

CCD camera automatic calibration technology and ellipse recognition algorithm

Changku Sun (孙长库), Xiaodong Zhang (张效栋), and Yunxia Qu (屈云霞)

State Key Laboratory of Precision Measuring Technology and Instruments, Tianjin University, Tianjin 300072

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A novel two-dimensional (2D) pattern used in camera calibration is presented. With one feature circle located at the center, an array of circles is photo-etched on this pattern. An ellipse recognition algorithm is proposed to implement the acquisition of interest calibration points without human intervention. According to the circle arrangement of the pattern, the relation between three-dimensional (3D) and 2D coordinates of these points can be established automatically and accurately. These calibration points are computed for intrinsic parameters calibration of charge-coupled device (CCD) camera with Tsai method. A series of experiments have shown that the algorithm is robust and reliable with the calibration error less than 0.4 pixel. This new calibration pattern and ellipse recognition algorithm can be widely used in computer vision.

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Camera calibration is essential in computer vision. The objective of calibration is to endow computer vision system with the ability of accurate measurement by solving the camera parameters that characterize camera geometry and pose.

There are two different types of parameters, the intrinsic and extrinsic parameters^[1-3]. The intrinsic parameters include the lens focal length f , lens distortion factor k_1 , aspect distortion factor s_x , the principal point (C_x, C_y) , and scale factors (d_x, d_y) for the x and y pixel dimensions. The rotation matrix R and translation matrix T are the extrinsic parameters, which describe the position and pose of the camera.

Calibration methods have always been the research focus. Radial alignment constraint (RAC) method proposed by Tsai in 1987 is widely used in computer vision^[1]. The RAC realizes the reduction of the parameter space through extrinsic parameters estimation; and then using these estimated values, the intrinsic camera parameters can be derived by optimization. Compared with three-dimensional (3D) calibration patterns^[4], non-coplanar calibration is popular by virtue of the low cost and high precision, which is established by means of 2D pattern translation^[5,6].

In calibration process, it is crucial to determine the mapping relation between the interest calibration points in the 3D space and the corresponding points in the 2D image. The conventional 2D pattern is inconvenient to confirm the position of interest calibration points, because the original point circle location and the range of interest (ROI) selection need a lot of human intervention. There exists an improved method aiming at automation, but original point circle, located at a corner of the ROI, may be out of camera view field as pattern translates^[7]. In the following contents, a calibration technique with a new 2D circle pattern and corresponding ellipse recognition algorithm will be introduced in detail. The new calibration technique proposed boasts full-automation and high reliability meanwhile guarantees the calibration precision.

There are a wide variety of patterns available for camera calibration. 2D pattern with the circle array is simple

and easy-realized. In addition, circle is insensitive to the threshold value in image processing. Therefore, it can ensure the calibration precision. In camera calibration process, 2D pattern is usually located at several discrete positions to simulate 3D pattern. The process is called the non-coplanar calibration.

Figure 1 illustrates the conventional circle pattern. It is a glass plate, on which an array of photo-etched circles is located with the same size and the even distribution. The centers of circles are defined as the interest calibration points. In calibration process, human intervention is inevitable to select the ROI and origin. The circle at some corner of ROI is defined as the origin of the coordinate system in the captured image (in Fig. 1).

The new circle pattern is shown in Fig. 2. It is also a glass plate with an array of photo-etched circles. The arrangement rule of the circles is the same as the conventional one. However attention should be focused on a bigger circle located at the center, which is called feature circle. It will be defined as the origin point. Without the location of ROI, all of the whole circles can be detected by one robust algorithm described following. 3D space coordinate system will be established through pattern moving as shown in Fig. 3. The origin is the feature circle center in the first position. The line that links the centers of the horizontal circles is X_w axis, to which Y_w

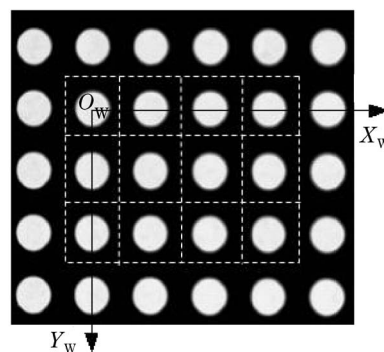


Fig. 1. Conventional circle pattern.

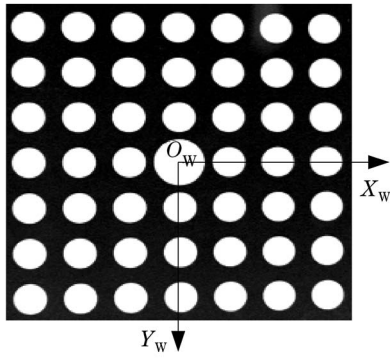


Fig. 2. New circle pattern.

