly, \( \theta_{e} \) is proportional to the amount of solder in the solder joint, and it is in the range between 16°–22°.

A. Lighting Design

For a reflecting surface, the incoming angle is equal to the outgoing angle; therefore, we can use a light source which has a 2θ angle with a CCD camera to let the camera catch the solder joint surface images, as shown in Fig. 4. We can also use \( \theta_{l}, \theta_{e}, \theta_{p} \) as reference angles and catch a set of three solder joint images. Based on these images, we can derive a slant map and a set of regional features for the solder joint defect classification.
III. EXPERIMENT

For the PCB inspection system, we use the following equipment:

1) Epix 4Meg video frame grabber;
2) Watec Wat-203 CCD camera;
3) hemispherical lighting system with LED array and light source controller, as shown in Fig. 5.

The LED array light source is developed for this system which can provide a controllable lighting condition from different position/orientation to extract different slant angles for the solder joint. The inspection system is integrated on a 486 PC and uses C++ as the programming language.

The SMT components on a PCB can be inspected using the flow chart shown in Fig. 6.

The first phase of the solder joint inspection is the inspection for bridge solder joint. We can use a direct projecting light from the top and take a binary image from the CCD camera. Then, the whole image is divided into several imagelets, each containing an area between two neighboring solder pads. If there is a solder joint across the imagelet, then a pair of bridged solder joints is identified.

The second phase of the solder joint inspection is the inspection for solder joint defects. This kind of inspection is difficult from a 2-D image, for the reflecting nature of the solder joint surface can make the 2-D image saturated, and a lot of detailed solder joint information will be missed. Therefore, we use structured light in our system to evade the problem caused by reflection, and the images taken can then be used to derive a slant map.

There are three reasons why we choose a slant map for our inspection system.

1) For on-line inspection, we need a technique that requires minimal computation. The slant map can be easily derived without too much computation.
2) We need a technique that can represent the shape of the solder joint surface, which means background and other irrelevant information can be easily eliminated. The slant map can provide us with useful and concise solder joint shape information.
3) The slant map can represent the three slant angles \( \theta_e \cdot \theta_l \cdot \theta_n \).

The second phase inspection process starts with taking three separate images from the same solder joints with lighting conditions corresponding to \( \theta_e \cdot \theta_l \cdot \theta_n \). The results can be represented on the slant map using three different color regions (i.e., red, green, and blue) as shown in Fig. 7. The red region represents the lighting condition projecting from 18° to 26°, the green region represents the lighting condition projecting from 32° to 44°, and the blue region represents the lighting condition projecting from 66° to 78°.

Based on lighting conditions with different projecting angles, we can then overlap these three images taken from different lighting conditions. We take threshold values as 70, 130, and 145 to segment the red, green, and blue regions, respectively, then overlap these three regions to derive the slant map. The slant map can be used to extract the following features:

1) shape of these three regions;
2) geometric relationship between these three regions.

These three regions have different meanings to the solder joint. The red region represents the slant angle \( \theta_l \). A solder pad with good solderability will have an arc-shaped red region appear on the edge of the solder joint. A slant map without the red region could mean that the solderability of the solder pad is poor or the surface tension of the solder paste is not
good enough. The blue region represents the slant angle $\theta_c$, as well as the solderability of the component lead or the angle between the component lead and solder pad. If the blue region appears on the edge of the lead as shown in Fig. 7, then it means the solder has a good solderability.

The green region represents the slant angle $\theta_s$, which can be used to distinguish good (concave) and bad (convex) solder joints. For a concave solder joint such as that shown in Fig. 8(a), when we scan from the edge of the solder pad to the lead, we will pass the red region, then the green region, then the blue region, finally reaching the component lead. However, for a convex solder joint, the red region can be found to be surrounded by the green region, as shown in Fig. 8(b)–(e).

In contrast to a good solder joint, which has a red–green–blue region distribution when scanning, a solder joint with surplus solder will have a blue–green–red distribution when scanning, as shown in Fig. 8(f), and a solder joint with insufficient solder will have a large area of red region near the component lead.

