# A General Model and Calibration Method for Spherical Stereoscopic Vision

Weijia Feng[a], Juha Röning[b], Juho Kannala[b], Xiaoning Zong[a], Baofeng Zhang*[a],
[a]State Key Laboratory of Precision Measuring Technology and Instruments, Tianjin University, Tianjin, China; [b]Infotech Oulu and Department of Electrical and Information Engineering, University of Oulu, Finland

## ABSTRACT

In geometric calibration of stereoscopic cameras the object is to determine a set of parameters which describe the mapping from 3D reference coordinates to 2D image coordinates, and indicate the geometric relationships between the cameras. While various methods for stereo cameras with ordinary lenses can be found from the literature, stereoscopic vision with extremely wide angle lenses has been much less discussed. Spherical stereoscopic vision is more and more convenient in computer vision applications. However, its use for 3D measurement purposes is limited by the lack of an accurate, general, and easy-to-use calibration procedure. Hence, we present a geometric model for spherical stereoscopic vision equipped by extremely wide angle lenses. Then, a corresponding generic mathematical model is built. Method for calibration the parameters of the mathematical model is proposed. This paper shows practical results from the calibration of two high quality panomorph lenses mounted on cameras with 2048x1536 resolutions. Here, the stereoscopic vision system is flexible, the position and orientation of the cameras can be adjusted randomly. The calibration results include interior orientation, exterior orientation and the geometric relationships between the two cameras. The achieved level of calibration accuracy is very satisfying.

**Keywords:** spherical stereoscopic vision, panomorph lens, general geometric and mathematical model, parameter calibration

## 1. INTRODUCTION

Stereoscopic vision is a relatively mature field in computer vision, and the stereo method has been investigated in the literature. Most of these studies use ordinary lenses with a limited field of view (FOV). The geometry of ordinary cameras can be well approximated by the pinhole camera model. As is well known, the 3D-information can only be computed points which are simultaneously observed by both cameras. Hence, a blind area exists, as shown in Figure 1. However, using a pair of panomorph or fish-eye images the overlap region of the FOV can be expanded to the entire area covered by the two cameras [1]. Recently, spherical stereoscopic vision is more and more common in computer vision applications especially for automatic driving assistance [2] [3], UAV altitude estimation [4], forest inventory [5], city modeling [6] and 3D measurement [7] applications. But, it use for 3D measurement purposes is limited by the lack of an accurate, generic, and easy-to-use calibration procedure.

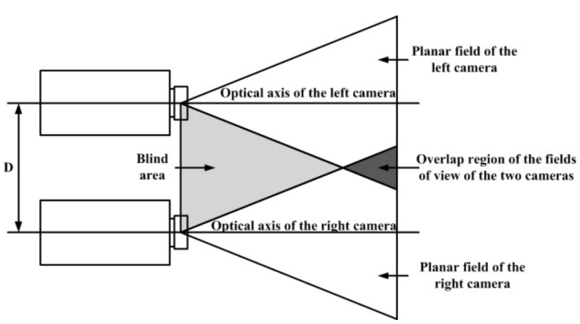


Figure 1. Using two normal cameras, the 3D information can only be captured by the overlapped gray region, and a blind area (shown in gray) exists between these regions.

*zhangbaofeng@tjut.edu.cn; phone +8613323357699; fax +8602260215622;

