Accuracy evaluation of optical distortion calibration by digital image correlation

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ABSTRACT

Due to its convenience of operation, the camera calibration algorithm, which is based on the plane template, is widely used in image measurement, computer vision and other fields. How to select a suitable distortion model is always a problem to be solved. Therefore, there is an urgent need for an experimental evaluation of the accuracy of camera distortion calibrations. This paper presents an experimental method for evaluating camera distortion calibration accuracy, which is easy to implement, has high precision, and is suitable for a variety of commonly used lenses. First, we use the digital image correlation method to calculate the in-plane rigid body displacement field of an image displayed on a liquid crystal display before and after translation, as captured with a camera. Next, we use a calibration board to calibrate the camera to obtain calibration parameters which are used to correct calculation points of the image before and after deformation. The displacement field before and after correction is compared to analyze the distortion calibration results. Experiments were carried out to evaluate the performance of two commonly used industrial camera lenses for four commonly used distortion models.

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1. Introduction

The digital image correlation (DIC) method is an easy-to-use and reliable method of non-contact full-field optical measuring methods [1]. Since its invention in the 1980s [2,3], it has been widely used in the full-field measurement of morphologies and deformations [4–6]. The principle of the DIC method is to find matching interesting regions with precise locations between the subsets in both the reference image and the target image using a correlation function, consequently realizing full-field deformation measurements. The typical displacement measuring accuracy achieved when using the DIC method is a few percent pixels [6], where the main factors influencing the accuracy of displacement measuring are interpolation bias [7,12], image noise [8,12], lens distortion [9], shape function [10] the subset size [10,11], etc.

With the extensive use of digital cameras in various industries, image measurement techniques have rapidly developed [13]. In some specific areas such as digital image correlation methods, high levels of accuracy of image measurements are required [6–12], where the lens optical distortion is an important factor that affects the imaging precision of a given digital camera [14,15]. While there are many forms of optical lens distortions, improvements in the lens manufacturing process have led to a situation where the leading distortions are radial and tangential [16]. For a variety of real lenses, image distortions unavoidably exist due to lens aberrations, misalignment of optical elements and non-parallelism between the image and sensor planes [9]. The relative distortion of the whole field of view in most industrial lenses is usually 1%–2% [9,14,15]. These distortions will cause greater deviations in the calculation of the strain field [9,23]. Therefore, the distortion of the imaging system must be strictly tested before accurate image measurement is carried out.

Several lens distortion measurement methods have been proposed to restore the geometrical fidelity of images. Most methods use calibration objects, among them, the camera calibration method based on the plane template proposed by Zhang is widely adopted because of its convenience of operation [17,18]. This method needs to establish a parametric distortion model in advance and then solve for the distortion parameters. However, whether the model is matched or not and the precision evaluation of the calibration results is always a problem to be solved. Another strategy is to directly compare a theoretical image with an image captured by camera to determine the lens distortion. For example, using a camera to capture a standard grid, the degree of distortion of the mesh reflects the lens distortion, but this method cannot achieve sub-pixel accuracy of lens distortion measurements [19,20]. Using DIC to calculate the distortion fields was proposed by [21,22]. A correlation calculation is performed between a known numerical pattern and a picture of the same pattern printed or etched onto a plate. Printing errors, interpolation errors imparted during the image zooming process, and other effects were introduced. There is also a way to obtain lens distortion information by calculating the rigid body in-plane displacement field [23], where the accuracy of this method depends on the accuracy of

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the displacement calculation. However, this method only applies to the first order radial distortion model, and the operation is very troublesome and cannot be widely used. In [9], systematic errors in two-dimensional (2D) digital image correlation due to lens distortions were researched using this method. Due to the limitations of this method, they only discussed the first order radial distortion model and used a telecentric lens to eliminate the influence of out-of-plane displacements.

