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Optical fringe-reflection deflectometry with bundle adjustment

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ABSTRACT

Liquid crystal display (LCD) screens are located outside of a camera's field of view in fringe-reflection deflectometry. Therefore, fringes that are displayed on LCD screens are obtained through specular reflection by a fixed camera. Thus, the pose calibration between the camera and LCD screen is one of the main challenges in fringe-reflection deflectometry. A markerless planar mirror is used to reflect the LCD screen more than three times, and the fringes are mapped into the fixed camera. The geometrical calibration can be accomplished by estimating the pose between the camera and the virtual image of fringes. Considering the relation between their pose, the incidence and reflection rays can be unified in the camera frame, and a forward triangulation intersection can be operated in the camera frame to measure three-dimensional (3D) coordinates of the specular surface. In the final optimization, constraint-bundle adjustment is operated to refine simultaneously the camera intrinsic parameters, including distortion coefficients, estimated geometrical pose between the LCD screen and camera, and 3D coordinates of the specular surface, with the help of the absolute phase collinear constraint. Simulation and experiment results demonstrate that the pose calibration with planar mirror reflection is simple and feasible, and the constraint-bundle adjustment can enhance the 3D coordinate measurement accuracy in fringe-reflection deflectometry.

1. Introduction

The three-dimensional (3D) shapes of objects based on fringe projection has the advantages of enabling fast full-field measurements and high measurement accuracy, and they are widely applied in the 3D measurement of diffuse reflection surfaces [1,2]. The specular reflection phenomenon can also be utilized to reveal and perceive the 3D shape information for specular surfaces. However, it is difficult to inspect specular surfaces using visual measurements because cameras do not see the specular surface directly, but they see only the surrounding region through optical reflection. Over the past decade, according to the characteristics of fringe reflection, many scholars have proposed the fringe reflection for measuring specular surfaces by insteading the projector in structured light with a liquid crystal display (LCD) screen [3–6]. G. Hausler [7] proposed the utilization of phase-measurement deflectometry (PMD) to measure the slope and height data for a free-form specular surface. It is well known that ambiguous phenomena about the height and normal are always presented. The optical system architecture, which consists of more than two cameras and one LCD, or two LCDs and one camera, can be utilized to resolve the ambiguous problem [7], and the principle of PMD is prompted to stereo deflectometry [8]. Recently, L. Huang proposed modal phase measuring deflectometry [9] (MPMD) to simultaneously estimate the height and slopes of the surface under test using mathematical models, and MPMD can be extended to multicamera PMD systems. The phase measuring deflectometry (PMD) method has been applied in many optical fields. For example, Y. Tang and X. Su used a camera to take the deformation fringes on an aspheric surface to complete surface measurements [10]. T. Yuan and F. Zhang proposed a flexible geometrical calibration for PMD [11]. P. Su operated a framework using a Software Configurable Optical Test System (SCOTS) that is based on deflectometry for high-accuracy aspheric X-ray mirror metrology [12]. W. Li carried out an outstanding extensive applications in the primary mirror of the astronomical telescope E-ELT deformation measurement with deflectometry [13]. G. Hausler [14] proposed the use of deflectometry to measure a large spherical mirror with radii of curvature of up to 60 m.

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One of the core techniques employed for optical fringe-reflection deflectometry is system geometrical calibration. The objective of system calibration is to build the ray reflection geometry in a common coordinate system between the LCD screen and camera. The normal direction of the specular surface under test is achieved by determining the ray-reflection vector cross product in 3D space. The objective of gradient integration is to recover the 3D shape of the specular surface [15,16]. The quality of the gradient field largely depends on the system calibration, and the trueness of the slope data will be affected by the accuracy of the system calibration error. Thus, in optical fringe-reflection deflectometry, sophisticated system geometrical calibration is extremely important, and it is especially difficult to obtain geometrical calibration between the camera and LCD screen because the LCD screen does not lie within the camera's field of view. Recently, the application of specular reflection utilizing a markerless planar mirror more than three times can help to achieve system geometrical calibration. In addition, the camera calibration and geometrical calibration can be simultaneously optimized considering the concept of bundle adjustment [17–20], where uncertainties arise, and the calibration parameters usually tend to be somewhat consistent. This is because bundle adjustment is a nonlinear square least solution that includes initialization and iteration. The uncertainties depend on the initial linear solution for the pinhole imaging model and the setting convergence condition. The entire initial solution and iteration is based on the Gaussian noise assumption; thus, the final optimization solution is the maximum-likelihood estimation, and it may result in a few uncertainties in each convergence. Until recently, Xiao [21] proposed fringe-reflection photogrammetry, in which the binary gratings are replaced by optical fringes. The effect of camera defocusing can still maintain a good sine property for fringes, and it is helpful for locating the feature points based on absolute phase information in optical fringes. The optical-ray forward-triangle intersection is used to measure 3D coordinates, replacing the slope and height measurement approach. Further, the correspondence matching is implemented effectively with the binary grating. Actually, the essence of fringe-reflection photogrammetry is similar to that of deflectometry, and in this paper, we refer to the proposed approach as fringe-reflection deflectometry for 3D coordinate measurements.

In this study, the authors implement planar reflection in fringe-reflection deflectometry to make the forward-triangle intersection perform within the camera frame, and to apply constraint-bundle adjustment in 3D coordinate refinement for a specular surface, which improves the accuracy of the measured points. In fringe-reflection deflectometry, lens distortion should be carefully considered to compensate for a pinhole model that describes the imaging process, and the 3D coordinates can also be improved by the constraint-bundle adjustment with absolute phase line-of-sight propagation. To improve the flexibility of fringe-reflection deflectometry, a planar mirror without any control points was utilized to calibrate the geometrical pose between the camera and LCD. A flat mirror is directly used to reflect the fringes on the LCD more than three-times, and a fixed camera is used to receive the reflection fringes. Then, the geometrical pose relationship between the LCD and camera is estimated. The incident light and reflected light corresponding to each pixel of the camera are marked under the camera coordinate system for the ray-triangle intersection, and the 3D coordinates of the specular surface are measured. Experimental results show that the poses' geometrical calibration can be used to realize the fringe-reflection deflectometry simply and flexibly, and constraint-bundle adjustment can resolve the lens distortion problem to enhance the measurement accuracy and precision.

2. Principle of fringe-reflection deflectometry

The schematic diagram of fringe-reflection deflectometry is shown in Fig. 1. The fringes are displayed on LCD screens located in two different positions, and the deformed fringes that are reflected from the specular surface are captured by a fixed camera. The system structure is a model of one camera and two LCDs in the fringe-reflection technique [9]. Here, the principle of fringe-reflection deflectometry is interpreted as follows: the absolute phase on the incident ray and reflected ray maintains consistency, and the absolute phase located in the camera's imaging plane can match the corresponding absolute phase that is located at the two positions, LCD1 and LCD2, using optical-ray reverse tracking. Therefore, the 3D coordinates of A, B, and C can be determined according to the direct intersection of the incident and reflected rays. The same phase point on two different LCD positions determines the incident light, such as A1A2, B1B2, and C1C2, and the reflected light is determined by the camera's optical center and the same phase-point image coordinates. Therefore, in the camera coordinate system, the fringe-reflection deflectometry is completed according to the ray-triangle intersection. In the final optimization step, all the estimated parameters, including the camera intrinsic parameters, distortion coefficients, geometrical pose, and 3D coordinates, are refined simultaneously using constraint-bundle adjustment.

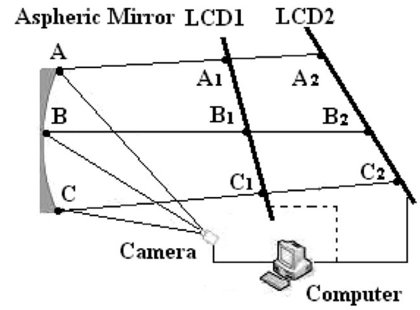

Fig. 1. Schematic diagram of fringe-reflection deflectometry.

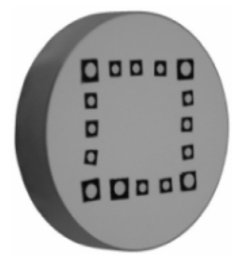

Fig. 2. Schematic of calibration mirror with control points.

As opposed to the system structure proposed by H. Guo [22], the two LCD positions in Fig. 1 are no longer strictly parallel. It is obvious that the device in Fig. 1 is simpler and more convenient in actual measurements without any mechanical device. However, to complete the triangle intersection to determine the three coordinates of A, B, and C, both the reflected and incident light should be unified in the same world coordinate system, which requires us to determine the position relationship between the camera and the LCD. In the scheme proposed by Petz [6], the pose between the camera and LCD screen is estimated using a calibration planar mirror with some control points. Fig. 2 shows a schematic of the calibration mirror in Petz's method. However, the precise coordinates of the control points on the calibration mirror should be known, and they need to be measured using the photogrammetric method. It is obvious that the coordinates of the control points measured by photogrammetry [23] will increase the measurement time cost.

3. Pose estimation using planar mirror reflection

In fringe-reflection deflectometry, in order to simplify the pose estimation between the camera and the LCD screen, namely geometrical pose calibration, and to avoid the extra coordinate-measurement task for control points pasted on the planar mirror, a planar mirror without any control points is used to achieve geometrical pose estimation be-