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Flexible digital projector calibration method based on per-pixel distortion measurement and correction

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ABSTRACT

When a digital projector is applied in high precision applications, the intrinsic parameters and distortion characteristics should be calibrated precisely. In this paper, a flexible full-field projector calibration method is proposed without any approximate distortion model. With planar homography theory and fringe projection technique, the projector distortion characteristic on each pixel can be measured independently and an initial distortion map is generated. The intrinsic parameters are calibrated afterwards. Then, the initial distortion map can be refined by correcting the non-perpendicularity between the optical axis and image plane. The original pattern to be projected is corrected with the refined distortion map. Thus, the calibrated projector can be regarded as an ideal projector conforming to the pinhole model. Experimental results show a nearly ideal residual map for the corrected projection pattern. In addition, the proposed calibration method is flexible without any sophisticated ancillary equipment or complicated procedure.

1. Introduction

The digital projector has been widely studied in academia and applied in industrial fields due to its advantages of high contrast, flexible programming and low cost. In some high-precision applications, such as precision measurement and advanced manufacturing, accurate calibration techniques should be studied to alleviate the influence caused by the lens distortion of the digital projector. What's more, non-distorted patterns are required in some fields. For example, in the field of structure light measurement, particularly in fringe projection profilometry (FPP) [1], the projector should be calibrated precisely to obtain three-dimensional (3-D) point cloud accurately. In rapid prototyping applications, the digital projector acts as a programmable mask generator for photopolymer resin curing and the accuracy of the projected pattern is directly relevant to the prototyping quality [2]. In the precise augmented reality (AR) applications, digital projector is adopted as an optical indicator showing the virtual target marks on the working object [3]. The accuracy of the projector calibration result affects the final indication accuracy directly. Thus, precise and reliable calibration method, which enables the digital projector to work effectively and unleashes its potential in these high precision fields, is of great importance.

The optical structure of a projection system can be regarded as a reverse of an imaging system. In recent years, calibration technique for the imaging system (camera) has been studied extensively and a rich variety of camera calibration algorithms have been reported. However, the camera calibration methods cannot be applied to projector directly due to the inverse travelling direction of light in projection system. So many special studies have been carried out on projector calibration [4–8]. According to the representation method of lens distortion, the projector calibration methods can be grouped into two types: methods based on parametric models and methods based on lookup tables (LUT).

The projector calibration methods based on parametric models, similar to the common calibration methods for camera, introduce the polynomial model to represent the radial and tangential distortion of the lens. The distortion coefficients are determined by numerical optimization techniques [7–12]. Ma et al. proposed a nonlinear iterative optimization method to correct the lens distortion errors in structured-light profilometry system. The experimental result showed that the root mean-square (RMS) error of the system was reduced eight times after distortion correction [10]. The calibration method proposed in Ref. [11] improved the projector model by considering higher order (up to fourth) of radial and tangential lens distortion. And the experiments demonstrated that this calibration method can improve the measurement accuracy by 47%. The radial distortion of projector in Ref. [12] was corrected by a curve of distorted radius vs. paraxial radius. It's worth mentioning that these methods can be implemented easily and flexibly only with a calibrated camera and a planar target.

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However, high optical efficiency and horizontal projecting posture (optical offset) of the projector are the primary considerations in the projection lens design. So the conventional distortion parameters for the imaging lens are not quite suitable for the projection lens, and the parametric distortion model may result in large residual after calibration.

Some other calibration methods are implemented by building lookup table (LUT) to record and compensate the distortion errors. In [13,14], the FPP system was regarded as a black box and a method based on LUT was adopted to establish the relationship between phase values and real dimension for each pixel. These methods need to position a diffuse reflection target precisely during the calibration, which were usually inconvenient and time-consuming. Han et al. improved the calibration accuracy of the structured light system with a plane-based residual error compensation method [15], which mainly compensated the lens distortion. In Ref. [16], a general imaging model was employed to describe the FPP system. This model was no longer dependent on the specific optical layout because it treated the projection and imaging system (lens distortion included) as a black box connecting pixels with the corresponding rays. In Ref. [17], the adaptive fringe patterns were generated by modifying the carrier phase to eliminate the projector distortion in phase-measuring profilometry. It's noteworthy that all of the above LUT methods are designed to reduce the error of the whole FPP system, rather than correct the error caused by projector lens distortion independently. So these methods are inappropriate for other applications which are not based on camera-projector measuring structure. Liu et al. [18] proposed a new projector calibration approach using photodiodes to directly detect the light emitted from a digital projector. A polynomial distortion representation was employed to reduce the residuals of the traditional distortion representation model. However, sophisticated equipment and complicated calibration procedure made it complex to implement.

