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A novel camera calibration method for deflectometry system

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Abstract

Phase measuring deflectometry (PMD) is a well-established method to evaluate specular surface shape by detecting gradient data. In a PMD measurement, camera calibration plays a significant role. Using classical camera calibration methods to calibrate PMD system, the root mean square (RMS) of reprojection error can only be achieved for around 0.3 pixels. Therefore improvement for an accurate camera calibration in a PMD system is a special focus for PMD research. In this paper, a novel calibration method is presented to enhance camera calibration accuracy in a deflectometry system. Before calculating the initial value of internal and external parameters of the camera, pixel-by-pixel distortions are compensated by the proposed algorithm based on active phase target. Experimental results demonstrate that the proposed calibration method can effectively reduce the RMS of reprojection errors to 0.0237 pixels.

Keywords: Camera calibration, distortion compensation, deflectometry, PMD

1. Introduction

Phase Measuring Deflectometry (PMD) is a well-established method to measure the form of specular surfaces by detecting gradient information [1-2]. To acquire a global shape, slope data has to be integrated, while this procedure is quite sensitive to systematic errors. In the system calibration process, camera calibration plays a significant role. However, root mean square (RMS) of reprojection error for traditional calibration method with passive target can only be achieved for around 0.3 pixels [3], which mainly restricts the shape measurement accuracy of PMD in hundreds of nanometers [2]. Recently, active phase target has been researched to enhance the calibration accuracy [4-6]. Compared to traditional 2D calibration target such as chessboard, the main advantage of this active technique is that higher accuracy of feature detection can be achieved. Besides the affection of feature detection to the camera calibration, distortion is another factor having impact on the calibration accuracy. Currently, most calibration methods treat the whole image having the same distortion parameters, which results that calibration error in image edge is bigger than those near image center. In this paper, a novel camera calibration method based on active phase target is proposed. Before calculating the initial value of internal and external parameters of the camera, pixel-by-pixel distortions are compensated by the proposed algorithm. The principle of the proposed method is described in section 2. Section 3 shows the experimental results, and section 4 gives conclusion and future remarks.

2. Principle

Pinhole model is usually adopted in a camera calibration work, where a homography is used to represent the relationship between targets expressed in world coordinate system and corresponding images in terms of pixel coordinate system. In this model, both internal and external parameters can be calculated based on a group of homographys. However due to distortion, pixels far away from image center cannot obey one linear mapping. Considering this, an active phase target can be used, where a dense map between camera pixels and their corresponding physical positions in LCD screen (the world coordinate system) can be built through phase value. Hence, if one accurate homography can be obtained initially, pixel-by-pixel distortions can be compensated according to this reference homography. The following sections will discuss how to get the reference homography and then compensate pixel-by-pixel distortion.

2.1. Reference Homography

In order to obtain unique corresponding points in LCD screen for camera pixels, two mutually perpendicular absolute phase maps are needed, as shown in figure 1. To enhance the accuracy of the phase maps, eight-step phase shifting technique is used to eliminate the influence of nonlinearity and optimum frequency selection technique [7] is chosen to obtain an absolute phase map. In addition, a wiener filtering is also applied to eliminate random noise from the absolute phase maps.

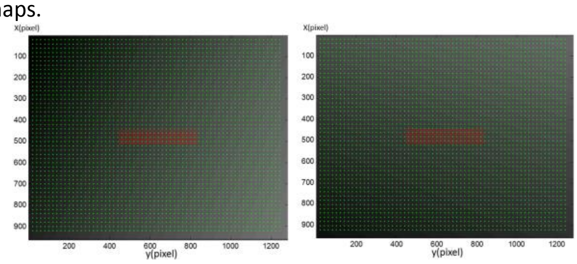

Figure 1. Two absolute phase maps are obtained. 39×7 red dots with a period of 10 pixels are chosen to calculate the reference homography and 62×46 green dots with a period of 20 pixels are used to calibrate the internal and external parameters of camera.

Since pixels near image center can be treated as having no distortion, we can use pixels marked red in figure 1 to calculate the linear mapping H_{ref} between camera pixels and their corresponding points in the world coordinate system based on equation 1. Besides, this linear mapping can be used as a reference homography to compensate the distortions of the whole image.