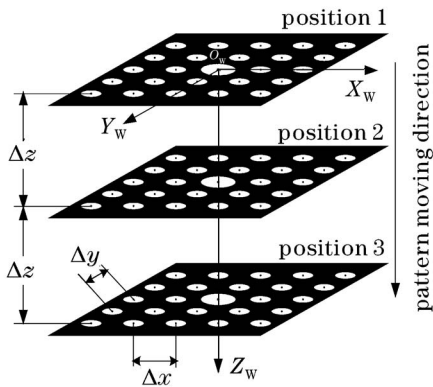


Fig. 3. Virtual 3D world coordinate system.

axis is perpendicular. The moving direction of the pattern is Z_w axis. The coordinate system conforms to the right-hand rule.

The out-of-field-view problem of the conventional circle pattern can be avoided by the central location of feature circle. Without ROI selection, all the circles in view field will be processed to provide the ample calibration points. This new calibration pattern is also utilized by Tsai method, and can implement the calibration task accurately and full-automatically.

Ellipse recognition algorithm is indispensable to the full-automatic calibration using the new pattern. Circle on the pattern is transformed to ellipse due to the perspective projection of the lens. It is crucial of the appropriate algorithm to implement the detection of interest calibration ellipse without manual location of ROI. The following recognition algorithm will complete this task. And besides, the center of ellipses, i.e., calibration points, can be calculated using fitting theory. The 3D space and 2D image coordinate systems can be established according to location of feature ellipse and relative position of these points.

Figure 4(a) displays the original image captured. The following algorithm is directly applied to the image after the simple threshold segmentation and contour detection as shown in Fig. 4(b), and the processed result of each step is displayed in Figs. 4(c) and (d).

Due to the limitation of the view filed and the experiment environment, the captured image has the redundant information. The image noise and imperfect ellipse will be concerned. They can be divided into two types,

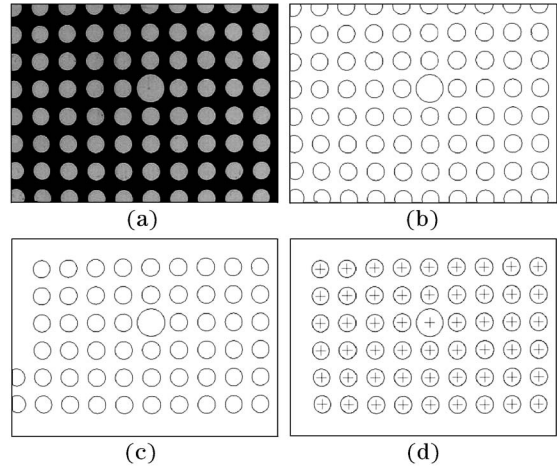


Fig. 4. The result of the image processing. (a) Original image, (b) image after contour detection, (c) eliminate non-closed contours, (d) ellipse fitting and center computing.

the non-ellipse and irresponsible ellipse contours. A two-stage method is developed to fulfill the purpose eliminating these data.

In the first step, non-ellipse contours will be removed. At first, the simple contour tracing algorithm is applied to the Fig. 4(b) to eliminate the non-closed borders. And then the following process is used to eliminate the rest of the non-ellipse contour.

For all of contours (except the feature ellipse), the radius of minimal enclosing circle r and the number of the border points N are just around the same values. Minimal enclosing circle (MEC) means the smallest circle that contains a set of points completely. It can be defined with the prune-and-search algorithm^[8]. Considering the existence of noise and imperfect ellipse contours, it is likely that some values may deviate far from the same values. Figure 5(a) is the points number statistic graph of Fig. 4(b) contours. One noise contour maybe contain a few border points, and non-closed borders are probably turned into the larger contour containing many border points after processing. The same instance will occur in the radius of MEC. All of such contours will be eliminated according to the appropriate threshold. Figure 5(b) is the statistic graph after eliminating. In this figure, the maximal value is assigned by the feature ellipse.

The area encircled by the closed contour with N points $\{(x_i, y_j) | 1 \leq i \leq N\}$ may be calculated as

$$S = \frac{1}{2} \sum_{i=1}^N (x_{i-1}y_i - x_iy_{i-1}). \tag{1}$$

The circularity value is defined as the ratio of contour area to MEC area, which is described as

$$C = S/(\pi \cdot r^2). \tag{2}$$

The circularity value of relative perfect ellipse contour cannot be too small. The non-ellipse contours will be removed according to this rule. In this process, the little lens distortion is allowable, therefore the threshold of circularity value is in the range of 0.6—0.7 after a mass of experiments. The processed result is shown in Fig. 4(c), and points number statistic of contours is shown in

