Performance analysis and evaluation of direct phase measuring deflectometry

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\textbf{A B S T R A C T}

Three-dimensional (3D) shape measurement of specular objects plays an important role in intelligent manufacturing applications. Phase measuring deflectometry (PMD)-based methods are widely used to obtain the 3D shapes of specular surfaces because they offer the advantages of a large dynamic range, high measurement accuracy, full-field and noncontact operation, and automatic data processing. To enable measurement of specular objects with discontinuous and/or isolated surfaces, a direct PMD (DPMD) method has been developed to build a direct relationship between phase and depth. In this paper, a new virtual measurement system is presented and is used to optimize the system parameters and evaluate the system’s performance in DPMD applications. Four system parameters are analyzed to obtain accurate measurement results. Experiments are performed using simulated and actual data and the results confirm the effects of these four parameters on the measurement results. Researchers can therefore select suitable system parameters for actual DPMD (including PMD) measurement systems to obtain the 3D shapes of specular objects with high accuracy.

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1. Introduction

Three-dimensional (3D) shape measurement techniques for diffuse objects have been widely used in manufacturing industries \cite{1,2} in applications such as quality inspection and reverse engineering. Full-field fringe projection techniques \cite{2-6} have been widely used to obtain the 3D shapes of these diffuse objects because they offer the advantages of noncontact operation, full-field acquisition, high accuracy, and fast, automatic data processing. Along with diffuse objects, specular surfaces also have a wide range of applications in various fields \cite{7}, including new energy generation, illumination, and aerospace and biomedical engineering. Therefore, to guarantee the technical performance and the visual appearance of specular products, it is essential to develop a method for measurement of specular surfaces. Phase measuring deflectometry (PMD) methods have been widely applied to provide accurate shape measurements because of advantages that include high dynamic range, full-field acquisition, noncontact operation, high accuracy and low cost \cite{8,9}.

In general, PMD uses the phase information that is calculated from reflected fringe patterns to obtain the slope data of the specular objects to be measured. A 3D shape is then reconstructed using two-dimensional (2D) local slope integration. Su et al. \cite{8,9} proposed a software-configurable optical test system for optical surface measurement and added an auxiliary lens to perform both mid- and high-spatial-frequency optical surface metrology. Huang et al \cite{10} built a monoscopic fringe reflectometric system using only one liquid crystal display (LCD) screen and one digital camera to perform dynamic shape measurements. Tang et al. \cite{11,12} measured the 3D shape of an aspheric mirror using the reflected rays and a ‘dummy paraboloid’. Xiao et al. \cite{13} proposed a flexible PMD system calibration method based on use of a mark- erless flat mirror. However, deviations during calculation of the slope will lead to error accumulation in the height calculations. To remove the slope integration requirements, many methods have been developed to build a relationship between slope and depth. Petz and Tutsch \cite{14} proposed a deflectometry system using one camera and two reference grat ing planes for pointwise computation of the absolute 3D object coordinates, while Guo et al. \cite{15} proposed a least-squares light incident-light tracking technique for specular surface measurement. During their measurement processes, both methods \cite{14,15} need to shift their LCD screens to different positions to determine the orientation of the incident ray relative to the slope, which leads to instability and thus inaccurate measurement results. Knauer et al. \cite{16} proposed a stereo deflectometry method to obtain the absolute slope and height based on calibration of the normals at the same point for two cameras. Feng et al. \cite{17} built a dual-camera fringe projection system to reconstruct dynamic 3D shapes by combining standard three-step phase-shifting fringe patterns with a
digital speckle image. However, calibration processes in dual-camera systems are complex. Recently, Huang et al. [18] presented a method for simultaneous estimation of the height and the slopes of a surface under test in PMD based on use of a mathematical model and optimization of the orientation of the screen geometry after pre-calibration of the PMD system.

To solve the above problems and build a stable measurement system, a direct PMD (DPMD) system [19] has been developed to form a relationship between the phase and the depth directly without the need for a slope integration procedure. The proposed system consists of two LCD screens, one beam splitter (BS) plate and one charge-coupled device (CCD) camera. The measurement results and the system performance are affected by the arrangements of the relevant component locations and the ways in which the parameters are set in a 3D measuring system [20]. However, to the best of our knowledge, there are no published works in the literature on evaluation of system performance and analysis of the effects of the system parameters on the measurement results in PMD. While this paper analyzes the system parameters quantitatively for DPMD, the proposed method can be applied to general PMD systems.