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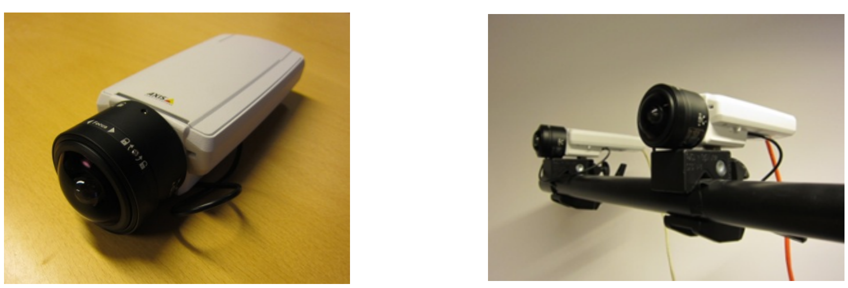
Stereoscopic vision calibration is the process of determining the internal, external parameters, distortion and the geometric relationships between two cameras. Single camera calibration is a key issue that affects the accuracy of stereoscopic vision system, which has been studied extensively[8,9,10,11,12,13,14]. A popular and practical algorithm is the technique developed by Tsai [8] using radial alignment constraint (RAC). Nevertheless, in this method, camera parameters initialization is required, and only radial distortion is considered. Zhang [9] proposed a flexible method for camera calibration by viewing a plane from different orientations. This algorithm assumes that the calibration pattern is an ideal plane, and ignores the actual errors in manufacturing. Heikkilä [10] accompanied pinhole camera model with lens distortion models for most conventional cameras with narrow-angle lenses. But, it is still not suitable for extremely wide angle lens such as panomorph lens and fish-eye lens. Weijia et al [11] designed different calibration patterns to calibrate the corresponding physical parameters of omnidirectional vision system individually. Because of the complex operation and many steps, it is hard to control errors [12]. Kannala [13] presented a generic camera model and calibration method for different kinds of lenses. The achieved level of accuracy is comparable to the previously reported state-of-the-art [14].

Although the spherical stereoscopic vision built by using panomorph or fish-eye lenses may have the whole FOV covered by the two cameras, the conventional pinhole camera model cannot be applied to them [15]. Taking fish-eye lens as an example, it is usually designed to obey one of the following projections: equidistance projection, stereographic projection, equi-solid-angle projection and orthogonal projection. Thus, it would be significant if we had only one model suitable for different types of spherical stereoscopic visions. In this paper, a binocular spherical stereoscopic vision calibration method based on a general spherical stereoscopic vision model is proposed. The general model describes the projection of one real world point to a pair of corresponding image pixels. The novel binocular spherical stereoscopic vision calibration method that requires that the vision system observes a planar calibration pattern with circular control points in different unknown positions. The world coordinates of these control points are not required. It can cope with any kinds of lenses having extremely wide FOV.

The remainder of this paper is organized as follows: First, in Section2, we build a flexible spherical stereoscopic vision system using two panomorph lenses. A geometric model for spherical stereoscopic vision is proposed. Thereafter, we present the general spherical stereoscopic vision model. Following that, the procedure for estimating the parameters of the general model is described. Finally, the experimental results and conclusions are presented in Section5 and Section6, respectively.

## 2. GEOMETRIC MODEL FOR SPHERICAL STEREOSCOPIC VISION

In this article, we build a spherical stereoscopic vision system using two high quality panomorph lenses YF360A-SA2 and double network camera AXIS P1346-E with 2048x1536 resolutions. The concept of panomorph optics consists of generating and controlling targeted and significant optical distortions to increase the number of pixels in the target zones of interest. Panomorph lenses have an increased resolution on the periphery (magnification factor) [15]. In addition, YF360A-SA2 and AXIS P1346-E are mounted on an greatly flexible camera bracket. Horizontal orientation, vertical orientation and the distance between two cameras can be adjusted randomly and easily. The novel flexible spherical stereoscopic vision system is shown in Figure 2 (b):



(a) (b)

Figure 2. (a) Panomorph Lens YF360A-SA2 and Network Camera AXIS P1346-E. (b) The flexible spherical stereoscopic vision system.

A generic geometric model of spherical stereoscopic vision system has been built to describe the transformation process of one real world point to a pair of corresponding image pixels. The proposed geometric model is depicted in Figure 3:

