Fisheye Image Correction Based on Three-Dimensional Control Field

Ruhao Song¹,², Guoqing Zhou¹*, Qingyang Wang¹, Yongfan Xie¹,² and Mengyuan Luo¹,²

¹Guangxi Key Laboratory of Spatial Information and Geomatics, Guilin University of Technology, Guilin, Guangxi, 541004, China
²College of Geomatics and Geoinformation, Guilin University of Technology, Guilin, Guangxi, 541004, China

*Corresponding author’s e-mail: gzhou@glut.edu.cn; 1051246241@qq.com.

Abstract. The fisheye image has severe distortions, which is not in line with human visual habits and brings inconvenience to its application. This paper classifies them into spherical structural distortion and optical distortion, and proposes a fisheye image correction method based on 3D control field. First, the spherical transformation radius and the optical center of the fisheye image are accurately solved, and the fisheye image is corrected by combining the spherical perspective projection; then, the distortion model of the fisheye camera is introduced into the DLT model to calibrate the optical distortion, and the results are used to recorrect the image. This method has been experimentally proven to be fast and effective.

1. Introduction
The fisheye lens is a special ultra-wide angle lens, one of the most effective ways to create a panoramic vision system. It has a large viewing angle (close to or even more than 180°), compact structure, clear imaging, and the images acquired in one shot contain more spatial information, and are widely used in fields such as visual navigation [1], target detection [2], environmental surveillance [3] and forest monitoring [4]. However, due to the short focal length and complex structure of the fisheye lens, the fisheye image has serious distortion, which does not conform to the perspective projection, let alone can’t meet the needs of accurate measurement. Therefore, if these distortions are not corrected, the fisheye images will not be used effectively.

In recent years, researchers in various fields have conducted a great deal of research on the problem of calibrating and correcting fisheye images. Currently, the main methods used for correction of fisheye images are projection transformation model based correction methods and calibration based correction methods. The main correction methods based on projection transformation models are spherical perspective models [5-6], columnar projection models [7], latitude and longitude models [8] and so on. The spherical perspective projection model requires a polynomial fit of a large number of sampling points to obtain the distortions parameters, which is computationally intensive, complex to fit, and has serious non-linear stretching of the correction image. Camera calibration is the determination of internal and external camera parameters as well as lens distortions [9-11]. Calibration based correction methods can achieve high calibration accuracy, but the method requires the establishment of a high-precision control field, and requires high precision experimental equipment and a more complex process.
For the above problems, this paper analyzes the structure of the fisheye lens, and divides the fisheye image distortions into two categories: 1) spherical distortions related to the spherical structure of the fisheye lens; 2) traditional optical distortions of the lens. For these two types of distortion, a step-by-step check calibration method is proposed.

2. Fisheye image correction

By analyzing the structure of the fisheye lens, it is considered that the fisheye image contains distortions in two aspects: 1) spherical distortions related to the spherical structure of the fisheye lens and 2) optical distortions of the lens [5]. The spherical perspective projection model establishes a one-to-one correspondence between the spherical point and the ideal perspective projection image point, through which the spherical projection model of the fisheye image is transformed to the perspective projection model [6]. The spherical perspective projection model can be used to correct the fisheye image.

2.1 Spherical Perspective Projection Model

According to the perspective projection model, the imaging model of ordinary optical lens is:

\[ r = f \tan \theta \]  \hspace{1cm} (1)

Eq. (2) is the equidistant projection model, which is the most widely used imaging mode of fisheye lens at present. This model is selected for this paper.

\[ r = f \theta \]  \hspace{1cm} (2)

As shown in Fig.1, the origin O is the lens center, the OUV plane is the actual imaging plane of the fisheye lens, OZ is the main optical axis, the coordinates of the image center O are \((u_0, v_0)\). Assume that there is a virtual central projection plane M at the plane \(Z=R\), corresponding to the direction of the coordinate axes parallel to those in the image plane OUV, and the equation of the projection sphere is \(U^2 + V^2 + Z^2 = R^2\). Suppose \(P\) represents a point in space and the point \(P'\) is projected onto the OUV image plane according to the equidistance projection to get the image point \(P''\) with coordinates \((u, v)\).

![Figure 1. Spherical perspective projection of a fisheye lens](image)

Specifically, the image that removes spherical distortion is derived from the central projection image, that is, imaging on the plane M. Therefore, if the image on the plane M can be calculated, the corrected image can be obtained. OP the connecting line intersects with the virtual image plane M at \(p'\), whose image plane coordinates are \((u', v')\). Then the relationship between \(p'\) and \(p''\) is:

\[
\begin{align*}
  u' &= \frac{r'}{r}(u - u_0) + u_0 \\
  v' &= \frac{r'}{r}(v - v_0) + v_0
\end{align*}
\]  \hspace{1cm} (3)

Substituting Eq. (1) and Eq. (2) into Eq. (3).
If the fisheye camera uses the perspective projection model, the image will become large. Besides, direct correction can cause image overlap or pixel blanking. Therefore, starting from the virtual image \( M \), this paper reverses the position of the current pixel on the fisheye image according to Equation (4) to obtain the perspective projection image, and the equation is as follows.

\[
\begin{align*}
\begin{bmatrix}
u' \\ v'
\end{bmatrix} &= \begin{bmatrix}
\frac{f}{r} \tan \left( \frac{r}{f} \right) (u - u_0) + u_0 \\
\frac{f}{r} \tan \left( \frac{r}{f} \right) (v - v_0) + v_0
\end{bmatrix}
\end{align*}
\]

(4)

3. **Calibration mathematical model of fisheye camera**

After the spherical distortion of the fisheye image is removed, but the optical distortion of the camera lens still exists, so the optical distortion parameters need to be calibrated.

3.1. **Fisheye lens optical distortion model**

It is generally considered that optical distortion mainly includes radial distortion, tangential distortion and thin prism distortion. The nonlinear distortion model can be obtained by superimposing the above three distortions.

\[
\begin{align*}
\Delta u &= (u - u_0)(k_1 r^2 + k_2 r^4) + p_1 (r^2 + 2(u - u_0)^2) + 2 p_2 (u - u_0)(v - v_0) + s_1 r^2 \\
\Delta v &= (v - v_0)(k_1 r^2 + k_2 r^4) + p_1 (r^2 + 2(v - v_0)^2) + 2 p_2 (u - u_0)(v - v_0) + s_2 r^2
\end{align*}
\]

(6)

Where \( r^2 = (u - u_0)^2 + (v - v_0)^2 \), \((u_0, v_0)\) is the coordinates of the image principal point, \( k_1, k_2 \) is the radial distortion parameters, \( p_1, p_2 \) is the tangential distortion, and \( s_1, s_2 \) is the thin prism distortion parameters.

3.2. **Direct linear transformation model**

The Direct linear transformation (DLT) is a more common data processing method in close range photogrammetry, which is generally used to solve the internal and external camera parameters and lens distortions parameters. Combining the DLT model with the distortions model of the fisheye camera to construct a calibration mathematical model, and the residual optical distortion parameters in the perspective image were calibrated, including the internal orientation parameters and distortion parameters. Substituting the fisheye lens optical distortion mode into the DLT model, the corresponding direct linear transformation model is as follows.

\[
\begin{align*}
\begin{bmatrix}
u' \\ v'
\end{bmatrix} + \begin{bmatrix}
\Delta u \\ \Delta v
\end{bmatrix} + \begin{bmatrix}
l_1 X + l_2 Y + l_3 Z + 1 \\
l_4 X + l_5 Y + l_6 Z + 1
\end{bmatrix} &= 0 \\
\begin{bmatrix}
u' \\ v'
\end{bmatrix} + \begin{bmatrix}
l_7 X + l_8 Y + l_9 Z + 1 \\
l_10 X + l_11 Y + l_12 Z + 1
\end{bmatrix} &= 0
\end{align*}
\]

(7)

Where \( u' \) and \( v' \) are both functions on \( f, u_0, v_0, u, v \), and \( l_i (i = 1, 2, ..., 11) \) is the transformation parameters. Solving this equation requires initial values \( f, u_0, v_0 \) and iterative solution with the pixel coordinates \((u, v)\) on the fisheye image as the observed values.

