Optik 126 (2015) 1394–1399

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

An on-line calibration method for camera with large FOV based on prior information

Ju Huo [a], Ning Yang [b], Ming Yang [b,*], Yongkun Wang [b]

[a] Department of Electrical Engineering, Harbin Institute of Technology, Harbin 150001, China
[b] Control and Simulation Center, Harbin Institute of Technology, Harbin 150080, China

ARTICLE INFO

Article history:
Received 5 March 2014
Accepted 15 April 2015

Keywords:
Vision measurement
Camera calibration
Prior information
Large FOV
On-line calibration

ABSTRACT

In the large dimensional vision measurement, the parameters of camera with large FOV (field-of-view) are easy to change for the influence of working conditions, which directly affects the precision of measurement. Concerning this issue, an on-line calibration method for camera with large FOV based on prior information is proposed. In this method, sufficient prior information is firstly obtained by the lights whose directions and positions in the space are known before measurement, so as to achieve the high accuracy pre-calibration of camera with large FOV, in which the initial values of camera parameters are acquired. During the measurement, on-line calibration is conducted with several fixed points in the FOV by combining EPnP algorithm, a pose estimation algorithm based on lines, and LM (Levenberg–Marquardt) optimization algorithm, which adjusts the parameters of camera in time. The experiments results show that the precision of the on-line calibration method is equal to that of the off-line traditional calibration methods, whose reconstruction error is within 2 mm with the FOV of 3000 mm × 4000 mm, while the method is less time consuming. The method in this paper is proved suitable for the on-line calibration of camera with large FOV.

1. Introduction

Large dimensional vision measurement technique is difficult but important in the industrial measurement, while calibration technique is the key to the precision of measurement. Traditional calibration methods can obtain higher precision among the existing methods, but they usually rely on the target too much. These methods of calibration require targets to cover the whole FOV, which are difficult and expensive to manufacture in the calibration of camera with large FOV [1–3]. Referring to the method of Zhang, Sun et al. [4] proposed a calibration method for camera with large FOV by splicing small targets into a large target based on planar homography, while Li et al. [5] spliced small targets into a large target through polynomial projective model with difference solution, in both of which the layouts of small targets are rigorously restricted. Yu et al. [6] proposed a calibration method, which utilized the intersection points of lines to construct a large scale target that cover the whole FOV of camera; however, the method ignores the camera distortion when calibration points are constructed, and the constructed calibration points are not uniformly distributed in the FOV, for which the precision of calibration is affected. Self-calibration does not need a target in the whole process, but neither the stability nor the precision can satisfy the requirements of the high precision calibration for the camera with large FOV [7–10]. In addition, calibration parameters are prone to change with an effect of working conditions such as temperature, vibration and so on, resulting in reducing the accuracy of measurement, where the on-line calibration is extremely important [11,12]. Li et al. [13] proposed a camera on-line recalibration framework using SIFT, but the precision and efficiency need further improvement for the application of large-scale measurement.

In this paper, an on-line calibration method for camera with large FOV based on prior information is proposed. In this method, abundant prior information is acquired firstly by the lights whose directions and positions in the space are known before measurement, and the high precision pre-calibration of camera with large FOV is carried out with the prior information, in which the accurate initial values of the camera parameters are acquired. Then, on-line calibration is implemented in the process of measurement with several fixed points in the FOV by combining EPnP algorithm, a pose estimation algorithm based on lines, and LM (Levenberg–Marquardt) optimization algorithm, which accurately adjusts the camera parameters in time. The paper is organized as follows. Section 2 analyzes the mathematical model of camera.

* Corresponding author. Tel.: +86 15045104681.
E-mail address: yn3714@163.com (M. Yang).

http://dx.doi.org/10.1016/j.ijleo.2015.04.024
0030-4026/

Section 3 describes in detail the on-line calibration method for camera with large FOV. Section 4 provides experimental results. Finally, Section 5 concludes the paper.

2. Mathematical model of camera

A camera is modeled by the usual pinhole [14,15]. The relationship between a 3D point $\boldsymbol{P}(x_w, y_w, z_w)$ and its image projection $\boldsymbol{p}(u_u, v_u)$ is given by

$$s\begin{bmatrix} u_u \\ v_u \\ 1 \end{bmatrix} = \begin{bmatrix} f_x & 0 & c_x & 0 \\ 0 & f_y & c_y & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \boldsymbol{R} & \boldsymbol{t} \\ \boldsymbol{0}^T & 1 \end{bmatrix} \begin{bmatrix} x_w \\ y_w \\ z_w \\ 1 \end{bmatrix}, \quad (1)$$

where s is a nonzero scale factor [16].

In the camera model, there are four intrinsic parameters: f_x and f_y are the scale factors along the image axes u and v, and (c_x, c_y) is the principle point. $\boldsymbol{R}$ and $\boldsymbol{t}$, called the extrinsic parameters, are the rotation matrix and the translation vector from world coordinate system to camera coordinate system, respectively. Note that the skew of two image axes is not considered in this paper.