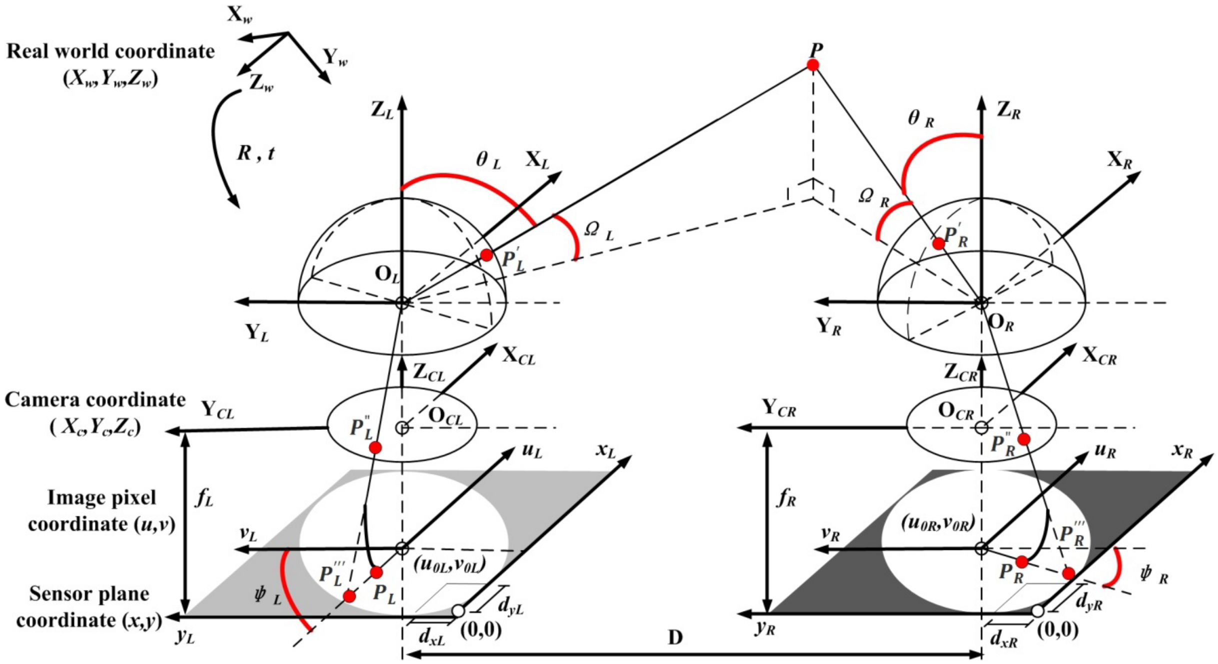



Figure 3. A general geometric model for spherical stereoscopic vision.

It is organized by Real World Coordinate $(\boldsymbol{X_W}, \boldsymbol{Y_W}, \boldsymbol{Z_W})$, Camera Coordinate $(\boldsymbol{X_C}, \boldsymbol{Y_C}, \boldsymbol{Z_C})$, Sensor Plane Coordinate $(\boldsymbol{x}, \boldsymbol{y})$ and Image Pixel Coordinate $(\boldsymbol{u}, \boldsymbol{v})$. Here $\boldsymbol{P}$ is one object point in the real world. $\boldsymbol{P_L}$ and $\boldsymbol{P_R}$ is the corresponding pixels in left and right image, respectively. If camera follows pinhole model, $\boldsymbol{P_L'''}$ and $\boldsymbol{P_R'''}$ will be the corresponding image pixels of $\boldsymbol{P}$. $\boldsymbol{\theta_L}$ and $\boldsymbol{\theta_R}$ is the incidence angle, $\boldsymbol{\psi_L}$ and $\boldsymbol{\psi_R}$ is the azimuth angle of $\boldsymbol{P}$ in images. Here, $\boldsymbol{d_x}$ and $\boldsymbol{d_y}$ represents the physical dimensions of each pixel in horizontal and vertical dimensions. The camera center $\boldsymbol{O_C}$ and its distance form the image plane is the focal length $\boldsymbol{f}$. $(\boldsymbol{u_0}, \boldsymbol{v_0})$ is the principal point of the image. Based on this generic geometric model, a mathematical model is derived to set up the relationship between the parameters.

