Low-cost design of a PCB imaging system based on laser triangulation

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Abstract: With the increasing miniaturization of electronic products, fanless design is required. The volume of electronic components, especially the height, is critical to the structural design of electronic devices. This paper proposes the design of on-line height measurement equipment based on commercial charge-coupled device (CCD), analyses the principle of height measurement of components, and explains the system composition and working principle of the measurement system. Moreover, it presents a comparative analysis of common methods for determining the center position, which include circle fitting, the gray centroid and extended method or Gaussian fitting, which generally lead to diverse results. The experimental results show that Gaussian fitting is better than other methods under realistic conditions, a three-dimensional model of the components is provided, and the error factors that affect measurement are analyzed.

1. Introduction

The continuous growth in demand for miniaturization of electronic devices, has prompted more focused research on developing fanless structure (no air cooling) to transfer heat. In essence, the volume of the components, especially the height, is very significant for the structural design of electronic devices. In the principle design stage or finished-product design stage of electronic products, how to quickly and cost-effectively detect the height of components after assembly is an urgent problem that needs to be addressed.

AOI (Automated Optical Inspection) [1] is a new type of testing technology that is developing rapidly. An AOI device detects common defects encountered in welding production based on optical principles. It utilises high-speed and high-precision visual processing technology to automatically detect various mounting errors and soldering defects on PCBs (Printed Circuit Boards), which can range from fine-pitch high-density boards to low-density large-size boards. An AOI device can provide online inspection solutions to improve production efficiency and welding quality. Many manufacturers have applied AOI testing equipment, however, general AOI measurement results have no information about the height of individual components. AOI equipment with height measurement capability is very expensive, and so is three-dimensional measuring instrument. In contrast, the 2D imaging CCD is a mature market-oriented product (open source), which drives the central position information of the device from the design blueprint of the PCB. The heights of the circuit components under test and the placement of the PCB are measured using a laser triangulation system, and this height information could be exported to a three-dimensional model.
1.1. Laser triangulation method
The high-performance laser triangulation method [2-34] has many advantages compared with other non-contact measurement methods. These include a wide range and offset distance, good stability, simple and accurate measurement, small volume, little environmental impact, high convenience for automated online detection, etc. In this paper, as one of the universal measuring tools, a one-dimensional laser triangulation displacement measurement system was adopted due to its characteristics of low-cost, simple structure, light weight and high measurement accuracy.

1.2. 2D displacement stage
The structure of the mechanical displacement transmission table used in this paper is generally simple. Although there are gaps and friction between mechanical parts, which could reduce the movement accuracy [5], the accuracy levels for measurement of the circuit board is sufficient. The positioning accuracy of the mechanical displacement transmission table is ± 0.05mm.

2. Working Principle
The working principle of the laser triangulation displacement measurement system is similar to that of object imaging in geometric optics. The semiconductor laser in the sensor sends a laser beam to the surface of the measured object. The diffusely reflected light on the surface of the measured object passes through the lens of the sensor and is imaged on a CCD detector. During the movement of the surface of the measured object, the position of the imaging point on the CCD detector also changes concurrently. In other words, the position information of the imaging point on the CCD detector is exactly the same as the position movement information of the object surface. The reason why this method is referred to as laser triangulation measurement method is because the laser beam emitted by the sensor has a triangular relationship with the light reflected by the surface of the object and imaged on the CCD detector. The laser triangulation method can be further subdivided into either a direct or oblique measurement method depending on the relationship between the light emitted from the laser and the surface normal of the measured object.

The schematic diagram illustrating the working principle of the direct incident laser triangulation measurement is shown in Figure 1. It can be seen that the laser light is incident perpendicularly on the surface of the measured object, and the geometric relationship can be expressed:

\[ a \tan \theta_2 = b \tan \theta_1 \]  
\[ x = \frac{a x' \sin \theta_1}{b \sin \theta_2 - x' \sin (\theta_1 + \theta_2)} \]

Figure 1. Schematic diagram of direct incidence trigonometry
The working principle of the component height measurement device proposed in this paper is that the host computer software reads information of each component on the PCB in OrCAD “*.DSN” file (contains position, layout outline, layer and packaging information), and also extracts the position information of each component to control the two-dimensional displacement stage and measure the height of each component. The host computer generates an STL(abbreviation for stereolithography) file, which is three-dimensional general model file containing the layout of the components and the height measurement information. The block diagram of the laser triangulation system is shown in the figure below.

