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Lens distortion correction for improving measurement accuracy of digital image correlation

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ABSTRACT

Digital image correlation is widely applied in the measurement of displacement and strain fields through detecting the laser or sprayed speckle on the specimen surface. Generally, the existing digital image correlation methods often met difficulties of low detection accuracy under the influence of lens distortion. To tackle such difficulties, the piecewise spline function is used to describe the distortion, and a continuous smooth distortion model can be obtained after eliminating the noises by means of the mean value filtering and smoothing spline algorithm. Since the proposed method corrects lens distortion on the pixel plane, it will provide opportunity to obtain unbiased displacement in digital image correlation. Experiment results verify that the proposed method eliminates the effect of lens distortion from displacements measurement by means of two-dimensional digital image correlation.

1. Introduction

Computer vision and digital image correlation (DIC) have been widely used in the field of experimental mechanics for full-field displacement and strain measurements [1–3]. In the experiments for analyzing material characterization, Two-dimensional DIC (2D-DIC) is often performed to get displacement and strain in the plane. Compared to Three-dimensional DIC, there are many advantages in 2D-DIC, as e.g. less equipment being used (only one camera and one LED lamp) and high accuracy for measurement [4].

During the implementation of 2D-DIC, the specimen surface should be placed parallel to the CCD sensor, and the speckle pattern on test planar specimen surface is imaged onto the camera's sensor plane to form a digital image. Subsequently, a pinhole camera model is typically adopted, which assumes the object geometry is proportional to what is displayed on the image plane. However, due to additional aberrations caused by the lens, there are distortions between the image and object. These distortions will be amplified by the pinhole camera model, and the errors in displacement and strain results due to camera lens distortion are more pronounced [5]. Because there are many deviations in the design and manufacture of lens, as e.g. lens aberrations, misalignment of optical elements, even using an expensive high-quality telecentric lens, image distortions unavoidably exist [6]. In this case, the lens distortion correction must be introduced to overcome this problem.

Recently, the error associated with lens distortion has been recognized and techniques to reduce the effect of an imperfect lens have been described. For example, Schreier et al. [7] proposed a new methodology to calibrate accurately any imaging sensor by correcting a priori for the distortion using a non-parametric model. Subsequently, the lens distortion in a high-speed imaging system is corrected by means of the similar technique in the literature [8], and the system can not only be correctly calibrated but can also be used as robust and accurate full field measurement systems in both 2D and 3D configurations. Another calibration procedure that incorporates a fine-pitched orthogonal cross-grating plate was used in Zhang's method [9]. In the method, a third-order polynomial distortion function was constructed to describe the distortion errors and the coefficients were determined by comparing node locations of the standard cross-grating plate with those in acquired images. More recently, one novel technique was proposed by Yoneyama [10,11] for the determination of the radial distortion amount of a low-cost zoom lens. In the technique, the additional in-plane displacements of the speckle pattern, due to lens distortion in rigid body translation, were measured by means of a complicated non-linear least squares method with an iterative procedure. To improve Yoneyama's work, the known coordinates of distorted image points, instead of ideal image points, are used in the distortion model in Pan's work [6], so that linear least squares method without the need of iteration calculation can be directly used to estimate the distortion coefficients.

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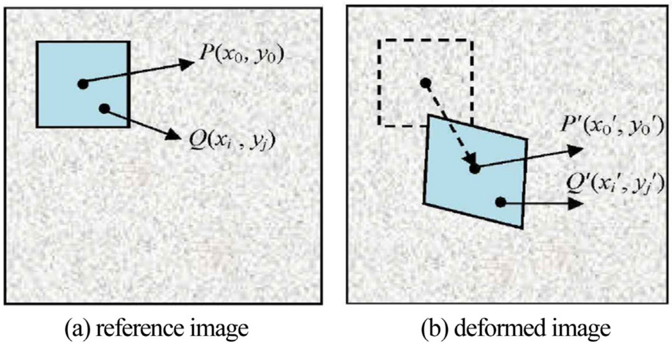

Fig. 1. Schematic illustration of a reference square subset before and after deformation.

The above methods mostly imposed a uniform distortion model to describe the whole image distortion. However, lens distortion can be regarded as a system error since camera and lens are fixed, and none of the distortion models will represent the image deformation exactly. The image deformation always contains some kind of distortion that can't be represented by the existing uniform model [12]. In other words, these distortion models cannot embody the real warping in each part of the image, especially in the region far away from image center. In addition, since the whole image in the view field is not used in the displacement and strain measurements, correcting the distortion of the whole image is not necessary. In this paper, a simple method is proposed to correct lens distortion in a region of interest on the pixel plane, and a rigid body translation test is performed in order to validate the proposed method.