A camera usually exhibits lens distortion, especially radial distortion. Let $\boldsymbol{p}_u(x_u, y_u)$ and $\boldsymbol{p}_d(x_d, y_d)$ be the distortion-free and distorted image coordinates, respectively. We have

$$\begin{cases} x_u = x_d(1 + k_1 r^2 + k_2 r^4 + k_3 r^6 \ldots) \\ y_u = y_d(1 + k_1 r^2 + k_2 r^4 + k_3 r^6 \ldots) \end{cases}, \quad (2)$$

where $r = \sqrt{x_d^2 + y_d^2}$; $k_1, k_2, k_3 \ldots$ are the coefficients of radial distortion. In this paper, we consider only the first term of radial distortion. The task of camera calibration is to determine the intrinsic parameters, extrinsic parameters and the lens distortion coefficient.

3. On-line calibration of camera with large FOV based on prior information

The on-line calibration of camera with large FOV based on prior information could be divided into two steps: pre-calibration and on-line calibration. In the pre-calibration, the exact initial values of camera parameters are acquired, which will be corrected in time by the means of on-line calibration in the process of measurement. As can be seen, the pre-calibration is just executed once before measurement, while the on-line calibration is implemented as long as the variations of parameters beyond the given thresholds in the whole process.

3.1. *Pre-calibration of camera with large FOV based on prior information*

In order to calibrate the camera, plenty of calibration points full of the FOV are the needed prior information. Assuming that there are n calibration points in the FOV, whose coordinates in the world coordinate system and image coordinate system are $\boldsymbol{x}_{wi}$ and $\boldsymbol{u}_i (i = 1, 2, \ldots, n)$ respectively, the calibration is converted to the optimization of the function shown in (3), and the solution c_p^* that makes F gain the extreme value is the appropriate result

$$F(c_p) = \sum_{i=1}^{n} \left| \boldsymbol{u}_i - C(c_p, \boldsymbol{x}_{wi}) \right|. \quad (3)$$

In the calibration of camera with large FOV, how to acquire enough prior information, i.e., the calibration points whose world coordinates are precisely known, is the key problem. In this paper, light spots, projected on the actual plane by lights whose positions and directions are given, are taken as the calibration points. The lights are from the measurement robot of SOKKIA, while the actual plane refers to the surface of object in front of camera, such as the wall surface in the measurement field. In the construction of calibration points, both the spatial point location function and the grid scanning function of measurement robot are employed. Specifically, the calibration points can be generated according to the following four steps:

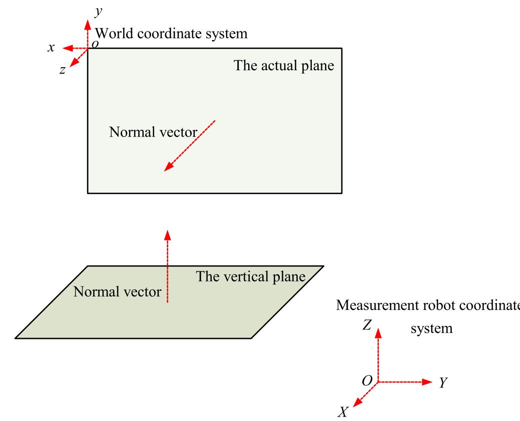

Fig. 1. Construction of the world coordinate system.

(1) Get enough points on the actual plane and its vertical plane by the measurement robot.
(2) Fit the actual plane and the vertical plane with the points acquired in step 1, and the corresponding plane equations are obtained.
(3) Take a point on the actual plane as the origin of the world coordinate system, while the normal vector of the actual plane is selected as the z axis, and the y axis is denoted by the normal vector of the vertical plane. According to the right-hand rule, the world coordinate system is established, as shown in Fig. 1; meanwhile, the relationship between world coordinate system and measurement robot coordinate system is acquired.
(4) Construct abundant calibration points on the actual plane by the measurement robot, whose world coordinates are acquired through the transformation of world coordinate system and measurement robot coordinate system. Meanwhile, the calibration points are captured by the camera.

After the calibration points are generated, their image coordinates are calculated, and Tsai two-step method is employed to calibrate the camera. In the pre-calibration, the measurement robot is adopted to construct the calibration points, whose precision is high enough; meanwhile, the quantity and distribution of the constructed calibration points can be set as desired, so the method presented in this paper can achieve the high precision pre-calibration of camera with large FOV.

3.2. *On-line calibration of camera with large FOV based on lines*

After the initial values of the camera parameters are acquired, on-line calibration for camera with large FOV is needed so as to reduce the impact of the camera parameters' variations for the precision of measurement. First, the intrinsic parameters are supposed to be invariable. Then the coordinates of the fixed points, which are fixed on the actual plane, in the camera coordinate system are calculated, and the extrinsic parameters are obtained by a pose estimation method based on lines. Finally, the camera parameters,