## 3. MATHEMATICAL MODEL FOR SPHERICAL STEREOSCOPIC VISION

In the field of computer vision, perspective projection model is widely used to solve the correspondence problem between the 3D object points and 2D image points. However, extremely wide angle lenses are designed to cover the whole hemispherical field in front of the camera and the FOV is usually more than or equal to 180º. It is impossible to project the hemispherical field of view on a finite sensor plane by a perspective projection. Therefore, the traditional 3D measurement model of the binocular system[16] is invalid to the spherical stereoscopic vision system which is built with panomorph or fish-eye lenses.

As shown in Figure3, the real world coordinate system is not identical with camera coordinate system. The motion between these coordinate systems is given by a rotation $\boldsymbol{R}$ and translation $\boldsymbol{t}$. Transform the object $\boldsymbol{P} = (\boldsymbol{x_W}, \boldsymbol{y_W}, \boldsymbol{z_W})^{\boldsymbol{T}}$ to $\boldsymbol{P'''} = (\boldsymbol{x_C}, \boldsymbol{y_C}, \boldsymbol{z_C})^{\boldsymbol{T}}$ which is on the camera:

$$P = RP'' + t \tag{1}$$

If the stereoscopic vision system is built by perspective cameras, by similar triangles, the point $(\boldsymbol{x_c}, \boldsymbol{y_c}, \boldsymbol{z_c})^{\boldsymbol{T}}$ in the camera coordinate frame will be projected to the point $\boldsymbol{P}''' = (\boldsymbol{x}, \boldsymbol{y})^{\boldsymbol{T}} = \left(\boldsymbol{f}\frac{\boldsymbol{x_c}}{\boldsymbol{Z_c}}, \boldsymbol{f}\frac{\boldsymbol{y_c}}{\boldsymbol{z_c}}\right)^{\boldsymbol{T}}$ in the image coordinate frame. In terms of homogeneous coordinates this perspective projection can be represented by a 3×4 projection matrix,

$$\begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = \begin{bmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{pmatrix} x_c \\ y_c \\ z_c \\ 1 \end{pmatrix} \tag{2}$$

To make our mathematical model more universal to various sorts of spherical stereoscopic vision systems built by panomorph or fish-eye lenses, in this paper, we adopt another generic camera model, not the same as (2), to different types of extremely wide angle lenses based on our previous studies, which is published and discussed on [13][14].

$$P''' = \begin{pmatrix} x \\ y \end{pmatrix} = r(\theta) \begin{pmatrix} \cos\psi \\ \sin\psi \end{pmatrix} \tag{3}$$

Here, $\boldsymbol{r}$ is the distance between the image point and the principal point, $\boldsymbol{\theta}$ is the angle between the principal axis and the incoming ray, and $\boldsymbol{\delta} = (\boldsymbol{\theta}, \boldsymbol{\psi})^{\boldsymbol{T}}$ is the direction of the incoming ray. The projections of extremely wide angle lenses are considered as a general form:

$$r(\theta) = k_1\theta + k_2\theta^3 + k_3\theta^5 + k_4\theta^7 + k_5\theta^9 \cdots \tag{4}$$

For computations, we need to fix the number of terms in (4). Experiments prove that the first five terms, up to the ninth power of $\boldsymbol{\theta}$, give enough degrees of freedom for good approximation of different projection curves. Thus, the radially symmetric part of the camera model contains the five parameters, $\boldsymbol{k_1}, \boldsymbol{k_2}, \boldsymbol{k_3}, \boldsymbol{k_4}, \boldsymbol{k_5} \cdots$.

To obtain a widely applicable model, there are also two distortion terms as follows:

one distortion term acts in the radial direction

$$\Delta_r(\theta, \varphi) = (l_1\theta + l_2\theta^3 + l_3\theta^5)(i_1 cos\psi + i_2 sin\psi + i_3 cos2\psi + i_4 sin2\psi) \tag{5}$$

and the other in the tangential direction

$$\Delta_t(\theta, \varphi) = (m_1\theta + m_2\theta^3 + m_3\theta^5)(j_1 cos\psi + j_2 sin\psi + j_3 cos2\psi + j_4 sin2\psi) \tag{6}$$

where the distortion functions are separable in the variables $\boldsymbol{\theta}$ and $\boldsymbol{\psi}$.

