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Accurate 3-D Measurement System Using the Pico Projector-Based Phase Shifting Techniques

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Abstract

The 3-D measurement system based on optical method is becoming widely applied. Among those methods, fringe projection techniques provide high resolution, whole-filed 3-D reconstruction of objects in non-contact manner. A custom-made LCD(Liquid Crystal Display) projector for inspection system using fringe projection and phase shifting is expensive and complex. In this paper, the 3-D measurement system using the pico projector is proposed for inexpensive and simple while maintaining high accuracy. Experiments have shown that proposed system is high accuracy. The proposed system applies to measurement of height of LED(Light Emitting Diode) Package.

1. Introduction

Recently, 3-D measurement system based on optical method is becoming widely used in areas, such as inspection, reverse engineering, medical and virtual reality[1]-[3]. A laser triangulation, a con-focal microscopy, a stereo vision, fringe projection techniques are those methods[4][5]. Among those, fringe projection techniques have been used for whole-filed 3-D object surface measurement in non-contact manner. Their method is well known for being able to measure 3-D object surface quickly and accurately[6].

A typical projector has been performed by analogue process, which involves the use of two gratings and a light source. The use of digital projector like LCD(Liquid Crystal Display) projector has been popular. But, custom-made LCD projector for inspection is expensive and complex, which make the 3-D measurement system using phase shifting techniques are hard to apply in real world[7][8].

In this paper, we propose a 3D measurement system using a pico projector-based phase shifting techniques. The pico projector, which is pocket projector, has been commonly used and its capacity is still under development. However, it is possible to replace custom-made LCD projector with the pico projector for inspection system with high accuracy. The proposed system is inexpensive and simple while maintaining high accuracy of the system using LCD projector.

The rest of this paper is organized as follows. In Section 2, we introduce LCD projector based phase sifting techniques. In Section 3, the proposed pico projector based phase sifting method is presented. In Section 4, the performance analysis of proposed system is evaluated in terms of measurement accuracy and repeatability. Then, the experimental results in measuring the heights of LED(Light Emitting Diode) package are shown. The conclusions are drawn in Section 5.

2. LCD based 3-D measurement system

2.1 LCD-Based system configuration

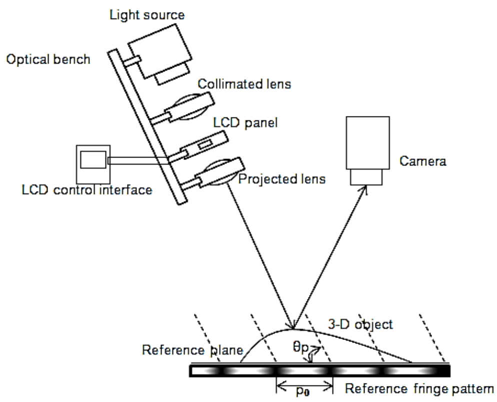


Figure 1. LCD-Based system.

A LCD based 3-D measurement system is shown in Figure 1. This system consists of a LCD projector, a camera, and the object to be measured also known as DUT(Device under test). The LCD projector projects sinusoidal fringe patterns onto the object, and then a camera captures the deformed sinusoidal fringe patterns by the surface of the object.

The LCD projector consists of LCD panel, LCD control interface, light source, collimated lens and projected lens. We can clearly see in Figure 1, the LCD projector is configured with many components, which makes the LCD based system complex and expensive to setup.

2.2 Principle of phase shifting technique[9]

Phase shift techniques for fringe analysis are widely used for a 3-D measurement system for inspection. These fringe analysis techniques provide high-resolution and accuracy over other fringe analysis methods.

If a sinusoidal fringe pattern is projected onto a reference plane, its intensity image I(x, y) can be expressed as

$$I_r(x, y) = a(x, y) + b(x, y) \cos \varphi(x, y), \quad (1)$$

where a(x, y) is the background intensity, b(x, y) is the fringe modulation, and φ_r(x,y) is the phase distribution at x, y coordinates. The phase φ_r(x, y) can be retrieved from Eq.1 using the phase-shifting algorithms.