The next Section describes the principle and the configuration of the developed DPMD system. The simulated DPMD measurement system is introduced in Section 3. Section 4 provides an analysis of the effects of the system parameters on the measurement results. Experimental results when using the actual system are provided in Section 5 and some concluding remarks are given in Section 6.

2. Principle of direct phase measuring deflectometry

A schematic diagram of the developed DPMD system is shown in Fig. 1. This system consists of two LCD screens, a CCD camera, and a BS plate. LCD' represents a virtual image of screen LCD via the BS. Screens LCD and LCD' are both parallel to the reference plane R. h is the height of a given point on the tested surface, d is the distance between screen LCD, (the virtual image of screen LCD') and reference plane R, and ∆d is the distance between LCD and LCD'. θ represents the angle between the normal vector of the reference plane and the incident ray from the camera, φ represents the double gradient angle of the point that is tested on the measured surface, δ1 represents the physical size of a single pixel unit on the LCD screen, and φı1 (φı1) and φı1 (φı1) denote the two different absolute phases on LCD, φı2 and φı2 denote the two different absolute phases on LCD. Both the absolute phases φı1 and φı2 are on the same incident ray that is reflected into the CCD camera from the mirror at the reference position. Both the absolute phases φı1 and φı2 are on the same incident ray that is reflected into the CCD camera from the measured surface. ∆L1 represents the distance between phases φı1 and φı1.

Fringe patterns are generated using software and are displayed on the two LCD screens. The intensity distribution of a single displayed fringe pattern can be expressed as

\[ I_d(x, y) = a(x, y) + b(x, y) \cdot \cos \left( \frac{2\pi}{P} \cdot x + \phi_0(x, y) \right) \]

where \( \phi_0(x, y) \) is the phase shift term, \( a(x, y) \) and \( b(x, y) \) account for the background intensity and the fringe contrast, respectively, and \( P \) is the period of the displayed fringes. The fringe patterns that are displayed on screens LCD and LCD' are reflected into the CCD camera via the surface under test and the mirror at the reference position to provide different viewpoints. After the absolute phase is calculated from the captured fringe patterns, the depth information can be obtained directly. In the following of equation derivation, the x and y coordinates are omitted for brevity.

From the geometric relations of the DPMD measuring system shown in Fig. 1, the following equations can be derived:

\[ (\phi_ı1 - \phi_ı2) \cdot d/L = \Delta d \cdot \tan \theta' \]

\[ (\phi_ı1 - \phi_ı2) \cdot d/L = \Delta d \cdot (\sin \theta' + \varphi) \]

\[ (d + h) \cdot \tan \theta' + \Delta L_1 = (d - h) \cdot \tan (\theta' + \phi) \]

\[ (\phi_ı1 - \phi_ı1) \cdot d/L = \Delta L_1 \]

\[ \phi_ı1 = \phi_ı \]

\[ \phi_ı2 = \phi_ı \]

By combining Eqs. (2)–(7), h can be calculated as

\[ h = \frac{\Delta d \cdot (\phi_ı1 - \phi_ı) - d \cdot [(\phi_ı1 - \phi_ı2) - (\phi_ı1 - \phi_ı2)]}{(\phi_ı1 - \phi_ı) + (\phi_ı1 - \phi_ı2)} \]

Eq. (8) demonstrates that ∆d and d affect the measurement results directly. Eq. (1) shows that P influences the fringe pattern distribution and Eqs. (2)–(5) indicate that θ' affects the phase distances between φı1 and φı2, φı1, and φı2, and φı1, and φı1. Therefore, the measurement results will be related to and affected by all the system parameters, including ∆d, d, θ', and P. Because the angle θ between the optical axis of the camera and the normal vector of the reference plane is a special value of θ', which can be calculated easily from the calibration of the camera, θ' can be replaced with θ in the system parameter analysis process. To calibrate the relationship between phase and height based on Eq. (8), it needs to determine not only two distances d and ∆d, but two absolute phase values for each pixel position reflected by the reference plane. After calibrating the measuring system, the height value at one CCD pixel is determined by two absolute phase values reflected from the reference plane plus two corresponding absolute phase values reflected from the specular objects for the two LCD screens. When a measured specular object tilts in both x and y directions, the corresponding absolute phase values φı1 (φı1) and φı2 reflected by the specular surface will be changed accordingly. Based on the mathematical model above, a simulated DPMD measurement system is constructed in the following section.

3. Simulated DPMD measurement system

The principle of the simulated specular measurement system is based on a combination of DPMD and a pinhole imaging model. It is therefore necessary to calculate not only the geometrical relationships between the two LCD screens and the specular surface but also that between the specular surface and the CCD camera.
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