Lens distortion correction by adjusting image of calibration target

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The dilemma of lens distortion in computer vision is a common and serious phenomenon, especially when a lens captures a wide-angle image or when an object is seized within a limited range. Using correction lens, phase plates or holographic gratings, mainly, makes the corrections. However, it is extremely difficult to accurately correct the distortion using attached optic components because the design of these components is complicated and commercially hard to attain.

In this paper, a method is proposed to correct the distortion using the lens aberration theory and image processing techniques. A calibration target is taken as the correct and acceptable objective. The captured or seized image of the calibration target is not equally divided as original and this pixels-shift contains the distortion information which could be corrected by image process software produced by the authors.

1 Introduction

Many kinds of lens aberration can show up or appear in an imaging system. The different types that afflict an imaging system depend entirely on the hardware used. Faulty or inferior grinding and polishing of lens elements generally causes lens distortion. In practice, the distortion is eliminated in expensive and more complex lenses, but the cheaper and more commonly used lenses are most vulnerable to this problem, especially near the perimeter of the image. If left uncorrected, the distortion reduces the precision. The radial distortion is quite visible, and can be detected by simply pointing the camera at any straight-edged surface and observing the bow in the imaged version. It is a common problem in cheap lenses, and has to be taken into account. If the distortion model is understood, then images can be corrected by image-processing software after the image is grabbed by the lenses and without need for any lens attachments.

To correct the distortion of a lens, a lens is placed in front of a calibration target and recorded the distortion image of the calibration target by a CCD camera. First, the thinning image is obtained using the thinning algorithm and this enables one to distinguish each radial line and scale. Second, the center of image is calculated. Finally, the distortion image is compared with a standard calibration target, which is inside the computer, to calculate the offset value of each specific checkpoint. These offset values are caused by the distortion, which is proportional to curvature of the lens. If a wide-angle lens grabbed the calibration target, it is shown that, the calibration target produced is of equal scale using first order ray-tracing techniques. But, in the real world, the image is seriously distorted. The scale between each radial line becomes increasingly closer at the perimeters of the lines. The lens designing software1 GENII is used to simulate the relationship between the object and the image and find the distortion, which dominates the five different kinds of aberrations2. It is only needed to calculate the offset values of each fringe, and the distortion of the whole lens can then be corrected.

2 Distortion of Refracting Surface

Distortion designates the condition in which objects in the object plane that are of different size and that are centered on the axis produce images in the plane of the screen, which are magnified by different amounts. When large objects are magnified more than small objects, pin-cushion distortion is obtained; and when small objects are magnified more than large objects, barrel distortion is obtained. When large objects are magnified by the same amount as small ones, the image is said to be orthoscopic, that is, free from distortion1.
To discuss the distortion produced by a single refracting surface, it is considered that the object surface is flat and normal to the axis at \( L \) (Fig. 1). \( H \) is an object height on the flat object surface. The image plane is conjugated to \( L \) at \( L' \) for paraxial rays. \( H' \) is the image depicted by primary ray from \( H \) through \( O \) to the image screen. The auxiliary axis from \( H \) through \( C \) penetrates the image screen at \( H'' \). If there is no distortion, \( H' \) must be at the same position with \( H'' \). It can be clearly detected when the aperture-stop is placed at the centre of curvature, all of the primary rays would pass through the refracting surface normally, to the centre of curvature. Therefore, a perfect projection image is got from the object. The primary ray from \( H \) coincides with the auxiliary axis at \( H' \) and also coincides with \( H'' \). Contrarily, the distortion occurs. The amount of distortion is the displacement from \( H' \) to \( H'' \). The chief ray crosses the auxiliary axis at \( H' \) and \( H'' \), which is the sagittal image and Petzval image of each \( H \). The equation for distortion can derive as follows:

\[
\text{Distortion} = E(Y^{1/3})
\]

where \( E \) is the distortion coefficient. Distortion increases approximately in proportion to the cube of \( Y \). In real world, distortion is the aberration-type classified as \( n \)th order and \( n \)th degree astigmatism.

### 3 Image Processing

In the system of the authors, the calibration target has 12 radial lines; 1 cm in diameter scale on each line began from the outer 2.0 cm of the centre. The distance from plate to CCD is 10 cm. The testing lens is a 6 mm /2.0 lens mounted on a 1/2" CCD video camera and located in front of the plate. This system was used by the authors to obtain a distortion image upon which a calibration target was being projected. They mainly utilized an image processing technique for dealing with the line pattern, which the CCD camera records, so that the required information could be obtained.

The first step is noise-suppression. The noise-suppression step is to filter the noise of the digitized image, and to enhance the connectivity of the broken segments. This step consists of isolated point deletion, dilation point deletion and missing point recovery.

The second step is histogram equalization and histogram extension. This is done in order to increase the contrast of the background and the object for the purpose of threshold. The third step is threshold. The purpose of threshold is to obtain the binary image and to classify the background and the object.

The final step is thinning, and in this step, a new thinning method is used to extract the skeleton of the fringe. The thinned pattern preserves the connection and the shape of the original pattern. In short, iterative deletions of the dark points are used (i.e., changing them to white) along the edges of a pattern until the pattern is thinned to a line drawing.