For practical applications, it may not be necessary to identify the type of solder joint defect for every solder joint. It is more efficient to separate the good solder joint from the defective solder joint, then identify the type of defect based on the features extracted from the slant map. The type of defect can then be used to improve the manufacturing process and eliminate solder joint defects.

### A. Inspection Rules

1) From the edge of the tin–lead solder pad, scan to the component lead; if the scan path crosses the red–green–blue region, then this solder joint is a good one, otherwise goes to rule 2) for defect classification.

2) Defect classification is as follows.

   a) If the area of the blue region is small near component lead and the area of the red region is big, then the solder joint is lacking solder, as shown in Fig. 9.

   b) If the red region is completely surrounded by the green region, then it is a convex solder joint. If the red region is not fully surrounded, but the red region goes all the way and covers the whole lead, then this solder joint has a serious surplus solder problem. Otherwise, if the red region extends to the edge of the solder pad, then the solder joint has a moderate surplus solder problem.

   c) The contour shape of the red region is affected by the solderability between the solder and the solder pad.

### IV. EXPERIMENTAL RESULTS

We use two sets of solder joints in our experiment. Images are taken using three different lighting conditions from these solder joints, and the results are shown in Fig. 10.

We can extract one slant map each for these two sets of solder joints, as shown in Fig. 11. The slant maps are analyzed using the inspection rules, and these two sets of solder joints are classified as lacking solder, convex solder joint, good (concave) solder joint, and bridged solder joint.

We can start the solder joint classification by scanning the slant map and recording the range of these three regions on the $Y$ and $X$ axes. Then, determine the geometric relation between
these three regions. Based on the classification rule 1), we can determine the quality of a solder joint using a threshold value.

If the solder joint is determined to be a defective one, then a further classification process can proceed to classify the type of solder joint defect. The center of the defective solder joint is used as an origin to scan the slant map in four directions (i.e., 0°, 45°, 90°, and 135°). We can use these eight scan lines to determine how the red region is surrounded by the green region.

1) If the red region is fully surrounded by the green region, then it is a convex solder joint.
2) If area 2 is all in the red region and in all other areas the red region is surrounded by the green region, as shown in Fig. 12(c), then the solder joint has serious surplus solder.
3) If area 6 is all in the red region and in all other areas the red region is surrounded by the green region, as shown in Fig. 12(d), then the solder joint has general surplus solder.
4) If only in area 2 the red region is surrounded by the green region and the red region dominates all other areas, as shown in Fig. 12(a), then the solder joint is lacking solder.

V. CONCLUSION

The following are widely used to determine the performance of a solder joint inspection system.
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(a) Slant map for the first set of solder joints. (b) Slant map for the second set of solder joints.

Fig. 11. (a) Slant map for the first set of solder joints. (b) Slant map for the second set of solder joints.

Fig. 12. The scanning results of different solder joints. (a) Lacking solder. (b) Convex solder joint. (c) Series surplus solder. (d) General surplus solder.

Table I

<table>
<thead>
<tr>
<th>Solder Joint Types</th>
<th>Classification Results</th>
<th>No.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>G</td>
<td>B</td>
</tr>
<tr>
<td>G(convex)</td>
<td>92.31</td>
<td>0</td>
</tr>
<tr>
<td>B(concave)</td>
<td>37.1</td>
<td>62.9</td>
</tr>
<tr>
<td>N(lacking solder)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>E(extend to pin)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>U(surplus solder)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>O(center convex)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C(bridged)</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

(b) False alarm 7.69%

4) Correct flaw classification.

A solder joint inspection system should have low false alarm, faults missed, and incorrect flaw classification ratios and have a very high correct flaw classification ratio. We used an 80-pin SMT component for our experiment, and the classification results are shown in Table I.

We can see that our system can fully detect the bridged solder joint, and the false alarm ratio is 7.69%. The system classifies some good (convex) solder joints as solder joints with too much solder (extend to pin). This system also makes some mistakes with convex and concave solder joints. It is sometimes hard to give a clear definition of the difference between a convex and a concave solder joints. This deficiency can be improved by adjusting the inspection rule. From the experimental results, we conclude that our solder joint inspection system has a high success rate on PCB solder joint inspection, and the slant map approach is computationally efficient.

REFERENCES


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