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Unified optical distortion correction method for imaging systems using a concise geometrical transformation model

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ABSTRACT

Since optical distortion has been a big trouble for various kinds of imaging systems, finding a simple correction method with wide applications is of significant importance. In this paper, we propose a unified and simple correction method, performing well for both photographic and projective imaging systems. The basic idea is regarding the optical distortion as geometrical deformation between the object and image, without considering the specific features of an optical system. First of all, a calibration template is employed to establish the geometrical transformation model (GTM) for the distortion of a built optical system. Two alternative algorithms are given to estimate the GTM in algebraic form. The computation is very simple because no intrinsic parameters of the optical system are needed to establish the GTM. Besides, the errors introduced by the fabricating and assembling process can be eliminated. Then, the corrected image of the photographic system or the pre-distorted image of the projective systems can be obtained accordingly utilizing the GTM. Experiments are conducted to demonstrate the effectiveness of our method with wide applications.

1. Introduction

Optical distortion describes the deviation between the ideal principal rays and real principal rays. Aspherical surfaces and freeform surfaces have been utilized to diminish the distortion and promote imaging performances [1–4]. However, when lager FOV and higher imaging resolution are demanded, the optical design itself usually cannot be further optimized to reduce the distortion [5–9], which means the subsequent computational (or called 'electric') correction is essential. Distortion is defined with several models, depending on the type of lens. The widely used radial distortion model was formulated by ray tracing based on classic aberration theory with rotational symmetry assumption [10]. Besides, plenty of models have been proposed to correct the distortion of more complicated systems. Here we concentrate on the distortion models for imaging systems. We will review several correction methods from two aspects: 1) the photographic imaging system, 2) the projective imaging system.

For normal and narrow FOV photographic systems, the radial and pin-hole models work well [11–13]. For the decentered or tilted lens, an extra tangential distortion was introduced in addition to the radial one to improve the accuracy [14]. A two-step metric calibration method using a non-linear distortion model was proposed in [15] to calibrate the non-linear camera lens distortion. Straight lines in 3D scenes combined with the circle fitting algorithm were utilized to correct the distortion of super wide fish-eye lenses, without the need for determining reference points or calibrating the camera [16]. A supplementary of the radial symmetry model was made in [17] with forward and backward models, deriving the distortion parameters accurately for fish-eye lens and common wide angle lenses. In [18], the whole image was non-uniformly calibrated from center to the edge with a region-separated adaptive algorithm based on the improved radial model. In [19], a trinocular system was calibrated using a set of constraint points defining the formation of the image, and a mathematical model was built based on the relative positions between the camera and the feature points to calculate the distortion coefficients. Many other methods, such as local correction method, midpoint circle algorithm, global fitting and local optimization method were adopted according to the characteristics of the optical system [20–22].

For projective systems such as the projectors, Head Mounted Displays (HMDs) [23], Virtual Reality (VR) and Augmented Reality (AR) devices, the general adopted correction idea is pre-warping the initial image source to offset the projection optics. The concrete calibration method varies along with the application. Working in tough environments, HMDs often yield out quite complex distortion. Rolland et al. proposed an efficient unwarping method based on a network interpolation using radial basis functions, to obtain more accurate predistortion image of HMDs

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[24]. The VR devices, such as Oculus Rift [7] can display wide field of virtual 3D scene for human eyes. These devices demand wide FOV and high imaging resolution to provide deep immersion sense, causing large distortion inevitably. The radial distortion model is suitable for VR devices because their optical systems are simple [25]. 2D images of multi-projectors can be utilized for natural 3D display system based on the reconstruction of light field (LF). The calibration of the distorted 2D images is needed to reduce the deformation of the reconstructed 3D scene [26–28]. An interesting way to correct the distorted image using a device fabricated with liquid crystal lens arrays was proposed in [29]. In our previous work [30], a calibration method based on FOV division is proposed to calibrate an avionic HMD and a micro-HMD with complex distortion.

To conclude, calibration methods vary along with the optical systems, which is inconvenient. Thus, finding a correction method with wide applications is challenging and attractive. As an extension to our previous work, a unified distortion correction method is proposed in this paper, working well for both photographic and projective imaging systems. This method works by firstly employing the calibration template to estimate the geometrical transformation model (GTM) for the distortion, and secondly correct the distorted image for the photographic system or calculate the pre-distorted image source for the projective system. Two alternative algorithms are given to calculate the algebraic form of the GTM in this paper. The corrected images of the photographic systems or the precious predistortion images for the projective systems can be obtained. As intrinsic or extrinsic system parameters are not needed, the theoretical and mathematical work is concise and the errors introduced by fabricating and assembling process can be eliminated.

