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The research of 3D small-field imaging system based on fringe projection technique

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ABSTRACT

This paper presents a 3D small-field imaging system by using the color fringe projection technique to measure the small objects having large slopes and/or discontinuous surface. A stereo microscope is used to generate a small-field projecting field and to capture the deformed fringe patterns on the measured small objects, respectively. Three fringe sets having the optimum fringe numbers are coded into one major color channel to generate color fringe patterns having the maximum fringe contrast of the captured fringe images. Through one channel of the stereo microscope, a DLP (Digital Light Processing) projector projects these generated color fringe pattern images onto the measured objects surface. From another channel, the fringe patterns are deformed with regard to the object surface and captured by a color CCD camera. The absolute phase of each pixel can be calculated from the captured fringe patterns by using the optimum three-fringe numbers selection method. Experimental results on measuring 3D shape of small objects show the accuracy and availability of the developed 3D imaging system.

Keywords: fringe projection, 3D small-field measurement, phase calculation, stereo microscope.

1. INTRODUCTION

With the development and maturity of modern industrialization, the demand for quantitative description of the objects is increasing and 3D (Three-dimensional) shape measurement of objects is always the hot issue. Optical 3D shape measurement techniques have been widely used in the fields of industrial design, biomedical, computer-aided design, online monitoring, clothing manufacturing and machine vision because of the advantages of non-contact operation, high accuracy, short measurement time, and high speed [1].

At present, the optical 3D measurement techniques are developed towards two extreme directions to measure large objects and small objects [2]. With the development of MEMS (Micro Electro Mechanical Systems) , it is becoming increasingly important to obtain the accurate 3D shape information of small components. MEMS integrates many elements like tiny sensors, digital signal processor, control circuit, communication units and power supply and so on [3]. MEMS has been widely used in aerospace, information communication, biology, chemistry, medicine, automatic control, consumer electronics, military and other fields because of its advantages of miniaturization, multi-function and high integration [4]. It is necessary to test the 3D shape of MEMS' components during the procedure of designing and manufacturing to satisfy quality assurance of products in the fields of advanced manufacturing. But the size of MEMS' components is in the range of micron and even submicron, so the traditional measuring methods cannot meet the need [5]. Besides, the application is very outstanding for small objects with large gradient and discontinuous shape. A long working distance microscope objectives is used to project the fringe patterns from the computer to the surface of the objects to be tested, and then the 3D shape data of the objects can be got based on the phase calculations [6,7].

Although a variety of small-field measurement techniques based on fringe projection have been proposed, they have some disadvantages of low accurate 3D shape because of low fringe contrast, incapability of measuring large gradient objects, and to name a few. The procedure of fringe projection techniques are the following: a group of fringe patterns are projected onto the measured object surface. From another point of view, the fringe patterns are deformed and are captured by an imaging device. The captured fringe patterns are demodulated to obtain the wrapped and then unwrapped phase maps, which correspond to the 3D shape of the measured objects. After 3D calibration of the imaging system to build up the relationship between the absolute phase and 3D depth, shape information is obtained [8].

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Many small-field fringe projection methods have been proposed to measure small-sized objects. A stereovision micromanipulation system was designed with the fringe patterns [9]. The spacing of the fringe patterns can be adjusted via software programming and provide a great convenience for the measurement of small objects. Because of the advantage of low cost and high precision, the system has a very broad application prospects. A method of phase measurement method by using a projector and long working distance objectives was proposed by C. Quan by using a projector and long working distance objectives [10] . In the fringes output port of the system, the shrunken fringes are projected by using a microscopes and ; in the sampling terminal of the system, the magnified fringe patterns are captured by the a camera. Acquiring 3D shape of small objects is well solved in the system. The possibility of microscopic interferometry technology has been proved by using stroboscopic lighting as a visual tool [11]. A new method called scanning fringe projection was proposed [12]. Zhao et al combined grating, microscopy and Fourier transform techniques to study the micro deformation measurements [13]. Vargas et al studied structured light projection method to measure the 3D structure of the microchip [14]. Moiré interferometry has been used as a tool for in-depth analysis of the interconnect chip package [15]. A miniaturized 3D shape measurement system was developed to measure teeth based on digital fringe projection method [16].