N measurements $I_1, I_2, \dots, I_N$ of I_{ref} are made with a phase increment of 2π/N for each measurement in order. From these measurements, phase distribution of a reference obtained by

$$\varphi_r(x, y) = \tan^{-1}\left(\frac{\sum_{n=1}^{N} I_n(x,y)\sin(\frac{2\pi n}{N})}{\sum_{n=1}^{N} I_n(x,y)\cos(\frac{2\pi n}{N})}\right). \quad (2)$$

We obtain the phase φ_o(x, y) of an object by using above method. The phase difference Δφ(x, y) can be determined as

$$\Delta\varphi(x, y) = \varphi_o(x, y) - \varphi_r(x, y). \quad (3)$$

The surface heights of the object is mapped to a phase function, and can be resolved by

$$h(x, y) = \frac{p_0}{2\pi} tan\theta_p \Delta\varphi(x, y), \quad (4)$$

where h(x, y) is the height of the object at x, y coordinates, p_0 is the period of sinusoidal grating in the reference plane and θ_p is the angle between the axis of projector and the reference plane.

3. Proposed 3-D measurement System

3.1 Pico-projector based system configuration

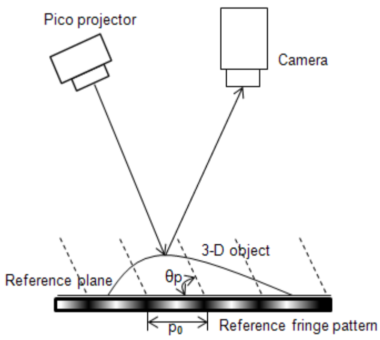


Figure 2. Proposed pico projector-based system

The proposed pico projector-based system is shown in Figure 2. We can see the proposed system is simple and inexpensive to setup a whole system for 3-D measurement. The proposed system consists of only a pico projector to project the fringe pattern and a camera to capture the deformed fringe patterns reflected from object.

The implementation of the proposed system is shown in Figure 3. The hardware specification to implement the proposed system is presented in Table 1. The angle between the axis of projector and the reference plane is 70 degrees. The resolution of the pico projector is 1280 x 800 for the input and 640 x 480 for the output. FOV(Field of View) of the camera is 23mm x 17mm. A projected area of pico projector is 75mm x 50~60mm. The projected area of the pico projector is larger than the FOV of the camera. It is because of the limit of the projection distance. It the minimum projection distance is shorter than 18cm, the focus of the projection becomes poor.

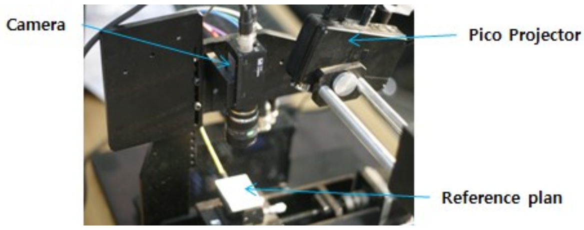


Figure 3. Implemented system

Table 1. Implemented system specifications.

Component	Model	Specifications	
Camera	teli cs8420	Resolution	768x582
Frame Grabber	Meteor2 -MC/4	Mode	RS-170A
		Resolution	640x480
Lens	Computar	Focal length	25mm
		Aperture	F1.4
		Extension Ring	7mm
Pico Projector	Optoma PK301	Output Resolution	640x480/ 854x480
		Input Resolution	640x480~ 1280x800
		Projection Distance	0.2mm~ 5mm

3.2 Procedure to measure the height of the object

The measurement procedure of the proposed system is the following.

1. *Generation of the fringe pattern*: The sinusoidal fringe pattern is generated using

$$I_{created}(x, y) = A + B\cos(\frac{2\pi}{P}x + \frac{\pi}{2}n), n = 0,1, \dots 5 \quad (5)$$

.

Variable A is the background intensity. B is the fringe modulation. P is the period of the fringe pattern.

2. *Projection of the sinusoid pattern*: First, The generated image is projected onto the reference plane by the pico projector. Second, the object to be measured is placed on the reference plane and then the generated image is projected again on to the object.
3. *Phase shift*: The computer-generated sinusoidal fringe pattern that displays on the pico projector digitally shifted in five phase steps, 0, π/2, π, 3π/2, 2π and then images are sequentially captured by the camera. Captured images corresponds $I_1, I_2,..I_5$.
4. *Calculation of the phase*: The phase of reference plane is extracted each using

$$\varphi_r(x, y) = \tan^{-1}\left(2\frac{I_1(x,y) - I_3(x,y)}{2I_2(x,y) - I_4(x,y) - I_0(x,y)}\right) \quad (6)$$

The Eq.6 is a simple error-compensating phase calculation algorithm[10]. The object to be measured is placed on the reference plane and then Step.2, 3 and 4 are repeated to obtain the phase value $\varphi_o(x, y)$ of the object.

