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Full-Field 3D Shape Measurement of Specular Surfaces by Direct Phase to Depth Relationship

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ABSTRACT

This paper presents a new Phase Measuring Deflectometry (PMD) method to measure specular object having discontinuous surfaces. A mathematical model is established to directly relate absolute phase and depth, instead of phase and gradient. Based on the model, a hardware measuring system has been set up, which consists of a beam splitter to change the optical path, and two LCD screens to display the same sinusoidal fringe patterns. By using model-based and machine vision method, system calibration is accomplished to provide the required parameters and conditions. The verification tests are given to evaluate the effectiveness of the developed system. The 3D shape of an artificial step having multiple specular surfaces and a concave mirror has been measured. Initial experimental results show that the proposed measurement method can obtain 3D shape of specular objects with discontinuous surface effectively.

Keywords: specular object 3D measurement, phase deflectometry, system calibration, discontinuous surface measurement, phase calculation

1. INTRODUCTION

With the development of Three-Dimensional (3D) optical shape measurement technique, it has been widely applied in the fields of reverse engineering, biological recognition and digitalization of cultural relics, etc., because of the advantages of high speed, non-contact, and high measurement precision. However, most of the existing techniques are applied to measure objects with diffused surface. There are a large number of transparent, black, and reflective objects in industrial applications. The research of shape measurement for these objects is still in the early stage. The main methods in industry are using coordinate measuring machine [1] or changing the surface characteristics by spraying paint [2]. Therefore, it is vital to study a direct optical shape measurement method for specular objects.

Phase Measuring Deflectometry (PMD) has been widely studied to test specular free-form surfaces [3-4] because of its advantages of non-contact operation, full-field, fast acquisition, high precision and automatic data processing qualities. PMD has been applied to measure aspheric mirror [5], dynamic specular surface [6], subsurface crack detection [7], and from micro-size [8] to large specular surface [9]. This kind of technique needs to display straight sinusoidal fringe patterns on a screen or to project the structured pattern onto a ground glass. From another viewpoint, the reflected fringe patterns via the tested surface appear deformed with regard to the slope variation of the surface and the modulated fringe patterns are recorded by an imaging (CCD) camera. Phase information in the deformed fringe patterns are demodulated to obtain the slope of the measured specular surface and then 3D shape of the tested surface can be reconstructed by integrating the gradients [10].

All the existing PMD methods just measure the local slope of smooth surfaces [11], instead of the actual 3D shape. In order to achieve the final goal, a two-dimensional (2D) integration procedure is necessary to reconstruct the shape from the measured derivatives, which is incapable of measuring multiple discontinuous surfaces. However, there are many complicated specular components during the intelligent manufacturing, for example, isolated and/or discontinuous surfaces on multi-mirror arrays [12]. Therefore, it is a challenging problem to fast full-field measuring 3D shape of specular objects with discontinuous surfaces.

This paper presents a novel PMD method to measure specular objects having isolated and/or discontinuous surfaces by directly building up the relationship between absolute phase and depth. When an LCD screen having the same fringe patterns is located at two known different positions, phase can directly relate to depth, instead of the slope of the measured specular surface. A plate beam splitter is used to realize the parallel design of the two screens to replace a mechanically moving screen to two positions. Sinusoidal fringe patterns having the optimum fringe numbers are generated by software and displayed on the two screens. A color CCD camera captures the two sets of deformed color fringe pattern images from a reflected viewpoint. After calibrating the system, depth information of a specular object can be directly obtained from the calculated phase map. Initial experimental results on an artificial step having multiple specular surfaces and a concave mirror show that the proposed measurement method can obtain 3D shape of specular objects with isolated and/or discontinuous surfaces effectively.

The following section introduces the principle of the proposed method. Section 3 presents calibration to obtain the system parameters. Some initial experiments on measuring specular objects are demonstrated in Section 4. Section 5 gives the conclusions and future directions.

2. MEASUREMENT PRINCIPLE

Figure 1 shows the schematic setup of the proposed full-field 3D shape measurement system of specular surfaces. The system mainly consists of two LCD screens, one color CCD camera and one beam splitter (BS).