By adding the distortion terms to (3), we obtain the distorted coordinates $\boldsymbol{P_d'''} = (\boldsymbol{x_d}, \boldsymbol{y_d})^{\boldsymbol{T}}$ by:

$$P_d''' = P''' u_r(\psi) + \Delta_r(\theta, \psi) u_r(\psi) + \Delta_t(\theta, \psi) u_\psi(\psi) \tag{7}$$

Here, $\boldsymbol{u_r}(\boldsymbol{\psi})$ and $\boldsymbol{u_\psi}(\boldsymbol{\psi})$ are the unit vectors in the radial and tangential directions.

The final step is to transform the sensor plane coordinates $\boldsymbol{P_d'''}$ into the image pixel coordinates $\overline{\overline{\boldsymbol{P}}} = (\boldsymbol{u}.\boldsymbol{v})^{\boldsymbol{T}}$. By assuming that the pixel coordinate system is orthogonal, we get the pixel coordinates from:

$$\overline{\overline{P}} = \begin{pmatrix} u \\ v \end{pmatrix} = \begin{bmatrix} m_u & 0 \\ 0 & m_v \end{bmatrix} \begin{pmatrix} x_d \\ y_d \end{pmatrix} + \begin{pmatrix} u_0 \\ v_0 \end{pmatrix} \tag{8}$$

$(\boldsymbol{u_0}, \boldsymbol{v_0})^{\boldsymbol{T}}$ is the principal point and $\mathrm{m_u}$and $\mathrm{m_v}$give the number of pixels per unit distance in horizontal and vertical directions, respectively.

At this point, the transformation process from one 3D object point to a 2D image pixel can be considered as complete. However, if the image pixel $\overline{\overline{\boldsymbol{P}}}$ is given, we still can't only rely on the backward model to uniquely determine the 3D object point $\boldsymbol{P}$. Since all of the 3D points which have the same projection point $\overline{\overline{\boldsymbol{P}}}$ will lie on the ray $\boldsymbol{\delta} = (\boldsymbol{\theta}, \boldsymbol{\psi})^{\boldsymbol{T}}$. In order to determine the object point $\boldsymbol{P}$ uniquely by triangulation, the geometric relationships between the two cameras of a spherical stereoscopic vision system need to be determined.

For any arbitrary point $\boldsymbol{P}$, if its non-homogeneous coordinates in the real world coordinates, left camera coordinates and right camera coordinates are: $\boldsymbol{X^w}, \boldsymbol{X^{cl}}$and $\boldsymbol{X^{cr}}$ , hence:

$$X^{cl} = R^{w\to cl} X^w + t^{w\to cl} \quad , \quad X^{cl} = R^{w\to cl} X^w + t^{w\to cr} \tag{9}$$

eliminate $\boldsymbol{X^W}$

$$X^{cl} = R^{w\to cl}\,(R^{w\to cr})^{-1}X^{cr} + t^{w\to cl} - (R^{w\to cr})^{-1}t^{w\to cr} \tag{10}$$

The geometric relationships between two cameras can be described as:

$$R^{lr} = R^{w\to cl}\,(R^{w\to cr})^{-1}$$
$$t^{lr} = t^{w\to cl} - (R^{w\to cr})^{-1}t^{w\to cr} \tag{11}$$

To sum up, all of the internal and external parameters of our stereo camera system have been presented.

## 4. CALIBRATING THE GENERAL MODEL

This section describes a procedure for estimating the parameters of the general model for the spherical stereoscopic vision. The calibration method is based on viewing a calibration pattern which contains control points in fixed positions. We propose two kinds of flexible calibration patterns which have aspect ratios 16:9 and 4:3, and can be displayed on a flat screen conveniently by using the full screen viewing mode of Acrobat Reader. In addition, a good accuracy can be achieved if circular control points are used [14].

