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A novel and accurate calibration method for cameras with large field of view using combined small targets

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ABSTRACT

Camera calibration accuracy is directly affected by the area and precision of targets. The low precision of large targets reduces camera calibration accuracy, whereas small targets lead to poor calibration results for their small size despite the high precision. To solve the problems, this paper proposes a calibration method for cameras with a large field of view, where multiple small high-precision targets are assembled to form combined small targets (CST). The main steps of the proposed calibration method are as follows. First, multiple high-precision small planar targets are distributed in the field of view of the camera to form a CST. The camera is placed for at least twice randomly to capture the CST images. Then, the feature points of CST are automatically located, and the intrinsic parameters of the camera are calculated based on the *H* matrix between each of the small planar targets and the image plane. All of the feature points of CST are united together by the transformation matrices between the coordinate frames of the small targets to obtain a large three-dimensional data field. Finally, the intrinsic parameters of the camera are optimized via the Levenberg–Marquardt algorithm. Simulation and real data experiments show that the calibration accuracy using the proposed method is close to that using a large target whose size is equal to the area enclosed by the small targets of CST, and is much better than that using a small target.

1. Introduction

The camera model represents the projective relationship between the measurement space and the CCD image plane of the camera. The aim of camera calibration is to determine the parameters of the camera model. Camera calibration has always been a key research topic in the fields of photogrammetry and computer vision. Camera calibration accuracy directly affects the measurement accuracy of the vision measurement system, such as robot visual navigation, reverse engineering, and virtual reality. Therefore, a simple and high-accuracy camera calibration method is of significant importance.

The existing calibration methods usually require different types of targets. Currently, although 3D targets [1–3] lead to high calibration accuracy, they are rarely used due to their mechanical difficulties and large size, which makes them unsuitable for a narrow measurement environment. The camera calibration methods using a 2D target [4–8] have greater flexibility than that using a 3D target. Among them, the camera calibration method proposed by Zhang [7] (Zhang method) is the most typical one, in which 2D target can be moved randomly. The advantages of Zhang method are that the calibration process is simple, flexible, and of high accuracy, therefore it has been widely applied in camera calibration. Meanwhile, the disadvantages of the method lie in that a large 2D target is required when calibrating cameras with large field of view, otherwise, if the 2D target is relatively small, the

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calibration accuracy may be poor. The camera calibration methods using a 1D target [9–11] can calibrate a single camera [9] only in the case of certain constraints, due to the limit of the co-linearity of the feature points on 1D targets, which restricts the application of 1D targets in the vision measurement system. In addition to the aforementioned target types, numerous camera calibration methods based on multiple balls [12–15] have been introduced. The camera calibration methods based on multiple balls can solve the intrinsic parameters of several cameras distributed in different angles at the same time, but large spheres are needed to calibrate cameras with large field of view. Other calibration methods using a rotating surface [16,17], sky star [18], and shadow of the sun [19–22] are also proposed in some papers, but these methods cannot achieve high-accuracy camera calibration. Meanwhile, self-calibration methods with no targets required can solve the intrinsic parameters of cameras according to the relationship between the corresponding points in multiple images [23–27]. Such methods are flexible, but of poor robustness, and are typically applied in vision systems that do not require a high calibration accuracy.

Zhang method is simple and practical, and has been widely applied in camera calibration. When a 2D target occupies a large proportion in the field of view of the camera, the method is of high calibration accuracy. But as the 2D target becomes smaller, calibration accuracy deteriorates sharply. Wider area occupied by the feature points of the target in the field of view of the camera results in more accurate calibration results. The feature points of a large target can fill the entire field of view of the camera, indicating high calibration accuracy. If we consider a large target as being composed of multiple independent small targets, why the camera calibration accuracy using multiple independent small targets is worse than that using a large target under the same condition, in terms of the position and number of target feature points? Analysis shows that the feature points of a large target constitute an entirety and cover the entire measurement space, so the calibration results reflect the perspective projection relationship between the big measurement space and the CCD image plane. However, the feature points of independent small targets do not form a whole entirety, and each small target covers a small measurement area, so the calibration results reflect the perspective projection relationship between the small measurement space and the CCD image plane. Thus, the calibration accuracy using a large target is better than that when independent small targets are used.

