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A plate beamsplitter based stereo phase measuring deflectometry for measuring specular structured surfaces

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Abstract
Accurate, fast, embedded and in-line three-dimensional (3D) measurement of specular structured surfaces is an ever-increasing demand in industry but also a great challenge for current metrology. Phase measuring deflectometry (PMD) is an important technique for form measurement of specular surfaces. However, there are problems that prevent PMD from achieving embedded and in-line measurement, such as large system volume and measurement shadows for measuring structured specular surfaces. For traditional PMD techniques, imaging sensor and fringe-displaying screen in a PMD system have to be separated on both sides of the normal of the measured surface in order to guarantee the imaging sensor can capture the reflected fringes through the reflection of the measured surface. This configuration results in large system volume. Here, we present a plate beamsplitter based stereo phase measuring deflectometry (BSPMD) to solve these problems. With the function of plate beamsplitter, imaging sensors and screen in BSPMD can be located in the same direction, which makes the volume of BSPMD is much reduced compared with traditional PMD system. In addition, the imaging sensors in BSPMD can capture the measured surface perpendicularly, which can significantly decrease structure shadows and increase valid measurement data. A comparison study between traditional PMD and BSPMD is conducted by measuring a specular step to show BSPMD has similar measurement accuracy, but smaller system volume compared with traditional PMD.

Keywords: Absolute measurement, specular surface measurement, structure surface measurement, stereo deflectometry

1. Introduction

It is important to measure the three-dimensional (3D) form of structured specular surfaces in several industrial arenas such as automotive manufacturing, precision manufacturing, aerospace, and intelligent lighting, because the 3D form accuracy of the structured surfaces has a direct influence on product quality and system performance [1]. It is a great challenge to make the measuring of structured specular surfaces to achieve accurate, fast, embedded and in-line 3D measurement [2]. Interferometry is a well-known measurement technique measuring surfaces based on optical interference principle, but it is difficult to be used in structured surfaces measurement due to the limitation of measurement principle [3]. Stylus profilometer [4] and Coordinate Measuring Machine (CMM) [5] have been widely used in industry for surface measurement. Stylus profilometer touches surface under test (SUT) by using a stylus tip and can achieves a few tens of nanometres measurement accuracy. CMM can be used to measure surfaces with complex geometric shape by using a probe moving along SUT. However, stylus profilometer and CMM are time-consuming. In addition, the stylus tip of these techniques can possibly damage the SUT. Moreover, stylus profilometer and CMM are difficult to be used in embedded measurement due to large volume.

Phase measuring deflectometry (PMD) is a well-known technique for 3D form measurement of specular surfaces with the advantages of non-contact, fast and full-field measurement compared with the above traditional measurement techniques [2]. Traditional PMD techniques focus on continuous surface measurement and can achieve submicron measurement accuracy with the help of the high sensitivity of gradient measurement [2]. To measure structured specular surfaces, Zhang et. al proposed direct phase measuring deflectometry (DPMD) which obtain form data of the SUT from phase data directly [6]. However, DPMD have a relatively low surface measurement accuracy compared with traditional gradient based PMD techniques. In order to improve measurement accuracy of DPMD, Wang et al. proposed a method for DPMD based on stereo algorithm [7]. However, because two screens are required to be used in DPMD, this technique has larger system volume than PMD systems with single screen, which results in difficulty in embedded measurement. Compared with DPMD, segmentation phase measuring deflectometry (SPMD) is also proposed for structured specular surfaces measurement but has obvious advantages in measurement accuracy and small system volume [8]. SPMD has similar configuration with tradition stereo deflectometry [9]. There are still problems for the configuration to achieve embedded measurement. One is the volume of the configuration is required to be further reduced for being put into a manufacturing system. Another problem is because the cameras have to capture SUT with an obvious tilt to the surface normal of the SUT, measurement shadows are inevitable when measuring structures with big depth.