There are $\boldsymbol{M}$ control points observed in $\boldsymbol{N}$ views. For each view, there is a rotation matrix $\boldsymbol{R_j}$ and a translation vector $\boldsymbol{t_j}$ describing the position of the camera with respect to the calibration pattern such that

$$X^c = R_jX + t_j,\ \ j = 1, \ldots ,\tag{12}$$

We choose the calibration plane to lie in the ***XY-plane*** and denote the coordinates of the control point $\boldsymbol{i}$ with $\boldsymbol{X^i} = (\boldsymbol{X^i}, \boldsymbol{Y^i}, \boldsymbol{0})^{\boldsymbol{T}}$. The corresponding homogeneous coordinates in the calibration pattern are denoted by $\boldsymbol{x_p^i} = (\boldsymbol{X^i}, \boldsymbol{Y^i}, \boldsymbol{1})^{\boldsymbol{T}}$, and the observed coordinates in the view $\boldsymbol{j}$ by $\boldsymbol{m_j^i} = \left(\boldsymbol{u_j^i}, \boldsymbol{v_j^i}, \boldsymbol{1}\right)^{\boldsymbol{T}}$.

**Step 1: Initialization of internal parameters**

At first, we use a simplified version of our multi-parameters camera model which contains only six non-zero internal parameters, i.e. the parameters $(\boldsymbol{k_1}, \boldsymbol{k_2}, \boldsymbol{m_u}, \boldsymbol{m_v}, \boldsymbol{u_0}, \boldsymbol{v_0})$ . These parameters are initialized using a priori knowledge about the camera. The initial values for $\boldsymbol{k_1}$ and $\boldsymbol{k_2}$ can be obtained by fitting the model $\boldsymbol{r} = \boldsymbol{k_1\theta} + \boldsymbol{k_2\theta^3}$ to the desired projection curve of one of the perspective projection, stereographic projection, equidistance projection, equisolid angle projection or orthogonal projection with *f=1*. With a full-fame lens, the best thing is probably to place the principal point $(\boldsymbol{u_0}, \boldsymbol{v_0})^{\boldsymbol{T}}$ to the image center. In pixel coordinates, the yield of view of a panomorph lens is mapped inside an ellipse. We can use the reported values of the pixel dimensions to obtain initial values for $\boldsymbol{m_u}$ and $\boldsymbol{m_v}$.

With the above internal parameters, we may back-project the observed points $\boldsymbol{m_j^i}$ onto the unit sphere centered at the camera origin. For each $\boldsymbol{m_j^i}$ the back–projection gives the direction $\boldsymbol{\delta_j^i} = \left(\boldsymbol{\theta_j^i}, \boldsymbol{\psi_j^i}\right)^{\boldsymbol{T}}$ and the points on the unit sphere are defined by $\boldsymbol{q_j^i} = \left(\boldsymbol{sin\,\psi_j^i\,sin\,\theta_j^i}, \boldsymbol{cos\,\psi_j^i\,sin\,\theta_j^i}, \boldsymbol{cos\,\theta_j^i}\right)^{\boldsymbol{T}}$.

**Step 2: Computation of homographies**

Since the mapping between the points on the calibration plane and on the unit sphere is a central projection, there exists a planar homography $\boldsymbol{H_j}$ so that

$$sq_j^i = H_jx_p^i \tag{13}$$

Here, $\boldsymbol{s}$ is a proportionality factor. We compute the initial estimate for $\boldsymbol{H_j}$ from the correspondences $\boldsymbol{q_j^i} \leftrightarrow \boldsymbol{x_p^i}$ by the linear algorithm with data normalization [18].

**Step 3: Initialization of external parameters**

The initial values for the external camera parameters are extracted from the homographies $\boldsymbol{H_j}$. It holds that

$$sq_j^i = H_j x_p^i = H_j \begin{pmatrix} X^i \\ Y^i \\ 0 \\ 1 \end{pmatrix} \tag{14}$$

$$sq_j^i = \begin{bmatrix} R_j & t_j \end{bmatrix} \begin{pmatrix} X^i \\ Y^i \\ 0 \\ 1 \end{pmatrix} \quad , \quad R_j = \begin{bmatrix} r_j^1 & r_j^2 & r_j^3 \end{bmatrix} \tag{15}$$

$$sq_j^i = \begin{bmatrix} R_j & t_j \end{bmatrix} \begin{pmatrix} X^i \\ Y^i \\ 0 \\ 1 \end{pmatrix} = \begin{bmatrix} r_j^1 & r_j^2 & t_j \end{bmatrix} \begin{pmatrix} X^i \\ Y^i \\ 0 \\ 1 \end{pmatrix} \tag{16}$$

