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Review

Review of phase measuring deflectometry

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ABSTRACT

As a low cost, full-field three-dimensional shape measurement technique with high dynamic range, Phase Measuring Deflectometry (PMD) has been studied and improved to be a simple and effective manner to inspect specular reflecting surfaces. In this review, the fundamental principle and the basic concepts of PMD technique are introduced and followed by a brief overview of its key developments since it was first proposed. In addition, the similarities and differences compared with other related techniques are discussed to highlight the distinguishing features of the PMD technique. Furthermore, we will address the major challenges, the existing solutions and the remaining limitations in this technique to provide some suggestions for potential future investigations.

1. Introduction

Quantitative three-dimensional (3D) shape metrology has already become the key technology in industrial applications for quality control, reverse engineering, precision manufacturing, and digitization of artwork [1–7]. Due to its high speed, non-contact, and non-destructive testing feature, optical 3D shape metrology is one of the major metrology techniques, especially suitable for the inspection of high-quality and valuable surfaces [6–13].

Depending on the field of view, the optical 3D shape metrology can be classified as pointwise or line-by-line scanning techniques [14, 15] and full-field vision-based measurement techniques [9, 16, 17]. The full-field vision-based methods include active and passive 3D vision approaches. The structured-light-illuminated 3D vision is one of the most typical active approaches. With the structured-light illumination, the out-of-plane depth information is coded and recorded with a digital camera. As a natural pattern in an optical shop, the fringe pattern is a classical solution of structured-light illumination. After the image acquisition of the fringe pattern(s), quantitative phase values can be retrieved with well-developed fringe analysis algorithms [18–22]. The fringe phases establish the correspondence between camera pixels and the illumination points. As a result, the geometry relations between system components can be built up to enable the 3D measurement of the Surface Under Test (SUT). Phase Measuring Deflectometry (PMD) is one of the optical 3D shape metrology techniques based on two-dimensional (2D) fringe phase measurement, especially for specular reflecting surfaces [13, 23–33].

In this work, we review the principle of PMD technique and the follow-up studies after its invention, compare the similarities and differences with other related measurement techniques, and discuss the major challenges, the current solutions, and their remaining deficiencies.

2. Fundamentals and concepts of PMD

The fundamental principle of PMD technique is the law of reflection. As described in Fig. 1, an angle change α of the SUT with respect to a reference orientation will introduce a doubled angle 2α to the reflected ray. Usually, the sight ray of a camera, or say the probe ray, is treated as the light source in PMD for easier understandings and analysis, although the light is actually illuminated from a Thin-Film-Transistor Liquid-Crystal Display (TFT LCD) screen in the physical process. In this review work, the PMD measuring process is considered as the probe rays from the camera are reflected by a specular SUT onto the TFT LCD screen.

As illustrated in Fig. 2, there are many possible height and slope combinations to explain the phase point observed by a single camera probe ray, which is called height-slope ambiguity in PMD. By tracing where the probe rays are deflected by the SUT in a geometrically known scene, the vectors of the surface normal, or x- and y-slopes, can be determined with proper regularization to the inverse problem in PMD with height-slope ambiguity. Based on the measured slopes, the quantitative surface topographic data can be reconstructed via numerical calculations. Iterative height reconstructions and slope calculations may be necessary to achieve self-consistent shape results [34].

Generally speaking, the implementation of a measurement with PMD include the following steps.

(1) Properly set up the camera(s) and screen(s) to ensure the field of view(s) can cover the desired measuring volume and place the specimen surface inside the measuring volume and then adjust its tip/tilt

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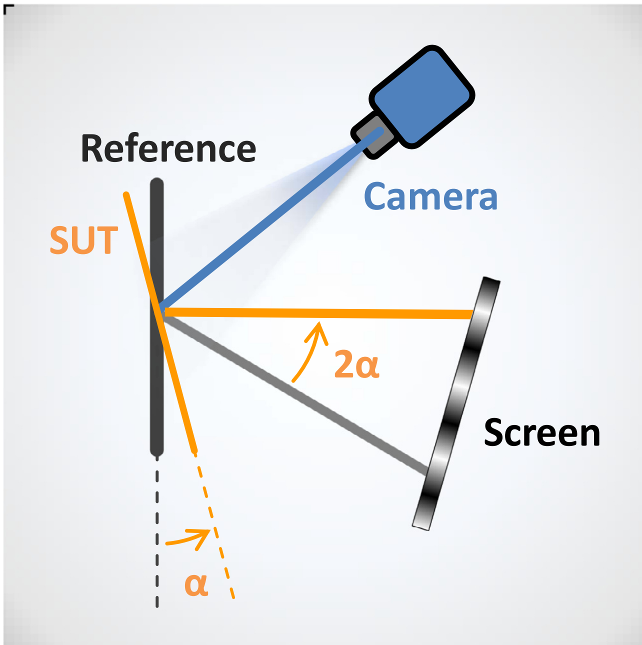

Fig. 1. The measurement principle of the PMD is based on the law of reflection. The reflected ray doubles the angle change introduced by the specimen slopes.

