Design of projection optical system for 3D defect detection on PCB

Xu Chen, Feng Xu*, and Suodong Ma*
Soochow University, Suzhou, Jiangsu, China
20185208029@stu.suda.edu.cn, xf750617@suda.edu.cn, masuodong@suda.edu.cn

Abstract. According to the practical experience of PCB defect detection in semiconductor industry, a projection optical system suitable for structured light detection device is designed by using a DMD chip. In order to realize the lateral projection of structured light stripe and improve the quality of system projection, the design of tilt back group of projection lens is adopted and the projection size is 57×32mm. The simulation results show that the illumination uniformity of the projection system on the measured surface is more than 85%, the fringe contrast is larger than 0.5, and the maximum height of the measuring device is 5mm, which provides a guarantee for practical application of structured light fringe for 3D defect detection on PCB.

1. Introduction
Shape information of objects is widely used in manufacturing industry, such as machinery, automobile, aerospace, clothing and toy manufacturing[1-4]. Three dimensional measurement technology, also known as three-dimensional shape measurement technology or three-dimensional contour measurement, is used to obtain the spatial coordinates of the points on the surface of the measured object. With the rise of surface mounting technology (SMT), the requirement of detection accuracy of PCB contour is higher and higher. For this reason, automatic optical 3D detection technology, which uses high speed and high precision visual processing technology to automatically check various mounting errors and welding defects on PCB, which making the production process of PCB more intelligent, greatly improves production efficiency and reduces labor cost, is becoming the trend of detection technology in SMT process[5-7]. Nowadays here are many technologies to solve the three-dimensional information, the grating projection measurement method is the main one. Based on the phase information of the projected light field modulated by different heights of the target surface, the three-dimensional information of the target is obtained through some specific techniques, e.g. Moire topography, Fourier transform profilometry (FTP), phase measurement profilometry (PMP), etc[8-9]. Compared with the traditional phase-shifting method based on physical grating projection, the projection optical system based on digital spatial light modulator (SLM) can project different images. Because of its unique flexibility, high brightness, high resolution and high image quality, it plays a very important role in fast digital phase-shifting fringe 3D measurement.

At present, the core optical module of 3D defect detection equipment is mainly composed of projection module and imaging module. While most researchers at home and abroad focus on the improvement and innovation of fringe analysis methods. As for the fringe projection part, the standardized.
Digital Micromirror Device (DMD) projection products provided by TI and other companies are mostly used directly, which is greatly limited for different application requirements. In order to realize different mounting errors and welding defects in the process of PCB detection, a fringe projection optical system based on the optical principle of DMD projection technology is designed for PCB 3D reconstruction in this paper.

2. Application requirement and optical index of projection system

A single lateral projection module and a fast changing three-step phase-shifting method are used to measure the three-dimensional contour of PCB. The system consists of projection module, imaging module and computer. The projection and imaging modules are controlled by computer. When working, the optical axis of the projection module and the optical axis of the imaging module maintain a certain angle, as shown in Figure 1.

![Figure 1](image)

The mathematical model of traditional three-dimensional measurement system. P, C is the light of the projector and the camera enter respectively, the lines of P and C are parallel to the reference plane, D is the distance between P and C, the distance between PC and the reference plane is expressed by L, OP and OC are the projection of P and C on the reference plane respectively, D is any point on the object surface, the lines of P, C and D intersect the points of P' and C' on the reference plane respectively, and d’ is the projection of D on the reference plane.

The phase height mapping formula of the object to be measured can be obtained by derivation.

\[ DD' = \frac{1}{2\pi fd + \Delta \phi} \]  \hspace{1cm} (1)

Where L, d and f are the system parameters of the measurement system, which can be obtained by calibration. The absolute phase difference is obtained from the reference and modulation fringes of the corresponding points, and the height information of the object surface can be obtained through the phase change[10].

In order to avoid the situation that some surfaces cannot be projected to stripes due to occlusion and improve the detection accuracy, two or four projection modules are generally used to project stripes from multiple directions. In order to ensure the reliability of phase-shifting fringe method in PCB 3D defect detection, the projection optical system should meet the following requirements:

1) The depth of field of the projection system is more than 6 mm in the direction of the projection optical axis;
2) The area of single detection on PCB is 50 mm×30 mm. Every eight pixels is required to be a fringe period, and there are four complete fringe periods per unit millimeter;
3) The angle between the optical axis of the projection module and the optical axis of the imaging camera is 30°;
4) The contrast ratio of projection fringe is more than 50%;
5) The periodic uniformity of the fringes in the projected region is more than 80%.
In this paper, the DLP4710 DMD chip produced by TI company is selected to design a single-chip digital fringe projection optical system according to the requirements of fringe sampling, coverage and other aspects. DMD chip is a bistable spatial light modulator, including movable micro mirror array, twisted arm, addressing electrode and storage layer. Each pixel of the addressing electrode is composed of a mirror, and the tilt angle of the mirror is controlled by the voltage signal. The micro mirror has only two working states: on (+12° or +17° state) or off (-12° or -17° state)[11].