Which implies $\boldsymbol{H_j} = [\boldsymbol{r_j^1} \;\; \boldsymbol{r_j^2} \;\; \boldsymbol{t_j}]$ , Hence,

$$r_j^1 = \lambda_j h_j^1, \qquad r_j^2 = \lambda_j h_j^2, \qquad r_j^3 = r_j^1 \times r_j^2, \qquad t_j = \lambda_j h_j^3 \tag{17}$$

Where $\boldsymbol{\lambda_j} = \pm\left\|\boldsymbol{h_j^1}\right\|^{-1}$. The sign of $\boldsymbol{\lambda_j}$ can be determined by requiring that the camera is always on the front side of the calibration plane. However, the obtained rotation matrices may not be orthogonal due to estimation errors. Hence, the singular value decomposition is used to compute the closest orthogonal matrices in the sense of Frobenius norm which are then used for initializing each $\boldsymbol{R_j}$.

**Step 4: Minimization of projection error**

If own full camera model with more than six parameters is used the additional camera parameters are initialized to zero at this stage. As we have the estimates for the internal and external camera parameters, we may compute the imaging function $\boldsymbol{\mathcal{P}_j}$ for each camera, where a control point is projected to $\boldsymbol{\widehat{m}_j^i} = \boldsymbol{\mathcal{P}_j}(\boldsymbol{X^i})$. The camera parameters are defined by minimizing the sum of squared distances between the measured and modeled control point projections

$$\sum_{j=1}^{N} \sum_{i=1}^{M} d(m_j^i, \widehat{m}_j^i)^2 \tag{18}$$

using the Levenberg-Marquardt algorithm.

**Step 5: Computation of the geometric relationships between two cameras**

In the course of calibrating procedures, the calibration pattern is stationary, and the location of the spherical stereoscopic vision system is constantly changing to view the pattern in different places. In each view, we will obtain corresponding $\boldsymbol{R_j^{w\to cl}}$ , $\boldsymbol{R_j^{w\to cr}}$ and $\boldsymbol{t_j^{w\to cl}}$, $\boldsymbol{t_j^{w\to cr}}$ to describe the situation of the left and right camera, respectively. Although these above mentioned parameters in different positions are not the same, but the geometric relationship between the left and right camera, $\boldsymbol{R^{cl\to cr}}$ and $\boldsymbol{t^{cl\to cr}}$, is unique. Each group of $\boldsymbol{R_j^{cl\to cr}}$ and $\boldsymbol{t_j^{cl\to cr}}$ can be obtained by (10) and (11).

## 5. CALIBRATING THE GENERAL MODEL

In this section, calibration result of the spherical stereoscopic vision system is presented. The system is constructed by a pair of network camera (AXIS P1346-E) with panomorph lens (YF360A-SA2), as shown in Figure2. The camera has a resolution of 2048×1536 pixels. The lens has a $182^0$ field of view and a total focal length of 1.15mm. A calibration pattern with aspect ratios 4:3 has been projected on a screen by projector. Figure 4 is the one pair of images captured by the panomorph lenses for the calibration of the spherical stereoscopic vision system. There is an ellipse area inside the image frame. Here, we used 13 pairs of images of the calibration pattern to calculate the internal and external parameters. There were 13×12×16 observed control points in total and they were localized by computing their gray-scale centroids.