This paper proposes a new method by projecting color sinusoidal fringe patterns to measure the complex shape of small objects with large gradient or discontinuous surface. A small-field fringe projection system has been developed. The system combines a stereo microscope, a color CCD camera and a DLP (Digital Light Processing) projector. The projecting system projects the generated fringe patterns onto the measured objects' surface via one channel of the stereo microscope. From another channel, the fringe patterns deformed by the objects' surface are captured by the CCD camera. The absolute phase of each pixel can be calculated from the captured fringe patterns by using the optimum three-fringe numbers selection method [17].

2. PRINCIPLE

2.1 Basic principle of the stereo microscope

The basic principle of the 3D optical small-field imaging system based on a stereo microscope is illustrated in Fig. 1. The stereo microscope can generate 3D images by using two independent optical channels. Two beams modulated by the measured objects are separated by two groups of objectives in the middle, also known as zoom lens, which form a certain angle from 12 degrees to 15 degrees. Then two beams whose magnification decided by the distance between the lenses in the middle are imaged by eyepieces. Two beams of light in the stereo microscope are not parallel, but form a certain angle.

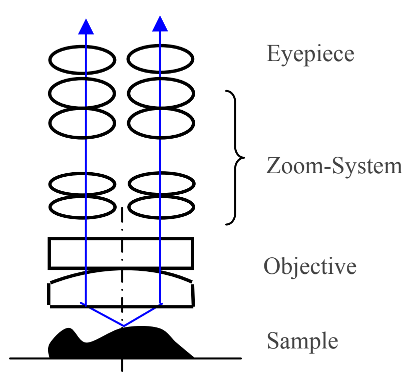


Figure 1. The basic principle of the stereo microscope

2.2 3D small-field imaging system

The basic layout of the 3D small-field measurement system is illustrated in Fig. 2. It mainly comprises a LightCrafter, a color CCD camera, a stereo microscope and a computer. Sinusoidal fringe patterns produced by the computer are projected onto the measured object surface through the LightCrafter and a set of optical lens (including the eyepiece, lens group and the objectives shared with the reflected light beam) in one channel of the stereo microscope. The sinusoidal fringes are deformed after being modulated by the measured objects and then reflected to another channel of the stereo microscope. The deformed sinusoidal fringe patterns are captured by the CCD camera and saved into the computer for post processing.

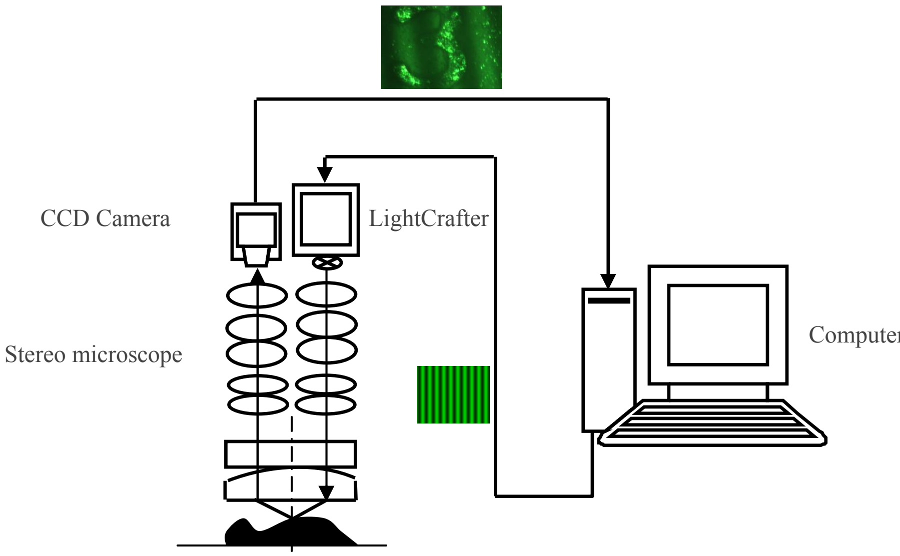


Figure 2. The basic layout of the 3D small-field measurement system

2.3 Phase calculation based on fringe projection

The principle of measuring 3D shape of the objects based on fringe projection is shown in Fig. 3. P and E are the center of the projector exit pupil and the camera entrance pupil respectively. L_0 is the distance from the camera entrance pupil to the reference plane. L is the length from the center of the projector exit pupil and the center of the camera entrance pupil. θ is the angle between the axis of the projection and the imaging system.