To solve these problems of SPMD, we present a plate beamsplitter based stereo phase measuring deflectometry (BSPMD). Imaging sensors and screen in BSPMD can be located in the same direction with the function of plate beamsplitter, which significantly reduces the volume of BSPMD compared with traditional configuration. In addition, the imaging sensors in BSPMD can capture SUT perpendicularly, which can significantly decrease structure shadows and increase valid measurement data. The paper is organized as following. The principle and method of the BSPMD is presented in Section 2. Section 3 verify the effectiveness of the method through experiments. A summary of the paper is addressed in Section 4.

2. Principle and method

2.1. Comparison of the configuration between tradition PMD and BSPMD

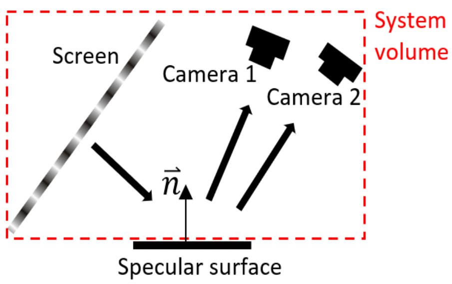

Figure 1. Configuration of traditional PMD system.

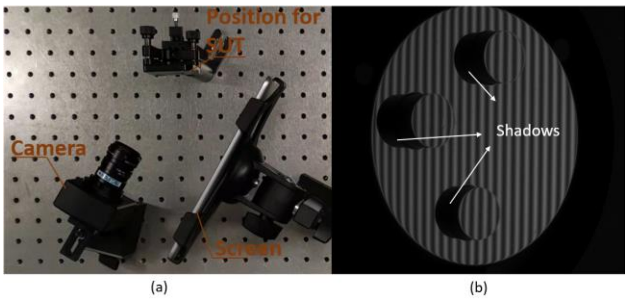

Figure 2. Illustration of problems of traditional PMD system. (a) A picture of PMD system with traditional configuration; (b) a captured picture of the structured specular surface with fringe information by traditional PMD system.

A screen displaying fringe patterns and an imaging sensor are necessary elements of a PMD system. The imaging sensor captures the fringe patterns displayed on the screen through the reflection of SUT and then calculates phase data of the captured fringe patterns. Form information of SUT is obtained based on the calculated phase data and geometric relationship of optical elements in PMD system. Figure 1 shows the configuration of a traditional PMD system with stereo imaging sensors. In order to guarantee the imaging sensors can capture the reflected fringes through the reflection of SUT, imaging sensors and the fringe-displaying screen in the PMD system have to be located separately on both sides of the normal of the SUT. Obviously, this configuration is not compact enough for embedded measurement. Another problem of traditional PMD configuration is illustrated in Fig. 2. Figure 2(a) shows the setup of a PMD system with traditional configuration. Figure 2(b) displays a captured picture of the structured specular surface with fringe information. Serious shadows can be observed in this picture because both screen light and camera ray illuminate obliquely on the SUT.

By contrast, the configuration of the proposed BSPMD is shown in Fig. 3. A plate beamsplitter is located at an angle of approximately 45 degrees on the front of the SUT, so that the fringe patterns displayed on the screen can be vertically projected on the SUT through the reflection of the plate beamsplitter. At the same time, the cameras can capture the SUT directly from the front through the plate beamsplitter. There are two obvious advantages of BSPMD compared with traditional PMD configuration. One is the system volume is significantly reduced by a more compact configuration design which can be distinguished by a comparison between Fig. 1 and Fig. 3. Fig. 4(a) shows a picture of the BSPMD system, which is quite small compared with PMD system with traditional configuration. Another advantage of BSPMD is that the shadows is avoided to a great extent. A captured picture of the structured specular surface by BSPMD system shown in Fig. 4(b) can be compared with Fig. 2(b) to address this point clearly. The reduction of measurement shadow effectively reduces invalid data and increases measurement efficiency.

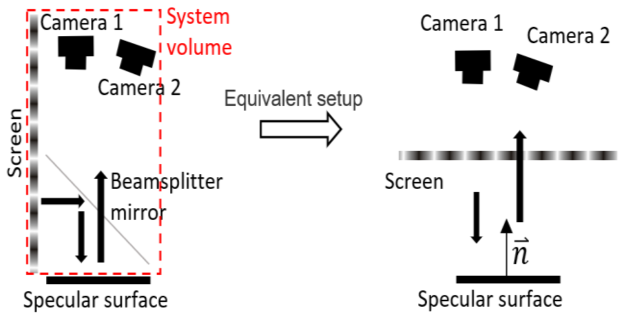

Figure 3. Configuration of BSPMD system.

