Stereo camera calibration for large field of view digital image correlation using zoom lens

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A R T I C L E    I N F O

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Digital image correlation
Zoom lens

A B S T R A C T

We propose a calibration method for stereo camera with a large field of view (FOV) using zoom lenses. We adopted Magill’s formula, using intrinsic parameters with small object distances to calculate intrinsic parameters with large object distances. We employed a regular sized calibration board to calibrate extrinsic parameters in the small FOV, using zoom lenses to reduce the FOV, and then calculated extrinsic parameters in the large FOV. Verification experiments showed 3D reconstruction error was approximately 1 mm when the FOV is about 6 × 6 m. The proposed calibration method will broaden the application range for 3D digital image correlation in scientific and engineering fields.

1. Introduction

Digital image correlation (DIC) is an easy-to-use and reliable non-contact full-field deformation optical method [1]. Since first proposed in the 1980s [2,3], DIC has been extensively used in many fields, but particularly for full-field topography and deformation [4–6] measurements. The basic principle is to select a reference sub-area within a reference image and find the exact position that matches it in the target image according to correlation criteria, and hence measure the images full-field deformation. Three-dimensional DIC (3D-DIC) combines DIC and stereo vision to accurately measure 3D surface topography and deformation for an object. 3D-DIC has many advantages compared with common interference based optical measurement methods in experimental mechanics (e.g. speckle interference, Moire, and holographic interference methods), such as white light source, no vibration isolation, large range, etc. Hence, 3D-DIC have become widely adopted in various fields over the past decade [7–10]. DIC displacement accuracy can reach several percent pixels [6], and factors affecting its accuracy mainly include interpolation bias [11,12], image noise [13,14], speckle structure [15–17], lens distortion [18,19], shape function and subset size [20,21], etc. 3D-DIC has been applied from micro to macro scale [22]. Large field-of-view (FOV) has been a recent research focus [23,24] due to increasing demand for high precision non-contact full-field measurement in engineering fields [25–27].

One remaining problem for large FOV 3D-DIC is calibrating stereo cameras, i.e., obtaining camera imaging model parameters, including intrinsic (optical center coordinates, image distance, imaging distortions) and extrinsic (position relationship between cameras) parameters for the camera pair. Calibration error expresses final measurement error, which cannot be overcome by improving image matching. Most current stereo camera calibration methods are based on Zhang’s plane [28], or Tsai’s two-step [29] calibration methods, which require the calibration object to be clearly imaged in, and occupy at least a third of, the FOV [5,28]. The calibration object also needs to be very large when the FOV is very large, and it is difficult and expensive to make large calibration objects, indeed large calibration objects cannot be placed at all under some experimental conditions. Genovese et al. proposed using a plane reflector and phase target to calibrate large FOV stereo cameras [30]. Although the proposed method was very innovative, the calibration process was too tedious for engineering applications. Xiao et al. [31] proposed cross-target calibration that still required a very large calibration object, but the calibration object was more portable. Shao [23] and Su [32] proposed self-calibration to calibrate extrinsic parameters using the objects surface texture. However, this approach sacrificed some scale information. Liu et al. [33] proposed combining multiple small calibration boards to calibrate a large FOV. This simplifies calibration construction and eases transport for large calibration boards, but calibration board placement remains a problem. Feng [34] and Sabato [35] are working on easing the calibration procedure for 3D-DIC using a sensor-based approach.

In order to avoid the use of large calibration board in the condition of large FOV, this paper presents a large FOV stereo camera calibration...
method using conventional size calibration board and zoom lenses. Camera lens combinations are usually determined based on the applied FOV and working distance. Lens used in the image measurement field are usually prime lenses because they provide better image quality than zoom lenses. Thanks to the advances in modern lens design capabilities, zoom lens image quality is now available for most measurement scenarios. The FOV at the telephoto end of a zoom lens is very small, and the calibration board can be correspondingly small. We can calibrate the extrinsic parameters of the stereo camera by using the images taken at the telephoto end.