2. Digital image correlation method

The digital image correlation method uses random speckle pattern to match the corresponding points precisely on two images [13–15]. As shown in Fig. 1, the left image is the reference image, and the right image is the deformed image. In the reference image, a square reference subset of $(2M+1)\times(2M+1)$ pixel centered at point (x, y) is picked. The matching procedure is to find the corresponding subset centered at point (x', y') in the deformed image which has the maximum similarity with the reference subset. For the best estimate of the displacements, a normalized cross-correlation coefficient, S, defined as follows:

$$S\left(x, y, u, v, \frac{\partial u}{\partial x}, \frac{\partial u}{\partial y}, \frac{\partial v}{\partial x}, \frac{\partial v}{\partial y}\right) = 1 - \frac{\sum F(x,y)G(x',y')}{\sqrt{\sum F(x,y)^2}\sqrt{\sum G(x',y')^2}}, \tag{1}$$

where $F(x, y)$ is the gray level value at coordinate (x, y) of one image and $G(x', y')$ is the gray level value at point (x', y') of the second image. The coordinates x' and y' after deformation are related to the coordinates x and y before deformation as

$$\begin{aligned} x' &= x + u + \frac{\partial u}{\partial x}\Delta x + \frac{\partial u}{\partial y}\Delta y \\ y' &= y + v + \frac{\partial v}{\partial x}\Delta x + \frac{\partial v}{\partial y}\Delta y, \end{aligned} \tag{2}$$

where u and v are the displacements for the subset centers in the x and y directions, respectively. The terms Δx and Δy are the distances from the subset center to point (x, y). Image correlation is performed by determining values for u, v, $\partial u/\partial x$, $\partial u/\partial y$, $\partial v/\partial x$ and $\partial v/\partial y$ which minimize the correlation coefficient S. Detail of digital image correlation with Newton–Raphson optimization given in articles by Sutton and co-workers [15].

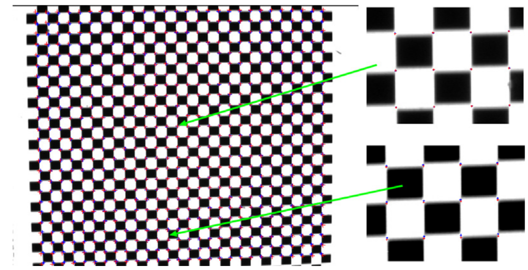

Fig. 2. The undistorted and distorted (extracted) points in the image (the red '+' is the point projected from world coordinate by linear model and the blue '*' is the point extracted) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

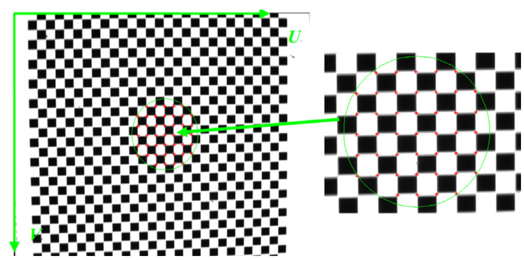

Fig. 3. The image of check board.

3. Distortion correction

In the image, the distribution of image distortion is not consistent. Even if the same motions occur in the specimen surface, different amount of motions in the sensor plane will be detected by the algorithms of 2D-DIC. This shows that there are the additional motions caused by image distortion in the detection results, and these motions corrupt the real measurements [16]. Therefore, the lens distortion should be corrected first before detection. Regarding the correction, the radial, decentering and prism distortions are often considered and described as a uniform mathematical model in the previous literatures [17–19]. In addition, in order to reduce the computational complexity, the model is usually simplified as the radial distortion model [6,10,11]. However, the image distortions are related to a specific imaging system and cannot be represented well by the uniform model. To improve the accuracy of distortion correction, a method without using a model is introduced to describe the distortion only in the region of interest in this paper, and the method mainly involves three steps:

3.1. Solving a linear camera model

As it is shown in Fig. 2, the deviation of the points near the center of the image is much smaller than the far ones'. Inspired by this phenomenon, a linear calibration is carried out by means of a check board. In the method, the feature points near the projection center are used to calibrate a camera without considering image distortion, as shown in Fig. 3. In this way, an accurate linear calibration model can be obtained by using the following equation:

$$s\begin{bmatrix} x_d \\ y_d \\ 1 \end{bmatrix} = H\begin{bmatrix} X_W \\ Y_W \\ 1 \end{bmatrix} \tag{3}$$

where x_d and y_d are the image coordinates of corner points extracted from the board image, and (X_W, Y_W, Z_W) is world coordinate of those; the homography H is a 3×3 matrix, and s is an arbitrary scale factor. If measurement is carried out only in the center region of image, the accuracy of measurement usually can be