Available online www.jocpr.com

Journal of Chemical and Pharmaceutical Research, 2014, 6(1):97-103

Research Article

ISSN : 0975-7384
CODEN(USA) : JCPRC5

Camera calibration optimization technique based on genetic algorithms

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ABSTRACT

Vision measurement technology is technology that gets information about measured object being imagined. Therefore, measurement accuracy is directly related to camera parameter calibration accuracy. As for the camera parameter calibration problem, this paper proposes a camera parameter calibration method based on genetic optimization algorithm. A more comprehensive camera imaging model can be built through the ideal pinhole model radial distortion, tangential distortion and distortion correction affine and non-orthogonal; A more comprehensive camera imaging model can be built through the ideal pinhole model radial distortion, tangential distortion and distortion correction affine and non-orthogonal; Using high-precision coordinate measuring machine and the luminous intensity adjustable infrared diode component to build a virtual three-dimensional calibration template provides high-precision calibration space calibration point of calibration . We can derivate reversely calibrated control points by calibration parameter to obtain regularized stereo calibration error 1.082 and Standard deviation of the thrust reverser 0.016. So the calibration method proposed in this paper is feasible and has good calibration accuracy.

Key words: Vision measurement Camera calibration Distortion correction Genetic algorithm

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INTRODUCTION

Vision measurement technology is a new measurement technology and a breakthrough of measurement concept. It will extend measure technology to bionic technology field [1].It also adapts to higher requirements of measurement technology in measuring precision, measurement range and measurement conditions with a new measuring way of thinking . The measured information is obtained by a CCD camera in visual measurement technique. Therefore, the CCD camera is one of the key components of vision measurement system and system performance depends on the calibration accuracy of CCD camera parameter [2,3]. In order to improve the performance of visual measuring system and reduce the CCD camera parameters' influence to overall performance to minimum, the CCD camera must be accurate [4,5]. The CCD camera parameter calibration algorithm based on. a genetic optimization algorithm has been proposed after researching the existing of camera parameter calibration algorithm and the characteristics of the camera model.

EXPERIMENTAL SECTION

CCD camera calibration model

CCD camera imaging model is a mathematical description of physical process from imaging of space objects to the camera image plane. And it can exactly grasp the geometric relationships between the objects and the images according to the model. On basis of colinearity pinhole imaging model, a more comprehensive model of the camera calibration being corrected by system aberration has been established in this paper.

In order to describe the camera imaging process though camera parameters, the world coordinate system(space coordinate system)，the camera coordinate system, pixel image coordinate system, the actual image coordinate system are necessary to be builted. The world coordinate system $O_wX_wY_wZ_w$ define a three dimensional space of a common coordinate system, according to the practical need to determine the coordinate system origin position and direction. The camera perspective projection center C is as to origin O_c of the camera coordinate system $O_cX_cY_cZ_c$, axes Z_c is perpendicular to the image plane of the camera; axes X_c and axes Y_c parallel to the horizontal axis and vertical axis of the pixel units correspondingly. The origin o_0 of pixels image coordinate system o_0uv is created on image plane in the upper left corner, axes u and v parallel to the horizontal axis and vertical axis of the pixel units corresponding. The origin o_1 of actual image coordinate system o_1xy is built on the node of the optical axis of the camera and the image plane of the camera, axes x and y is to the parallel to the horizontal axis and vertical axis respectively. The method of establishing the coordinate system is shown as Figure 1.

Camera parameters describe the relative position and direction between the world coordinate system and the camera coordinate system. Through a 3×3 rotation matrix R and a 3×1 translation vector T to describe. In order to set up the link between any P_{wi} in world coordinates and any p_i images coordinates. It needs to change the space coordinates transformation P_{wi} to the camera coordinate P_{ci}, transformation process can be expressed as

$$\mathbf{X}_c = \mathbf{R}\mathbf{X}_w + \mathbf{T} \tag{1}$$

Where $\mathbf{X}_c = (X_c, Y_c, Z_c)^T$； $\mathbf{X}_w = (X_w, Y_w, Z_w)^T$； $\mathbf{T} = (t_x, t_y, t_z)^T$； $\mathbf{R} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$; rotation matrix R is the unit matrix, it can express through the rotation Angle of passing around the Xc, Yc, Zc axis（Euler angle）, ω,φ,κ can be expressed as (figure 2).

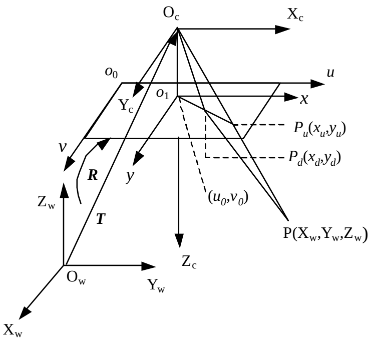

Fig. 1 Coordinate system transformation

$$\begin{cases} r_{11} = \cos\kappa\cos\varphi \\ r_{12} = \cos\kappa\sin\varphi\sin\omega + \sin\kappa\cos\omega \\ r_{13} = \sin\kappa\sin\omega - \cos\kappa\sin\varphi\cos\omega \\ r_{21} = -\sin\kappa\cos\varphi \\ r_{22} = \cos\kappa\cos\omega - \sin\kappa\sin\varphi\sin\omega \\ r_{23} = \cos\kappa\sin\omega + \sin\kappa\sin\varphi\cos\omega \\ r_{31} = \sin\varphi \\ r_{32} = -\cos\varphi\sin\omega \\ r_{33} = \cos\varphi\cos\omega \end{cases} \tag{2}$$

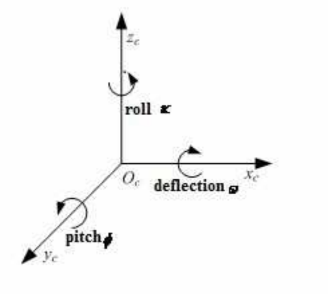

Fig. 2 Euclid angle expression

According to formula (1) and (2), the calibration parametersω,φ,κ can be determined to be

$$\begin{cases} \omega = \arctan\left(-\dfrac{r_{32}}{r_{33}}\right) \\ \varphi = \arcsin\left(r_{31}\right) \\ \kappa = \arctan\left(-\dfrac{r_{21}}{r_{11}}\right) \end{cases} \tag{3}$$

The camera's internal geometry and optical properties of the lens can be described by camera internal parameters. Camera internal parameters mainly include the effective focal length f and the image plane coordinates of the center (u_0,v_0). In the actual imaging system, a deviation of projection point offsetting the projection center will be occurred unavoidably because of the machining ad assembly errors of the lens and the CCD camera, and the introducing errors in the image acquisition process. Therefore, the ideal pinhole model can not meet the requirements and a more perfect camera imaging model must be adopted. On the basis of the pinhole imaging model, camera imaging model can be built after correcting the various distortion factors in the process of camera imaging, to calibrate camera parameters more precisely.

According to the characteristics of camera ideal pinhole imaging model, the correspondence between space coordinates of point $P_{ci}(X_{ci},Y_{ci},Z_{ci})$and ideal perspective projection on the image plane coordinates p_i（x'_i,y'_i） can be expressed as

$$\begin{bmatrix} x'_i \\ y'_i \end{bmatrix} = \frac{f}{Z_{ci}} \begin{bmatrix} X_{ci} \\ Y_{ci} \end{bmatrix} \tag{4}$$

Because of the digital image acquired by camera in the form of a two dimensional array is stored in the computer and the image plane position (u_i,v_i) of each pixel in the image coordinates is the pixel's rows and columns in the array, So there is not physical units showing the positions of the pixels in the image. Set d_x and d_y as a single physical size pixel in the x axis and y axis direction, then the transformation relation between Pixel Coordinates (u_i,v_i) of any pixel in the image pixels $o_1$xy and coordinate system (x_i,y_i) in the actual image $o_1$xy is as following:

$$\begin{bmatrix} x_i \\ y_i \end{bmatrix} = \begin{bmatrix} d_x\left(u_i - u_0\right) \\ d_y\left(v_i - v_0\right) \end{bmatrix} \tag{5}$$

Pinhole model is only an approximation model of camera imaging process. As the existence of various distortion factors in the process of actual imaging, the image by space coordinates points is not on the pinhole model ideal position（x'_i,y'_i）, however, the image is on plane position（x_i,y_i） influenced by distortion factor actually, For these two ,after distortion correction it can be expressed as:

$$\begin{bmatrix} x'_i \\ y'_i \end{bmatrix} = \begin{bmatrix} x_i + \delta x_i \\ y_i + \delta y_i \end{bmatrix} \tag{6}$$

Where $\begin{cases} \delta x_i = \delta x_{iRLD} + \delta x_{iTLD} + \delta x_{iAND} \\ \delta y_i = \delta y_{iRLD} + \delta y_{iTLD} + \delta y_{iAND} \end{cases}$

Radial distortion（$\delta x_{iRLD},\delta y_{iRLD}$） primarily is caused by a large off-axis angle and the manufacturing defects of lens, generated the optical center in the radial direction and gradually increases, can be approximately expressed as

$$\begin{bmatrix} \delta x_{iRLD} \\ \delta y_{iRLD} \end{bmatrix} = \begin{bmatrix} x_i\left(k_1 r_i^2 + k_2 r_i^4 + k_3 r_i^6\right) \\ y_i\left(k_1 r_i^2 + k_2 r_i^4 + k_3 r_i^6\right) \end{bmatrix} \tag{7}$$

Where $r_i=(x_i^2+y_i^2)^{1/2}$——the distance between the image points （x_i,y_i） and the camera optical axis;

k_1,k_2,k_3 ——Correction factor for the radial distortion

Tangential distortion （$\delta x_{iRLD},\delta y_{iRLD}$）mainly is caused by the curvature of the lens center is not strictly collinear, can be approximately expressed as

$$\begin{bmatrix} \delta x_{iTLD} \\ \delta y_{iTLD} \end{bmatrix} = \begin{bmatrix} p_1\left(r_i^2 + 2x_i^2\right) + 2p_2 x_i y_i \\ 2p_1 x_i y_i + p_2\left(r_i^2 + 2y_i^2\right) \end{bmatrix} \tag{8}$$

Where p_1,p_2 ——the tangential distortion correction coefficient

Affine and non-orthogonal distortion（$\delta x_{iRLD},\delta y_{iRLD}$） is mainly caused by horizontal and vertical pixel size of inconsistency and scanning image acquisition card arranged in error and the non pixel vertical line the distortion can be approximated as

$$\begin{bmatrix} \delta x_{iAND} \\ \delta y_{iAND} \end{bmatrix} = \begin{bmatrix} -b_1 x_i + b_2 y_i \\ b_1 y_i \end{bmatrix} \tag{9}$$

Where b_1,b_2 ——Affine and non- orthogonal distortion correction coefficient

In summary, within the parameters of CCD camera: effective focal length f, the center coordinates (u_0,v_0) of the image plane, radial distortion correction coefficient (k_1,k_2,k_3), the tangential distortion correction coefficient (p_1,p_2), distortion and non-orthogonal affine distortion correction coefficient (b_1,b_2).

Using evolutionary geneticalgorithm to calibrate camera parameters

The traditional optimal method of calibrating linear camera parameters is easy to fall into the poor of convergence and a situation of converging local extreme points；Meanwhile, the algorithm requires very high about the selection of initial point，If the initial is not good , it easily leads to the optimal results deviating from the true value or obtaining a local minimum；Further, since the objective function of the calibration of the camera parameters including many optimal variables ，This leads to the error of the global minimization is obtained on the basis of a large number of local minima extreme limit; Thus, sometimes leading to the final result of the optimization is the local optimal solution rather than a global optimal solution. A large number of engineering practices have proved that the genetic algorithm to nonlinear optimal problems has a good stability；Meanwhile, when using the genetic optimal algorithm to calibrate the camera，after the fitness function and chromosomal vector are determined，the solving process of problem has nothing to do with itself, easy to meet orthogonal rotation matrix constraints. Therefore, use genetic optimal algorithm to optimize the parameters for camera calibration.

Genetic algorithm is an intelligent evolutionary computation method，involves a large number of evolutionary control strategies and control parameters in the implementation process, by designing strategy variables and control parameter variables , coordinating the relation between various factors , which aim to achieving the best optimal results. Here, the problem of camera calibration parameters optimization based on genetic algorithms is described as a function F with a three-dimensional mathematical model ：

$$\mathbf{F}\left(\mathbf{S}(\alpha,\beta,\gamma,\zeta,\xi),\mathbf{V}(l,N,p_c,p_m,G_{\max}),f(\boldsymbol{\theta})\right) \tag{10}$$

Where S——Genetic strategy vector that determines the states of existence and the evolutionary way of the state；
V——Vector of control parameters affects the process state of the evolution；

f— Fitness function is transformed from the optimal objective function , the optimal problem of camera parameters is a minimal extreme problem；Among，the vector of chromosome θ consists of all calibrated camera parameters to be as genetic constitution，expressed as

$$\boldsymbol{\theta} = \{\omega, \phi, \kappa, t_x, t_y, t_z, f, d_x, d_y, u_0, v_0, k_1, k_2, k_3, p_1, p_2, b_1, b_2\} \tag{11}$$

Among，the respective components of the vector **S** and **V** of are described in Table 1.