However, this raises the issue of how to calibrate the intrinsic and extrinsic parameters at the short focal end (large FOV), and we divide this into two parts. For intrinsic parameters, Magill’s formula [36] shows that image distortion is related to object distance, and image distance is also related to object distance. Therefore, we can use a series of camera intrinsic parameters under close range imaging to calculate camera intrinsic parameters under long distance imaging in large-FOV experiments. We can then use a conventional sized calibration board for extrinsic parameters to calibrate rotation and translation matrix at the telephoto end. For the short focal length end, the rotation translation matrix can be calculated using extrinsic parameters at the telephoto end and image distance changes.

The remainder of this article is arranged as follows. Section 2 introduces Magill’s formula and builds a geometric model for a stereo camera with zoom lenses. Section 3 details accuracy verification experiments for the proposed method. Finally, Section 4 summarizes and concludes the paper.

2. Methodology

It becomes difficult to make a calibration board that matches the FOV when the measurement FOV is large. Therefore, we propose to calibrate intrinsic and extrinsic parameters separately.

Fig. 1 shows the proposed calibration process for a dual camera system with zoom lens. To calibrate the intrinsic parameters, we need to obtain object distance parameters and intrinsic parameters at various distances under conventional FOV conditions, and then calculate the intrinsic parameters under a large FOV using Magill’s formula. We then use a zoom lens’s telephoto end to calibrate extrinsic parameters with a conventional sized calibration board, and subsequently calculate the short focus end’s extrinsic parameters. Finally, the intrinsic and extrinsic parameters are combined and optimized to obtain the complete calibration parameters.

2.1. Three-dimensional digital image correlation (3D-DIC) and stereo camera calibration

The proposed 3D-DIC method is based on binocular stereo vision and DIC. Two cameras with fixed positions are used to photograph the object and image coordinates for the points to be measured in the left and right pictures are calculated by DIC. Then, 3D topology for the specimen surfaces are calculated by combining intrinsic parameters and relative positions between the two cameras (calibrated beforehand). The process to obtain intrinsic and extrinsic parameters for the camera pair is called stereo-camera calibration.

We use the pinhole camera model, forming scene views by projecting 3D points onto an image plane using a perspective transformation. This transformation can be expressed in homogeneous coordinates as

\[
\begin{bmatrix}
    x_i \\
    y_i \\
    1
\end{bmatrix} = 
\begin{bmatrix}
    f_x & c_x & t_x \\
    f_y & c_y & t_y \\
    0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
    R_{11} & R_{12} & R_{13} & t_1 \\
    R_{21} & R_{22} & R_{23} & t_2 \\
    R_{31} & R_{32} & R_{33} & t_3
\end{bmatrix}
\begin{bmatrix}
    X_w \\
    Y_w \\
    Z_w \\
    1
\end{bmatrix},
\]

where \((c_x, c_y)\) is a principal point, usually the image center; \((f_x, f_y)\) are the image distance expressed in pixels; \(t_x\) is the non-perpendicular angle for the camera sensor array; and \(a\) is a nonzero scale factor (these parameters and distortion parameters are called camera intrinsic parameters); \(R|T\) is the transformation between the world and principal coordinate systems, which are called extrinsic parameters; \((X_w, Y_w, Z_w)^T\) are the coordinates for a 3D point in the world coordinate system, and \((x, y)^T\) are the coordinates for the projection point in pixels.

We define the transformation from the world to camera principal point coordinate system as \(R|T^1\), the corresponding transformation for the right camera as \(R^1|T^1\), and the transformation from the left to right camera principal point coordinate system as \(R^1|T^2\) (Fig. 2). We use the plane model calibration method to obtain \(R^1|T^2\) [28], which requires two cameras to take a set of calibration board pictures simultaneously. We then solve for \(R|T^h\) by calibrating \(R^1|T^1\) and \(R^1|T^2\), and \(R|T^h\) is optimized by minimizing re-projection error.