5. *Measurement of the height of the object*: Phase difference value $\Delta\varphi(x,y)$ is calculated using Eq.3. The height of object is measured

$$h(x,y) = \frac{\Delta\varphi(x,y)}{m(x,y)+n(x,y)\Delta\varphi(x,y)}, \quad (7)$$

where m(x, y), n(x, y) is the system parameter by least-squares fitting method[11].

4. Experimental results and discussions

4.1 Performance evaluation of the proposed system

To evaluate the performance of the proposed system, we used gauge block made by Mitutoyo. The grade of this gauge block is 0(±0.12μm) which is the most accurate. The period of the fringe pattern generated by computer is 12 pixels, which corresponds to a projected fringe period of 0.8mm on the reference plane, and the range of the measurement is 2.2mm. We placed reference plane on the gauge block. By the height measured from reference plane using different size of gauge block, we can evaluate the accuracy of the proposed system. Parameters of the system m(x, y), n(x, y) in Eq.7 we calibrate the system by measuring the height of the reference plane placed on the gauge blocks which are exactly 1, 1.5, 2mm. We measured the height of the reference plane placed on the 1.25 mm gauge block. We experiments 30 times, 9 points each times shown in Figure 4. The result of measurement using 1.25 mm gauge block is presented in Table 2. The accuracy of the measurement is calculated using

$$\text{Accuracy} = \frac{1}{30}\sum_{i=1}^{30}(h_i - h_{true}), \quad (8)$$

where h_i is the measured height and h_{true} is the real height, which is 1.25mm. The standard deviation was 0.0041 mm. The worst case of the accuracy was 0.0141 mm. The accuracy of the result from proposed system was almost closer to the LCD based measurement system introduced in Section 2[8].

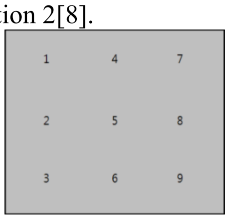
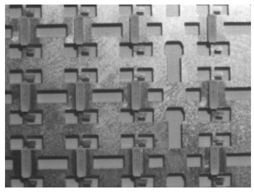


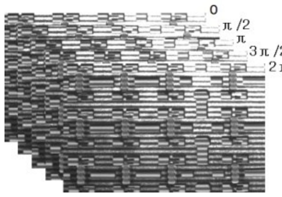
Figure 4. Measured points.

4.2 The application of the measurement for LED package

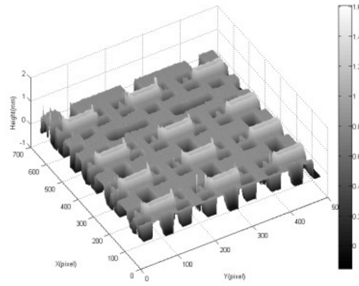
We applied the proposed system to measure the heights of surface of the LED package shown in Figure 5(a). When the fringe pattern is projected onto the LED package in Figure 5, the image captured by camera is shown in Figure 5(b). The period of the fringe pattern generated by computer was 12 pixels. We calibrate the system by measuring the height of the reference plane placed on the gauge blocks which are exactly 1, 1.25, 1.5, 2mm.



(a)



(b)



(c)

Figure 5. LED Package.

The heights of the surface of the measured LED package are shown in Figure 6.

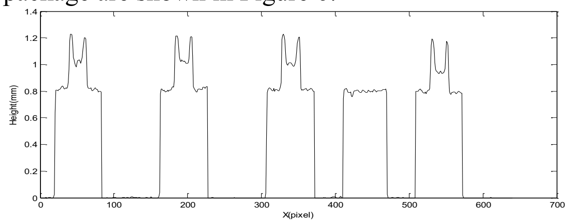
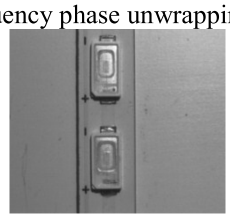


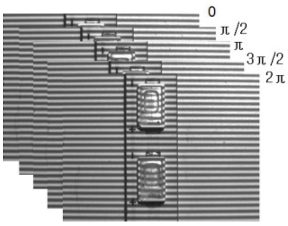
Figure 6. Profile sample of LED package.