By combining the flexibility of the parametric model based methods and the high-accuracy of the LUT based methods, a new projector calibration method is proposed based on per-pixel distortion measurement and correction. Planar homography is used to determine the ideal homogeneous linear relationship between the camera image plane and the projector image plane without intrinsic parameters. The spatial phase calculation technique is employed to get the real mapping relationship between each pixel on the camera and projector image planes. The corresponding ideal and real points on projector image plane are obtained by an identical point on camera image plane with homogenous and phase calculation respectively. An initial distortion map is generated with the corresponding points. Then, the intrinsic parameters of the projector are calibrated by the patterns corrected with the initial distortion map. Finally, a refine distortion map is generated to correct the error caused by the non-perpendicularity between the optical axis and the image plane, which has not been corrected in the full-field distortion correction based on the homography. The final calibration result of the proposed method contains a refined distortion map and its corresponding intrinsic parameters. After calibration and distortion correction, the projector can be regarded as an ideal projector that conforms to the pinhole model.

The proposed projector calibration method can fully represent the lens distortion using a directly measured distortion map, instead of using an approximate model in existing methods. The residual of the calibration result can be minimized because the systemic error caused by the approximate distortion model is eliminated. Furthermore, the proposed projector calibration method can be implemented conveniently and flexibly, because only some specific patterns are needed to be projected and there is no need to know the motions of the camera or projector during the whole calibration procedure. Moreover, the calibration and optimization process are based on pinhole model, so the proposed method can be directly applied in the existing applications.

The rest of the paper is organized as follows: In Section 2, some basic principles such as the pinhole model, planar homography and phase calculation are introduced. Based on these principles, the projector calibration method is proposed in Section 3. Experimental verification of the projector calibration method is given in Section 4 and Section 5 concludes this work.

2. Basic principles

This section introduces some basic principles and deductions and provides theoretical support to proposed calibration methods.

2.1. Camera and projector model

As cameras are generally much more accurate than projectors, high-resolution cameras with small-distortion lens are usually applied to calibrate the projectors. The camera is modeled by the usual pinhole. The relationship between the coordinate of a spatial point $\boldsymbol{p_s}$ and its corresponding image point $\boldsymbol{p_c}$ can be given as follows:

$$s\boldsymbol{p_c} = \boldsymbol{A_c}\boldsymbol{T_c}\boldsymbol{p_s} \tag{1}$$

where s is an arbitrary scale factor, $\boldsymbol{p_s} = [x_s \quad y_s \quad z_s \quad 1]^T$ is the homogeneous coordinate of a spatial point in the object space and $\boldsymbol{p_c} = [u_c \quad v_c \quad 1]^T$ is the corresponding homogeneous coordinate in camera image space. $\boldsymbol{T_c} = \begin{bmatrix} r_{c11} & r_{c21} & r_{c31} & t_{cx} \\ r_{c12} & r_{c22} & r_{c32} & t_{cy} \\ r_{c13} & r_{c23} & r_{c33} & t_{cz} \\ 0 & 0 & 0 & 1 \end{bmatrix}$ is the camera extrinsic matrix, which represents the transformation from the object coordinate system to the camera coordinate system, with rotation matrix $\begin{bmatrix} r_{c11} & r_{c21} & r_{c31} \\ r_{c12} & r_{c22} & r_{c32} \\ r_{c13} & r_{c23} & r_{c33} \end{bmatrix}$ and translation vector $[t_{cx} \quad t_{cy} \quad t_{cz}]^T$, and $\boldsymbol{A_c} = \begin{bmatrix} f_{cx} & \gamma_c & u_{c0} & 0 \\ 0 & f_{cy} & v_{c0} & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$ is the camera intrinsic matrix which represents the transformation from the camera coordinate system to the image space, with the focal length in pixels (f_{cx}, f_{cy}), the principal point (u_{cO},v_{cO}) and the skew factor γ_c.

A projector can be regarded as inverse of a camera and the ideal pinhole model can be also applied to the projector [4]:

$$s\boldsymbol{p_p} = \boldsymbol{A_p}\boldsymbol{T_p}\boldsymbol{p_s} \tag{2}$$

where $\boldsymbol{p_p} = [u_p \quad v_p \quad 1]^T$ is the corresponding homogeneous coordinate in projector image space. $\boldsymbol{T_p} = \begin{bmatrix} r_{p11} & r_{p21} & r_{p31} & t_{px} \\ r_{p12} & r_{p22} & r_{p32} & t_{py} \\ r_{p13} & r_{p23} & r_{p33} & t_{pz} \\ 0 & 0 & 0 & 1 \end{bmatrix}$ is the projector extrinsic matrix, and $\boldsymbol{A_p} = \begin{bmatrix} f_{px} & \gamma_p & u_{p0} & 0 \\ 0 & f_{py} & v_{p0} & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$ is the projector intrinsic matrix.

2.2. Planar homography

Homography matrix, which is a nonsingular 3×3 matrix, is used to define the homogeneous linear transformation from a plane to another in the projective space [19]. In this paper, the planar homography is used to express the homogeneous linear relationship between the camera image plane and the projector image plane. As shown in Fig. 1, x-y plane of the object coordinate system coincides with the target plane. According to the pinhole camera model, coordinates of a target point on the target plane and its image point on the camera image plane satisfy the following relationship: