A corrected method of distorted printed circuit board image*

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This paper proposes a corrected method of distorted image based on adaptive control. First, the adaptive control relationship of pixel point positions between distorted image and its corrected image is given by using polynomial fitting, thus control point pairs between the distorted image and its corrected image are found. Secondly, the value of both image distortion centre and polynomial coefficient is obtained with least square method, thus the relationship of each control point pairs is deduced. In the course of distortion image processing, the gray value of the corrected image is changed into integer with bilinear interpolation. Finally, the experiments are performed to correct two distorted printed circuit board images. The results are perfect and the mean square errors of residual error are tiny.

Keywords: distortion correction, adaptive control, printed circuit board image, mean square error of residual error

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1. Introduction

Image distortion is prevalent in imaging systems such as a coupled charge device (CCD) or complementary metal oxide semiconductor system[1−3] and so on, and it is caused by a big field etc. during capturing the image in the system. Distortion affects the quality of the image, thus it can not reflect the actual information of the image, so distortion correction is very important.[4−8]

It is studied extensively all over the world in the field of the distortion correction of image because of its importance, and multiple significant achievements have been obtained.[4−8] For example, Xiao *et al.*[4] proposed a spherical perspective projection model to correct the image distortion according to the imaging feature of panoramic annular lens, and the tangential and radial distortions were corrected greatly through simulation and real-image experiments. Asari *et al.*[5] proposed a new approach for nonlinear distortion correction in endoscopic images based on least squares estimation, and the distortion-correction model was applied to several gastrointestinal images and the results were presented. Yu *et al.*[6] presented one target distortion testing method for distortion measurement and calibration, and the distortion of wide-angle CCD camera system with focal length of 2.6 mm was repeatedly measured and calibrated, the calibrating precision was within 0.3%. Helferty *et al.*[7] presented a distortion correction technique that could automatically calculate correction parameters, and it was applicable to any distortion correction situation without precise knowledge of horizontal or vertical orientation.

In this paper, because radial distortion is primary in the distortion of printed circuit board (PCB) image captured by CCD camera, we adopt the following method to correct distorted PCB images effectively. First, polynomial fitting[9,10] is used to change the corresponding relationship of pixel points between the distorted image and its corrected image from the polar coordinate system to the Cartesian coordinate system. Proper control point pairs are found between the distorted image and its corrected image, by adopting least square method,[11−13] corresponding coordinates of control point pairs are obtained between the distorted image and its corrected image by adaptive control relationship. Lastly, the gray value of the correctd image is changed into integer by adopting gray reconstruction of bilinear interpolation.[14,15]

To verify the correctness of the theoretical analy-

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sis, a distorted pane test image is corrected effectively by adopting the method proposed in this paper at first, and then two distorted PCB images captured by CCD camera are corrected effectively by adopting the same method. And the errors in the experiments are tiny by calculating mean square error of residual error in corresponding pixel point coordinates, so we can obtain high correction precision.

2. Basic principle

2.1. Corresponding relationship of coordinates of adaptive control point pairs

In the Cartesian coordinate system, we can suppose that a certain pixel point coordinate in the distorted image produced on account of geometrical distortion is (x, y), and it is (u, v) in the corrected image. In the polar coordinate system $O'r'$, the distance from the pixel point coordinate $A(x, y)$ to the distortion centre $C(x_c, y_c)$ is r', and the angle between the beeline AC and the x axis is θ' in the distorted image. And they are r and θ in the corresponding corrected image in the polar coordinate system Or, (u_c, v_c) denotes correction centre.

To the distorted image, there is the following relationship in the system $O'r'$:

$$\begin{cases} r' = \sqrt{(x - x_c)^2 + (y - y_c)^2}, \\ \cos\theta' = \frac{x - x_c}{r'}, \quad \sin\theta' = \frac{y - y_c}{r'}. \end{cases} \tag{1}$$

In the system Or, after being corrected, the new pixel point location (u, v) in the corrected image that maps the pixel point location (x, y) in the distorted image can be obtained as

$$\begin{cases} u = u_c + r\cos\theta, \\ v = v_c + r\sin\theta. \end{cases} \tag{2}$$

There are radial distortion, tangential distortion and eccentric distortion among the categories of distortion in PCB image captured by CCD camera. Radial distortion is the distortion that follows radial direction from optical centre, and it has barrel distortion and pillow distortion.[16]

The radial distortion is primary among the categories mentioned above, and other kinds are unimportant, so we can think that the distortion is purely radial distortion in general, then the polar angle is unchanged in the distorted image and the corresponding corrected image. When we adopt the polynomial fitting,[9,10] the mapping from distortion space to correction space can be expressed as

$$\begin{cases} r = \sum_{n=1}^{N} a_n r'^n, \\ \theta = \theta', \end{cases} \tag{3}$$

where a_n is polynomial coefficient.