We sampled one profile, which is drawn across the surface of the LED package, where the value of y coordinate is 280 in pixel, to see the result more clearly in Figure 6. The heights of the measured inside LED package are very close to real value, 1.0mm. The heights of the measured boundary of the LED package were also close in real value 1.2mm.

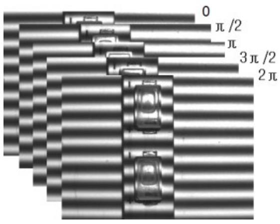
We also experiments with LED BLU package shown in Figure 7(a). In this case, the heights of LED BLU are over the range of the measurement. To expand the range of the measurement while sustaining the high accuracy, we used two-frequency phase unwrapping method [12].



(a)



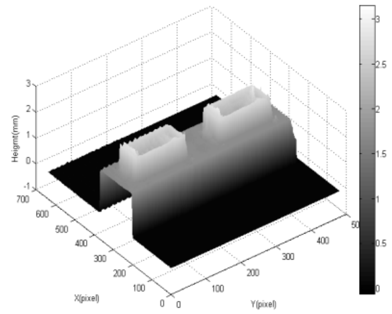
(b)



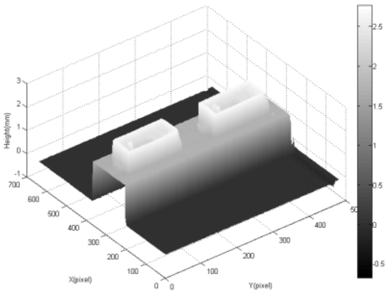
(c)

Figure 7. LED BLU Package.

When the fringe pattern, whose the periods are 12 and 30 pixels, generated by computer is projected onto the LED BLU package each in Figure 7(a), the image captured by camera is shown in Figure 7(b) and (c). When the fringe pattern of the period, 30 pixels is projected, the period of the projected fringe pattern is 2.0 mm and the range of the measurement is 5.5 mm. We calibrate the system by measuring the height of the reference plane placed on the gauge blockss 1, 1.5, 2, 2.5, 3 mm.



(a)



(b)

Figure 8. The measurement of LED BLU package

The surface of the measured LED BLU package using the fringe pattern of the period, 30pixels is shown in Figure 8(a). The surface of the measured LED BLU package using two-frequency phase unwrapping method is shown in Figure 8(b). We can clearly see the accuracy is kept when two-frequency phase unwrapping method is used to measure the surface. We sampled one profile, crossing the surface of the LED BLU package, where the value of y coordinate is 200 in pixels, to see the result more clearly in Figure 9.

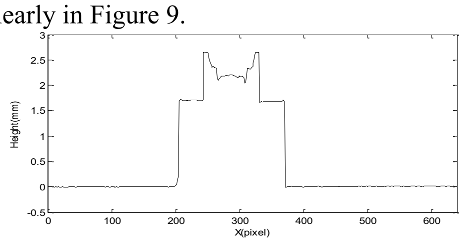


Figure 9. Sampled profile of height of LED BLU package

5. Conclusion

In this paper, a 3-D measurement system using a pico projector is presented. We showed that the proposed system has accuracy close to the other 3-D measurement system using the LCD projector by experiments. The proposed system was successfully demonstrated measuring the heights of LED package and LED BLU package.

A 3-D measurement system using pico projector is inexpensive and simple. From the experiments, we present showed that the pico-projector based system still sustain the high accuracy close to the LCD based system. We expect the proposed system can be applied in real system for much reduced cost.

Reference

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Table 2. Measurement repatablity and accuracy for the 1.25mm gauge block from pico projector-based system

Point Number	1	2	3	4	5	6	7	8	9	Mean
Mean(mm)	1.2587	1.2566	1.2469	1.2486	1.2641	1.2578	1.2435	1.2569	1.2561	1.5041
Standard deviation (mm)	0.0040	0.0034	0.0052	0.0045	0.0032	0.0045	0.0049	0.0037	0.0032	0.0041
curacy(mm)	0.0087	0.0066	-0.0031	-0.0014	0.0141	0.0078	-0.0065	0.0069	0.0061	0.0043