From the aforementioned summary of the previous work performed in this field, it can be seen that methods based on a plane template of operation are convenient, but there is no accurate assessment to ensure correctness. Methods that use DIC to calculate the distortion fields between numerical patterns and printed patterns will introduce additional factors, and the operation is troublesome. Other methods that calculate the rigid body in-plane displacement field have high accuracy, but they have strong limitations and are inconvenient to use. To address these problems, an experimental method to evaluate the accuracy of the widely used camera calibration method, as based on a plane template, is presented in this paper. An image is displayed on a liquid crystal display (LCD) screen before and after translation and captured by a digital camera. After that, we calculate the in-plane rigid body displacement field using the DIC method to reflect the optical distortion of the lens. The distortion parameters were calibrated, and the distortion of the calculated points was hence corrected. Finally, the displacement field before and after correction was compared. This paper is organized as follows. In Section 2, we discuss four types of commonly used optical distortion parametric models and how to use these parametric models to correct distorted images. Section 3 describes the experimental methods and experimental setup. In Section 4, the experimental results are analyzed, and the performance of the two commonly used industrial camera lenses for four commonly used distortion models are discussed.

2. Optical distortion and distortion correction

2.1. Imaging principle

The functions in this section use a so-called pinhole camera model (Fig. 1). In this model, a scene view is formed by projecting three-dimensional (3D) points onto an image plane using a perspective transformation.

\[
\begin{pmatrix}
    s_0 \\
    s_1 \\
    \vdots \\
\end{pmatrix} = A[R|T]M',
\]

or

\[
\begin{pmatrix}
    x' \\
    y' \\
    z' \\
\end{pmatrix} = A[R|T]M,
\]

where:

- \((X, Y, Z)\) are the coordinates of a 3D point in world coordinate space;
- \((X_0,Y_0)\) are the coordinates of the projection point in pixels;
- \(A\) is a matrix of intrinsic parameters;
- \((f_x,f_y)\) is a principal point that is usually at the image center;
- \(f_x, f_y\) are the focal lengths expressed in pixel units;
- \(f_x, f_y\) is a parameter that represents the nonperpendicularity of a camera sensor array;
- \(s\) is a nonzero scale factor.

The joint rotation-translation matrix \([R|T]\) is called a matrix of extrinsic parameters. It is used to describe the camera motion around a static scene, or vice versa, rigid motion of an object in front of a still camera. That is, \([R|T]\) translates coordinates of a point \((X;Y;Z)\) to a coordinate system, fixed with respect to the camera. The transformation above is equivalent to the following (when \(z \neq 0\):

\[
\begin{pmatrix}
    x' \\
    y' \\
    z' \\
\end{pmatrix} = \begin{bmatrix}
    X \\
    Y \\
    Z \\
\end{bmatrix} + T
\]

(3)

2.2. Radial and tangential distortions

Real lenses usually have some amount of distortion, mostly radial and slight tangential [16]. The pinhole camera model that considers the influence of radial and tangential distortions is schematically shown in Fig. 2.

We use \(x_0, y_0\) to denote the coordinates of a point in the distorted image, where \(x_0, y_0\) denote the coordinates of a point in the distortion-free image, and \(a_x, a_y\) represent the displacement change caused by the distortions.

\[
\begin{align}
    x_d &= x_{0d} + a_x \\
    y_d &= y_{0d} + a_y
\end{align}
\]

(4)

For a radial distortion:

\[
a_x = k_1 r^2 + k_2 r^4 + k_3 r^6 + \cdots
\]

(5)

Decomposition to the x-coordinate system:

\[
\begin{align}
    a_x &= \sum_{n=1}^{\infty} k_n (x^2 + y^2)^n \\
    a_y &= \sum_{n=1}^{\infty} k_n (x^2 + y^2)^n
\end{align}
\]

(6)

For a tangential distortion [21]:

\[
\begin{align}
    a_x &= (2xy \cos \varphi_0 - (3x^2 + y^2)) \sin \varphi_0 \sum_{n=1}^{\infty} s_n (x^2 + y^2)^n \\
    a_y &= (2xy \cos \varphi_0 - (x^2 + 3y^2)) \sin \varphi_0 \sum_{n=1}^{\infty} s_n (x^2 + y^2)^n
\end{align}
\]

(7)

Since the tangential distortion is small, the first-order form can be written as:

\[
\begin{align}
    a_x &= 2p_1 x y + p_2 (3x^2 + y^2) \\
    a_y &= 2p_1 x y + p_2 (3y^2 + x^2)
\end{align}
\]

(8)

This paper discusses four distortion models widely used in image processing, machine vision and other fields, namely: the first-order, second-order, third-order radial distortion models and the eight-parameters distortion model from Open Source Computer Vision Library (OpenCV).

When the third-order radial distortion model is adopted, the imaging formula (3) should be rewritten as:
\[
\begin{bmatrix}
 x \\
 y \\
 z
\end{bmatrix} =
\begin{bmatrix}
 X \\
 Y \\
 Z
\end{bmatrix} + T
\]

\[x' = x/z\]
\[y' = y/z\]
\[x'' = x'(1 + k_1 r^2 + k_2 r^4 + k_3 r^6)\]
\[y'' = y'(1 + k_1 r^2 + k_2 r^4 + k_3 r^6)\]
\[x_d = f_x x'' + f_s y'' + c_x\]
\[y_d = f_y y'' + c_y\]

When using the eight-parameter distortion model from OpenCV, the imaging formula (3) should be rewritten as:

\[
\begin{bmatrix}
 x \\
 y \\
 z
\end{bmatrix} =
\begin{bmatrix}
 X \\
 Y \\
 Z
\end{bmatrix} + T
\]

\[x' = x/z\]
\[y' = y/z\]
\[x'' = x'(1 + k_1 r^2 + k_2 r^4 + k_3 r^6) + 2p_1 x'y' + p_2 (r^2 + 2x'^2)\]
\[y'' = y'(1 + k_1 r^2 + k_2 r^4 + k_3 r^6) + p_1 (r^2 + 2y'^2) + 2p_2 x'y'\]
\[r^2 = x'^2 + y'^2\]
\[x_d = f_x x'' + f_s y'' + c_x\]
\[y_d = f_y y'' + c_y\]

If we can obtain the internal parameters and distortion parameters in the above imaging formula by calibration, we can correct the distortion of the image coordinates to distortion-free image coordinates.

The distortion correction formula for the third-order radial distortion model is [14,15,24]:

\[y'' = (y_a - c_y)/f_y\]
\[x'' = (x_a - c_x - f_y g(r)/f_s\]
\[x' = x''/(1 + k_1 r^2 + k_2 r^4 + k_3 r^6)\]
\[y' = y''/(1 + k_1 r^2 + k_2 r^4 + k_3 r^6)\]
\[r^2 = x'^2 + y'^2\]
\[x_d = f_x x' + c_x + f_s y'\]
\[y_d = f_y y' + c_y\]

The correction formula for the eight-parameter distortion model of OpenCV is [24]:

\[y'' = (y_a - c_y)/f_y\]
\[x'' = (x_a - c_x - f_y g(r)/f_s\]
\[x' = [x'' - 2p_1 x'y'' - p_2 (r^2 + 2x'^2)]/(1 + k_1 r^2 + k_2 r^4 + k_3 r^6)\]
\[y' = [y'' - 2p_2 x'' - p_1 (r^2 + 2y'^2)]/(1 + k_1 r^2 + k_2 r^4 + k_3 r^6)\]
\[r^2 = x'^2 + y'^2\]
\[x_d = c_x + f_x x' + f_s y'\]
\[y_d = c_y + f_y y'\]

Formula (11) and (12) is the approximate solution of formula (8) and (10) respectively. Previous work assumed that deviations caused by the distortions is relatively small [14,15,24], so that the approximation does not introduce a large error. However, the goal of this paper is to analyze the accuracy of the distortion calibration, and we do not wish to introduce other forms of error. Therefore, we need to analyze how much this error will affect the final results. Thus, we used the OpenCV distortion model and a group of distortion parameters obtained in our experiments. We used this set of distortion parameters to add distortion to a set of pure rigid body translation data (Fig. 3(a1) and (a2)), and then used this set of distortion parameters and Eq. (12) to correct them (Fig. 3(b1) and (b2)). The theoretical displacements in X (U-field) was 31 pixels, and the theoretical displacements in Y (V-field) was 0 pixels.

It can be seen from the simulations that the distortion correction formula introduces a 0.06-pixel bias under the aforementioned conditions, which is undesirable. So, an iterative method is proposed to perform the distortion correction, where the original formulae are used to calculate the corrected data, and then approximate terms in the formulae are re-
placed with the new data. The results of iterations 1, 2 and 3 are shown in Fig. 4. It can be seen that the improved distortion correction method is very accurate, and the simulation value converges to the theoretical value.

3. Experiment

Nowadays, the distortion calibration method based on a plane template is widely used. The verification method of the distortion calibration method is usually to take a standard orthogonal grid image with a short focus and fisheye lens and observe the geometric correctness of the

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Fig. 3. Distortion correction simulation: (a1) U-field with lens distortion; (a2) V-field with lens distortion; (b1) corrected U-field; (b2) corrected V-field.

Fig. 4. Results of iterations 1, 2 and 3: (a1) (b1) (c1) corrected U-field minus the theoretical U-field with iterations 1, 2, and 3, respectively; (a2) (b2) (c2) corrected V-field with iterations 1, 2, and 3, respectively.
image after correction. It is difficult to use the above method for some industrial camera lenses with small distortions. In some specific areas, such as digital image correlation methods, the accuracy of the image measurement has very high requirements, thus the distortion correction accuracy of the imaging system needs to be controlled to a few percent. Therefore, a more accurate experimental evaluation method is needed.

Lens distortion can cause an in-plane rigid body displacement field to become an inhomogeneous displacement field. In our experiment, an image was displayed on an LCD screen before and after translation, which was captured with a digital camera. After that, the in-plane rigid body displacement field was calculated using the DIC method to reflect the lens distortion. The distortion parameters were calibrated, and the distortion of the calculated points was corrected with the distortion parameters. We then compared the displacement field before and after correction, and if the displacement field tended to be uniform after correction, this meant that the calibration results were good.

3.1. Experimental setup

Fig. 5 shows the experimental setup that was built and used in this work. Two lenses were used in the experiment, labeled as lens 1 (Schneider Xenoplan 1.4/23-0902) and lens 2 (Compuar MH2520), which had focal lengths of 23 mm and 25 mm, respectively. Before recording images, the light path had to be adjusted to ensure that the optical axis of the camera was vertical to the screen, as shown in Fig. 5. The following steps describe how to adjust the experimental devices to meet the requirements:

1. Turn on the camera and place the screen 1 (Amark 19W80PS) in the appropriate position, making sure that the camera focuses on the screen and has the correct exposure.
2. Move screen 1 and place the laser pen and the beam splitter in the position shown in Fig. 5.
3. Turn on the laser pen. Watch screen 2 and adjust the laser pen and the beam splitter. Note that the laser spots (point 1, point 2, point 3) shown in Fig. 5(a1) must be located at the center of the image captured by the camera.
4. Put screen 1 back. Adjust the screen and the mirror to make sure that the laser spots on the mirror, and the incident light and the reflected light coincide with each other (Fig. 5(a2)).

After the light path was adjusted, we removed the laser pen, the beam splitter and the thin mirror. Taking the picture as the reference image, we then moved the speckled picture ten pixels horizontally (corresponding to approximately 31 pixels in the imaged picture) with Photoshop, and used this picture as the target image. In addition, we needed to obtain calibration data, so after the speckled pictures were taken, we removed screen 1 and took a set of calibration images. The calibration board used here was 12 × 9, 8 mm. The procedure used for lens 2 was the same as for lens 1.

3.2. Experimental parameter setting

The camera (IDS) was about 400 mm away from screen 1. In order to meet the optimal speckle standard proposed by Y. Su [7,8], a digital speckled pattern with a speckle diameter of one pixel and a duty ratio
Table 1
Internal parameters and distortion parameters of lens 1.

<table>
<thead>
<tr>
<th>distortion models</th>
<th>OpenCV distortion model</th>
<th>first-order radial distortion model</th>
<th>second-order radial distortion model</th>
<th>third-order radial distortion model</th>
</tr>
</thead>
<tbody>
<tr>
<td>fx</td>
<td>4210.946</td>
<td>4184.295</td>
<td>4191.659</td>
<td>4191.418</td>
</tr>
<tr>
<td>fy</td>
<td>4211.630</td>
<td>4197.964</td>
<td>4198.347</td>
<td>4198.949</td>
</tr>
<tr>
<td>fs</td>
<td>−2.276</td>
<td>3.340</td>
<td>−7.875</td>
<td>−8.012</td>
</tr>
<tr>
<td>cx</td>
<td>1021.618</td>
<td>1054.383</td>
<td>1036.018</td>
<td>1034.173</td>
</tr>
<tr>
<td>cy</td>
<td>943.670</td>
<td>956.486</td>
<td>941.481</td>
<td>943.364</td>
</tr>
<tr>
<td>k1</td>
<td>−0.259</td>
<td>−0.214</td>
<td>−0.261</td>
<td>−0.254</td>
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<tr>
<td>k2</td>
<td>0.577</td>
<td>0.594</td>
<td>0.395</td>
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Table 2
Internal parameters and distortion parameters of lens 2.