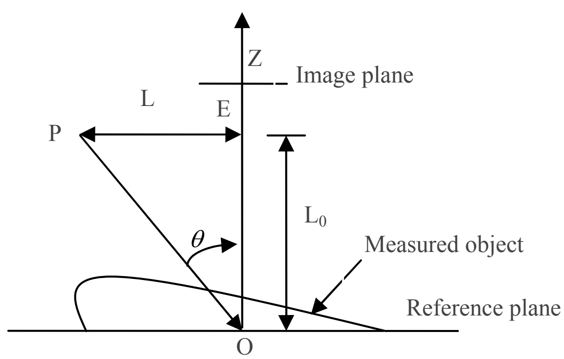


Figure 3. The principle of measuring 3D shape of the objects based on fringe projection

Because of its high precision and strong anti-interference ability, four-step phase-shifting method is widely used in 3D shape measurement of the objects. Comparing with three-step phase-shift method, it can eliminate higher harmonic and has shorter acquisition time by comparing with five steps or more. Four fringe patterns with phase shift of π/2 can be represented:

$$I_1(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y)]$$
$$I_2(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y) + \pi/2]$$
$$I_3(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y) + \pi]$$
$$I_4(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y) + 3\pi/2] \quad (1)$$

where, $I'(x,y)$ is the average intensity, $I''(x,y)$ is the contrast of fringes, $\phi(x,y)$ is the phase to be determined which corresponds to the height value of the measured objects. $I'(x,y)$, $I''(x,y)$ and $\phi(x,y)$ are three unknown variables. The phase field $\phi(x,y)$ can be accurately calculated by the following equation:

$$\varphi(x,y) = \arctan\frac{I_4(x,y) - I_2(x,y)}{I_1(x,y) - I_3(x,y)} \quad (2)$$

The phase value $\phi(x,y)$ calculated by using phase-shifted method has a unique value in a phase cycle. However, because there are multiple sinusoidal fringe patterns in the measuring field, $\phi(x,y)$ shows distributions for serrated periodicity. In order to measure the small objects having large slopes and/or discontinuous surface, the absolute phase of each pixel can be calculated from the fringe patterns captured by CCD camera via using the optimum three-fringe numbers selection method [17].