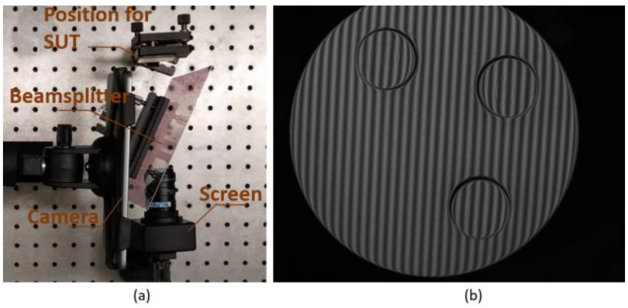

Figure 4. Illustration of advantages of BSPMD system. (a) A picture of BSPMD system; (b) a captured picture of the structured specular surface with fringe information by BSPMD system.

2.2. System calibration of BSPMD system

System calibration is an important step before the measurement of PMD and the key influence of the measurement accuracy. Figure 5 illustrates the calibration method of BSPMD. m_1 and m_2 represent pixel point in term of imaging sensor 1 and imaging sensor 2, respectively. Their corresponding physical point on equivalent screen are expressed as M_1 and M_2, respectively. $\{L\}$ denotes coordinate system of the equivalent screen. $\{C_1\}$ and $\{C_2\}$ represent camera coordinate system of imaging sensor 1 and imaging sensor 2, respectively. $\{P_1\}$ and $\{P_2\}$ denotes pixel coordinate system of the imaging sensors, respectively. The aim of the calibration is to obtain the relationship between $\{L\}$ and phase coordinate system, the relationship between camera coordinate system and pixel coordinate system, and the transformation matrix between $\{L\}$, $\{C_1\}$ and $\{C_2\}$, respectively. The relationship between $\{L\}$ and phase coordinate system can be calculated by knowing pixel size and resolution of the applied screen. Based on pinhole model, the relationship between camera coordinate system and $\{L\}$ can be obtained according to Eq. (1) by putting a flat mirror at several arbitrary mirror positions.

$$s \cdot \boldsymbol{m} = \boldsymbol{A} \cdot [\boldsymbol{R}' \quad \boldsymbol{t}']\boldsymbol{M}' \tag{1}$$

where s is scale factor. $\boldsymbol{m}$ represents camera pixels. $\boldsymbol{M}'$ denotes corresponding physical points of $\boldsymbol{m}$ on virtual equivalent screen after the reflection of the flat mirror. $\boldsymbol{R}'$ and $\boldsymbol{t}'$ are the rotation matrix and translation matrix of the relationship, respectively. The rotation matrix $\boldsymbol{R}$ and translation matrix $\boldsymbol{t}$ of the relationship between camera coordinate system and $\{L\}$ can be calculated based on Eq. (2).

$$\begin{cases} \boldsymbol{R} = (1/(\boldsymbol{I} - 2\boldsymbol{n}\boldsymbol{n}^T))\boldsymbol{R}' \\ \boldsymbol{t} = (1/(\boldsymbol{I} - 2\boldsymbol{n}\boldsymbol{n}^T))(\boldsymbol{t}' - 2d\boldsymbol{n}) \end{cases} \tag{2}$$

where $\boldsymbol{n}$ is the normal vector of the flat mirror and d is the distance from the flat mirror to the centre of imaging sensor.

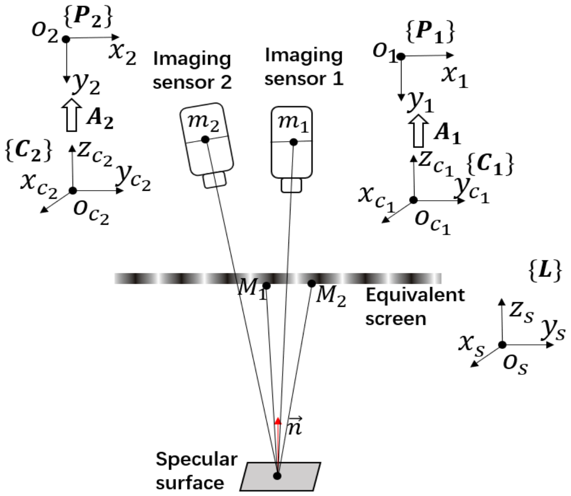

Figure 5. Illustration of the calibration of BSPMD.