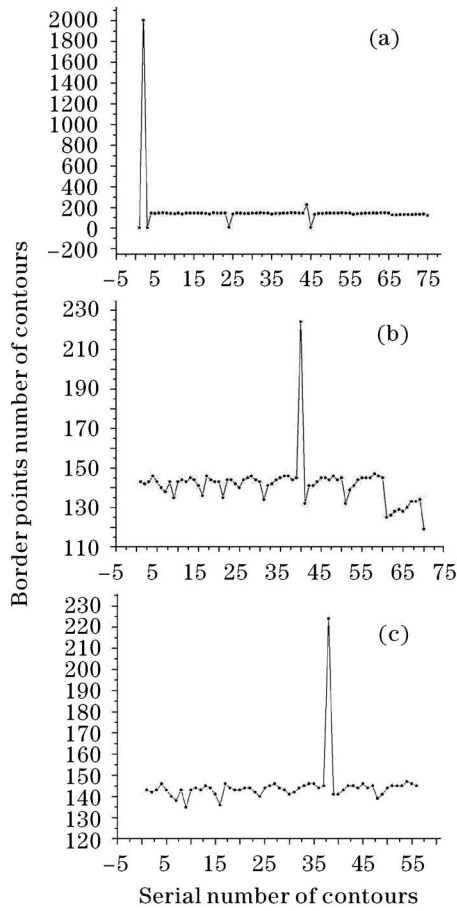


Fig. 5. Statistic graph of contours border points.

Fig. 5(c).

In second step, irresponsible ellipse contours will be deleted. Hu moment values of the shape are invariants to translation, rotation, and scale change^[9]. On the basis of the Hu moment invariants, three similarity variables I_1 , I_2 , and I_3 may be defined as

$$\begin{cases} I_1(A, B) = \sum_{k=1}^7 \left| \frac{1}{M_k^B} - \frac{1}{M_k^A} \right| \\ I_2(A, B) = \sum_{k=1}^7 |M_k^B - M_k^A| \\ I_3(A, B) = \max_k |(M_k^B - M_k^A)/M_k^A| \end{cases}, \quad (3)$$

where A and B are border points collection of the closed contours; $M_k^A = \text{sgn}(h_k^A) \log_{10} |h_k^A|$; $M_k^B = \text{sgn}(h_k^B) \log_{10} |h_k^B|$, where h_k is the k -order Hu moment. When A and B are identical, $I_1 = I_2 = I_3 = 0$; otherwise the worse the similarity of two contours is, the bigger the three similarity values are. In this stage, the precise ellipse recognition is processed according to the similarity values of calibration ellipses and the feature ellipse. The calibration ellipses with big similarity value are taken as irresponsible contours. The thresholds of three similarity values are assigned value of 0.001. So the contours can be removed further.

Finally, ellipse fitting and center computing will be carried out. Figure 4(d) illustrates the result after all steps. The crosses are located at the centers of the ellipses, and defined as the calibration points.

Mintron MTV-368P charge-coupled device (CCD) camera with resolution of 500×582 and the lens of 16 mm are adopted in the experiments. The new calibration pattern has been photo-etched a 11×11 array of circles, with the center distance of 15 mm, and the feature circle's diameter of 15 mm, the rest circles' diameter of 10 mm, and the accuracy of 0.01 mm.

In the experiments, the pattern is moved along the track in 10-mm steps, leading to 5 images captured in discrete positions. Three arbitrary images are picked up to perform camera calibration with the RAC method. Totally, there are 10 groups of calibration results gained through experiments. Table 1 is an excerption of the calibration results and the standard deviation δ . It demonstrates that the calibration technique is reasonably robust.

Table 1. Calibration Results and Standard Deviation

Group	Focal Length	Distortion	Scale Factor s_x	Frame Center (pixel)	
	f (mm)	Factor k_1		C_x	C_y
1	16.879	7.285×10^{-4}	1.017224	458.297	218.945
2	16.868	7.352×10^{-4}	1.017275	458.593	219.154
...
10	16.881	7.164×10^{-4}	1.017280	460.805	217.507
δ	0.023	0.000	0.000	2.034	3.091

Table 2. Experimental Results for Confirming the Reliability

x_w	y_w	z_w	x_f	x'_f	$ x'_f - x_f $	y_f	y'_f	$ y'_f - y_f $
(mm)	(mm)	(mm)	(pixel)	(pixel)	(pixel)	(pixel)	(pixel)	(pixel)
0	-15	40	434.085	434.367	0.282	262.075	262.289	0.214
-30	45	40	302.586	302.728	0.141	534.591	534.465	0.126
-75	-15	40	104.722	104.845	0.123	270.208	270.361	0.153
45	-45	40	636.502	636.657	0.155	121.491	121.611	0.120
45	30	40	642.442	642.715	0.273	462.352	462.689	0.338

With the calibrated camera parameters, computer frame coordinate (x'_f, y'_f) can be derived from the 3D space coordinate (x_w, y_w, z_w) . The first three images will be selected to recover the parameters and infer the image coordinates of the last image. The inferred factual values and their deviations are shown in Table 2. Considering the paper width, only the data of 5 groups are given. The table infers that the deviation between the two values is less than 0.4 pixel, which indicates that this technique is reliable.

In summary, it is introduced in this paper that a novel circle pattern in camera calibration, with its corresponding image-processing algorithm. The revised calibration technique boasts full-automation and efficiency in the process of camera calibration and guarantees the measurement precision at the same time. The experimental results firmly verify the practicability and reliability of this new ellipse recognition algorithm. These advantages prove that this camera calibration method is competent for the computer vision field.

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