![Figure 2: Schematic diagram of micro mirror][11]

As shown in Figure 2, the reflection characteristics of each working state to the beam are shown in the figure. When the micromirror is in the on state, the beam is reflected and projected onto the screen, and the pixels are displayed in the bright state. When the micro mirror is in the off state, the reflected beam cannot enter the projection objective, and the pixels are displayed in the dark state. The light intensity ratio of the dark state is stronger, so the extinction treatment is needed. Flat state refers to the light energy similar to plane reflection generated by the micro mirror in the switching process, and the reflection of light energy by the interval between the pixel units. The light intensity of this part is relatively weak, but it exists in both the bright state and the dark state, which also needs reasonable consideration in the design.

In order to meet the above requirements, the key design indexes are as follows:
1) The illumination area is 10.368×5.832 mm;  
2) The illumination uniformity is more than 85%;  
3) The DMD direction NA of lighting system is 0.1;  
4) The NA of projection lens is 0.1;  
5) The magnification of projection lens is 5.67×;  
6) The projection size is 57×32 mm;  
7) The projection accuracy is 30 μm;  
8) The inclination angle is 30°;  
9) The depth of field is more than 6 mm.

3. Design of lighting path
Considering the advantages of LED, e.g. small size, long service life, green environmental protection, high speed, low power consumption, low cost etc, is selected as the light source in designed optical system. Compound eye lens is a uniform light device, and the telecentric structure is used to design the projection lens. The main optical elements include collimating lens, lens array, condenser and TIR prism. The parameters of each element are not independent, they are closely related to the illumination effect of DMD chip.

In the design process of projection light system, another index to be considered is the energy utilization ratio of the system, i.e. the ratio of the light energy from the light source to the projection chip and that to the target screen. In addition to the inevitable absorption and scattering and reflection loss of the material of the optical element itself, the factors affecting the energy utilization mainly depend on the matching of the optical expansion of the system. Optical spread is a very important concept in non-imaging optical design, which is used to describe the geometric characteristics of beams with a certain aperture and cross-sectional area. The optical expansion is defined as:

\[
E = n^2 \int \cos \theta dA d\Omega
\]
Where $E$ is the optical expansion, where $\theta$ is the angle between the target area $\partial A$ and the central axis of the solid angle $\partial \Omega$. For a flat object with uniform spatial angle distribution, the optical expansion $E$ can be expressed as\cite{11}:

$$E = \pi A \sin^2 \theta = \frac{\pi A}{4 F^2}$$

(3)

$\theta$ is the divergence angle of the beam, and $F$ is the numerical aperture of the beam.

According to the relationship of optical expansion, in DMD direction $F = 5$, area $A = 10.368 \times 5.832 \text{mm}$, we can calculate the side length of LED light emitting surface is 0.928 mm. Select the device LEB-P1W produced by OSAM company with large unit luminous intensity as the light source, design the matching collimating mirror, compound eye lens and relay mirror, and simulate them in the optical software. The light path and DMD surface illumination are shown in the figure below.

Figure 3: Illumination simulation diagram

Figure 4: Illumination effect

4. Projection optical system diagram

The projection system projects the fringe image on the DMD to the surface of the object to be measured according to the requirements. It usually adopts unilateral telecentric design, that is, telecentric in the DMD direction. At the same time, there is an included angle of 30° between the projection optical axis and the imaging optical axis in the measurement. In order to ensure the imaging quality, it is necessary to adjust the DMD to make it form an angle of 5.8° with the vertical optical axis. In this paper, it is realized by the back group of the deflection lens.
In the design of projection system, DLP4710 chip is used as object plane and projection plane as image plane, which is the reference plane in Figure 1. The objective numerical aperture of the projection lens is 0.1, the magnification is 5.67, the projection size is $57 \times 32$ mm, the tilt angle is $30^\circ$ and the projection accuracy is $30 \, \mu\text{M}$. The MTF value of the system is greater than 0.8 when 8 pixels are taken as a sinusoidal fringe period and 4 pairs of lines per millimeter.