The matching relationship in the Cartesian coordinate system between the pixel point coordinates (u, v) in the corrected image and that of (x, y) in the distorted image can be deduced from Eqs. (1) to (3) as

$$\begin{cases} u = u_c + \left\{\sum_{n=1}^{N} a_n[(x - x_c)^2 + (y - y_c)^2]^{n/2}\right\} \\ \qquad \times \dfrac{x - x_c}{\sqrt{(x - x_c)^2 + (y - y_c)^2}}, \\ v = v_c + \left\{\sum_{n=1}^{N} a_n[(x - x_c)^2 + (y - y_c)^2]^{n/2}\right\} \\ \qquad \times \dfrac{y - y_c}{\sqrt{(x - x_c)^2 + (y - y_c)^2}}. \end{cases} \tag{4}$$

Therefore, there is corresponding relationship one by one between the (u, v) and the (x, y).

In a corrected image, the correction centre (u_c, v_c) can be chosen by ourselves. In order to obtain the value of coordinates (u, v) from Eq. (4), we must calculate the distortion centre (x_c, y_c) and the polynomial coefficient $a_n (n = 1, 2, \ldots, N)$, so we can choose control points $(u_1, v_1), (u_2, v_2), \ldots, (u_L, v_L)$ whose number is L, and their corresponding coordinates in the distorted image are $(x_1, y_1), (x_2, y_2), \ldots, (x_L, y_L)$. And on the basis of these control point pairs, we can adopt least square method[11−13] to obtain the value of distortion centre (x_c, y_c) and polynomial coefficient $a_n (n = 1, 2, \ldots, N)$, so we can ascertain the mapping relationship between the (u, v) and the (x, y) from Eq. (4).

Aiming at these control point pairs whose number is L, according to least square method,[11−13] the following equation must be satisfied when we fit the u coordinate from Eq. (4)

$$\sum_{k=1}^{L} \left\{ \left\{ \sum_{n=1}^{N} a_n[(x_k - x_c)^2 + (y_k - y_c)^2]^{n/2} \right\} \frac{x_k - x_c}{\sqrt{(x_k - x_c)^2 + (y_k - y_c)^2}} \right\} [(x_k - x_c)^2 + (y_k - y_c)^2]^{t/2}$$

$$= \sum_{k=1}^{L} (u_k - u_c)[(x_k - x_c)^2 + (y_k - y_c)^2]^{t/2}, \tag{5}$$

where $t = 1, 2, \ldots, N$.

As to v coordinate from Eq. (4), we can obtain the following equation with the same method:

$$\sum_{k=1}^{L} \left\{ \left\{ \sum_{n=1}^{N} a_n [(x_k - x_c)^2 + (y_k - y_c)^2]^{n/2} \right\} \frac{y_k - y_c}{\sqrt{(x_k - x_c)^2 + (y_k - y_c)^2}} \right\} [(x_k - x_c)^2 + (y_k - y_c)^2]^{t/2}$$
$$= \sum_{k=1}^{L} (v_k - v_c)[(x_k - x_c)^2 + (y_k - y_c)^2]^{t/2} \tag{6}$$

It can be seen from Eqs. (5) and (6) that the corresponding relationship of the adaptive control point pairs (u, v) and (x, y) can be obtained.

It is obvious that both Eqs. (5) and (6) are Nth order polynomial with the same unknown parameters $a_n (n = 1, 2, \ldots, N)$ whose number is N, there are also unknown parameters x_c and y_c, so the total unknown parameters of both equations are $N + 2$. What is more, both Eqs. (5) and (6) have the same number of equations which is N. Suppose all equations have keys, then the total equations must exceed or equal that of the unknown parameters, namely, the condition of $2N \geq N + 2$ must be satisfied, then we can obtain $N \geq 2$.

When $N \geq 2$ in Eqs. (5) and (6), we can obtain the x_c, y_c and $a_n (n = 1, 2, \ldots, N)$, and then the corresponding relationship of the coordinates between the (u, v) and the (x, y) from Eq. (4). What is more, the corresponding relationship is adaptive.