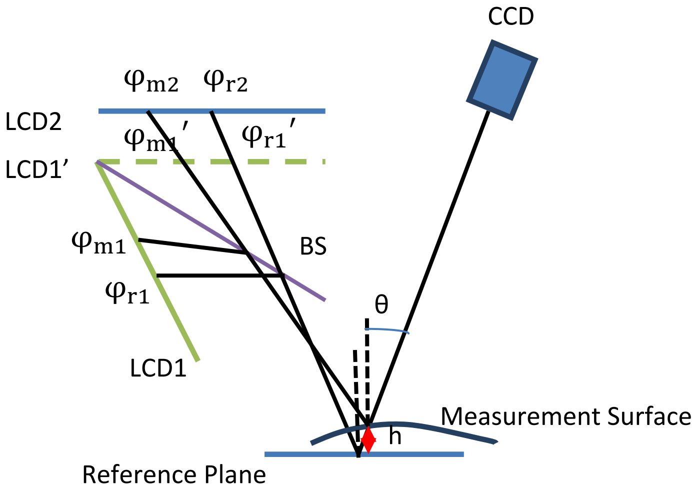


Fig. 1 Schematic setup of the system

BS is adjusted in one proper position, so that a virtual image LCD1´ of LCD1 is parallel to LCD2, just like two LCD screens located in two different positions, as illustrated in Fig. 2. Moreover, the two screens are parallel to a reference plane. Therefore, the plate beam splitter is used to realize the parallel design of the two screens to replace a mechanically moving screen to two positions LCD1´ of LCD2 along normal of the reference plane. This design has the following advantages: 1) Two sets of fringe patterns can be generated to replace one screen movement during measurement; 2) No movement parts during measurement, so there is no effect on resultant data from movement; 3) Two sets of fringe patterns can be captured simultaneously by a color CCD camera when the fringe patterns coded into different color channel of two LCD screens.

Figure 2 is used to derive geometric relationship between absolute phase and depth of the proposed full-field 3D shape measurement system. The distance between LCD1´ and LCD2 is Δd and the distance between the reference plane and LCD1´ is d.

When the same sinusoidal fringe patterns having the optimum fringe numbers are generated by software and displayed on the two LCD screens, they are reflected and deformed by the reference mirror and the specular surface under test. The deformed fringe patterns are captured by the CCD camera from another viewpoint for post processing.

The corresponding phase of each point on the screen can be determined by multiple-step phase-shifting or Fourier transform algorithm [13]. Considering the speed and accuracy, four-step phase-shifting algorithm plus optimum three-fringe number selection method [14] will be used to calculate the wrapped phase data and the absolute phase map value pixel by pixel, respectively.

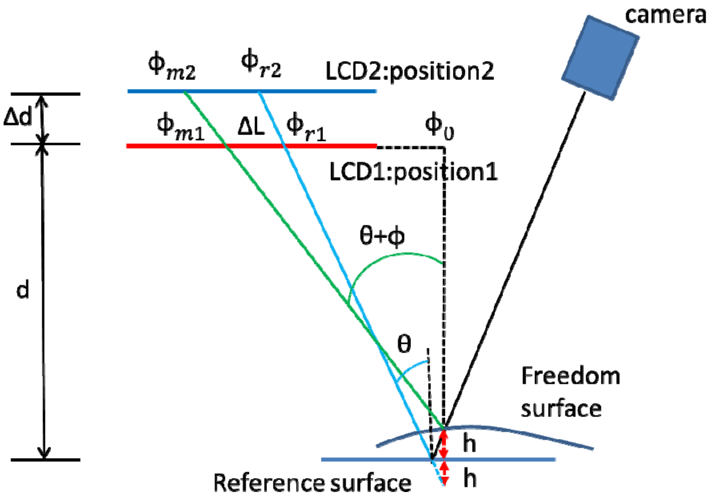


Fig.2 Measuring principle

Assuming the imaging system is a pinhole projection, two rays of light are displayed and reflected into the CCD camera through a tested surface and a reference mirror, as illustrated in Fig. 2. The two incident rays correspond to the same reflection light. The phase of the two incident rays is φ_{r1} and φ_{r2} on the reference mirror and φ_{m1} and φ_{m2} on the measured freeform surface. θ is the angle between one incident ray and normal vector of the reference mirror, and θ+φ is the angle between the other incident ray and normal vector of the measured specular surface. The period of the displayed fringe pattern on the screen is q. Δl is the distance on LCD1 between the two incident rays because of height and gradient of the measured surface. Parameter h stands for height of the measured specular surface with respect to the reference mirror. φ