Table 1 Notation of variables

Vector **S**		Vector **V**	
Symbol	Meaning	Symbol	Meaning
α	Coding strategy	l	Individual coding length
β	Select the initial population	N	The initial population size
γ	Selection operator	p_c	Crossover parameters
ς	Crossover	p_m	Mutation operator parameters
ξ	Mutation operator	$G_{\max}$	Maximum evolution algebra

Fitness function is the bridge and link associated the actual optimal problems with genetic algorithm，It will express the optimal objective as a function of influencing factors, through the evaluation of population fitness value of each individual to find the best combination of factors and achieve the problems of optimization. Camera calibration parameters is to make the camera image obtained by the imaging model and the actual image point coordinates of the square of distance between the observed values（u'_i，υ'_i） i=1,2,...,n and the obtained values （u_i，υ_i） i=1,2,...,n is the minimum. Therefore, the definition of fitness function is

$$f(\boldsymbol{\theta}_r) = \sum_{i=1}^{n} \{[u'_i(\boldsymbol{\theta}_r) - u_i(\boldsymbol{\theta}_r)]^2 + [v'_i(\boldsymbol{\theta}_r) - v_i(\boldsymbol{\theta}_r)]^2\} \tag{12}$$

Among，（$u'_i(\theta_r)$，$\upsilon'_i(\theta_r)$） is the chromosome vector θ_r and the calibration control points Pi, obtained by the use of the camera imaging model pixel coordinate; （$u_i(\theta_r)$，$\upsilon_i(\theta_r)$） is the actual coordinate of image observation between chromosome θ_r and calibration corresponding to the control point P_i.

In summary shows that the goal of the optimal camera parameter calibration is through determining the minimum value of the fitness function f(θ) to determine the optimal calibration results

$$\boldsymbol{\theta}_0 = \arg\min_{\theta} f(\boldsymbol{\theta}) \tag{13}$$

RESULTS

To validate the proposed camera calibration method parameter optimization, calibrating Kodak Megaplus1.4i camera parameters . Camera manufacturers provide physical parameters : the image plane size , focus, horizontal and vertical axis of a unit pixel size. Camera manufacturers provide the physical parameters: image plane size 1316pixel×1035pixel, focal length f=12mm, Horizontal and vertical directions of the unit pixel size $d_x=d_y=6.8\mu m$.

Through the analysis of the existing controlled points based on the provided a calibration method, using of infrared light-emitting diodes with CMM probe moves in the space constructed a large size virtual three-dimensional calibration template (Figure 3). On the one hand, overcoming the large-size three-dimensional calibration template processing, calibration difficulties shortcomings, meeting the large size of the camera vision measurement system within the parameters of the special requirements of accurate calibration; On the other hand, the calibration of the spatial distribution of control points is consistent with the actual measurement range , easy to achieve global optimization parameter calibration .

Calibration experiment used coordinate measuring machine is Brown & Shape 's Gloab Image 153010, It has a measurement range 1500×1000×3000mm^3. Measurement uncertainty U_{95}=(3.0+L/333)μm, the unit of L is m .As shown in figure 4.

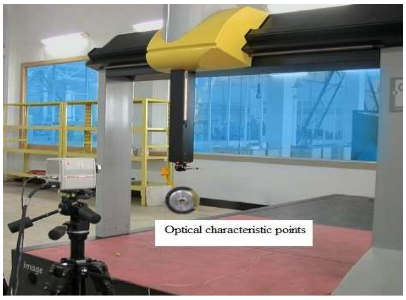

Fig. 3 Device for camera parameters calibration

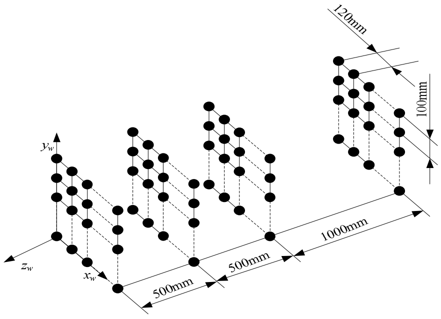

Fig. 4 Dummy solid calibration template

For optimization using genetic algorithm to optimize the camera parameter calibration, need to set genetic algorithm parameters . As shown in table 3

Table 3 Parameters setup of GA

Set the parameters	Choose to calculated parameters	Crossover operator parameters
Number of values	0.08	0,1
Mutation operator parameters	Population size	Maximum running times
2,200,3	40	200

Based on the initial parameters in Table 3, generating a search scope of the optimized camera calibration parameters. Optimal Solving the calibration template 320 calibration controlled points of the 440 controlled points provided by the virtual three-dimensional calibration optimization solutions by genetic optimization algorithm, and ultimately determine the camera intrinsic parameters. Calibration results are shown in Table 4.