A novel calibration method for cameras with large field of view based on combined small targets (CST) is proposed in the paper. Multiple high-precision small targets are distributed in the field of view of the camera to form CST. The camera captures images of CST for at least twice randomly. The feature points of the CST are merged together by the transformation matrices between the small targets to form an integral 3D data field for camera calibration. Compared with that of independent small targets, the calibration results of the proposed method better reflect the perspective projection relationship between the measurement space and the CCD image plane of the camera. Moreover, camera calibration accuracy is higher.

The rest of this paper is organized as follows. In Section 2, the camera model is described simply. The basic principle of the CST is introduced in Section 3. In Section 4, the basic principle of the proposed method is introduced in detail. The proposed calibration method is verified by synthetic experiments in Section 5 and real data experiments in Section 6. Conclusions are drawn in Section 7.

2. Camera model

The homogeneous coordinates of point P in the world coordinate frame (WCF) and the camera coordinate frame (CCF) are $\boldsymbol{q}_w = [x_w, y_w, z_w, 1]^T$ and $\boldsymbol{q}_c = [x_c, y_c, z_c, 1]^T$, respectively. The undistorted homogeneous coordinate of P in the image coordinate frame in pixels (I_pCF) and the image coordinate frame in mm (I_mCF) are $\boldsymbol{p}_u = [u, v, 1]^T$ and $\boldsymbol{p}_n = [x_n, y_n, 1]^T$, respectively.

The perspective projection model of the camera is as follows:

$$\rho\ \boldsymbol{p}_u = \rho\ \boldsymbol{K}[\boldsymbol{R}\quad \boldsymbol{t}]\boldsymbol{q}_w = \begin{bmatrix} a_x & \gamma & u_0 \\ 0 & a_y & v_0 \\ 0 & 0 & 1 \end{bmatrix}[\boldsymbol{R}\quad \boldsymbol{t}]\boldsymbol{q}_w \tag{1}$$

where ρ represents the non-zero scale factors, $\boldsymbol{K}$ denotes the intrinsic parameter matrix of the camera, u_0 and v_0 are the coordinates of the principal point, a_x and a_y are the scale factors in the image u and v axes, and the parameter γ is the skew of the two image axes. $\boldsymbol{R}, \boldsymbol{t}$ represent the rotation matrix and the translation vector from WCF to CCF, respectively.

Only the radial distortion coefficients of the camera lens are taken into account in the paper. $\boldsymbol{p}_d = [u_d, v_d, 1]^T$ denotes the distorted homogeneous image coordinate of P in I_pCF. The relationship between $\boldsymbol{p}_d$ and $\boldsymbol{p}_u$ can be expressed as

$$\begin{aligned} u_d &= u + (u - u_0)(k_1 r^2 + k_2 r^4) \\ v_d &= v + (v - v_0)(k_1 r^2 + k_2 r^4) \end{aligned} \tag{2}$$

where $r = \sqrt{x_n^2 + y_n^2}$, k_1, and k_2 are radial distortion coefficients. (x_n, y_n) is the undistorted image coordinate of P in I_mCF.

3. CST model

Small planar targets are distributed in the field of view of the camera to form CST. Due to the invariant positional relationship between the small targets, they can be closely integrated into a whole target by the transformation matrices to form an integral 3D data field of the feature points, as shown in Fig. 1.

The coordinate frame of CST (TCF) $O_T x_T y_T z_T$ is established based on the coordinate frame of the first small target of CST. $\boldsymbol{R}_{Ti}, \boldsymbol{t}_{Ti} (i = 1, \ldots, n-1)$ denote the rotation matrixes and translation vectors from the coordinate frame of the other small targets (S_iTCF $i = 1,2,\ldots,n$) $O_i x_i y_i z_i \quad (i = 1, \ldots, n)$ to TCF. n is the number of the small targets in CST.