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Whole-field high precision point to point calibration method

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A R T I C L E I N F O

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A B S T R A C T

The traditional camera calibration methods based on internal parameters and external parameters employ a uniform analytic function to meet the requirements of statistical optimization. It may fail in describing the whole measurement volume properly when the distortion is strong. A novel whole-field point to point calibration method is proposed, in which the mapping relationship between the pixel coordinates and world coordinates of each individual spatial point is described by look-up tables. To guarantee the high calculation accuracy of the world coordinates of each spatial point, a virtual telecentric optical projection technology is used to encode the phase of each spatial position by loading a carrier frequency to establish a virtual world coordinate system. Then the mapping tables between the eponymous pixel and the corresponding virtual world coordinates of each calibrated position with known height can be established employing polynomial fitting or interpolation methods. At last, the real world coordinates of each spatial point are calculated by removing the additional displacement caused by the carrier frequency. Employing our method, errors caused by system installation and lens distortion, etc. can be effectively ruled out. An exhaustive comparison between the proposed calibration method and the traditional 3D stereo target calibration (3DSTC) method based on pinhole model with optimization strategy is given. Our method yields more accurate calibration results than 3DSTC method because it is closer to the real physical model. Experiment results show the feasibility and validity of the proposed method. It is recommended to be used in monocular measurement system when higher accuracy is requested.

1. Introduction

The active fringe projection profilometry (FPP) [1] based on triangulation measurement principle, due to its advantages of non-contact, high precision, high speed and low cost [2–4], has been widely applied in various fields, such as industrial inspection, quality control, machine vision, movie stunts, biomedicine, etc. Generally, fringe projection profilometry are mainly divided into monocular measurement technology and binocular measurement technology. The binocular measurement system with two cameras and a projector measures the profile of the tested object from different perspectives simultaneously, and the 3D coordinate information of the object is acquired through stereo matching and camera calibration [5]. While in the monocular measurement system, in order to obtain the 3D shape information of the measured object, the depth information within measurement volume is obtained by phase-height mapping, and the x-y coordinates of the spatial point are obtained by camera calibration.

In the monocular measurement technology based on the structured light projecting, many popular phase analysis methods have been proposed, such as Moire profilometry [6], Fourier transform profilometry(FTP) [7,8], phase measuring profilometry(PMP) [9,10], modulation measurement profilometry [11], etc. Among them, the phase shifting technique, due to the high phase calculation accuracy, is applied to obtain the phase information corresponding to the height distribution of the tested object. However, the explicit relation between the phase and the height is not easy to obtain accurately because the geometry parameters and other parameters of the explicit calibration model are not easily obtained accurately [12]. In order to obtain the high accuracy phase-height mapping, the implicit calibration model has attracted the interest of researchers [13–18]. Zhou et al. [13] proposed a direct phase to height algorithm and described the phase-height mapping relationship with linear polynomial fitting method. Considering the defocus and the aberration, in Refs. [14–18], quadratic and higher order polynomial fitting methods were given to reduce the fitting error. References [19–21] establish the look-up tables utilizing piecewise fitting method to further improve the phase-height mapping accuracy. Therefore, high accuracy phase-height mapping relationship for each individual pixel can be established by the above proposed method, respectively.

In monocular measurement system, high accuracy calculation of the x-y coordinates of the spatial point is also needed for guaranteeing the accuracy of 3D reconstruction. The x-y coordinates are obtained by the camera calibration. The quality of the camera calibration directly influences or even determines the overall performance of the measurement system [22]. The traditional camera calibration methods are based on

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the parameterized analytical model. The relationship between the pixel coordinates and its corresponding world coordinates of the whole measurement volume is described by the internal and external parameters based on pinhole imaging model combined with parameter optimization operation [23]. The typical camera calibration methods can be generally divided into two categories: high precision 3D stereoscopic target calibration [24] and 2D plane target calibration [25,26]. The camera calibration method based on 3D calibration targets has high calibration accuracy, but high-precision 3D stereoscopic calibration targets are not easy to be manufactured and maintained. The manufacture and maintenance of the 2D plane target is relatively simple, so many researches focus on the 2D plane target calibration. 2D plane target calibration is carried out by calculating the internal and external parameters from extracted feature points and employing the geometry constrain of target. In Ref. [25], Tsai proposed two-step calibration method based on RAC, in which most of the equations were linear equations, and the complexity of parameter solution was reduced. The disadvantage of Tsai's method is that only the radial distortion was considered in the calibration model. Zhang [26] proposed a more popular camera calibration method to simplify the calibration process, in which, a flat 2D target can be placed with arbitrary poses and orientations. Zhang's method has been widely used in many fields to calibrate camera because of its advantages of quick, simple operation and high precision. There are other methods used to improve the accuracy of the camera calibration, including improving the extraction accuracy of feature points [27,28] and the optimization of estimating the camera parameters [29,30]. All in all, the camera calibration methods based on internal and external parameters are widely applied in 3D measurement technology. However, in actual measurement, the proposed 2D calibration methods based on pinhole imaging model and parameter optimization operation just guarantee that the measurement results are statistically optimal in the whole measurement volume after least square optimization. But it cannot guarantee that the calibration result is most optimal for each measurement point. In high accuracy measurement based on monocular measurement system, besides establishing the phase-height mapping for each space point, performing a more accurate camera calibration is very important for 3D reconstruction. Independently calibrating each pixel of camera to guarantee the most optimal x-y coordinates calculation for each measurement point is expected. Thus, a more accurate pixel-based camera calibration method is proposed in this paper.