3. EXPERIMENTS AND RESULTS

3.1 Hardware system

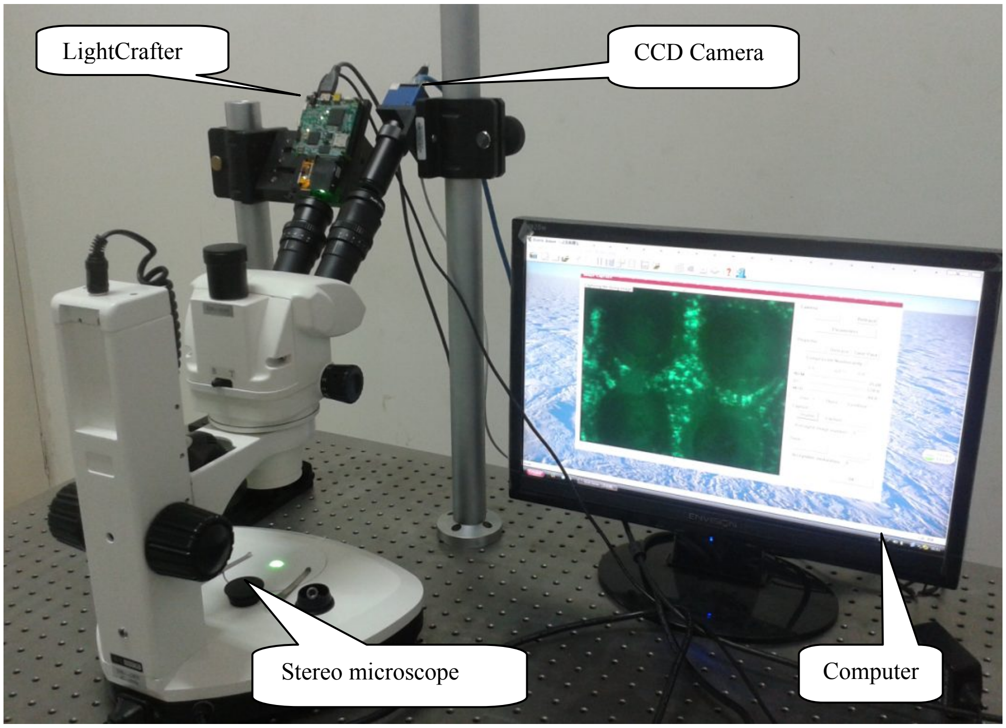


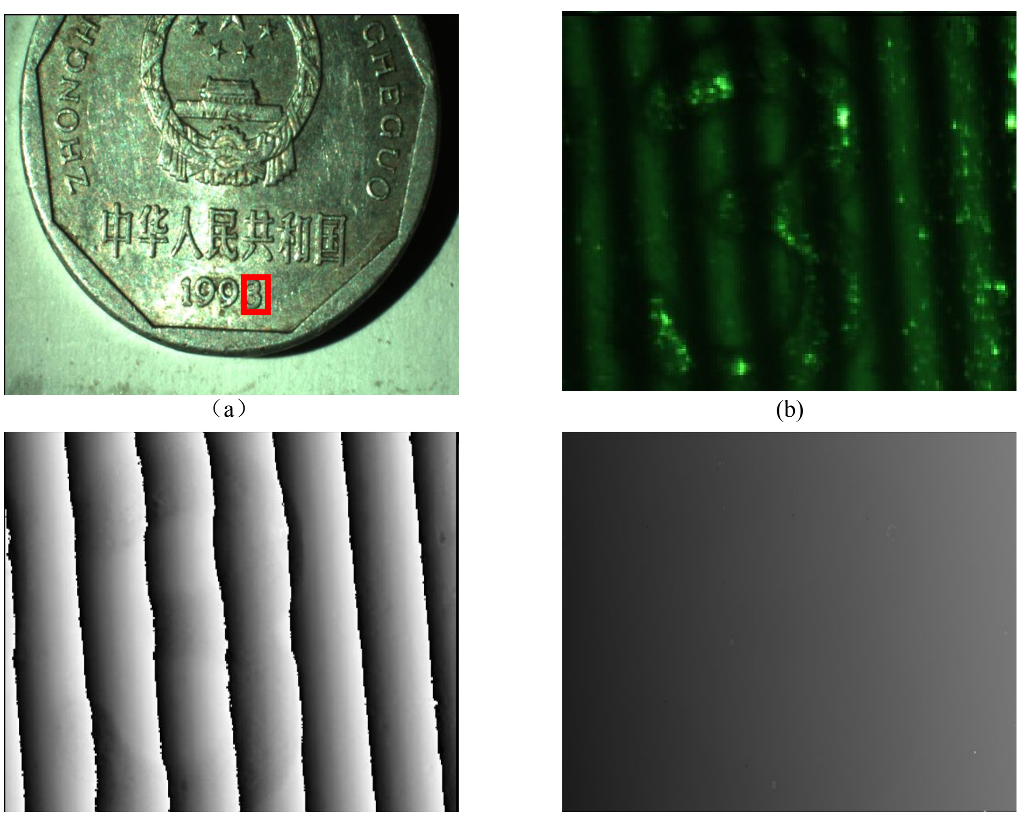
Figure 4. The hardware of the developed 3D system