![Block Diagram of Laser Triangulation Measurement Device](image)

Figure 2. A block diagram of the laser triangulation measurement device

The position of the laser point on the detector is used to calculate the distance to the ICs on the PCB. There exist many different algorithms for laser spot center detection which include circle fitting[6], the gray centroid method[7] or Gaussian fitting[8]. Basically, these algorithms can be divided into either edge-based algorithms or intensity-based algorithms. Edge based algorithms use the edge information of an image, whereas intensity-based approaches focus on the intensity profile of the laser spot.

2.1. Gray centroid algorithm

The laser spot center is calculated by a gray-scale weighted calculation of the geometric center of the spot, yields the two-dimensional coordinates of the laser spot center on the detector are calculated according to the formula:

\[
x_c = \frac{\sum x_p p}{\sum p}, \quad y_c = \frac{\sum y_p p}{\sum p}
\]

where \(x_c\) and \(y_c\) is the centroid of \(x\) and \(y\) dimensions, \(x\) and \(y\) is the pixel in \(x\) and \(y\) dimensions, respectively, and \(p\) is the pixel intensity.

This could also be extended to an arbitrary exponent \(k\), resulting in

\[
x_{ck} = \frac{\sum x_p p^k}{\sum p^k}, \quad y_{ck} = \frac{\sum y_p p^k}{\sum p^k}
\]

2.2. Circle fitting algorithm

For the circle fitting methods, the center and radius of the laser spot are calculated with the help of its edge points, which are extracted in the step of edge detection. A circle is fit into the set of edge points

\[
(x - x_c)^2 + (y - y_c)^2 = r^2
\]

where \(r\) denotes the radius of the laser spot. By applying the least squares method to minimise the residuals between the edge points and the circle, the values of \(x_c\), \(y_c\), and \(r\) can be determined.

2.3. Gaussian fitting algorithm

The Gaussian fitting method is considered as a very accurate approach, and it makes use of the Gaussian distribution that a laser spot typically exhibits. The center of the laser spot is then computed by minimizing a least squares problem between Gauss curve and the laser spot profile. The intensity distribution \(I_{x,y}\) is given by
\[ I_{x,y} = \max \left( I_0 \right) \cdot \exp \left( -\frac{(x-x_c)^2}{2\sigma_x^2} - \frac{(y-y_c)^2}{2\sigma_y^2} \right) \]  

where \( I_0 \) is the max intensity of whole CCD, and \( \sigma_x \) and \( \sigma_y \) are the standard deviations in \( x \) and \( y \) directions, respectively.

### 3. Experimental setup

Since a product's PCB requires fanless heat dissipation, a tight installation space would affect the heat dissipation capability of each protruding structure. Therefore, it is necessary to check whether the safety distance between the device and the structure meets the set requirements. Parameters provided in the document are not accurate as the chip manual datasheet has a tolerance range of 0.5mm for the outline package of the components, and the components of different batches may differ even more. This is the reason why we exploit the experiment setup to conduct the tests.

The device experimental setup steps are as follows: the circuit board is stably placed on an anti-static sponge, the original information of the circuit board is calibrated, and the offset is calculated using software. Then, the position information of the converted component is deviated 0.5mm from the \( x \) and \( y \) direction, respectively, that is, 4 points of a component test, and sent to the two-dimensional stage and the commercial CCD (DAHENG MER-500-14GM) [9]. The actual height information of each electrical component is recorded, and the 4 pieces of height information are used to check whether there is warping in the welded part of the component. The 3D model in “.stl” format is exported to the designer to check for structure interferences. Figures 3 and 4 are the two-dimensional stage drive board communication board (open source) and the two-dimensional stage equipped with a laser and CCD.

As shown in Figure 5, on the top side of the PCB, there are 4 components, which are power MOSs (Metal-Oxide-Semiconductor Field-Effect Transistor), and additional protruding structures are required for heat dissipation. As shown in Figure 6, on the bottom side of the PCB, the space of the structure is limited. The top and bottom sides of the PCB are shown in Figure 3 and Figure 4, respectively.

![Figure 3. 2D stage driver board communication board (Open-source)](image)

![Figure 4. Hardware system (including LD and CCD)](image)
In the AD(Altium Designer: a PCB design software), select “Export Spectra Design file”. The file format is unassuming to understand. The boundary of the circuit board is calculated according to the path signal. The value ranges of the first and second columns in the path signal correspond to the X and Y directions of the PCB. The dimensions are in “mili-inch” and converted to metric “mm”, that is, 188mm and 232mm. Note that if you use the data file containing “rect pcb”, the real PCB boundary size should be modified because “rect pcb” includes the width of the line.