The world coordinate system \((X_w, Y_w, Z_w)^T\) is artificially defined, hence to simplify calculation we define the world coordinate system to coincide with the principal coordinate system for the left camera. Therefore, \(R\) becomes a unit matrix and \(T\) a zero vector for the left camera in (1), and \(R|T\) is the transformation from the principal coordinate system for the left camera to that for the right camera. Thus, (1) can be simplified to

\[
\begin{align*}
    x_i' &= c'_x + f_x X_w + f_y Y_w \\
    y_i' &= c'_y + f_x X_w + f_y Y_w \\
    x_i' &= c'_x + f_x R_{11} X_w + f_y R_{12} Y_w + f_z R_{13} Z_w + t_x \\
    y_i' &= c'_y + f_x R_{21} X_w + f_y R_{22} Y_w + f_z R_{23} Z_w + t_y \\
    x_i' &= c'_x + f_x R_{31} X_w + f_y R_{32} Y_w + f_z R_{33} Z_w + t_z \\
    y_i' &= c'_y + f_x R_{31} X_w + f_y R_{32} Y_w + f_z R_{33} Z_w + t_z
\end{align*}
\]

Solving (2) provides the world coordinates for points to be measured from pixel coordinates in the left and right images.

2.2. Intrinsic parameters calibration

The intrinsic parameters for the left and right cameras at short focus are required, i.e., \((f_x, f_y, c_x, c_y, k_1, k_2)\). Since \(f\) represents the non-perpendicular angle for the camera sensor array, it is not affected by the
using least squares, and
(Fig. 3)

\[ F \] with magnification \( \delta r \), parameters under actual measurement conditions by calibrating the parameters. Therefore, we used Magill’s formula, to infer intrinsic it difficult to create a large calibration board to calibrate the intrinsic and pixel coordinates with distortion, respectively. A large FOV makes principal point system, imaging plane, imaging plane with distortion, and pixel coordinates with distortion, respectively. A large FOV makes it difficult to create a large calibration board to calibrate the intrinsic parameters. Therefore, we used Magill’s formula, to infer intrinsic parameters under actual measurement conditions by calibrating the intrinsic parameters under several close distances. Magill’s formula can be expressed as
\[ \delta r = \delta r_{\text{in}} - m_1 \delta r_{\text{in}}. \] with magnification
\[ m_1 = \frac{F}{(S - F)}, \] where \( F \) is the lens focal length; \( S \) is the distance to the object plane that the lens is focused onto; \( \delta r \) is the focal distortion on the object plane; \( \delta r_{\text{in}} \) is the distortion for infinity focus; and \( \delta r_{\text{in}} \) is the distortion for inverted infinity focus (i.e., if the lens is reversed so that front element becomes rear element and vice versa).

In order to facilitate the calculation of the distortion parameters, Substituting (5) into (4),
\[ \delta r = \delta r_{\text{in}} - \frac{F}{(S - F)} \delta r_{\text{in}}. \] establishing a parametric expression for the distortion parameters with respect to the object distance,
\[ (S - F) \delta r = (S - F) \delta r_{\text{in}} - F \delta r_{\text{in}}. \] We can obtain \( \delta r_{\text{in}} \) and \( \delta r_{\text{in}} \) by solving (7) using least squares, and subsequently use these for (6) to predict distortion parameters \( (k_1, k_2) \) at any distance.