<table>
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<tr>
<th>distortion models</th>
<th>OpenCV distortion model</th>
<th>first-order radial distortion model</th>
<th>second-order radial distortion model</th>
<th>third-order radial distortion model</th>
</tr>
</thead>
<tbody>
<tr>
<td>fx</td>
<td>4686.985</td>
<td>4614.884</td>
<td>4679.897</td>
<td>4671.105</td>
</tr>
<tr>
<td>fy</td>
<td>4686.429</td>
<td>4615.565</td>
<td>4679.446</td>
<td>4670.582</td>
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<tr>
<td>fs</td>
<td>−0.218</td>
<td>−0.353</td>
<td>−0.075</td>
<td>−0.038</td>
</tr>
<tr>
<td>cx</td>
<td>993.424</td>
<td>971.787</td>
<td>989.449</td>
<td>990.405</td>
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<tr>
<td>cy</td>
<td>956.120</td>
<td>939.023</td>
<td>956.343</td>
<td>953.163</td>
</tr>
<tr>
<td>k1</td>
<td>0.302</td>
<td>−0.332</td>
<td>−0.156</td>
<td>−0.094</td>
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<tr>
<td>k2</td>
<td>−2.472</td>
<td>−2.507</td>
<td>−4.421</td>
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<tr>
<td>p1</td>
<td>2.015</td>
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<td></td>
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<td>p2</td>
<td>−0.0004387</td>
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<td></td>
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<tr>
<td>k3</td>
<td>0.3780</td>
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<td>16.416</td>
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<td>k4</td>
<td>0.4529</td>
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<td>k5</td>
<td>0.2534</td>
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<tr>
<td>k6</td>
<td>−0.3517</td>
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Table 3
Statistical results of the two lens and the four models.

<table>
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<tr>
<th>Before correction</th>
<th>distortion models</th>
<th>OpenCV distortion model</th>
<th>first-order radial distortion model</th>
<th>second-order radial distortion model</th>
<th>third-order radial distortion model</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1,(pixel)</td>
<td>30.9517</td>
<td>30.9614</td>
<td>30.9646</td>
<td>30.9635</td>
<td>30.9628</td>
</tr>
<tr>
<td>σu1,(pixel)</td>
<td>0.4405</td>
<td>0.0241</td>
<td>0.0472</td>
<td>0.0269</td>
<td>0.0267</td>
</tr>
<tr>
<td>V1,(pixel)</td>
<td>0.6415</td>
<td>0.6390</td>
<td>0.6396</td>
<td>0.6387</td>
<td>0.6389</td>
</tr>
<tr>
<td>σv1,(pixel)</td>
<td>0.1761</td>
<td>0.0109</td>
<td>0.0261</td>
<td>0.0109</td>
<td>0.0108</td>
</tr>
<tr>
<td>U2,(pixel)</td>
<td>33.5228</td>
<td>33.5242</td>
<td>33.5271</td>
<td>33.5245</td>
<td>33.5237</td>
</tr>
<tr>
<td>σu2,(pixel)</td>
<td>0.4549</td>
<td>0.0244</td>
<td>0.1417</td>
<td>0.0303</td>
<td>0.0310</td>
</tr>
<tr>
<td>V2,(pixel)</td>
<td>−0.1435</td>
<td>−0.1448</td>
<td>−0.1444</td>
<td>−0.1449</td>
<td>−0.1448</td>
</tr>
<tr>
<td>σv2,(pixel)</td>
<td>−0.1448</td>
<td>0.0285</td>
<td>0.0478</td>
<td>0.0300</td>
<td>0.0319</td>
</tr>
</tbody>
</table>

Fig. 6. Generated digital speckle and the imaged speckle: (a1) generated digital speckle; (a2) speckle pattern imaged by lens 1; (a3) speckle pattern imaged by lens 2.