![Figure 5: Projection light path diagram](image)

![Figure 6: MTF curve](image)

![Figure 7: Defocus MTF](image)

The design results show that the angle between the reference plane and the projection optical axis is $30^\circ$, as shown in Figure 5. It can be seen from figure 6 that the MTF value can reach larger than 0.8 when four pairs of lines are per millimeter. At the same time, it can be seen from Figure 7 that the MTF value can still reach larger than 0.5 after moving 3 mm behind the working face, meeting the requirement of projection depth of more than 6 mm.
5. Overall system simulation diagram
The above designed lighting and projection light path are combined into a complete projection system and put into the optical simulation software for ray tracing, as shown in Figure 8. After simulation, the intensity distribution on the projection surface is shown in Figure 9. The whole projected area is 57mm × 32mm, the illumination uniformity is more than 85%, and the projection accuracy is 30 μm.

![Projection system simulation](image)

**Figure 8: Projection system simulation**

![Illumination map on reference plane](image)

**Figure 9: Illumination map on reference plane**

A group of sinusoidal digital fringes are input into DMD chip, and the original picture is shown in Figure 10. Since the sampling point of a fringe period is 8 in phase-shifting method, a sinusoidal period is characterized by 8 micro mirrors. In order to verify that the system has enough detection range and depth of field after projection, the structured light pattern at the focusing and defocusing position of 3mm is simulated in the optical analysis software. The simulation results are shown in Figure 11. Among them, Fig. 11(a) represents the simulation effect picture with an offset of 3mm away from the lens relative to the focusing position; Fig. 11(b) represents the simulation effect picture with an offset of 3mm away from the lens relative to the focusing position; Fig. 11(c) represents the simulation effect picture with an offset of 3mm towards the lens relative to the focusing position. Compared with Fig. 11(b), the contrast of Fig. 11(a) and Fig. 11(c) is reduced due to defocusing, but the MTF value is still above 0.5, which provides a good support for the later phase and height calculation.
6. Conclusion

Based on the practical application of fringe three-step phase-shifting method to detect 3D defects of PCB board, a 3D defect detection projection optical system based on DLP4710 chip is designed by using the advantages of digital fringe projection technology, such as fast, high accuracy and high contrast. The projection adopts telecentric optical structure to achieve large depth of field projection, so as to meet the detection needs of PCB board with height less than 5mm. The simulation results show that the illumination of the projection system on the projected surface makes full use of the illumination energy received by DMD chip, and has high uniformity; The contrast of the sinusoidal fringes generated by DMD projected by the projection system is greater than 0.5 in the whole test space, the fringe period is uniform, and it is suitable for 3D defect detection in the area of 57mm\times 32mm, which improves the detection speed of PCB, meets the design requirements, and has good realizability in engineering application.

7. References

[1]. CHEN Xiao-rong, CAI Ping, SHI Wen-kang. The latest development of optical non-contact 3D profile measurement. J. Optics and Precision Engineering, 2000, 39(1): 143-149.

[2]. SU Xian-yu, ZHANG Qi-can. Dynamic 3-D shape measurement method. J. Optical and Laser in Engineering, 2010, 48(2) : 191-204.

[3]. Wei Xiao Bao. 2019. Research on Key Technologies of 3D Mesurement Based on Digital Fringe Projection. Ms D Thesis. Hangzhou: Zhejiang University.

[4]. Xiao Liang. 2019. Research on Three-dimensional Measurement Technology of Binocular Vision Based on Coded Structured Light Projection. Ms D Thesis. Hefei: Hefei University of Technology.

[5]. He Rongfang. 2014. Three-dimensional Online Inspection Technology for defects of SMT Packaging Circuit Board. Ms D Thesis. Tianjin: Tianjin University.

[6]. Liu Bin. 2010. Study on Key Techniques of Automatic Optical Inspection System for 3D Micro Size Measurement. Ms D Thesis. Tianjin: Tianjin University.

[7]. Jiahua Wang. 2019. Research on Key Techniques of Fringe Projection 3D Measurement. Ph D Thesis. Xi'an: Xi'an Polytechnic University.

[8]. Lin Wang. 2019. Research on 3D Measurement Technology of Phase-coding Structured Light. Ms D Thesis. Nanchang: Nanchang Hangkong University.

[9]. CHEN Fang-han, ZHAO Guang-yu, JIANG Shi-long, PENG Wen-da. 2015. Optical System Design of DMD Digital Fringe Projection Based on the Application of 3-D Defect Inspections. J. ACTA PHOTONIC ASINICA. 44, 2 (February 2015), doi: 10.3788/gzxb20154402.0222002.

[10]. Xu Han. 2019. Research on 3D Fringe Projection Measurement Method Based On Time Phase Unwrapping. Ms D Thesis. Nanchang: Nanchang Hangkong University.

[11]. Bixiang Qu. 2013. Optical Design of the DLP Projection System Based on GRE LED Lighting. Ms D Thesis. Hangzhou: Zhejiang University.