According to the size of measured objects, a 3D small-field imaging system is developed whose measuring field is 5mm x 5mm. The system consists of the following parts: a projecting system, an imaging system, a stereo microscope and a computer. The hardware of the developed 3D system is shown in Fig. 4. The projecting system is a DLP LightCrafter from Texas Instrument. The DLP LightCrafter is designed on the basis of 0.3WVGA DLP chip with the physical resolution of up to 608 x 684 pixels. Because of its advantage of supporting the high-speed and reliable spatial light modulator, the DLP chip is mainly used for the projector. The stereo microscope is from Shanghai optical instrument company with the model of SX-5. Coincidentally, the fringe patterns projected by the projector are enlarged, so a stereo microscope is needed to reduce the field size. The stereo microscope also has many advantage, such as large scene depth, imaging upright and clearly, relatively high precision, long working distance and with a 3D stereo feeling and so on. The camera used in the article is the latest ultra-compact industrial camera from SVS Company with its model is ECO424 and the resolution is 640 x 480 pixels. The camera is selected because of its advantage of high transmission rate, signal-noise ratio and ingenious mechanical shape. The processing module of the camera supports external trigger mode and internal trigger mode. The real result has shown that the camera has high stability, its driver software is easy to install and it is easy to realize the secondary development.

Because the projecting field of the LightCrafter is large, it cannot meet the need of small-field measuring and the stereo microscope is used to generate a small projection field of 5mm x 5mm. The projector has a certain angle between optical projecting axis and horizontal direction, so a goniometer is placed below the projector to adjust the angle of the projector and let the projector optical axis parallel to the horizontal direction. In the imaging system, the color CCD camera captures the deformed fringe patterns images from another channel of the stereo microscope. The computer controls the projector and the CCD camera to save, display and process the captured fringe pattern images.

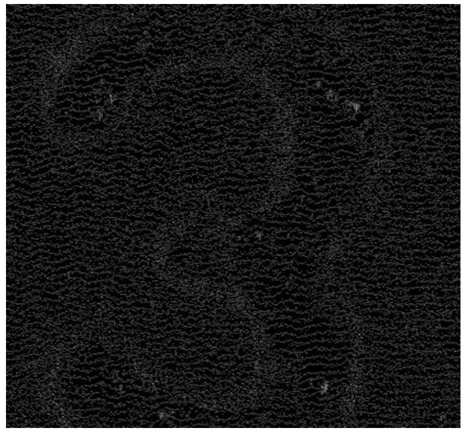
Three groups of sinusoidal fringe patterns having the optimum three fringe numbers are generated by software in a computer and projected onto the surface of measured objects according to the color and texture of the surface of the measured objects. Each group of four fringe patterns has phase shift for 90 degrees. From another point of view, the CCD camera captures the deformed fringe pattern images and saves them into the computer for the post processing.

3.2 Experiments and results



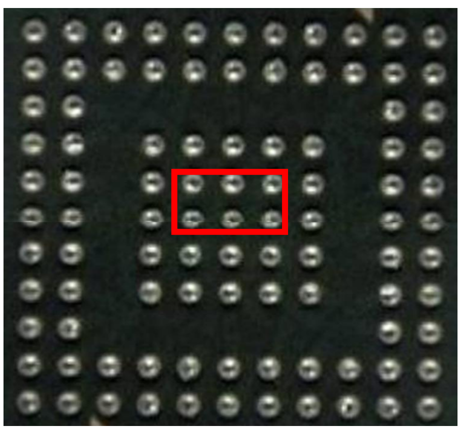
(a) (b)

(c) (d)

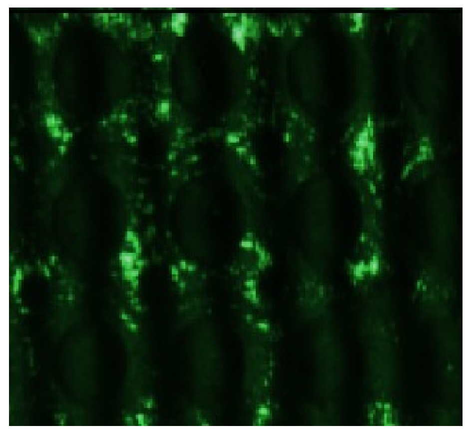


(d)