For the convenience of derivation, a second-order radial distortion model is used in this paper. But, the proposed calibration method suitable for higher order models. Based on our previous work [18], the second-order radial distortion model is suitable for most lenses. We can use a ruler or laser rangefinder to measure distance \( D \) from the camera to the object of interest, expressing object distance as \( S = D + d \), where \( d \) is an unknown constant. If \( f \) is the image distance, then
\[ \frac{1}{D + d} + \frac{1}{f} = \frac{1}{F}. \] where \( d \) and \( F \) are unknown quantities. Since \( f \) is normally expressed in pixels, we need the conversion \( \beta \) between pixels and millimeters and express (8) in millimeters,
\[ \frac{1}{D + d} + \frac{1}{F \beta} = \frac{1}{F}. \] We can obtain \( \beta \) from factory parameters for the camera or iteratively calculate it directly (grayscale camera, \( \beta = 3.69 \) \( \mu \)m/pixel). For example, \( (\beta, d, F) \) can be obtained by parameter optimization over three sets of calibration data at different distances. Let
\[ h_i(\beta, d, F) = \frac{1}{D_i + d} + \frac{1}{f \beta} - \frac{1}{F} \] be the objective function, then we can obtain \( (\beta, d, F) \) by solving
\[ (\beta, d, F) = \text{argmin}_{i=1}^{n} h_i^2. \] Thus, we obtain the object distance \( (S) \), and \( f_1 \) and \( f_2 \) can be calculated by measuring \( D \) between the camera and object of interest in a large FOV.

In order to verify the validity of Magill’s formula, we carried out a verification experiment. We calibrated the distortion parameters at ten distances (Table 1). As shown in Fig. 3, through the above method, the first nine groups of data were used to calculate the distortion of the tenth group, and the results showed a high degree of agreement.

All the intrinsic parameters except \( (c_x, c_y) \) can be calculated by the proposed method. Since optical center coordinates are caused by misalignment between sensor and installation port center positions, the values do not correlate with the imaging distance. We use the average value of the optical center coordinates obtained in conventional FOV as the initial value of \( (c_x, c_y) \) under large FOV.

### 2.3. Extrinsic parameters calibration

For zoom lens we use the telephoto end to calibrate the intrinsic and extrinsic parameters for a camera pair with a regular sized calibration board. Fig. 4 shows the FOV for a stereo camera at different focal lengths. Both intrinsic and extrinsic parameters change as the cameras are adjusted from telephoto to short focal conditions. Intrinsic parameters can be calculated from the object distance, as described in Section 2.2. To obtain the extrinsic parameters at the short focal end, we calibrate extrinsic parameter \( R^i | R^j \) at the telephoto end first.

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**Table 1**

<table>
<thead>
<tr>
<th>Distance (mm)</th>
<th>( c_x )</th>
<th>( c_y )</th>
<th>( f_1 )</th>
<th>( f_2 )</th>
<th>( k_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1064.798</td>
<td>983.306</td>
<td>4503.965</td>
<td>4502.986</td>
<td>-0.525</td>
</tr>
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<td>152</td>
<td>1059.192</td>
<td>971.699</td>
<td>4360.746</td>
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</tr>
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<td>974.095</td>
<td>4312.999</td>
<td>4311.592</td>
<td>-0.347</td>
</tr>
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<td>4287.47</td>
<td>4287.458</td>
<td>-0.309</td>
</tr>
<tr>
<td>254</td>
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<td>951.801</td>
<td>4249.246</td>
<td>4249.234</td>
<td>-0.28</td>
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<td>4205.814</td>
<td>4205.434</td>
<td>-0.238</td>
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<td>4179.425</td>
<td>4179.473</td>
<td>-0.215</td>
</tr>
<tr>
<td>509</td>
<td>1068.332</td>
<td>972.947</td>
<td>4166.936</td>
<td>4167.032</td>
<td>-0.19</td>
</tr>
<tr>
<td>650</td>
<td>1079.033</td>
<td>986.8</td>
<td>4131.49</td>
<td>4131.34</td>
<td>-0.164</td>
</tr>
<tr>
<td>900</td>
<td>1072.913</td>
<td>982.778</td>
<td>4127.8</td>
<td>4127.55</td>
<td>-0.154</td>
</tr>
</tbody>
</table>
World coordinates at the short focal end are shifted by a fixed distance in the optical axis direction compared with the telephoto end.

\[
\begin{align*}
X'_{w} &= X_{w} \\
Y'_{w} &= Y_{w} \\
Z'_{w} &= Z_{w} + (f_{long} - f_{short})
\end{align*}
\]  

where \( f_{long} \) is the image distance obtained when the telephoto end is calibrated; and \( f_{short} \) is the image distance obtained at the short focal length as shown in Section 2.2.

The projection relationship conforms to (2) at the telephoto end with the left camera principal point coordinate system as the world coordinate system. Extrinsic parameter \( R^{b} \) does not change as the focal length changes to the short focal end, but \( T^{b} \) does. Thus, we only need to know the new \( T^{b} \). We use a small dot in the upper right corner to indicate the parameter at the short focal end.

There is a new transformation matrix \( R^{b} | T' \) when the lens changes from telephoto to short focal, describing the transition from the new left camera principal point coordinate system to the new right camera principal point coordinate system. The rotation-translation from the new left camera to the new right camera principal point coordinate systems can be expressed as

\[
\begin{bmatrix}
R_{11} & R_{12} & R_{13} & t_{1}' \\
R_{21} & R_{22} & R_{23} & t_{2}' \\
R_{31} & R_{32} & R_{33} & t_{3}' \\
\end{bmatrix}
\begin{bmatrix}
X'_{w} \\
Y'_{w} \\
Z'_{w} - (f_{long} - f_{short}) \\
\end{bmatrix}
\]

\[
\times
\begin{bmatrix}
0 \\
0 \\
1 \\
\end{bmatrix}
\]

\[
+ \begin{bmatrix}
0 \\
0 \\
(f_{long} - f_{short})
\end{bmatrix}
\]

Solving (13),

\[
\begin{align*}
t_{1}' &= t_{1} - R_{13}(f_{long} - f_{short}) \\
t_{2}' &= t_{2} - R_{23}(f_{long} - f_{short}) \\
t_{3}' &= t_{3} - R_{33}(f_{long} - f_{short}) + (f_{long} - f_{short})
\end{align*}
\]  

Thus, to calculate extrinsic parameters for the short focal end, we need to know the image distance difference between the telephoto and short focal end, and extrinsic parameters calibrated at the telephoto end. Image distance and extrinsic parameters at the telephoto end can be obtained by conventional calibration, and image distance at the short focal end as shown in Section 2.2.

Thus, we have a process to calibrate extrinsic parameters for a stereo camera using zoom lenses. We can obtain the complete intrinsic and extrinsic parameters following Section 2.2, and subsequently calculate image coordinates for corresponding points in the left and right images using the 3D-DIC method. Since we then have the coordinates for corresponding points in the left and right camera images and complete intrinsic and extrinsic parameters, we can optimize the parameters by minimizing epipolar error or bundle adjustment (BA), as convenient [32]. This paper optimized the parameters by minimizing epipolar error,

\[
\arg\min_{R,T,A} \sum_{i=1}^{n} \sum_{j=1}^{m} (A_i^{-1} \cdot p_i^j \cdot R^b \cdot (T^b \times (A_j^{-1} \cdot p_j^j))).
\]
set of intrinsic parameters for the cameras, which project the image point $p$ onto the principal point coordinate system. The optimization of (15) relies on the coordinates for corresponding points. Therefore, it is recommended that corresponding points occupy most of the FOV.

3. Experiment

We performed an intrinsic parameter calibration experiment to verify the effectiveness of the intrinsic parameter calibration method proposed in Section 2.2. The calibration results were then used to 3D reconstruct a wall approximately $6 \times 4$ m. It was difficult to find suitable reference with accurate size information since the FOV was so large, hence we pasted some markers on the wall and measured the distances between markers with a steel ruler, and subsequently compared 3D reconstruction results with the measured distances.

Two 5 megapixel cameras (PointGrey, $3376 \times 2704$ pixel, $3.69 \mu m$/pixel) were used, with 11–40 mm zoom lenses (Soyo ltd). The measurement system was 7412.8 mm away from the object of interest, and distance between cameras and object were measured by laser rangefinder (ProsKit NT-85, distance accuracy $= 1.5$ mm). Distance between the two cameras $\approx 1$ m.