4. **EXPERIMENT**

4.1. **3D control field**

In order to establish the relationship between the coordinates of image points on fisheye images and the coordinates of corresponding spatial points, an indoor 3D control field was established in this study, as
shown in Figure 2(a). The control field is 6.5m long, 1.5m wide, and 4.0m high, with a three-layer steel frame structure, and the distance between two adjacent steel frames is 0.75m. There are 30 metal pillars, and 10 ground control points (GCPs) are evenly distributed on each metal pillar, totaling 300 GCPs to meet the requirement that the number and distribution of marking points can be full width and uniform when taking images, as shown in Figure 2(b). The control field is well lit and can be used for multi-angle photography at different heights and angles. There is an indium steel ruler under the control field, which is used as the standard for measurement.

The GCPs are selected from 40mm×40mm white square reflective sticker, the center uses precision cross wire, the GCP center cross wire engraved line width is 0.5mm, not only convenient for precision observation, its graphics are also conducive to the extraction of digital photo marker point center. Fix the control point on the metal pillars to keep the relative position of the mark point stable for a long time, as Figure 2 (c). In order to observe all the GCPs as much as possible and reduce the measurement error, two measuring stations with a height of 1.15m were set up at 4.8m in front of the left and 3.2m in front of the right of the control field.

Figure 2. Indoor 3D control field

After calculation, it is finally obtained that the average value of the control field point RMSE is \( m_s = 0.368 \) mm, and the average value of elevation RMSE is \( m_h = 0.114 \) mm.

4.2. First step of calibration

According to the discussion in Section 3.2, in order to solve Eq. (7), it is first necessary to solve for \( f, u_0, v_0 \). In this study, we first find the circular edge of the image using morphological methods, and then calculate the initial value of the circular center coordinates based on the the curve equation, which is applied to the subsequent image. The results are shown in Table 1.
4.3. **Second step of calibration**

A Canon 70d camera with a Canon 8-15 mm fisheye lens was chosen to collect raw fisheye images. Figure 3(a) shows the original fisheye images collected in this experiment.

Based on the result of first calibration, the second step is carried out to check the parameters related to optical distortion. The calibration model and method designed in Section 3.2 are used to get the results as shown in Table 2. According to the calibration parameters of the camera, the image in Fig. 3(a) is gradually corrected by using the designed method. The results are shown in Fig. 3(b).

### Table 1. Optical center and spherical radius of fisheye image

| $u_0$/pixel | $v_0$/pixel | $r$/pixel |
|-------------|-------------|-----------|
| 1806        | 1226        | 1915      |

### Table 2. Camera calibration results

| Intrinsic parameters (pixel) | $u_0$ | $v_0$ | $f$ |
|-----------------------------|-------|-------|-----|
|                             | $1.815246 \times 10^3$ | $1.214188 \times 10^3$ | $1.342140 \times 10^3$ |
| Distortion parameters       | $k_1$ | $k_2$ | $k_3$ | $p_1$ | $p_2$ | $s_1$ | $s_2$ |
|                             | $3.844979 \times 10^{-8}$ | $-1.121549 \times 10^{-13}$ | $7.422245 \times 10^{-20}$ | $-2.2669645 \times 10^{-6}$ | $4.013583 \times 10^{-6}$ | $7.005113 \times 10^{-6}$ | $-4.593737 \times 10^{-12}$ |

From the correction results, it can be seen that the image distortion has been fully corrected, and the resulting image is in line with the habits of human eyes, which can meet the application requirements.

![Figure 3. Original image (a) and corrected image (b)](image)

**5. CONCLUSION**

This paper presents a method for fisheye camera calibration and fisheye image correction based on a 3D control field. In the first step of calibration, the optical center of the fisheye image and the spherical transformation radius are first obtained and combined with the spherical transformation model to correct the fisheye image and remove the spherical distortions. Based on the spherical distortions correction result in the first step, the optical distortions model of the image is constructed in the second step, and the distortions parameters are introduced into the DLT model to construct the check model of the distortions parameters, and the compensation of the optical distortions of the image is realized according to the distortions parameters. The experimental results prove that the method proposed in this paper is effective and practical.
Acknowledgments

This paper is financially supported by the National Natural Science of China (the grant #: 41961065 and 41431179), Guangxi Science and Technology Base and Talent Project (the grant #: Guike AD19254002); the Guangxi Innovative Development Grand Program (the grant #: GuikeAA18118038 and GuikeAA18242048); Guangxi Natural Science Foundation for Innovation Research Team (the grant #: 2019GXNSFGA245001), Guilin Research and Development Plan Program (the grant #: 201902102), the National Key Research and Development Program of China (the grant #: 2016YFB0502501) and the BaGuiScholars program of Guangxi.

References

[1] Moreau, J., Ambellouis, S., & Ruichek, Y. (2017). Fisheye-based method for GPS localization improvement in unknown semi-obstructed areas. Sensors, 17(1), 119.
[2] Krams, O., & Kiryati, N. (2017, August). People detection in top-view fisheye imaging. In 2017 14th IEEE international conference on advanced video and signal based surveillance (AVSS) (pp. 1-6). IEEE.
[3] Kokka, A., Pulli, T., Poikonen, T., Askola, J., & Ikonen, E. (2017). Fisheye camera method for spatial non-uniformity corrections in luminous flux measurements with integrating spheres. Metrologia, 54(4), 577.
[4] Berveglieri, A., Tommaselli, A., Liang, X., & Honkavaara, E. (2017). Photogrammetric measurement of tree stems from vertical fisheye images. Scandinavian Journal of Forest Research, 32(8), 737-747.
[5] Pi, Y., Xin, L., & Chen, Z. (2017). Calibration and Rectification of Fisheye Images Based on Three-Dimensional Control Field [J]. Acta Optica Sinica, 37(1), 11-15.
[6] Li, X., Pi, Y., Jia, Y., Yang, Y., Chen, Z., & Hou, W. (2018, February). Fisheye image rectification using spherical and digital distortion models. In MIPPR 2017: Multispectral Image Acquisition, Processing, and Analysis (Vol. 10607, p. 106070G). International Society for Optics and Photonics.
[7] Xu, Y., Zhou, Q., Gong, L., Zhu, M., Ding, X., & Teng, R. K. (2013). High-speed simultaneous image distortion correction transformations for a multicamera cylindrical panorama real-time video system using FPGA. IEEE Transactions on Circuits and Systems for Video Technology, 24(6), 1061-1069.
[8] Wenhao, S., & Geng, Y. (2014). A fisheye image correction method based on longitude Model [J]. Computer Technology and Development, 24(10), 38-46.
[9] Zhou, G., Tang, X., & Yuan, B. (1996, October). Distortion model selecting and accuracy evaluation for CCD camera calibration. In Proceedings of Third International Conference on Signal Processing (ICSP’96) (Vol. 2, pp. 875-878). IEEE.
[10] Zhou, G, Baozong, Y., & Xiaofang, T. (1996). The intrinsic and extrinsic factor of CCD calibration: distortion model and signal to noise ratio. Acta Electronica Sinica, 11.
[11] Zhou, G., Jiang, L., Huang, J., Zhang, R., Liu, D., Zhou, X., & Baysal, O. (2018). FPGA-based on-board geometric calibration for linear CCD array sensors. Sensors, 18(6), 1794.