In the AD software, select "Reports-> Bill of Materials", after clicking to select the components "Commet", "Designator", "Center-X (mm)", "Center-Y (mm)", "Layer", and then select the export format ".csv", that is, Comma Delimited file, as shown in Figure 7. In this way, we can obtain the position information of all the components, and use MATLAB, LABVIEW or Python program to convert the device position on the circuit board into the control commands required for the two-dimensional stage.

The test steps of the test device adopted in this article are as follows:

(1) Read the BOM list file that the user is concerned about.
(2) Analyse the code, location, layer, and quantity of components.
(3) Classify the position information of the components according to k-means++ clustering method [10].
(4) Perform the shortest path planning on the area clustered by the location in Step (3).
(5) Zero the 2D stage test, according to the edge of the circuit board or the marked point.
(6) Scan the height of the components one by one.
(7) For the double-sided boards, flip the circuit board and repeat Steps (5) to (6).
(8) Read the DSN file.
(9) Dissect the X and Y dimensions of the outer contour of each component.
(10) Multiply the X and Y dimensions of the outer contour and measured height of each component by the unit cube.
(11) Generate heights information in EXCEL, as well as STL models of the circuit boards and components.

4. Experimental results

In this section, a comparison of the test results of typical algorithms in practical applications is given. Under the actual imaging conditions of the electronic devices production line, due to the imprinting and marking on the surface of the integrated chip, as shown in Figure 8, the laser spot reflected on the device surface is not only affected by speckle noise, as shown in Figure 8(c), but also the influence of irregular points and lines. Some studies have shown that similar occlusions before detecting objects have a great impact on the laser spot measurement results, especially the relative measurement sensitivity[11]. As described, the results of the conventional algorithm introduced in this paper show differences in imaging conditions, as shown in Figure 9 below.

Figure 8. (a) Top-side of PCB after surface mount (b) Bottom-side of PCB after surface mount (c) Laser spot on MOS chip after surface mount

Figure 9. The results of different laser spot center algorithm

Comparing the actual measured data, the error statistics is shown in Table1 below.

| Algorithm             | Mean Δρ(mm) |
|-----------------------|-------------|
| Gray centroid (k=1)   | 0.11        |
| Gray centroid (k=2)   | 0.13        |
| Gray centroid (k=3)   | 0.15        |
| Gray centroid (k=4)   | 0.17        |
| Circle fitting        | 0.10        |
| Gaussian fitting      | 0.09        |
\[ \Delta \sigma = \left[ (\Delta x)^2 + (\Delta y)^2 \right]^{1/2} \] is the global position error, whereas \( \Delta x \), \( \Delta y \) are the horizontal and vertical position errors, respectively.

In the established test system, we tested an irregular circuit board of size 46mm by 53mm, and obtained the height data of the measured device. There are 13 components in total on the device, which take 2 minutes to scan, and almost about half of the time for zeroing and flipping the PCB board. In general, the measurement speed and accuracy can meet user requirements. The three-dimensional model exported by software is shown in Figure 10-12.

![Figure 10. PCB top side components heights](image1)

![Figure 11. PCB bottom side components heights](image2)

![Figure 12. PCB Sectional View in STL file format](image3)

Through field measurement and preliminary analysis, it is determined that the errors mainly come from the following aspects:

The algorithm error of laser spot center could be reduced by adjusting the CCD exposure so that the max intensity of the laser spot is close to saturation and not overflowing the CCD charge well. The measurement error of the laser stage can be reduced by multi-point average or median measurement. The user can choose the number of average points and the average method. The structure of the two-dimensional stage can be strengthened and optimized in the future. The error caused by the accuracy of the two-dimensional stage stepping motor, the minimum step control could be adjusted through the software according to the size of the component is 0.05mm. Under the high-precision stepper-motor subdivision operation, the scanning speed will decrease. The host computer software can read the DSN file to obtain the component size, and then perform different subdivision motor control scans for different size components. As for the error caused by the step loss of the 2D stage stepper motor, at the current scanning speed, periodic calibrating the reference point of the 2D stage can be considered. The PCB itself has some height error caused by warping and uneven placement. The surface area near the four corners and edge points of the PCB were measured to reduce the PCB height error. The experimental results show that Gaussian fitting is better than other methods in actual condition. The open-source two-dimensional stage could be optimized and restructured, and the test accuracy could be further improved.

5. Conclusion

We have solved the problems of low cost and high reliability of measuring the heights of components on a PCB. The PCB components height measurement platform was built by the commercial CCD and the open source hardware and software were also set up. The experimental results show that Gaussian fitting is better than other methods under actual conditions. The error factors that affect the measurement have been analyzed. The proposed system has made it possible to measure the height of the components after PCB assembly, which can provide reference for the iterative design of manufacture.
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