3.1. Intrinsic parameters calibration experiment

Fig. 6(a) shows the experimental setup for the intrinsic parameters calibration experiment. The laser rangefinder was attached to the cameras with optical axis parallel to the camera optical axis. The zoom lens was adjusted to the short focal end. Specific calibration steps are as follows:

1. Adjust the zoom lens to the short focal end.
2. Select an imaging distance and choose a calibration board suitable for the current FOV.
3. Adjust the camera to focus clearly and measure current distance with the laser rangefinder.
4. Take multiple (more than 8) pictures of the calibration board and perform single camera calibration.
5. Repeat steps 2 to 4 until at least 3 sets of data are obtained (we used 7 sets of data in this experiment).
6. Calculate parameters $(k, d, F, \delta r_{-\infty}, \delta r_{+\infty})$ following Section 2.2.

Tables 2 and 3 show calibration results for left and right camera intrinsic parameters with respect to imaging distance. $c_x$ and $c_y$ are almost constant for the different imaging distances, consistent with our assumptions regarding optical center coordinate stability. Thus, we are justified to assume the optical center coordinates for the large FOV is the same as that for the conventional FOV.

We then calculated $d, F, \delta r_{-\infty}$ and $\delta r_{+\infty}$ by substituting the data in Tables 2 and 3 into (7) and (11). Fig. 6(b) and (c) show the curve corresponding to (10) with known constant terms $\delta r_{-\infty}$ and $\delta r_{+\infty}$. The proposed model was highly consistent with experimental data.

Table 4 shows the final intrinsic parameters at this imaging distance from substituting imaging distance (7412.8 mm) into (5) and (8).
Z. Gao et al.

3.2. Accuracy verification and 3D reconstruction

After calibrating the intrinsic parameters of the camera, we performed a complete stereo camera calibration, and reconstructed the wall topography (≈ 6 × 4 m) using the calibration results. Fig. 7 shows the experimental setup. Distance between the measurement system and object of interest was measured by laser rangefinder \( D = 7412.8 \) mm. The calibration board was with 12 × 9 at 90 mm spacing). Fig. 8(a1) and (a2) show the calibration board with camera zoom lens at the telephoto end. Fig. 8(b1) and (b2) show wall images taken at the telephoto end, and Fig. 8(c1) and (c2) show wall images taken at the short focal end. The FOV at the telephoto end is much smaller at the short focal end, and the calibration board occupies a larger FOV at the telephoto end.

Table 2

<table>
<thead>
<tr>
<th>Distance (mm)</th>
<th>( c_x )</th>
<th>( c_y )</th>
<th>( f_x )</th>
<th>( f_y )</th>
<th>( k_1 )</th>
<th>( k_2 )</th>
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<tbody>
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<td>245</td>
<td>1674.741 1393.393</td>
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<td>1596</td>
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Table 3

<table>
<thead>
<tr>
<th>Distance (mm)</th>
<th>( c_x )</th>
<th>( c_y )</th>
<th>( f_x )</th>
<th>( f_y )</th>
<th>( k_1 )</th>
<th>( k_2 )</th>
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Table 4

<table>
<thead>
<tr>
<th>Parameters to be evaluated and intrinsic parameters for this imaging distance.</th>
<th>Left camera</th>
<th>Right camera</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d )</td>
<td>0.0032</td>
<td>0.0032</td>
</tr>
<tr>
<td>( F )</td>
<td>13.11 mm</td>
<td>13.10 mm</td>
</tr>
<tr>
<td>( \delta r_{∞} )</td>
<td>−0.228</td>
<td>−0.234</td>
</tr>
<tr>
<td>( \delta r_{−∞} )</td>
<td>1.072</td>
<td>0.714</td>
</tr>
<tr>
<td>( f_x )</td>
<td>3559.34</td>
<td>3575.54</td>
</tr>
<tr>
<td>( f_y )</td>
<td>3558.56</td>
<td>3577.66</td>
</tr>
<tr>
<td>( c_x )</td>
<td>1676.07</td>
<td>1706.40</td>
</tr>
<tr>
<td>( c_y )</td>
<td>1392.22</td>
<td>1395.19</td>
</tr>
<tr>
<td>( k_1 )</td>
<td>−0.23016</td>
<td>0.121</td>
</tr>
<tr>
<td>( k_2 )</td>
<td>0.13281</td>
<td>0.13</td>
</tr>
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</table>

