

# 3D MEASUREMENT, RECONSTRUCTION AND NAVIGATION THROUGH PANORAMIC PHOTOGRAPHY<sup>1</sup>

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## ABSTRACT:

In photogrammetric applications the use of a digital panoramic camera with 360° field of view may provide an interesting alternative to conventional methods. In this paper, the structure and panorama generation process of our line-CCD-based panoramic system was presented. Specially, we employed a circular fish-eye lens for its large vertical field of view (180°), thus introducing severe distortions to images taken. Different from previous distortion correction methods for wide-angle (usually smaller than 180°) cameras, we used a self-calibrating method with straight-line spherical perspective projection constraint to obtain intrinsic distortion parameters. After retrieving undistorted panorama, the system allows 3D measurement through two spherical images taken from the same location but vertically separated by a so-called baseline. Through fisheye imaging model, it is easy to know the distances of features from the upper camera position and then the distance between two 3D points. There are encouraging results which show the high-precision metric positioning and measuring capability of digital line-CCD-based panoramic system.

## 1. INTRODUCTION

Digital panoramic imaging techniques have found growing interest in photogrammetry in the past few years. The fields of application vary from web-based animation, in-room monitoring, video conferencing, tourist purposes, weather forecast to metric measurement and 3-D reconstruction.

There are four main approaches for panoramic imaging: (a) Single frame-based camera with image mosaicing technique, (b) mirror techniques, (c) near 180° technique, and (d) scanning 360° technique (Schneider & Maas, 2003b). In the first method a series of regular images is taken with some overlap. This is the traditional method, and a panorama is produced by stitching the individual images together. The method is low in costs but due to longer processing times it is less suitable for real-time applications and has other disadvantages (e.g. discrete tie points are needed in the areas of overlap). The second method is using direct or indirect reflections on a mirror. In principle the mirror techniques can be partitioned into two groups: Single mirror (convex mirror: parabolic, spherical, conical, hyperbolic mirrors) and double mirror omnidirectional (i.e. conical and/or round-concave and parabola-concave mirror). The advantage of this method is its high capturing rate, but the resolution of the image is low. The third method relates to a fixed image camera with a long and narrow film format. The format 6x17 cm is the industry standard for commercial panorama work. Since it is not a real panoramic camera it needs more images to cover the surrounding scene. Only the last is a truly panoramic camera. It captures the full surrounding view in one scan. The camera operates by rotating around the vertical axis. A linear array CCD sensor captures the scenery as a continuous set of vertical scan lines. This kind of camera is popular for indoor imaging, landscape recording, tourism advertising and Internet

representations. The advantages of this technology with respect to the others are (Amiri Parian & Gruen, 2003):

- (a) High resolution imaging, and potentially high precision 3D object reconstruction.
- (b) High information content, since a single image contains a full 360° scan.

Therefore, we designed our panorama system basing on rotating linear array and also employed a circular fish-eye lens for its large vertical field of view.

This paper is organized into the following sections: Section 2 describes the structure of our line-CCD-scanning panoramic system and its capturing process. In section 3, an automatic distortion correction method using straight-line spherical perspective projection is introduced to calibrate the intrinsic distortion parameters of our 180° fisheye lens. Section 4 presents its application in 3-D distance measurement. The experiments of measurement and accuracy analysis are shown in Section 5. Finally, Section 6 gives a brief conclusion.

## 2. STRUCTURE OF SENSOR SYSTEM AND PANORAMA GENERATION

The configuration of the camera system is shown in figure 1. The camera system contains three parts: camera head, optical part, and high precision turntable with a stepmotor to rotate the Linear Array. The essential parameters of the camera head are listed in Table 1. The camera head is connected to the PC with a bi-directional fiber link for data transmission and camera control. The optical part of the system uses 8mm Sigma circular

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fish-eye lens. The camera head is mounted on a high precision turntable. It consists of a servomotor which is directly controlled by PC, and a gearsystem to reduce the motor revolution speed. Rotation speed is pre-selectable and corresponds to the exposure time and line rate. Due to the introduction of fish-eye lenses with 180° vertical field of view, as the camera rotates about its vertical axis, it captures a complete spherical image. Before its rotating, a special method allows the projection center to be positioned on the rotation axis.

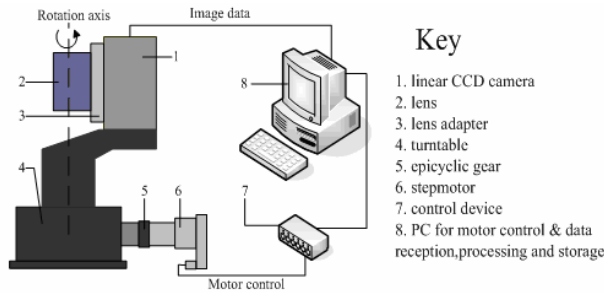


Figure 1. Structure of the panoramic system

Technical Specifications		
Radiometric resolution	dynamic/	8 bit per pixel – 3×8 bit per color(RGB)
Number of pixel in linear array(vertical resolution)		2048 pixels per line
Pixel size		14microns
Max. vertical Exposure Angle		180°
Line Rate		1.0kHz – 9.2kHz

Table 1. Essential parameters of the camera head



Figure 2. A section of one panorama we took

The panorama generation can be summarized as follows:

- Step 1.Focus the camera
- Step 2.Adjustment of principal point (make sure it lies on rotation axis)
- Step 3.Set the rotation speed and rotation angle
- Step 4.Image acquisition and storage

### 3. SELF-CALIBRATING OF FISHEYE LENS

In many computer vision application, including robot navigation, 3D reconstruction, image-based rendering, and single view metrology, cameras with wide-angle or fish-eye lenses are often employed for a large field of view. Images taken with these imaging devices often have significant distortions. Therefore, it is quite important to establish an efficient method of calibration to determine the camera distortion coefficients. A fish-eye camera’s FOV is around 180 degrees, but a wide-angle camera’s FOV is usually around 100 degrees.

The existing calibration methods for wide-angle camera based on straight-line planar perspective projection constraint cannot be directly used for fish-eye cameras because of its around 180° FOV(Devernay & Faugeras, 2001). In this paper, we use a novel self-calibrating method for our 180° fish-eye lens. It is well known that the spherical perspective projection model is a convenient way to represent FOV around 180 degrees, and that, under spherical perspective projection, images of straight lines in space have to be projected into great circles in the spherical perspective images. Using this straight-line spherical perspective projection constraint, we find out the mapping between a fish-eye image and its corresponding spherical perspective image, thus solving the calibration problem.

#### 3.1 Fisheye Imaging Model

Fisheye imaging model describes a mapping from 3D space points to 2D fish-eye image points. We introduce the spherical perspective projection into the fish-eye imaging model and divide the imaging model into three concatenated steps as follows(Xianghua Ying, Zhangyi Hu & Hongbin Zha, 2006):

Step 1: Transform the 3D world coordinates of a space point into the 3D camera coordinates:

$$P_w = (X, Y, Z)^T \rightarrow P_c = (X_c, Y_c, Z_c)^T \quad (1)$$

Step 2: The space point is perspective projected onto a unit sphere centered at the projection center (see Figure 3). If  $p$  is the spherical projection of the space point, we have:

$$p = \frac{P_c}{\|P_c\|} = (\sin \phi \cos \theta, \sin \phi \sin \theta, \cos \phi) \quad (2)$$

Where  $p = (\sin \phi \cos \theta, \sin \phi \sin \theta, \cos \phi)^T$  is the unit directional vector, and  $(\phi, \theta)$  is the 2D spherical coordinates of the spherical point.

Step 3: The spherical projection point  $p$  is mapped to point  $m$  on the image plane due to fish-eye lens distortions.

$$m = D(p) \quad (3)$$

Where  $m = (x, y)$  and  $D$  is the so-called fisheye distortion model.

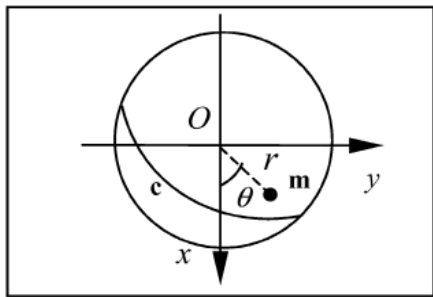
Let  $(\phi', \theta')$  be the polar coordinates of  $m$ . In our experiments, we use fifth degree polynomials to represent fisheye radial and tangential distortion models:

$$r = D_R(\phi) = \sum_{i=1}^5 a_i \phi^i, \theta = D_T(\theta) = \sum_{i=1}^5 b_i \theta^i, \quad (4)$$

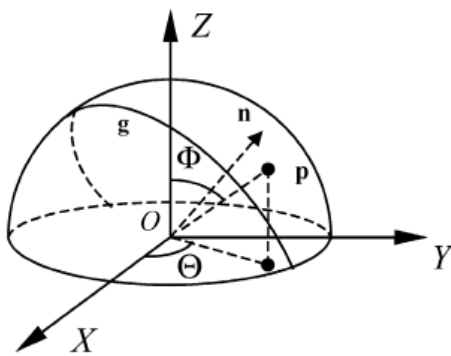
where  $a_i$  are radial, and  $b_i$  are tangential distortion parameters. Among these parameters,

$$b_5 = \frac{1 - b_1 - 2\pi b_2 - 4\pi^2 b_3 - 8\pi^3 b_4}{16\pi^4}, \quad (5)$$

So there are only four independent parameters for tangential distortion.