Figure 5 shows the use of genetic algorithms to optimize in the process of solving , evolving the relationships between algebra and optimization evolutionary of the objectives ,the optimization of search results rapidly converge to the optimal solution with the generation increases of evolutionary.

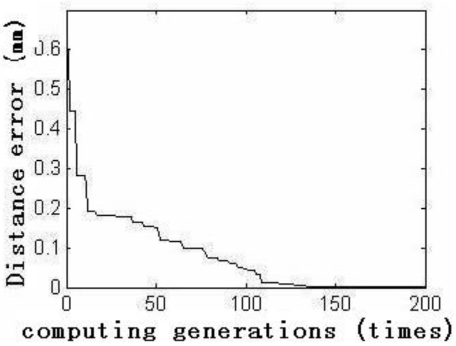

Fig. 5 Formulation of Optimization object and computation generation

To evaluate the accuracy of the calibration parameters using normalized stereo calibration error NSCE and set distorted image coordinate precision calibration results as the evaluation criteria :

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1. Stereo calibration error NSCE normalization formula is defined as

$$NSCE=\frac{1}{n}\sum_{i=1}^{n}\left[\frac{\left(X_{ci}^{'}-X_{ci}\right)+\left(Y_{ci}^{'}-Y_{ci}\right)}{Z_{ci}^{'}\left(f_u^{-2}+f_v^{-2}\right)/12}\right]^{1/2} \tag{14}$$

Where, （X'_{ci}，Y'_{ci}，Z'_{ci}） —— to calibrate the ideal values of the control point coordinates in the camera coordinate, can be determined by (X_{wi},Y_{wi},Z_{wi}).

（X_{ci}，Y_{ci}） ——the corresponding measurement value, can be determined by the image point coordinates（u_i，υ_i）. When NSCE≈1 calibration method has good performance.

Involved in optimizing the use of calibrated 320 control points calculated normalized stereo calibration error NSCE=1.028 , indicating that the algorithm has good performance.

Table 4 Calibration result of the camera internal parameters

Parameters	f (mm)	u_0 (pixel)	v_0 (pixel)	d_x (μm)
Calibration values	12.088	-13.752	5.468	6.810
Parameters	d_y (μm)	k_1	k_2	k_3
Calibration values	6.803	-9.854×10^{-4}	4.855×10^{-4}	7.246×10^{-7}
Parameters	p_1	p_2	b_1	b_2
Calibration values	2.142×10^{-5}	-6.061×10^{-5}	8.182×10^{-5}	-3.113×10^{-5}

2. The image distortion coordinate accuracy, will not optimize the control of the calibration of the image 120 of the observed value of the coordinates of the calibration control points from the three-dimensional space coordinates using the distortion factors to consider calibration model to obtain a distance between the estimated value of the difference as accuracy evaluation criteria. Figure 6 is a dot between the actual value and the estimated difference in distance .

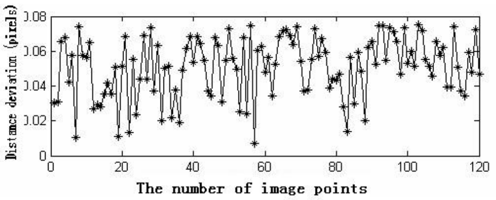

Fig. 6 the discrepancy between real value and estimated result

Inverse calculation involved 120 image points (not involved in optimizing calibration) of the actual coordinate values using the known spatial calibration control points obtained by the camera imaging model the distance between the coordinate values of the mean error of 0.050 pixels, the standard deviation is 0.016 pixels , combined with analysis of figure 6 shows that the proposed algorithm has higher calibration accuracy.

CONCLUSION

This paper proposed the method of calibrated camera parameters optimization based on the genetic algorithm. In the ideal pinhole model, establishing a more comprehensive amendment calibration model based on the parameters; providing space for calibration control points through a virtual three-dimensional high-precision calibration template; establishing a legacy camera parameters optimization models and mathematical description of the fitness function. Finally, the experiment proves that the method is feasible, with high calibration accuracy, which meets precisely calibrated technical requirements of the visual measurement techniques camera parameters.

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