According the geometric relationship in Fig. 2, the following equations can be deduced.

$$(\varphi_{r1} - \varphi_{r2})q/2\pi = \Delta d\tan\theta \tag{1}$$

$$(\varphi_{m1} - \varphi_{m2})q/2\pi = \Delta d\tan(\theta + \varphi) \tag{2}$$

$$(d + h)\tan\theta + \Delta l = (d-h)\tan(\theta+\varphi) \tag{3}$$

$$(\varphi_{r1} - \varphi_{m1})q/2\pi = \Delta l \tag{4}$$

From the above four Eqs. (1)-(4), height of the measured specular surface is

$$h = \frac{\Delta d(\varphi_{r1} - \varphi_{m1}) - d[(\varphi_{r1} - \varphi_{r2}) - (\varphi_{m1} - \varphi_{m2})]}{(\varphi_{m1} - \varphi_{m2}) + (\varphi_{r1} - \varphi_{r2})}. \tag{5}$$

This equation clearly shows that height information can be directly calculated from the captured fringe patterns only if two parameters d and Δl, and phase information on the reference plane are known beforehand. Because the optimum three-fringe numbers selection method will be used to calculate the absolute phase pixel by pixel, the specular objects having isolated and/or discontinuous surfaces can be measured by the proposed method.

In order to simultaneously capture the deformed fringe patterns on a specular surface, the fringe patterns can be displayed through red channel on one screen and blue channel on the other screen. A color CCD camera captures the two sets of deformed color fringe pattern images from a reflected viewpoint.

3. SYSTEM CALIBRATION

In order to obtain 3D shape data, it is an important step to build up the relationship between absolute phase and depth, which is called calibration. In this paper, we just calibrate the relationship between absolute phase and depth. It is out of the scope of this paper with regard to pixel position to transverse coordinate values. According to the derived mathematical model in Eq. (5), there are two parameters, called Δd and d, needing to be determined beforehand.

Based on the method of machine vision, the two parameters will be determined. Two high accurate plane mirrors have been manufactured. One is the common mirror having an ideal plane surface, called M1. Surface of the other mirror has ring markers with known distance in between, called M2. The two mirrors are used to calibrate parameters of Δd and d, which will be elaborated in the following parts.

3.1Calibration of Δd

The mirror M1 will be originally placed in the reference position and the surface of M1 is parallel to LCD2 and LCD1´, as illustrated in Fig. 3.

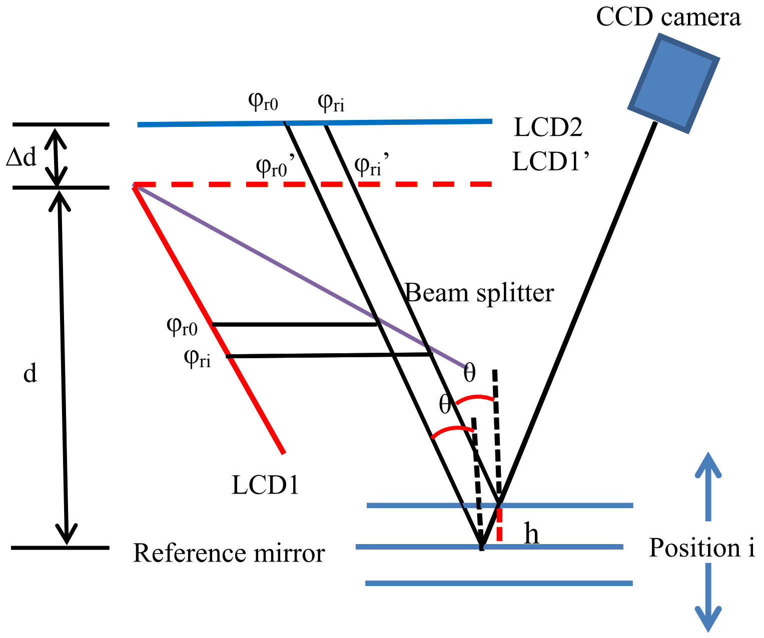


Fig. 3 Diagram of calibrating Δd

A high accurate translating stage will be used to locate M1 at several known positions along the normal direction of the mirror M1. At each mirror position, fringe pattern sets having the optimum fringe numbers will be generated and displayed on LCD2 and LCD1´. The displayed fringe patterns are reflected by the plane mirror M1 and captured by the CCD camera from another viewpoint for post-processing.