3. Experiments

An experiment is conducted to test the performance of the proposed BSPMD system. A flat mirror with fringe information is used as phase target to calibrate the system parameters based on the method described in section 2.2. Figure 6 shows the phase target in a calibration position of the calibration process. Reprojection error of most calibration points are within 0.5 pixels as shown in Fig. 7. A specular step gauge is measured by the BSPMD system and measurement result is compared with that obtained with traditional stereo camera PMD system. Figure 8 shows the calculated phase value of the step gauge in tradition PMD system. Figure 9 shows the calculated phase value in BSPMD system. Comparison of measurement result of tradition PMD system and BSPMD system is shown in Fig. 10. It is obvious that there are a great many of missing data in the measurement result of tradition PMD system due to structure shadow. By contrast, the measurement quality of the BSPMD system is much better. Table 1 shows measurement difference of structure height between PMD and BSPMD. Measurement result of CMM is used as a benchmark to evaluate the measurement accuracy of PMD and BSPMD. It is clear that BSPMD has similar measurement accuracy with traditional PMD system.

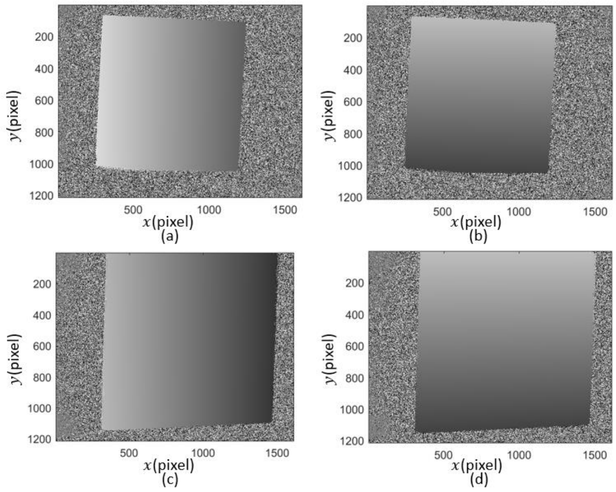

Figure 6. Phase target in one calibration position of the calibration process. (a) Phase target along horizontal direction of camera 1; (b) phase target along vertical direction of camera 1; (c) phase target along horizontal direction of camera 2; (d) phase target along vertical direction of camera 2.

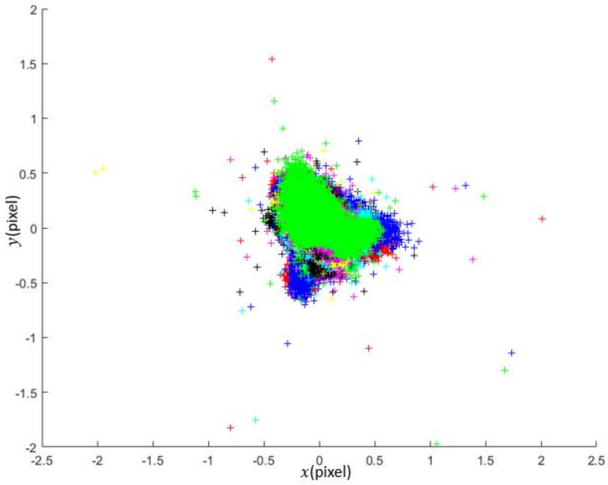

Figure 7. Calibration result.

