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Enhancement of measurement accuracy of optical stereo deflectometry based on imaging model analysis

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A R T I C L E I N F O

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A B S T R A C T

This paper represents a novel analysis method to improve the measurement accuracy of an optical stereo deflectometry system. A novel imaging model is proposed to research the relation between the phase uncertainty and the normal uncertainty of a stereo deflectometry system. By comprehensively considering the influence on the sampling phase error and the normal error, the system's screen pixel size and the period of fringe displayed on the screen are analyzed to enhance the measurement accuracy. To verify the proposed method, experiments using a common LCD (liquid crystal display) monitor and a screen with Retina Display have been investigated respectively. Experimental results demonstrate using the screen with Retina Display can significantly improve the measurement accuracy of a stereo deflectometry 2.38 times in accuracy due to the ultra-fine pixel size. A stereo deflectometry system based on the proposed method has been built to measure a standard flat mirror and a standard concave mirror. The global measurement accuracy of the flat mirror and the concave mirror can reach 69.7 nm and 96.8 nm respectively.

1. Introduction

The three-dimensional (3D) shape measurement of objects is becoming increasingly important in many applications. Many optical measurement methods have been developed for the 3D measurement of diffuse objects [1,2]. However, the measurement of specular surface remains a challenge because of the reflecting property. Interferometer can measure smooth surface with high accuracy [3–5]. However, most interferometers have a small range of measurements and are not suitable for the form measurement of large freeform surface. Deflectometry is an essential optical technique to obtain the form information of freeform specular surfaces [6–11]. Depth information of the measured surface can be obtained based on the relationship between the depth and the phase value [12]. However, in order to increase measurement accuracy, most deflectometry systems, such as SCOTS (software configurable optical test system) [13], screen movement-based deflectometry [14], and stereo deflectometry [15,16], calculate the surface information by reconstructing a 3D data based on the calculated normal data of the measured surface.

There are numbers of factors affecting the measurement accuracy of a deflectometry system. One important factor is the calibration accuracy of the geometrical relationship between the system components [17]. Novel calibration approaches and algorithms, such as holistic calibration approach [18], iterative optimization calibration algorithm [16], and calibration approach with iterative distortion compensation algorithm [19], have been researched to improve the system calibration accuracy of stereo deflectometry system. In addition, performance of the deflectometry system is affected by the arrangements of the relevant component locations. Zhao et al. [20] analyzed the influence of four system geometrical parameters on a DPMD (direct phase measuring deflectometry) system. Since a fringe-displaying screen is the necessary component of most deflectometry systems, the imperfect performance of the screen affects the measurement accuracy as well. Petz et al. [21] researched the influence caused by the flatness variation of the display surface, the refraction effects in the transparent layers, grayscale and color characteristic problems. The measurement of deflectometry is based on phase calculation. Therefore phase error is a significant error source for a deflectometry system. Methods have been researched to compensate the random phase error and the nonlinear phase error in deflectometry. Yue et al. [22] proposed a carrier removal method to remove the nonlinear carrier phase. Wu et al. [23] proposed a possible phase error-reduction method which integrates several methods for congeneric errors in fringe projection profilometry to reduce the random noise and the nonlinear response noise in deflectometry. However an important factor that is not considered in the above researches is sampling phase error. Because continuous sinusoidal fringe patterns are sampled by the screen's pixels during the display process, the sampling error introduces obvious phase error. Since the surface information is reconstructed based on the calculated normal data for stereo deflectometry, the analysis of the normal uncertainty is essential for the enhancement of the measurement accuracy. Knauer et al. [9] researched the relation between the phase uncertainty and the uncertainty of the measured normal based on diffraction limited. Zhao et al. [20] made virtual experiments to show that the mea-

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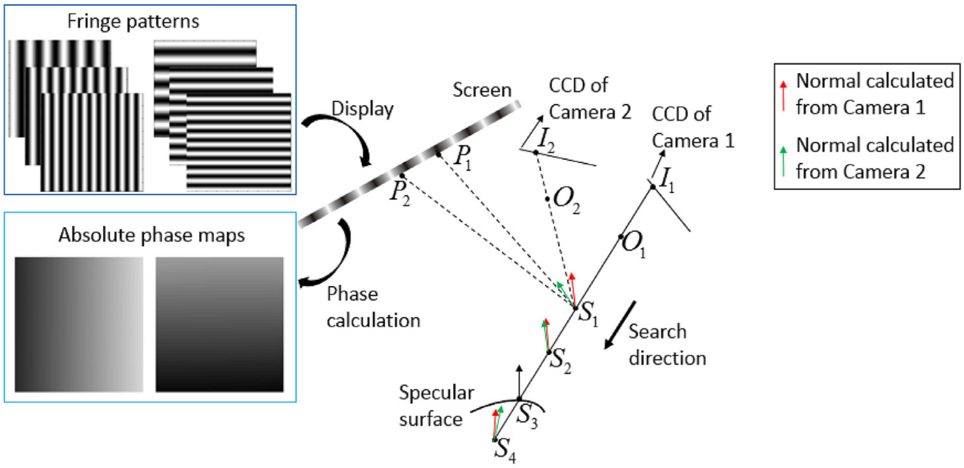

Fig. 1. The measurement principle of stereo deflectometry.