According to the geometric relationship of the parameters in Fig. 3, the following equations can be obtained.

$$(\varphi_{ri}{}'-\varphi_{ri})\frac{q}{2\pi} = \Delta d\tan\theta \qquad (6)$$

$$(d+h)\tan\theta - \Delta l = (d-h)\tan\theta \qquad (7)$$

$$\Delta l = (\varphi_{ri}{}'-\varphi_{r0}{}')\frac{q}{2\pi} \qquad (8)$$

where φr0 and φr0´ are the absolute phase value on LCD2 and LCD1´(virtual image of LCD1) respectively, when the plane mirror is at the reference plane position. φri and φri´ are two phase values corresponding to the same camera pixel when M1 moves to a new position i. Parameter h is the translated distance along normal of the mirror surface by the stage. These parameters of q, d, Δd, Δl and θ have the same meanings as before.

Based on Eqs. (6)-(8), the following relationship holds

$$\Delta d=2h(\varphi_{ri}' - \varphi_{ri})/(\varphi_{ri}' - \varphi_{r0}') \qquad (3.4)$$

In principle, one known translating depth h and the corresponding phase values can determine the parameter Δd. In order to improve the accuracy of calibration, the translating stage should move to several known positions to build up an over-determined equation set.

3.2 Calibration of d

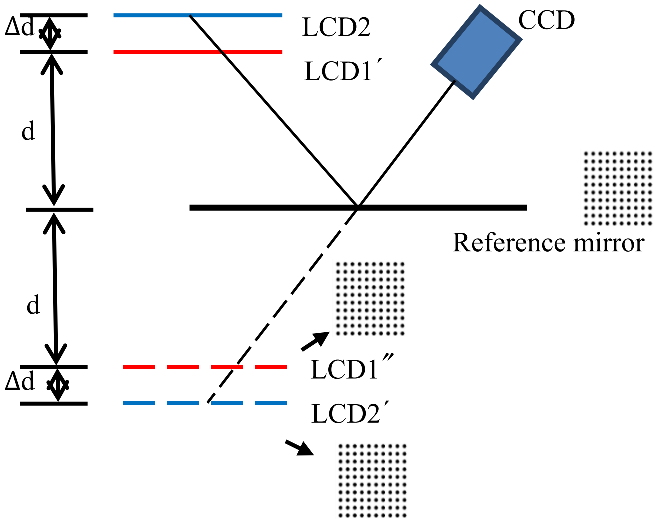
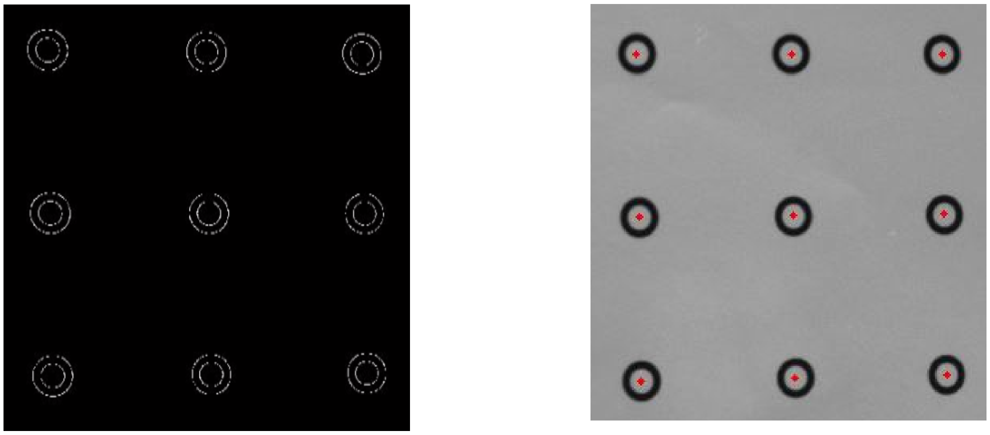


Fig. 4 Diagram of calibrating d



(a)

(b)

Fig. 5 Processed results of M2. (a) Extracted edge of each ring markers, and (b) red dot denotes the fitted center of the ring marker.

The mirror M2 will be used to determine the distance d between the reference and LCD1´, as illustrated in Fig. 4.

The internal parameters of the CCD camera are calibrated by using the common camera calibration method [15,16]. M2 is located in the reference plane and the camera can capture the ring marker on the mirror surface. After extracting the inner and outer edge of each ring marker, the center of all the markers can be determined by using the least square fitting of ellipse [17]. Figure 5 demonstrates partial processed markers on the mirror M2. Because the distance between neighboring ring markers is known beforehand, the external parameters R and T of M2 can be obtained in the camera coordinate system [18]. R and T refer to the rotation matrix and translating vector.

The same ring markers lattice are generated by software and displayed on LCD1. Reflected by the surface of M2, CCD camera can view and capture them at the position LCD1" (the virtual image of LCD1´), as illustrated in Fig. 4. As the same previous procedure of determining the center of ring markers, the external parameters R and T of LCD1"can be obtained in the camera coordinate system.

Since the external parameters of both M2 and LCD1" are obtained in the same camera coordinate system, their distance d can be determined.

4. EXPERIMENTS AND RESULTS

4.1 Experimental system

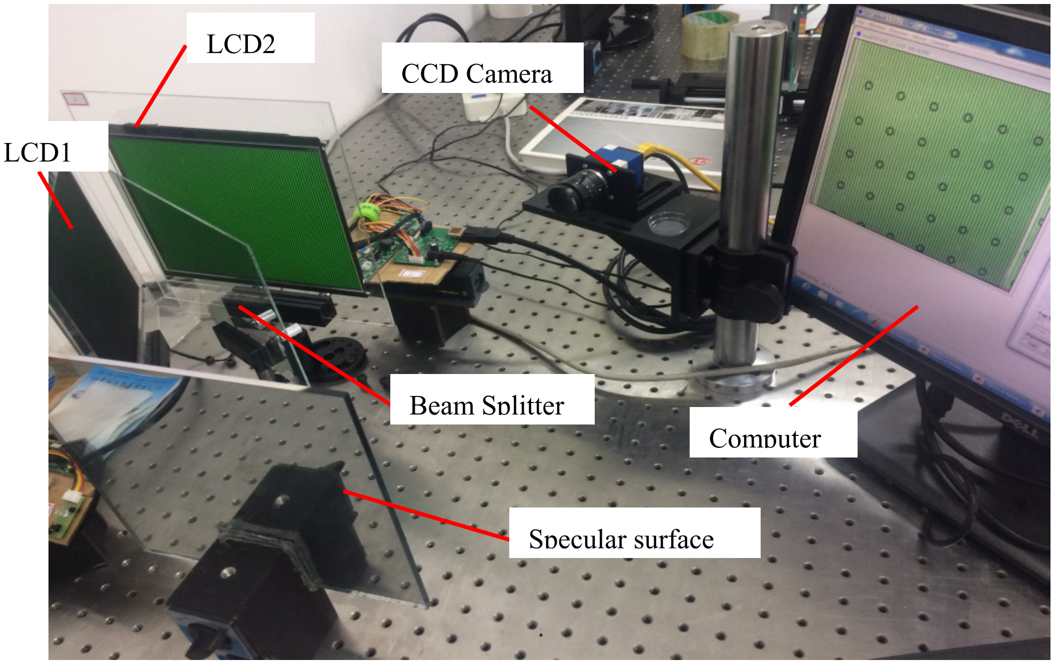


Fig. 6 Hardware of the system

A full-field 3D shape measurement system has been developed to obtain the 3D shape by displaying the same fringe pattern onto LCD screens, as illustrated in Fig. 6. The hardware system consists of a computer, a CCD camera, two LCD screens and a plane beam splitter. The two LCD screens are from LG. The used camera is the latest industrial camera from SVS Company with the model of ECO655 and the resolution of 2050 x 2448 pixels. The camera supports external and internal trigger mode.