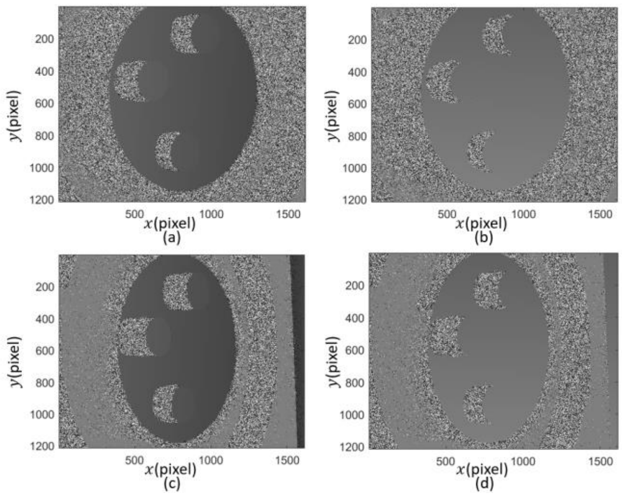

Figure 8. The calculated phase value of the specular circle mirror in tradition PMD system. (a) Phase value along horizontal direction of camera 1; (b) phase value along vertical direction of camera 1; (c) phase value along horizontal direction of camera 2; (d) phase value along vertical direction of camera 2.

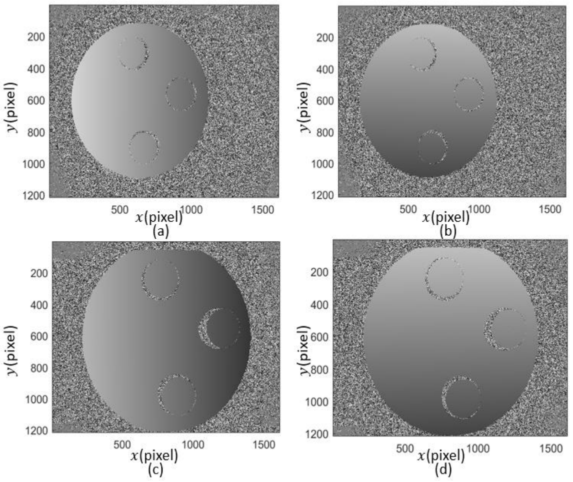

Figure 9. The calculated phase value of the specular circle mirror in BSPMD system. (a) Phase value along horizontal direction of camera 1; (b) phase value along vertical direction of camera 1; (c) phase value along horizontal direction of camera 2; (d) phase value along vertical direction of camera 2.

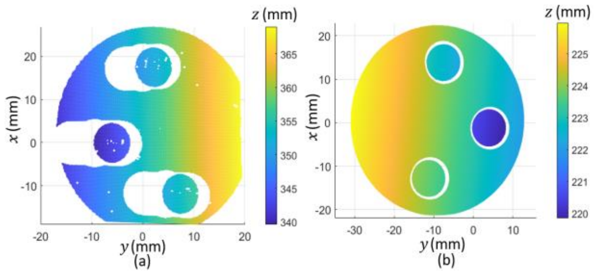

Figure 10. Comparison of measurement result of tradition PMD system and BSPMD system. (a) 3D form of the specular circle mirror measured by traditional PMD system; (a) 3D form of the specular circle mirror measured by BSPMD system.

Table 1 Comparison of the specular circle mirror measured based on traditional PMD and BSPMD

	Structure height 1 (mm)	**Structure height 2 (mm)**	**Structure height 3 (mm)**
CMM	5.617	3.676	4.672
PMD	5.626	3.682	4.661
BSPMD	5.580	3.710	4.610

4. Conclusions

A new configuration of PMD system is proposed in this paper. There are two advantages of the proposed configuration compared with traditional PMD configuration. Firstly, the proposed configuration can significantly decrease the system volume of PMD system, which shows a usefulness when PMD is used for embedded measurement. Secondly, both screen and imaging sensors in the proposed configuration can vertically capture SUT, which can dramatically reduce the measurement shadow caused by the measured structures and increase the valid measurement data. Experimental results verified the effectiveness of the proposed configuration. With the benefit of the applied beamsplitter, the presented technique has considerable advantages of compact configuration, light weight, and reducing insignificant measurement error caused by structure shadows, compared with the exciting PMD techniques based on the conventional configuration. These advantages make the proposed technique show great performance in portable, embedded measurement for discontinuous specular surfaces. Next step, a portable system will be built based on the proposed configuration for embedded measurement.

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