The paper is organized as follows. Section 2 describes the calibration process and explains how the geometrical transformation model is computed. Section 3 gives several experimental results to demonstrate the effectiveness of our method for both photographic and projective imaging systems.

2. Proposed calibration method

First of all, we will explain the geometric transformation model for the distortion of an imaging system. Conventionally, the distortion is divided into two types: (1) the radial distortion found in most symmetric optical systems, (2) the tangential distortion caused by the asymmetric designs or fabrication errors. Both radial distortion and tangential distortion are essentially geometrical deformation, causing no resolution reduction. Thus, an imaging system can be treated as a geometric transmission system. The input information is the set of points of the object, while the output information is the detected distorted points in images. Therefore, the geometrical transformation model (GTM) is utilized with good reason.

A calibration template is utilized to compute the GTM, as shown in Fig. 1. I(x, y) and P(u, v) denote one pair conjugate points of the imaging system. The rectangle ABCD comprised of four adjacent dots denotes a sub-FOV. EFGH denotes the detected image of ABCD. The following notation will be used throughout the paper:

(x, y): the coordinates of a point of the object.

(u, v): the detected image coordinates of (x, y).

(u', v'): the precise image coordinates of point (x, y), which is predefined by uniformly dividing the imaging FOV in this paper.

(x', y'): the coordinates of the pre-distorted location corresponding to the point (x, y).

For each coordinates, a subscript i represents i-th point in the calibration template that we used to estimate the GTM.

The calculated GTM is utilized in two different ways: 1) for photographic system, the image (displayed on image sensors such as CCD, CMOS, etc.) is corrected directly, 2) for projective systems, the object (image sources such as LCD, LCOS, OLED, etc.) need to be pre-distorted to offset the system's distortion.

The proposed calibration method has the following steps:

1. The GTM is estimated in an algebraic form using a calibration template.
2. If it's an imaging system, correct the image utilizing GTM with the detected distorted image. Else, calculating the pre-distortion object with the pre-defined precise projected image.

A calibration template is used to obtain the real distortion of a built system, as shown in Fig. 1. Fig. 2 is the flow diagram of our proposed method. Two algorithms are proposed to compute the GTM.

2.1. Algorithm 1: global polynomial fitting

Generally, the distortion's nonlinearity would be aggravated for larger FOV, so that the nonlinear polynomial will be employed in this algorithm. The basic idea of the global polynomial fitting (GPF) algorithm is establishing one polynomial to model the distortion.

For photographic system, the algebraic form of the GTM is given by:

$$u'_i = \sum_{m,n=0} k_{umn} u_i^m v_i^n.$$
$$v'_i = \sum_{m,n=0} k_{vmn} u_i^m v_i^n. \tag{1}$$

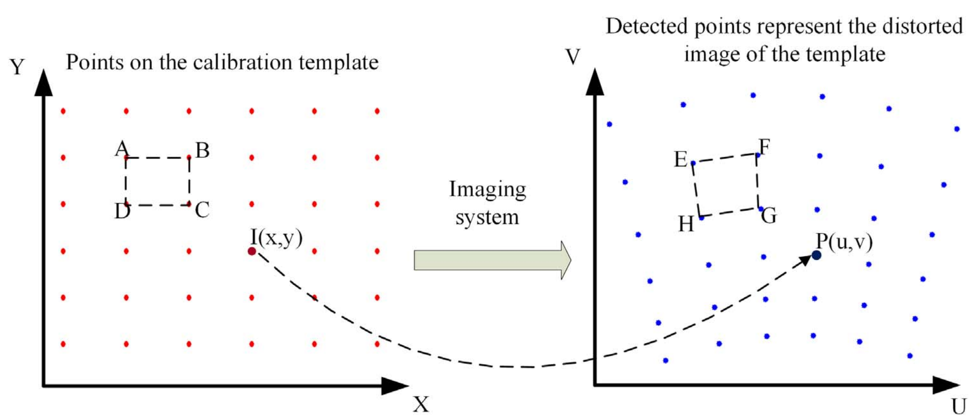

Fig. 1. A calibration template is utilized to find the correspondence between the scene and image points.