The relative position of the two LCDs and beam splitter were adjusted to let LCD2 be parallel to the virtual image LCD1´ of LCD1. After the parameters of Δd and d have been calibrated by the described method in Section 3, reflected surface can be measured by the developed system.

4.2 Initial measurement results

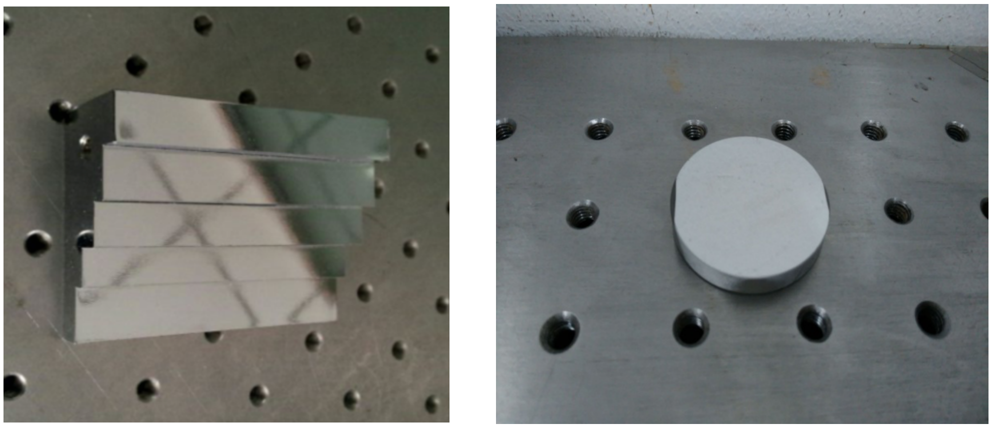


Fig. 7 The tested targets. (a) artificial step, and (b) concave mirror.

A manufactured step having multiple discontinuous specular surfaces and a concave mirror were tested by the developed system, as shown in Fig. 7.