The higher the power in the polynomial is, the larger the number of coefficients is, it will lead the computational burden to increase rapidly.[15] In addition, the expression of relative distortion including terms of the power two and power three of the radial distortion is beneficial in terms of accuracy.[17] Therefore, for general distortion correction of image, in order to obtain a simple and accurate corresponding relationship of coordinates of the (u, v) and the (x, y), we demand $N = 3$ from Eqs. (5) and (6).

2.2. Gray-level interpolation

Because integer positions in the corrected image $g(u, v)$ can map into noninteger positions in the distorted image $f(x, y)$, gray-level interpolation[14,15] is necessary in the course of distortion image processing. In this case, the gray-level interpolation on the surrounding pixels is used to obtain the approximate pixel gray-level information. Bilinear interpolation is an usual gray-level interpolation method, and we use it to produce more satisfied results in this paper.[14,15]

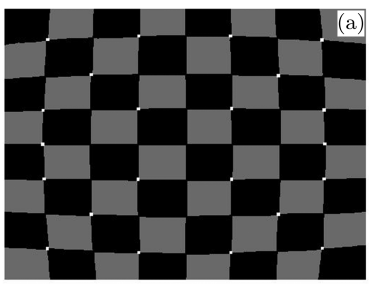
Thus, the gray value of the image $g(u, v)$ after being corrected can become integer because of gray reconstruction of bilinear interpolation.[14,15] If there is noise in the actual course of correction, median filter designed by us can wipe it off.

3. Results and analyses of experiments

3.1. Results of experiments

First, a distorted pane test image of 768×576 in pixel is corrected with the method proposed in this paper in order to incarnate better corresponding relationship of coordinates of control point pairs between the distorted image and its corrected image. And correction centre selected in the corrected image is (384, 288), and $N = 3$ in Eqs. (5) and (6).

The distorted pane test image and the coordinates of selected control points whose number is 22 are shown in Fig. 1(a), the image and the coordinates of corresponding control points in the undistorted image are shown in Fig. 1(b), the deferent corrected image after denoising by median filter and coordinates of corresponding control points are shown in Fig. 1(c).



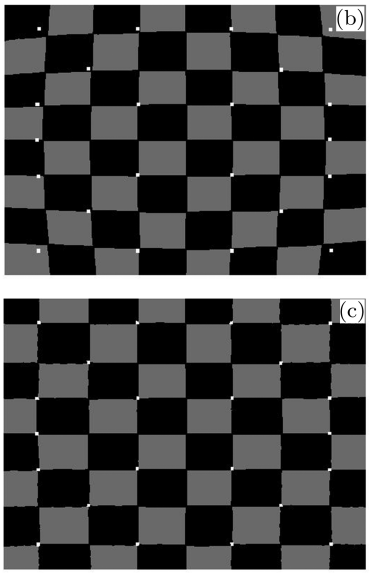


Fig. 1. Results of the experiment of pane test image. They are (a) distorted image and its control points coordinates, (b) distorted image and the coordinates for the image with no distortion of corresponding control points, and (c) deferent corrected image and its control points coordinates.

Obviously, the coordinates of control points in the corrected image are changed in comparison with that of the distorted image. And the corresponding relationship of the coordinates in the control point pairs between the distorted image and the corrected image is adaptive.

And then, another correction experiment is made in two distorted PCB images with the same method proposed in this paper. Both images have the size of 768×576 in pixel and the character of barrel distortion, and correction centres selected in both images are (384, 288).

Distorted PCB images I and II captured by CCD camera are shown in Figs. 2(a) and 2(c) respectively. It can be seen that the distorted components in the two images are very evident. And the erect beelines which are situated on the leftmost and the rightmost in the image I are obviously outstanding, and they are changed into curves. There are also some obvious curves because of distortion in the image II.