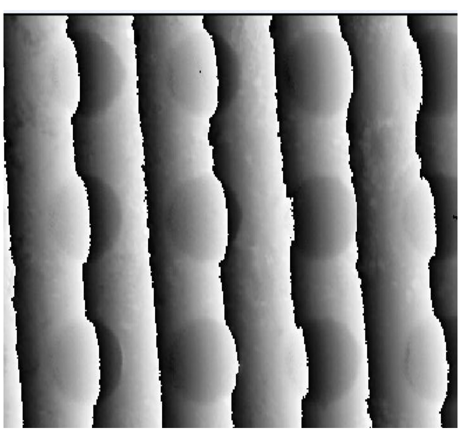
Figure 5. Experimental results of one number on the coin. (a) the photo of the coin and the measured region marked by a red rectangle, (b) the captured fringe pattern, (c) the wrapped phase map, (d) the unwrapped phase map, (e) 3D representation of the measured results.



(a)

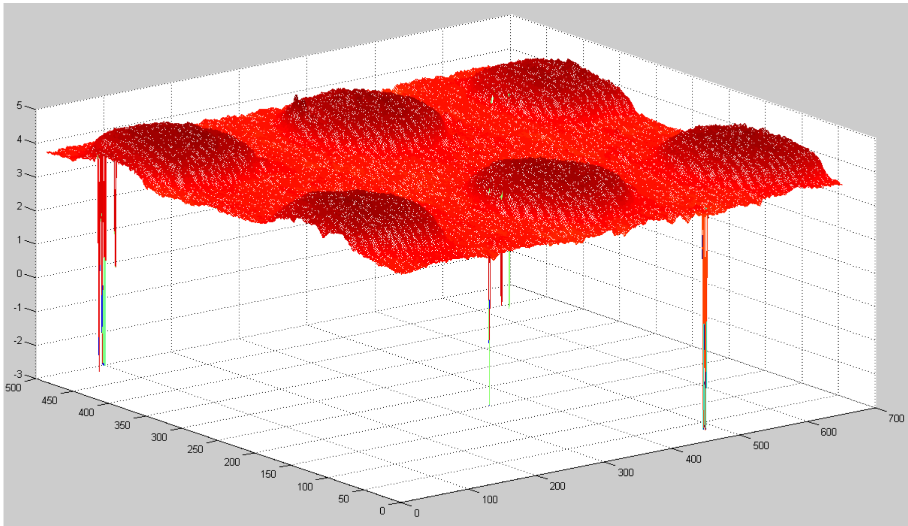


(b)



(c)

(d)



(e)

Figure 6. Experimental results of the BGA. (a) the photo of the BGA and the measured region marked by a red rectangle, (b) the captured fringe pattern, (c) the wrapped phase map, (d) the unwrapped phase map, (e) 3D representation of the measured results.

Two small parts of objects were measured by the developed 3D imaging system, as illustrated in Fig. 5 and Fig. 6. To choose the appropriate color channels, the generated fringe patterns are projected onto the measured objects surface. The color channel having the best fringe contrast has been chosen to project fringe patterns. The captured deformed fringe patterns on the measured objects are shown in Figs. 5 (b) and 6 (b). Figures 5 (c) and 6 (c) demonstrate the wrapped phase maps by using four-step phase-shifting method. After applying the optimum three-fringe numbers selection method to the obtained wrapped phase maps, the absolute unwrapping phase maps can be calculated, as shown in Figs. 5 (d) and 6 (d). Figure 5 (e) and 6 (e) give the shape of the measured objects from the obtained unwrapped phase maps. The experimental results show that the proposed 3D small-field imaging system accurately and reliably measures the 3D shape of small objects.