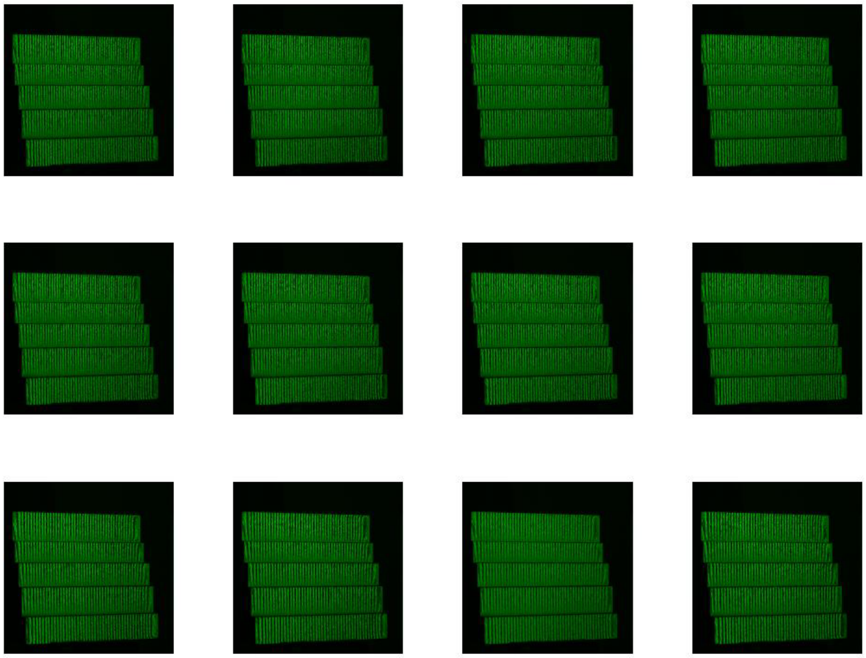


Fig. 8 Captured fringe patterns reflected by step surface

Twelve fringe patterns having the optimum fringe numbers of 100, 99, and 90 are generated in software and sequentially displayed onto the two screens. The reflected fringe patterns by the mirror surface are deformed and captured by the triggered CCD camera, as demonstrated in Fig. 8. The projected fringe numbers in the first, second and third row are 100, 99, and 90, respectively. In each row, there is 90 degrees phase shift in between. Figure 9 shows three wrapped phase maps are calculated by using the four-step phase-shifting algorithm from the captured fringe pattern images. The absolute phase of each pixel is determined by the optimum three-fringe selection method [14]. Using the calibrated parameters of Δd and d, the depth data are obtained, as shown in Fig. 11. These initial results show that the proposed method can directly measure specular object having isolated and/or discontinuous surfaces.

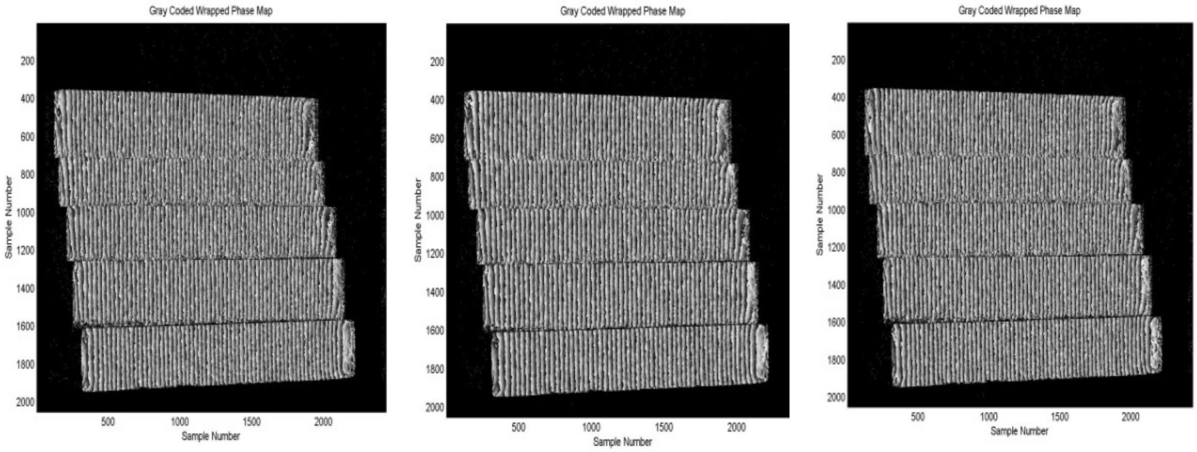


Fig. 9 Three wrapped phase maps on the step surface

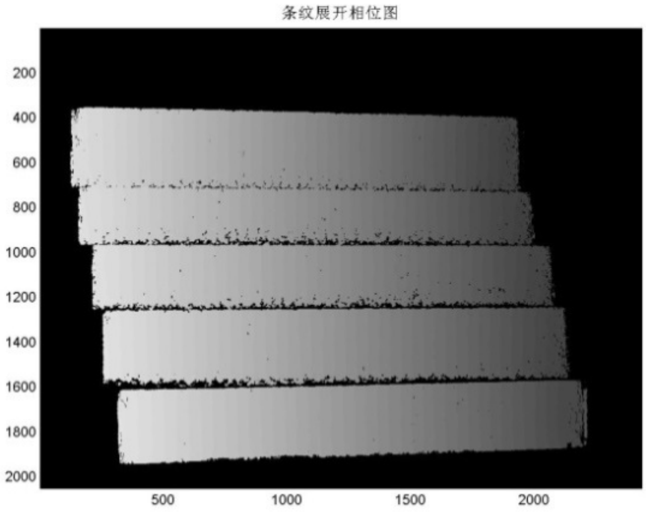


Fig. 10 The absolute phase map of the step surface

Using the same procedure as measuring the artificial step surface, depth data of the concave mirror are obtained, as shown in Fig. 12.