4. Analysis

The work below was carried out with the help of PMLAB’s DIC-3D software. The DIC method was used to calculate the speckled image taken in the experiment, where the subset size was 29×29 pixels and
the step size was 7 pixels. For the same set of calibration images, four distortion models were used to calibrate the camera’s internal parameters and distortion parameters. The calibration algorithm of the OpenCV distortion model was derived from PMLAB’s DIC-3D software, and the calibration algorithm of the 1st, 2nd, 3rd-order radial distortion models was taken from VIC-3D software.

4.1. In-plane rigid body displacement field bias caused by lens distortion

Fig. 7 Shows the U-field and V-field calculated by 2D-DIC. If there was no lens distortion, theoretically U-field and V-field are all uniform. The V-field center was not zero, which can be seen as the screen x direction and the camera x direction do not coincide (however, this does not affect the rationality of this experiment).

4.2. Results of the distortion correction

The distortion parameters were calculated using the same set of calibration images used in the different distortion models, and the results are shown in Tables 1 and 2. fx, fy are the focal lengths expressed in pixel units. fs is a parameter that represents the nonperpendicularity of a camera sensor array. cx, cy are coordinate values of principal point. k1, k2, k3, k4, k5, k6 are radial distortion parameters. p1, p2 are tangential distortion parameters.

By using formulae (11) and (12) and the above-mentioned distortion parameters, the corrected displacement field can be obtained.

It can be seen that the results of the two lenses show that the widely used first-order radial distortion model is the worst of all the models considered here, and it cannot describe the distortions of the two industrial camera lenses (Figs. 8 and 9).

The experimental image size was 2048×2048, and in practice the test object was generally located at the middle of the image. Therefore, the error analysis was performed for the middle of the image (1600×1600). We usually assumed that the effects of distortion are negligible at r=0, so we took the mean value of 400 points around the optical center as the exact value (U1,V1,U2,V2), and the standard deviation (σu1,σv1,σu2,σv2) of all points in the analysis area was obtained. The smaller the standard deviation, the better the results. As can be seen from Table 3, the complex distortion model (OpenCV distortion model) does not have more advantages than the simpler 2nd and 3rd-order radial distortion models of the industrial lenses with better processing technology (lens 1). However, the complex distortion model (OpenCV distortion model) of lens 2 has a better ability to adapt, which we suggest is due to lens 2 having a larger tangential distortion than lens 1.

5. Conclusions

An experimental method was presented to evaluate camera distortion calibration accuracy in this paper, which is easy to implement, has high precision, and is suitable for a variety of commonly used lens. Mechanical displacement errors are avoided when using this method, and the method guarantees that the displacement field is an in-plane rigid body translation. The widely used lens calibration method based on a plane template was evaluated in the study. However, this method is not limited to the evaluation of this calibration method, and other calibration methods may be used. Our simulations found that the commonly used distortion correction formula in the usual experimental conditions will introduce roughly a 0.06 pixel deviation; hence an iterative formula is recommended for high-precision experiments. Four types of commonly used distortion models were used for two common industrial camera lenses, and it was found that the widely used first-order radial distortion model cannot describe the two commonly used industrial lens. The complex distortion model (OpenCV distortion model) does not have more advantages than the simpler 2nd and 3rd-order ra-
Fig. 8. Corrected displacement field of lens 1: (a1) (a3) (a4) corrected U-field using OpenCV, first-order radial, second-order radial, third-order radial distortion model respectively; (b1) (b2) (b3) (b4) corrected V-field using OpenCV, 1st-order radial, 2nd-order radial, 3rd-order radial distortion models, respectively.
Fig. 9. Corrected displacement field of lens 2: (a1) (a2) (a3) (a4) corrected U-field using OpenCV, first-order radial, second-order radial, third-order radial distortion model, respectively; (b1) (b2) (b3) (b4) corrected V-field using OpenCV, first-order radial, second-order radial, third-order radial distortion model, respectively.
dial distortion models for industrial lenses with better processing technology, but the complex distortion model has better adaptability.

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