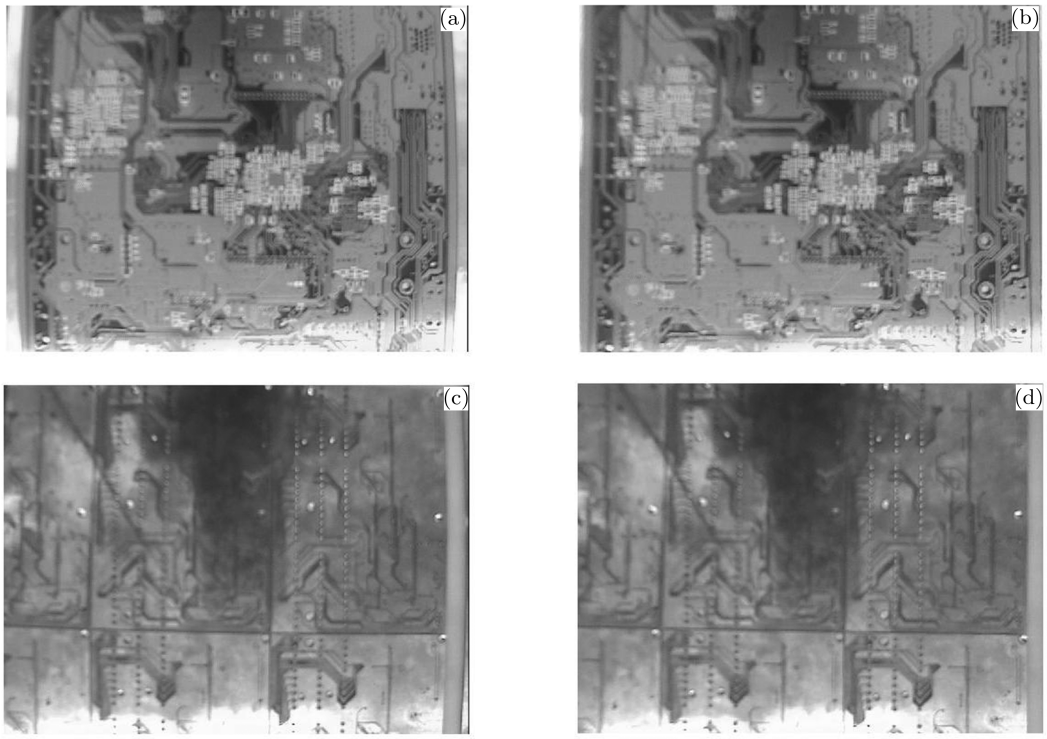


Fig. 2. Results of the experiment of PCB images. They are (a) distorted PCB image I, (b) corrected PCB image I from (a), (c) distorted PCB image II, and (d) corrected PCB image II from (c).

In order to obtain actual image information, we use the two images to make an actual correction experiment by adopting the method proposed in this paper, and the results of correction are shown in Figs. 2(b) and 2(d) respectively.

It is obvious that the distorted components in the two images can be renewed better. The curves situated on the leftmost and the rightmost in the image

I are changed into erect beelines obviously, and some curves caused by distortion in the image II are also changed into beelines.

3.2. Analyses of experiments

On the condition of MATLAB 7.0 and PC with Genuine Intel(R) CPU T2080, 1.73 GHz and 1 G memory, we can obtain correction precision by calculating mean square error of residual error in corresponding pixel point coordinates, i. e. δ_u and δ_v can be obtaind by the following equations:[18]

$$\begin{cases} \delta_u = \sqrt{\dfrac{1}{N-1}\sum_n (u_n - u_{\ln})^2}, \\ \delta_v = \sqrt{\dfrac{1}{N-1}\sum_n (v_n - v_{\ln})^2}, \end{cases} \tag{7}$$

where (u_n, v_n) and $(u_{\ln}, v_{\ln})$ are pixel point coordinates in corrected images and ideal images after fitting respectively.

And the values of δ_u and δ_v in the three images mentioned above are shown in Table 1.

Table 1. Values of δ_u and δ_v (unit: pixel).

image	δ_u	δ_v
distorted pane test image	0.120	0.115
distorted PCB image I	0.121	0.116
distorted PCB image II	0.122	0.117

It is obvious that the errors in the experiments are tiny.

The discrepancy between the ideal value and the actual value is due mainly to the following factors:

(i) in order to decrease computational burden, the power in the polynomial used by us is three, so we can not obtain ideal corrected image without distortion, and the error can not be avoided;

(ii) in this paper, we take no account of tangential distortion and eccentric distortion in the categories of distortion in PCB image captured by CCD camera because of their unimportance;

(iii) it is difficult to acquire real ideal image because of the nonlinearity of CCD.[19]

4. Conclusions

The PCB image captured by CCD camera will produce distortion inevitably because of big field and so on, and the distortion will affect the quality of image. On the basis of adaptive control relationship between the distorted image and its corrected image, the distorted image is corrected effectively by adopting the method proposed in this paper.

We use the theory proposed in this paper to correct the pane test image and the two actual PCB images which all have distorted phenomena. The results verify the correctness of the theoretical analysis.

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