4. CONCLUSION

This paper presents a 3D small-field measuring system based on color fringe patterns projection techniques. A stereo microscope has been used to generate small-field projecting field and imaging field. According to the color and texture of the measured objects, appropriate color channel is chosen to project the generated fringe patterns, so the captured fringe patterns have the maximum fringe contrast. The small objects having large slopes and/or discontinuous surface can be measured by the optimum three-fringe numbers selection method. Some experimental results on measuring the 3D shape of one number on the coin and the BGA show the accuracy and availability of the developed 3D small-field imaging system.

In the following work, 3D calibration will be carried out to establish the relationship between 3D data and phase maps [18,19]. Another direction is to use composite color fringe projection techniques to reduce the acquisition time.

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REFERENCES

[1] Z. H. Zhang, "Review of single-shot 3D shape measurement by phase calculation-based fringe projection techniques," Opt. Laser Eng. 50, 1097-1106(2012).

[2] J. Bruning, "Digital wavefront measuring interferometer for testing optical surfaces and lenses," Appl. Optics. 13(11), 2693-2703(1974).

[3] W. Osten, "Optical Microsystems metrology," Opt. Laser Eng. 36, 75-76(2001).

[4] W. Robert, F. Matthias, K. Klaus and H. J. Tiziani, "Testing micro devices with fringe projection and white-light interferometry," Opt. Lasers Eng. 36, 141-154(2001).

[5] J. M. Huntley and H. O. Saldner, "Error-reduction methods for shape measurement by temporal phase unwrapping," Opt. Soc. Am. 14, 3188-3196(1997).

[6] S. Zhang, D. V. D. Weide and J. Oliver, "Superfast phase-shifting method for 3-D shape measurement," Opt. Express. 18(9), 9684-9689(2001).

[7] E. Dalhoff, E. Fisher, S. Kreu et al, "Double heterodyne interferometry for high precision distance measurements," SPIE. 2252, 379- 385(1995).

[8] M. Idesawa, "High-precision image position sensing methods suitable for 3-D measurement," Opt. Lasers Eng. 10(3-4), 191- 204(1989).

[9] H. E. Cline, "Lorensen W E and Holik A S, Automatic moiré contouring," Appl. Opt. 23(10), 1454-1459(1984).

[10] C. Quan, X. Y. He and C. F. Wang, "Shape measurement of small objects using LCD fringe projection with phase shifting," Opt. Commun. 189(1-3), 21-29(2001).

[11] Petitgrand et al, "3D measurement of micromechanical devices vibration mode shapes with a stroboscopic interferometry microscope," Opt. Lasers Eng. 36, 77-101(2001).

[12] C. R. Coggrave and J. M. Huntley, "Optimization of shape measurement system based on spatial light Modulators," Opt. Eng. 39(1), 42- 51(2000).

[13] B. Zhao and A. Asundi, "Microscopic grid methods-resolution and sensitivity," Opt. Lasers Eng. 36, 437-450(2001).

[14] Vargas, Koninckx and Quiroga, "Three-dimensional measurement of microchips using structured light technique," Optical Engineering. 47, 053602(2008).

[15] Miller, R. Mikel, Mohammed and Ilyas, "Quantitative strain analysis of flip-chip electronic packages using phase-shifting moiré interferometry," Opt. Laser Eng. 36, 127-139(2001).

[16] L. C. Chen and C. C. Huang, "Miniaturized 3D surface profilometer using digital fringe projection," Meas. Sci. Technol. 16, 1061-1068(2005).

[17] Z. H. Zhang, C. E. Towers and D. P. Towers, "Time efficient color fringe projection system for 3D shape and color using optimum 3-frequency selection," Opt. Express. 14, 6444-6455(2006).

[18] Z. H. Zhang, H. Y. Ma, T. Guo, S. X. Zhang, J. P. Chen, "Simple, flexible calibration of phase calculation-based three-dimensional imaging system," Opt. Lett. 36, 1257-1259(2011).

[19] Z. H. Zhang, S. J. Huang, S. S. Meng, F. Gao, X. Q. Jiang, "A simple, flexible and automatic 3D calibration method for a phase calculation-based fringe projection imaging system," Opt. Express. 21, 12218-12227(2013)