$$sm = HM \quad (1)$$

2.2. Pixel-by-pixel Distortion Compensation

Using the above linear mapping model, given one camera pixel m_{real}, we can obtain its theoretical position expressed in pixel coordinate system through its corresponding position M_{real} and the reference homography, where M_{real} is expressed in the world coordicate system. Since random noise has been removed by filtering and the LCD screen is treated as an ideal plane, deviation between the real pixel m_{real} and its theoretical position can be seen as systematic errors caused by distortion, which can be calculated according to equation 2. For different relative poses of LCD screen and camera, this deviation for certain pixel should be the same. Therefore, by compensating the distortion with the corresponding average deviation E_{ave} according to equation 3, the calculated pixel m_{ture} should be in the correct position in the pixel coordinate system under the linear mapping model. Then, the corrected pixels are used to calculate the homography for the whole image, to derive the initial value of internal and external parameters of camera, and to obtain the final results through bundle adjustment.

$$Error = hnormalise(H_{ref}M_{real}) - m_{real} \quad (2)$$

Where $hnormalise(\,)$ means normalising matrix of homogeneous coordinates to a scale of 1, and m_{real} is the homogeneous coordinate of one pixel.

$$m_{ture} = m_{real} + E_{ave} \quad (3)$$

3. Experimental Results

To verify the method proposed above, a practical camera calibration is carried out. The camera to be calibrated is a CCD sensor (Pixelink camera with a resolution of 1280×960) with a 12 mm lens. A LCD monitor (Dell E151Fpp with a resolution of 1024×768) is used as the active target. During the whole calibration process, data from 8 relative poses of LCD screen and camera are captured, and fixed pixels marked as green dots in figure 1 are chosen as control points. The distortion error for the chosen pixels is shown in figure 2. Figure 3 amplifies the top-right corner of the distortion error map. In order to show the advantage of the proposed method, we compare the proposed method with Zhang's method [3] using the same control points to calibrate the internal and external parameters of camera, as shown in figure 4. After applying a 7×7 wiener filtering to the absolute phase maps, the root mean square (RMS) of the reprojection error is reduced from 0.1151 pixel to 0.0486 pixel using Zhang's method. When the proposed method is applied, the RMS is reduced from 0.0833 pixel to 0.0237 pixel. The final calibration results of the two methods are shown in figure 5.

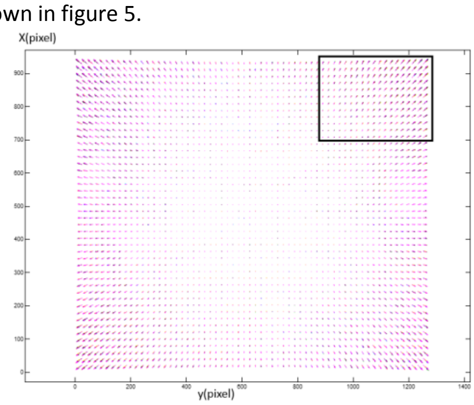

Figure 2. The distortion error for the chosen pixels.

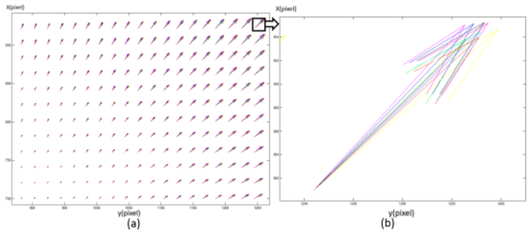

Figure 3. The amplified distortion error map for the chosen pixels, 8 colors represent the distortion for one pixel in 8 relative poses of screen and camera. (a) amplified map for the top-right corner of figure 2; (b) amplified map for the top-right pixel.

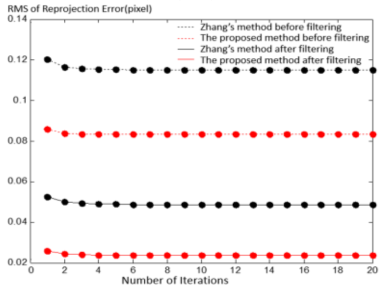

Figure 4. The comparison between the proposed method and Zhang's method using the same calibration data.

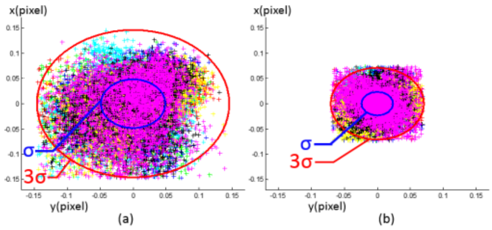

Figure 5. The reprojection error of the two methods. (a) Zhang's method; (b) the proposed method.

4. Conclusion and future work

In this paper, a novel camera calibration technique based on active phase target is proposed. Pixel-by-pixel distortions are compensated before the calculation of the initial value of internal and external parameters of camera. Experimental results show that, under the same condition, calibration accuracy of the proposed method is 2 times better than Zhang's method. The proposed calibration method can be used not only in deflectometry system but also in the camera calibration of a general imaging system. Next step, a deflectometry system will be calibrated to test the significance of the proposed method.

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