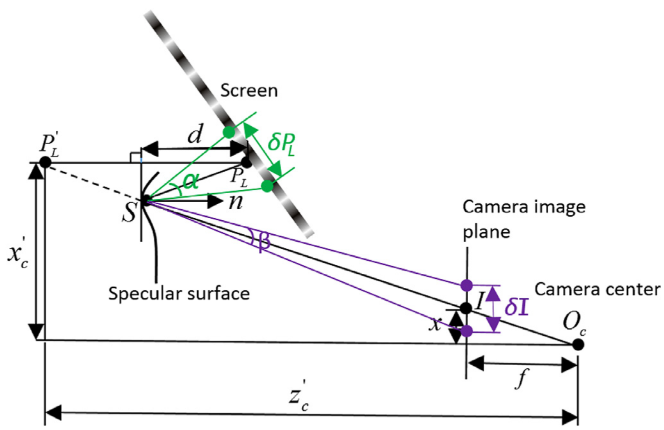

Fig. 2. The imaging model for the analysis of normal uncertainty.

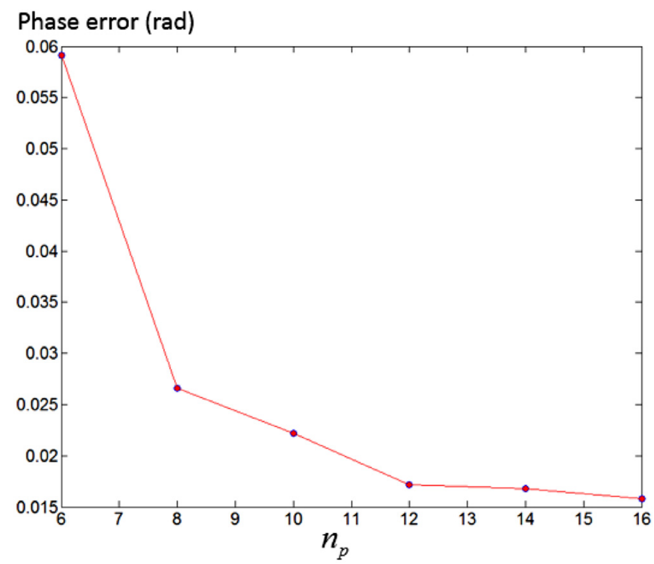

Fig. 3. The variation of phase error along with n_p.

surement error gradually increases with the increasing of the period of fringe on the screen for deflectometry. However, the experiments were conducted without considering the sampling phase error and ignored that the change of the period of fringe can influence the measurement accuracy indirectly by affecting the phase uncertainty.

A novel imaging model is proposed to research the relation between the phase uncertainty and the normal uncertainty of a stereo deflectometry system. By comprehensively considering the influence on the sampling phase error and the normal error, the system's screen pixel size and the period of fringe on the screen are analyzed to enhance the measurement accuracy.

2. Principle

The measurement principle of stereo deflectometry is demonstrated in Fig. 1. The stereo deflectometry system consists of a screen and two CCD (charge coupled device) cameras with optical center O_1 and O_2 respectively. Two groups of mutually perpendicular phase-shifting fringe patterns with different fringe frequencies [24] are displayed on the screen in sequence, and are captured by the cameras through the reflection of the measured surface. After applying phase-shifting and phase unwrapping technique [25,26], two mutually perpendicular absolute phase maps for each camera are obtained. For an arbitrary point S_1 of space, the location of its image I_1 on the CCD of Camera 1 can be calculated based on system calibration [19]. The corresponding position P_1 on the screen can be calculated based on the orthogonal phase values of I_1. Therefore, a normal vector of S_1 can be calculated based on a triangular relationship consisting of the space point S_1, the image point I_1 on the CCD of Camera 1, and the corresponding point P_1 on the screen. Based on the same principle, another normal vector of S_1 can be calculated based on a triangular relationship consisting of the space point S_1, the image point I_2 on the CCD of Camera 2, and the corresponding point P_2 on the screen. Since these normal vectors are overlapped only when S_1 is on the measured surface, a primary 3D data and the corresponding normal vectors of the measured surface can be obtained by searching the space points and matching the normal vectors in terms of the two cameras. Then the optimized overall shape of the measured surface is integrated based on the obtained normal vectors [27].

Since the measurement accuracy of stereo deflectometry is determined by the accuracy of normal calculation, an imaging model is built to analyze the uncertainty relation between the phase uncertainty and the normal uncertainty, as demonstrated in Fig. 2. One physical point P_L on the screen of stereo deflectometry is captured by the camera through