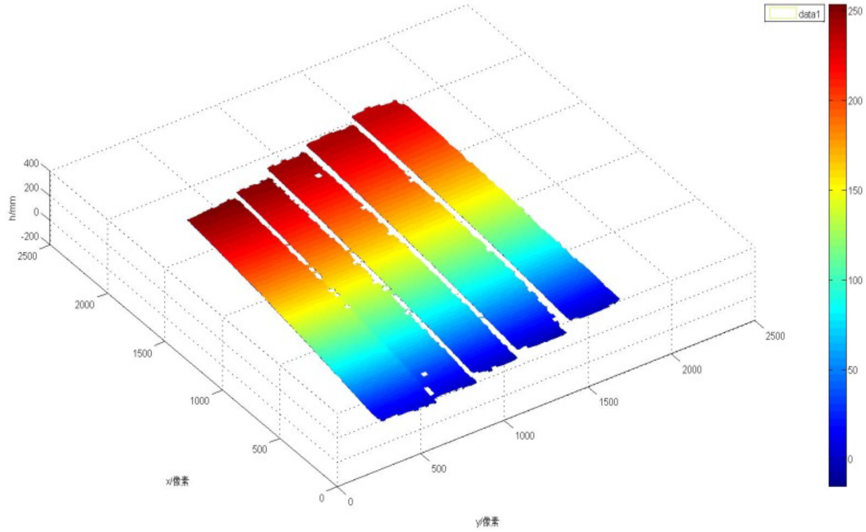


Fig. 11 Depth data of the measured specular step (Unit mm). The X and Y axes represent the pixel position.

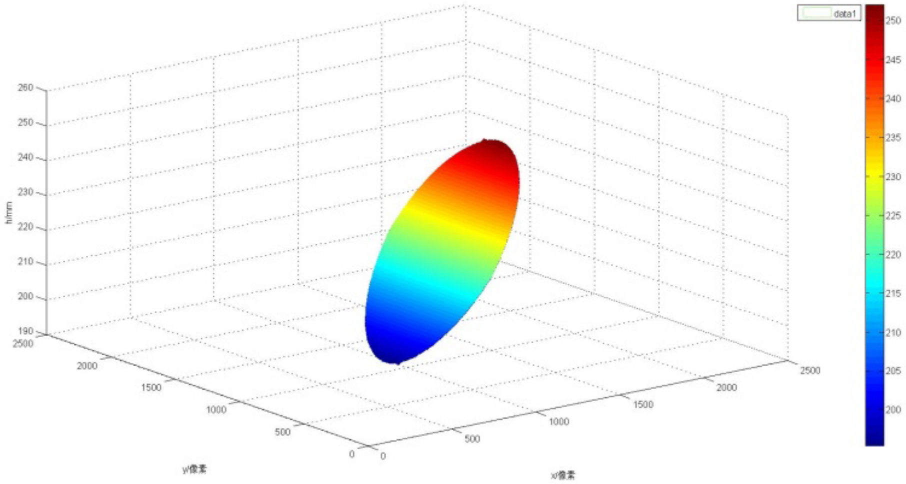


Fig. 12 Depth data of the measured concave mirror (Unit mm). The X and Y axes represent the pixel position.

5. CONCLUSION

This paper presents a new full-field 3D shape measurement method of specular surfaces by using direct relationship between absolute phase and depth. Two LCD screens and one beam splitter have been used to realize the design of two parallel screens. The same fringe pattern sets are displayed on the two screens and reflected by the specular surfaces of the measured objects. Two absolute phase maps are obtained from the captured fringe patterns by using four-step

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phase-shifting algorithm and the optimum three-fringe numbers selection method. After two parameters of the system have been calibrated by using machine vision method, depth data can be directly derived from the obtained absolute phase map. Because depth directly relates to absolute phase without needing gradient integration, the proposed method can measure specular objects having isolated and/or discontinuous surfaces. Initial experimental results on measuring an artificial step with multiple specular surfaces and a concave mirror show that the developed system effectively obtains their depth data.

Next research directions of the proposed method are the following several parts. (1) Capturing speed: the generated fringe patterns will be coded into different color channels of the two LCD screens and then captured simultaneously by the corresponding color channels of a color CCD camera. (2) Accuracy: efficient calibration methods will be applied to obtain more accurate parameters and the performance will be evaluated by using other optical metrology. (3) Error analysis: effects of all kinds of error sources on the measurement results, such as non-parallelism of the two screens, inaccuracy of the calibrated parameters of Δd and d.

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