In their thinning method, the authors modify the coding method of Arcelli & Sanniti, to encode the fringe pattern. This coding method consists of
forward scanning (from bottom right to top left), which will mark the whole pixels of the image, using different numbers to distinguish the boundary and core from the object. Then, the new ‘saving-deletion rule’ is utilized to save or delete these marked pixels, and therefore, the outer boundary, which does not destroy the skeleton shape, will be deleted gradually. The above steps are repeated, and the line skeleton is obtained. This thinning algorithm is used to get the thinned line and compensated the lost pixels of each line. In order to determine the sampled pixels of each radial line, 12 sets of lines have been selected which run through the centre every 30 arc degrees, and counted the coordination of the cross-point of each line. The checkpoints would be 25 pixels for each radial line.

4 Experimental Results

The standard pattern with the radial lines and scale is used for calibration target (Fig. 2). As a result, the image captured by CCD camera of the target will be displaced from the ideal image and the image will not be geometrically similar to the target. Distortion is the aberration-type classified as nth order and nth degree astigmatism. Accordingly, the correction to the distortion aberration polynomial is:

$$e = \sigma r^2 + \mu r^4 + \tau r^5 + \cdots$$  \hspace{1cm} (2)

where \( r \) is the object height.

The coefficients, \( \sigma, \mu \) and \( \tau \) are the coefficients of third, fifth, and seventh order distortion, respectively. The coefficients of distortion can be found by measuring the relationships between the crossing grid-points in the target and the image. If a particular coefficient is negative, the corresponding distortion is said as "barrel distortion"; if a particular coefficient is positive, the corresponding distortion is said as "pin-cushion distortion".

It is clear from a scrutiny of the aberration polynomials that, there exists quantitative non-linearity of the magnification transformation and the distance from the image centre to the local part. Here, the magnification transformation is modified by dividing the image from two, to ten circular regions and establishing ten transfer functions by experimental calibration. Here, a second order polynomial \( f_i(r) \) is used to approximate the scaling function of every local region (Fig. 3). The cross marks in Fig. 3 can provide the relative location to calculate the scaling factor.

$$f_i(r) = a_i r^2 + b_i r + c_i$$ \hspace{1cm} (3)

where \( a_i \), \( b_i \) are the scaling factor.
\( c_i \) is a compensation factor.

Fig. 2 — Calibration target

Here, three specifications of the distortion correction system are asserted:

1. The number of the circular rings is adjustable.
2. The intervals of the circular rings can be different for practical consideration.
3. The continuity of the scaling functions should be preserved i.e.

\[ f_i(r) = f'_{i+1}(r) \] \hspace{1cm} \ldots (4)

and \( f'_i(r) = f'^{'}_{i+1}(r) \)

where \( r = r_i \), the scaling value \( m_i \) is the same for the continuity in the boundary.

\[ m_i = a_i r_i^2 + b_i r_i + c_i \] \hspace{1cm} \ldots (5)

\[ m_i = a_{i+1} r_{i+1}^2 + b_{i+1} r_{i+1} + c_{i+1} \] \hspace{1cm} \ldots (6)

In order to preserve the continuity, assume that, the deviation of distortion aberration polynomials of an \( i \)th region is also equal to that of \( (i+1) \)th region in the boundary.

\[ 2a_i r_i + b_i = 2a_{i+1} r_{i+1} + b_{i+1} \] \hspace{1cm} \ldots (7)

If the image is divided to \( n \) circular rings, then we have \( n \times 3 \) equations to solve \( n \times 3 \) unknowns.

Fig. 4(B) is the correct image of Fig. 4(A). These results are examined at the location of checkpoints in the centre of the circular ring. Table 1 shows the value of error, which is the discrepancy of the location of checkpoints and the corresponding correct points. The sequence of checkpoints 1 to 10 is arranged from the centre to the edge of the image. This simple operation can be seen without more complex polynomials used for interpolation, still can fit a great number of nearby pixels correctly.

<table>
<thead>
<tr>
<th>Check point</th>
<th>Error value in Fig. 4(B)</th>
</tr>
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<tbody>
<tr>
<td>#1</td>
<td>0 pixel</td>
</tr>
<tr>
<td>#2</td>
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<tr>
<td>#9</td>
<td>1 pixel</td>
</tr>
<tr>
<td>#10</td>
<td>2 pixel</td>
</tr>
</tbody>
</table>

5 Conclusion

It is known that, distortion is a problem in optical design. It is the ultimate goal of lens designing engineers to eliminate this problem, especially in wide-angle lens design. In the proposed method, distortion can be corrected by a software method.

The distortion image contains the lens defect directive. To use a calibration target is economic and it is less complicated to obtain data. The authors have demonstrated that, with a calibration target, it is possible to correct the distortion of a lens. However, in their experiments, using the equal scale calibration target, the outer scale will be closer and hard to recognize the scale near the boundary of the
target, a different scale calibration target can be designed to overcome the problem.

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References