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A novel dual-camera calibration method for 3D optical measurement

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ABSTRACT

A novel dual-camera calibration method is presented. In the classic methods, the camera parameters are usually calculated and optimized by the reprojection error. However, for a system designed for 3D optical measurement, this error does not denote the result of 3D reconstruction. In the presented method, a planar calibration plate is used. In the beginning, images of calibration plate are snapped from several orientations in the measurement range. The initial parameters of the two cameras are obtained by the images. Then, the rotation and translation matrix that link the frames of two cameras are calculated by using method of Centroid Distance Increment Matrix. The degree of coupling between the parameters is reduced. Then, 3D coordinates of the calibration points are reconstructed by space intersection method. At last, the reconstruction error is calculated. It is minimized to optimize the calibration parameters. This error directly indicates the efficiency of 3D reconstruction, thus it is more suitable for assessing the quality of dual-camera calibration. In the experiments, it can be seen that the proposed method is convenient and accurate. There is no strict requirement on the calibration plate position in the calibration process. The accuracy is improved significantly by the proposed method.

1. Introduction

1.1. Background

In the past decades, digital cameras have been widely used in metrology, imaging and optical science and engineering [1–4]. Calibration plays a significant role in many applications, such as optical measurement and computer vision [5–8]. As an essential technique for optical measurement, camera calibration has been widely studied.

The relationship between 3D world and 2D camera image is created by the calibration methods. Usually pinhole model is used to describe the relationship map. Based on pinhole model, there are several classical methods, such as the methods developed by Tsai [6], Heikkila [7], etc. In 2001, Zhang present a flexible method [8], where either the camera or the planar pattern can be moved freely and the calibration procedure is easily repeatable without redoing any measurements. The intrinsic parameters are estimated through a linear process. Final values for all parameters are calculated after a non-linear optimization that aims to minimize the mean reprojection error. Actually, all these algorithms estimate an initial closed-form solution by solving an over-determined system of linear equations. These algorithms differ mainly in their estimation of the initial solution. The initial estimates then proceed through a non-linear optimization process. Usually, the objective is to minimize the error of pixel coordinates [6–8]. For example, the mean reprojection error is widely used in classic methods [6–8], which represents the error between real image coordinates and reprojected coordinates according to the calibration results.

Factors influencing camera calibration accuracy are evaluated in ref. [9–12], where several errors and objective functions are researched, such as the error of distorted pixel coordinates, the error of undistorted pixel coordinates, the distance with respect to the optical ray, etc. These errors are intuitive but sensitive to digital image resolution, camera field-of-view, etc. [9,10]. Thus, the normalized calibration error is proposed to overcome this sensitivity by measuring the error between the back-projected area and the pixel rectangle [13]. All the evaluations are based on the applicability of single camera calibration.

The calibration results create a map from 3D to 2D. If we want to recover a 3D point in space, more information is required. A common approach is the stereo vision by dual-camera system. The special relationship in dual-camera system is essential and widely researched, for example, the epipolar line of stereo vision, and the space intersection method [14–17].

Actually, the dual-camera system is quite different from single camera. For the latter, the 3D coordinates cannot be calculated without additional information. Thus the evaluation value of 2D pixel coordinates are used to assess the calibration quality, as mentioned before [6–8,12].

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However, these errors are obtained by single camera and image point, which are not the reconstruction result of 3D point.

In the case of dual-camera system, the 3D point can be easily obtained according to the camera parameters [16]. The pixel distance error on image plane may lead to diverse 3D metric distance error at different position. Calibration method is developed to minimize the metric distance error [16]. The inherent epipolar constraint is combined with constant distance constraint to enhance the optimization process. In [17], a method based on active vision is developed. The effect of non-perpendicularity of camera motion is eliminated. The parameters, such as scale factors, principal point, and distortion factors are calculated independently. Thus the strong coupling of the parameters is eliminated.

Hanning compares the error functions with regard to the 3D-reconstruction problem [18]. The projective error function measures the distance between the projected prototype and the observed image points. The reprojective error function denotes the distance between the prototype and the reprojected rays which are determined by observed points.

Furthermore, the dual-camera system calibration is researched in ref. [19]. The system is employed to perform 3D reconstruction. It seems that the mean reprojection error should not be used to assess the quality of system calibration. It is reasonable to hypothesize that the mean reconstruction errors would be proper. The method in ref. [19] is taken by restrict conditions within visual experiments, where the calibration plate is straightly moved along Z axis.

In this paper, a precise and flexible calibration method for dual-camera system is presented. The method is based on the error of reconstruction results. In the calibration process, there is no strict requirement on the calibration plate position. The relative positional relationship between the cameras are calculated with less degree of coupling. The precise 3D coordinates are calculated by space intersection method, and the mean error of the reconstruction results is used to assess and optimize the parameters. That is, the final calibration results correspond to the best reconstruction results of the dual-camera system.

In Section 1.2, the classical method is introduced and discussed. In Section 2, the proposed method is presented. In Section 3, the simulation and experiments are presented. And the conclusion is in Section 4.

1.2. Classic calibration of stereoscopic system

In the beginning, a stereoscopic system made of two cameras in canonical configuration is analyzed.