Table 5

<table>
<thead>
<tr>
<th>Extrinsic parameters at the telephoto and short focal ends.</th>
<th>( a )</th>
<th>( β )</th>
<th>( γ )</th>
<th>( T_x )</th>
<th>( T_y )</th>
<th>( T_z )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telephoto end</td>
<td>−0.196</td>
<td>5.936</td>
<td>0.351</td>
<td>−929.083</td>
<td>−9.266</td>
<td>42.199</td>
</tr>
<tr>
<td>Short focal end</td>
<td>−0.196</td>
<td>5.936</td>
<td>0.351</td>
<td>−931.151</td>
<td>−9.334</td>
<td>42.457</td>
</tr>
</tbody>
</table>

The distances between the markers were measured using a steel ruler, with each distance measured five times. Fig. 8(b1) shows the markers serial numbers. The calibration board was with 12 × 9 at 90 mm spacing). Fig. 8(a1) and (a2) show the calibration board with camera zoom lens at the telephoto end. Fig. 8(b1) and (b2) show wall images taken at the telephoto end, and Fig. 8(c1) and (c2) show wall images taken at the short focal end. The FOV at the telephoto end is much smaller at the short focal end, and the calibration board occupies a larger FOV at the telephoto end. Finally, extrinsic parameters at the short focal end were combined with intrinsic parameters at the short focal end, as discussed in Section 3.1. Table 6 shows the optimal complete intrinsic and extrinsic parameters at the short focal end, obtained by minimizing epipolar error.

We attached five markers on the wall (Fig. 8(b1) and (b2)) to verify 3D reconstruction accuracy using the proposed calibration method. Fig. 8(b1) shows the marker serial numbers. Distances between markers were measured using a steel ruler, with each distance measured five times.
times and averaged. In order to better show the reliability of our 3D reconstruction results, we calculated the distances between the corners of the wall (represented by \(D_c\)) and the distance between the beam and the wall (represented by \(D_b\)) and compared them with the results of a laser rangefinder. Table 7 compares measured and reconstructed distances. In the in-plane direction, there was only approximately 1 mm random error between the 3D reconstructed and physically measured results. However, there is a systematic deviation of 5 mm (relative error 0.35%) in the depth direction. This deviation may be due to the large depth difference between the beam and the wall. The distortion parameters used in the measurement system are calculated according to the distance between the wall and the camera, which cannot well describe the distortion at the depth of the beam.

Figs. 9 and 10 show 3D reconstruction of the wall surface using the calibrated system after verifying 3D reconstruction accuracy.

4. Conclusions

This paper proposed an easily implemented calibration method for large-FOV stereo vision that addressed several traditional calibration method limitations. In particular, the proposed 3D-DIC method used Magill’s formula to infer intrinsic parameters and zoom lenses to change the FOV, allowing the calibration of extrinsic parameters with a conventional sized calibration board. Accurate stereo vision calibration is an important prerequisite for accurate large-FOV stereo vision measurement. We also evaluated dimensional accuracy for the proposed method. 3D reconstruction error was apparently random with approximately 1 mm magnitude for a FOV of \(\approx 6 \times 6\) m.

The main limitation for the proposed method is that the cameras use zoom lenses, which could limit application scope. However, most modern zoom lenses can adequately replace fixed focus lenses. The proposed calibration method provides opportunities for high-precision measurement applications using stereo vision methods for large FOVs, such as materials science, civil engineering, automotive, and aerospace engineering.

CRediT authorship contribution statement


Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References