It should be noted that the camera calibration methods that involve the liquid crystal display (LCD) and phase-shifting methods have attracted many scholars' attention due to the following two advantages. First, the LCD screen manufactured by large scale integrated circuits and lithographic techniques has high resolution, and its pixel pitch is uniform and known [31]. Second, the feature detection is both accurate and flexible owing to the advance of the fringe analysis technique [32]. For instance, Ref. [33,34] use the LCD to generate accurate checkerboard calibration patterns, and Ref. [27] uses the LCD to display phase-shifting fringes to improve the camera calibration precision. The application of LCD ensures the precision of the target and improves the accuracy of the feature detection. However, the main principle of the above camera calibration methods is still based on internal and external parameters model, that is, a uniform analytic function is employed to meet the requirements of statistical optimization. The calibration result satisfies the global optimum, but it cannot guarantee that every measurement point in the system is optimal. Our method is to calibrate each point in the measurement space separately.

In our method, a LCD screen is vertically installed on a high precision translation stage and moved along the direction of the camera optical axis. Each pixel on LCD can be regarded as feature points with high accuracy. The sinusoidal fringe patterns are displayed on the LCD screen. The phase carried within the fringes at each calibration position can be extracted employing multistep phase-shifting technology accurately. To guarantee the high calculation accuracy of the world coordinates of each spatial point, a virtual telecentric optical projection technology is introduced to encode the phase of each spatial position by loading a carrier frequency. The encoded phase is used to calculate virtual spatial position coordinates of each spatial point. That is, a virtual world coordinate system is established. In other words, the adding of carrier frequencies avoids the ambiguity in establishing the look-up tables. The mapping tables between the phase of the eponymous pixel and the corresponding virtual world coordinates at each calibrated position with known height can be established employing polynomial fitting or interpolation methods. The world coordinates of each spatial point can be calculated by removing the additional displacement caused by the carrier frequency. As a comparison, some feature points with known 3D coordinates randomly extracted from the measurement volume to perform traditional 3DSTC with least square optimization. The distance of two spatial points is calculated by our method and the 3DSTC method, respectively. The results are contrasted with the actual physical distance. The comparison shows that the proposed calibration method yields more accurate calibration results than 3DSTC method does. Therefore, in the high precision measurement based on monocular measurement technology, both high accuracy phase-height mapping and high accuracy pixel to pixel camera calibration are expected. Our work in this paper is recommended in the application of high accurate measurement based on monocular measurement technology.

The rest of the paper is organized as follows: Section 2 illustrates some related techniques used in the point to point calibration method, such as, the phase-shifting method, the camera model and the traditional 3DSTC method. Section 3 explains the proposed calibration method and presents the calibration procedures. Section 4 presents some experimental results, including the comparison between the proposed method and 3DSTC method to verify the performance of the proposed calibration method, and Section 5 summarizes this paper.

2. Principles

2.1. High precision phase acquisition technology

Phase-shifting technique has gained great popularity in the area of optical metrology owing to its high phase calculation accuracy. There are a variety of popular phase shifting algorithms for 3D measurement, including three-step, four-step and N-step (N > 3), etc. In general, the more steps are used, the better the accuracy can be achieved. For an N-step phase-shifting algorithm, the kth projected fringe image can be mathematically represented as follows:

$$I_k(x,y) = B(x,y) + A(x,y)\cos(\phi(x,y) + 2k\pi/N) \quad (1)$$

where $k = 0,1,\ldots N-1$ and $B(x, y)$ represents the average intensity, $A(x, y)$ indicates the intensity modulation, and $\phi(x, y)$ denotes the phase to be solved. The tangent of the phase can be calculated by Eq. (2).

$$\phi(x,y) = -\tan^{-1}\left[\frac{\sum_{k=1}^{N} I_k \sin(2k\pi/N)}{\sum_{k=1}^{N} I_k \cos(2k\pi/N)}\right] \quad (2)$$

The nature of the arctangent function produces the wrapped phase $\phi(x, y)$ with a range from $-\pi$ to π. A temporal or spatial phase unwrapping algorithm is needed to obtain a continuous phase map [35]. In the proposed point to point camera calibration method, the accurate absolute phase distribution carried by fringes is needed to calculate the world coordinates of spatial points. Therefore, multistep phase-shifted technique is used to get rid of the influence of nonlinearity of fringe patterns as much as possible for obtaining the high accurate phase information [36].

2.2. Camera model

The most common camera model is the pinhole model augmented by parameters of radial and tangential distortion [23]. Applying the pinhole camera model, the relationship between a spatial point and its