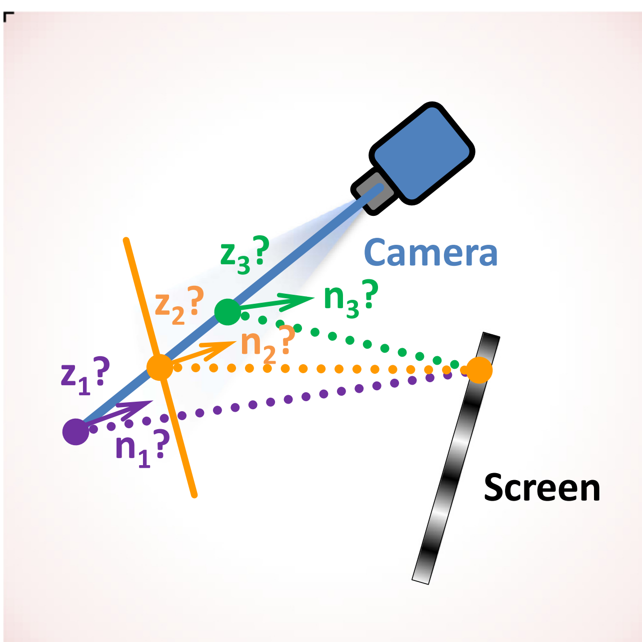

Fig. 2. For the same camera probe ray and its corresponding phase point on the screen, there are many possible solutions with different height-slope combinations.

to make the camera(s) see the fringe patterns on screen(s) via the reflection by the SUT.

(2) Capture the fringe images of the reflected pattern from the SUT.
(3) Analyze the fringe patterns to retrieve two-directional 2D phase information, and furthermore, the x- and y-slope values.
(4) Reconstruct the height information from slope datasets which is also known as the 2D integration process.

2.1. Setups of PMD

The main devices for a general PMD include a digital camera, a TFT LCD monitor, a specimen stage, and a computer. Computer-generated fringe patterns are sequentially displayed on the TFT LCD screen. The camera captures the reflection images of the displayed fringe patterns via a specular reflecting SUT. The SUT shape is reconstructed by solving an inverse problem with the captured images. Owing to the height-slope ambiguity described in Fig. 2, several different kinds of regularization approaches with the corresponding setups are proposed to resolve this ill-posed problem.

To measure micron-level out-of-plane deformation or discrepancy from a pre-known shape, the monoscopic PMD illustrated in Fig. 3 is a simple and effective solution with the initial shape regularization [25], which assumes the shape after deformation is very close to the reference [35, 36], or the SUT is very similar to the pre-known shape [37]. Self-consistent height and slope results can be obtained via iterations [34].

For different requirements and corresponding regularization in actual measurements, the PMD system may adopt additional components (*e.g.* screens, distance sensors, or cameras). By introducing additional patterns in the optical path as shown in Fig. 4(a), the reflected ray can be determined by the two or more points of intersection on the shifted screen [26, 38–40]. In Fig. 4(b), an additional distance sensor can be used to regularize the ill-posed problem in the monoscopic PMD by providing a reference distance [41]. Fig. 4(c) and (d) describe the height values can be searched by minimizing the discrepancies of the SUT normal vectors calculated from two or multiple cameras [24]. These cameras can be served by a single screen as Fig. 4(c) or several screens as Fig. 4(d). In addition, some recently proposed new configurations require other constraints, such as parallel screens and reference plane [42].

2.2. Image acquisition

In PMD measurement, a camera captures the reflection of the patterns displayed on a screen through the specimen surface. There is a trade-off between the spatial resolution and the angular resolution in image acquisition. If the camera is focused on the specimen surface, the measurement gets the best spatial resolution, but the angular resolution will not be the optimum due to the defocusing of the screen patterns. If the camera is focused on the reflection of the screen pattern, the measurement achieves the best angular resolution but a lower spatial resolution comparing to the previous case. In practice, the cameras are usually focused on the SUT for the following practical considerations.

(1) High spatial resolution is a common requirement for 3D shape measurement, if achievable.
(2) The patterns displayed on the screen in PMD are typically sinusoidal fringes which are smooth intensity curves and the phase calculation is not very sensitive to a small amount of out-of-focus effect;
(3) There is less influence from the pixel grids of TFT LCD screen. Owing to the defocusing effect, the TFT LCD pixel grids almost disappear in the camera image, which is preferable. On the other hand, when the camera focuses on the reflection of the screen pattern, the images will record the TFT LCD pixel grids, which introduces an additional error source to the follow-up fringe analysis process.

2.3. Fringe analysis and slope calculation

Once the fringe patterns are captured, the fringe phases need to be retrieved by using the well-developed fringe analysis method as one of the most significant intermediate results. The fringe analysis includes fringe demodulation and phase unwrapping.

2.3.1. Fringe demodulation

Fringe demodulation allows retrieving the wrapped phase values from the captured fringe intensity image(s). According to the required