➢ *Pin-hole model*

The two cameras can be modeled by the usual pin-hole [8], where the relationship between a 3D point M and its image projection m_l and m_r is given by

$$\rho_l\begin{pmatrix} m_l \\ 1 \end{pmatrix} = K_l\left(R_l|T_l\right)\begin{pmatrix} M_w \\ 1 \end{pmatrix},\ K_l = \begin{bmatrix} f_{xl} & 0 & u_{0l} \\ 0 & f_{yl} & v_{0l} \\ 0 & 0 & 1 \end{bmatrix} \tag{1}$$

$$\rho_r\begin{pmatrix} m_r \\ 1 \end{pmatrix} = K_r\left(R_r|T_r\right)\begin{pmatrix} M_w \\ 1 \end{pmatrix},\ K_r = \begin{bmatrix} f_{xr} & 0 & u_{0r} \\ 0 & f_{yr} & v_{0r} \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

where l and r denote the left and right camera, respectively. M_w denotes the coordinate of point M in 3D world coordinate system, which can be described by $M_w=(X_w,Y_w,Z_w)^{\mathrm{t}}$. m_l and m_r are the perspective projections of M in the image plane of left and right camera respectively, which can be described by $m_l=(u_l,v_l)^{\mathrm{t}}$, and $m_r=(u_r,v_r)^{\mathrm{t}}$ in image coordinates. ρ_l,ρ_r are arbitrary scale factors. (R_l,T_l) are the extrinsic parameters, which are the rotation matrix $R_{l3\times3}$ and translation vector $T_{l3\times1}$ that relate the world coordinate system to the left camera coordinate system. K_l and K_r are the camera intrinsic matrixes, which include the focal lengths f_{xr}, f_{yr} and f_{xl}, f_{yl}, the principal point (u_{0l}, v_{0l}) and (u_{0r}, v_{0r}).

Due to the distortion, the normalized pinhole image coordinates m_l and m_r are transformed into the normalized distorted image coordinates ${m_l}^d$ and ${m_r}^d$, respectively, which can be described through distortion coefficients k_{1l}, k_{2l}, k_{1r}, k_{2r}, as following,

$$m_l^d = [1 + k_{1l}r_l^2 + k_{2l}r_l^4]m_l \tag{3}$$

$$m_r^d = [1 + k_{1r}r_r^2 + k_{2r}r_r^4]m_r \tag{4}$$

where r_l is the distance between m_l and (u_{0l}, v_{0l}).

➢ *Optimization by mean reprojection error*

The mean reprojection error has been widely used for the classic calibration methods, such as Zhang's method [8].

Assuming that we use images i=1,2,…n of a 2D calibration template. There are calibration points j=1,2,…s on the template. The optimization function is shown in Eq. (5).

$$C = \sum_{i=1}^{n}\sum_{j=1}^{s}\left(\left\|m_l^{ij} - \hat{m}_l^{ij}(k_{1l}, k_{2l}, K_l, R_l^i, T_l^i, M^j)\right\|^2\right) \tag{5a}$$

$$\begin{aligned} C = \sum_{i=1}^{n}\sum_{j=1}^{s}\Big(&\left\|{m_l}^{ij} - {\hat{m}_l}^{ij}(k_{1l}, k_{2l}, K_l, {R_l}^i, {T_l}^i, {M_w}^j)\right\|^2 \\ &+\left\|{m_r}^{ij} - {\hat{m}_r}^{ij}(k_{1r}, k_{2r}, K_r, {R_r}^i, {T_r}^i, {M_w}^j)\right\|^2\Big) \end{aligned} \tag{5b}$$

where ${m_l}^{ij}$ and ${m_r}^{ij}$ are the real image coordinates of the jth point in the ith image. ${\hat{m}_l}^{ij}(k_{1l}, k_{2l}, K_l, {R_l}^i, {T_l}^i, {M_w}^j)$ and ${\hat{m}_r}^{ij}(k_{1r}, k_{2r}, K_r, {R_r}^i, {T_r}^i, {M_w}^j)$ are the reprojected image coordinates calculated by using the calibrated parameters.

Eq. (5a) describes the mean reprojection error for single camera calibration, such as the left camera. In case of dual-camera calibration, Eq. (5b) is the mean reprojection error, which is used to assess the quality of calibration.

In summary, the classic calibration algorithm is shown in Fig. 1.

As mentioned before, the dual-camera system is calibrated as two separate monocular systems. It simply merges two independent objective functions to achieve stereoscopic calibration by Eq. (5b). Therefore, there is obvious difference between dual-camera system and two monocular systems, as follows.

(1) There is a fixed positional relationship between the two cameras of binocular system, which does not change according to different positions.

(2) Based on the spatial relationship, the precise 3D coordinate of measured object can be reconstructed by the binocular vision system. 3D reconstruction (or 3D measurement) is the main function of binocular vision system.

Thus, the main problems with this approach include: (1) the optimization process involves in all parameters, which contain several couplings between parameters, such as the coupling between rotation and translation parameters and the fixed relationship between the two cameras. (2) Generally, dual-camera systems are designed for 3D reconstruction, while Eq. (5) is the error of 2D image coordinates in the image plan. Thus the optimized objective for camera calibration and 3D reconstruction results are inconsistent. It can be concluded that a more precise model and a more flexible calibration method are required.

A novel approach is presented by using 3D reconstruction error. And the relationship between the two cameras is considered and calculated properly. The method is given as follows.

2. New method for dual-camera system calibration

The stereoscopic dual-camera system model and the calibration process are presented in Sections 2.1 and 2.2, respectively.