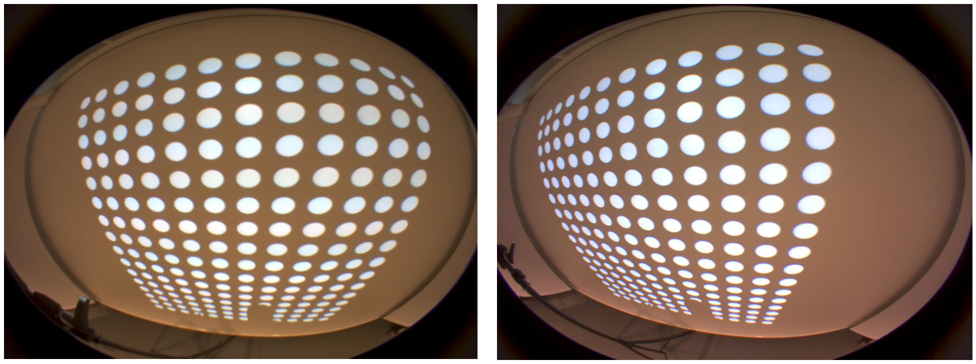


Figure 4. Images captured by the two panomorph lenses for the calibration of the spherical stereoscopic vision system

The internal parameters calibration result is illustrated in Table 1 which shows the RMS residual errors in pixels and the values of the parameters.

TABLE 1. Internal parameters calibration result

| | Left camera | Right camera | | Left camera | Right camera | | Left camera | Right camera |
|---|---|---|---|---|---|---|---|---|
| RMS residual errors in pixels | 0.8280 | 0.7925 | $k_4$ | 0.2928 | 0.5353 | $i_4$ | -0.0335 | -0.3155 |
| $k_1$ | 0.8343 | 0.9091 | $k_5$ | -0.0827 | -0.1636 | $m_1$ | -0.0086 | -0.0342 |
| $k_2$ | 0.4563 | 0.5495 | $l_1$ | 0.1290 | 0.0223 | $m_2$ | -0.0766 | -0.0718 |
| $m_u$ | 294.9848 | 299.9514 | $l_2$ | 0.0278 | -0.0618 | $m_3$ | -0.0548 | -0.1503 |
| $m_v$ | 233.4001 | 232.5818 | $l_3$ | 0.0458 | 0.0979 | $j_1$ | -0.0643 | 0.3218 |
| $u_0$ | 501.9822 | 490.7397 | $i_1$ | 0.1263 | 0.0001 | $j_2$ | 0.0597 | -0.7726 |
| $v_0$ | 423.0243 | 421.4076 | $i_2$ | 0.1893 | 0.0183 | $j_3$ | 0.0627 | 0.7126 |
| $k_3$ | -0.3847 | -0.6620 | $i_3$ | 0.1061 | 0.0180 | $j_4$ | -0.0528 | -0.0703 |

There are thirteen groups of $\boldsymbol{R}_j^{w\to cl}$ , $\boldsymbol{R}_j^{w\to cr}$ and $\boldsymbol{t}_j^{w\to cl}$, $\boldsymbol{t}_j^{w\to cr}$ which can be estimated by applying the calibration algorithm described in section 4. However, the relative orientation of the two cameras is identical. According to formula (10), the rotation matrix is

$$R^{cl\to cr} = \begin{pmatrix} 0.999958352554411 & -0.00300252146825658 & -0.0158530205667485 \\ 0.00297405722117520 & 0.999963824514041 & -0.00486951631349569 \\ 0.0358869077234104 & 0.00482849421023068 & 0.999971014560481 \end{pmatrix}$$

, and the translation matrix is

$$t^{cl\to cr} = (-24.3253948571628 \quad -1.10224564788995 \quad 5.99123314154657)$$

## 6. CONCLUSION

The conventional pinhole camera model cannot be applied to spherical stereoscopic vision constructed by extremely wide angle lenses, because such as panomorph and fish-eye lens may have a wider than hemispherical FOV. In this paper, a spherical stereo calibration technique is proposed to cope with this problem. A general system model has been presented, which is generic, easily expandable and precise. The calibration method is based on viewing a planar calibration pattern with circle control points. In addition, a flexible binocular spherical stereo stereoscopic vision system has been built. The experiment shows that the achieved level of accuracy for internal and external parameters is satisfying. The results are promising considering especially the aim of using binocular spherical stereo stereoscopic vision system in measurement purposes.

## ACKNOWLEDGMENTS

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