(a)



(b)

Figure 3. (a) An ideal fisheye image  
(b) The corresponding spherical perspective image

### 3.2 Fisheye Camera Calibration

From the discussions above, we know that there are totally 9 distortion parameters required to be calibrated: 5 radial and 4 tangential distortion parameters. They are obtained by minimizing the sum of errors, more specifically, the squares of

spherical distances from mapped points to their corresponding best-fit great circles. A great circle can be determined by two parameters  $(\Phi, \Theta)$  which are the directional angles of the normal vector for the plane containing the great circle in the 3D Cartesian coordinate system whose origin is located at the spherical center.

Our correction process consists of the following three steps:

Step1: Use frame CCD camera with fisheye lens to acquire a distorted image. Select a small set of points along image curves of space lines in the actual fisheye image. Do curve fitting with nonlinear least-squares minimization method. Let  $L$  represent the number of the sample image curves and  $N_j (j = 1, \dots, L)$  represent the number of the sample points on the  $j^{th}$  image curve.

Step 2: Initialization of distortion parameters with reasonable values.

Distortion Correction Parameters:

$$a_1 = \frac{\alpha}{w}, b_2 = b_3 = b_4 = b_5 = 0.0, \quad (6)$$

Where  $\alpha$  is the fisheye camera FOV and  $w$  is the width of fisheye image.

$$b_1 = 1.0, b_2 = b_3 = b_4 = 0.0 \quad (7)$$

Parameters of Best-Fit Great Circles:

Let  $n$  be the normal vector for the plane containing the best-fit great circle, and  $A = (p_1, p_2, \dots, p_N)$  represent  $N$  spherical points obtained from the initial correction parameters and points along image curve.

$$An = 0 \quad (8)$$

Through SVD decomposition of  $A$ , the solution for  $n$  is obtained as the eigenvector corresponding to the smallest eigenvalue, then  $(\Phi, \Theta)$  can be easily computed from  $n$ .

Step 3: minimize objective function to get optimized values for parameters.

The objective function is constructed as:

$$\mathcal{E} = \sum_{j=1}^L F(n_j) = \sum_{j=1}^L \left[ \sum_{i=1}^{N_j} (p_{i,j}^T n_j)^2 \right] \quad (9)$$

Where  $n_j = (\sin \Phi_j \cos \Theta_j, \sin \Phi_j \sin \Theta_j, \cos \Phi_j)^T$  is the normal vector for the plane containing the  $j^{th}$  best-fit great circle.

The Levenberg-Marquardt optimization technique is used to perform this minimization.

#### 4. IMMERSIVE 3-D DISTANCE MEASUREMENT

Using the symmetrical radial and decentering parameters to correct every vertical line, we obtain an undistorted panorama, thus making it impossible to realize accurate quantitative measurements. Given two images taken from two camera locations vertically spaced by the length of the baseline  $B$ , it is easy to know the distance  $r$  of a feature  $F$  from the upper camera position.  $(\varphi_{up}, \theta_{up})$  and  $(\varphi_{low}, \theta_{low})$  represent its spherical coordinate location in upper and lower images.  $\varphi$  is the azimuthal coordinate and  $\theta$  is the polar coordinate ( $\theta = 0$  is the image north pole (the "ceiling"), and  $\theta = \pi$  is the image south pole (the "floor")).

$$r = B \cdot \frac{\sin \theta_{low}}{\sin(\theta_{up} - \theta_{low})} \quad (10)$$

Taking the upper camera position to be the world's origin, the coordinates of point  $F$  are expressed in spherical coordinates as  $F(\varphi_{up}, \theta_{up}, r)$ .

The distance  $L$  between two 3D points  $F_A(x_1, y_1, z_1)$  and  $F_B(x_2, y_2, z_2)$  in space can be calculated :

$$\begin{aligned} L &= \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \\ x &= r \sin \varphi \sin \theta \\ y &= r \cos \varphi \sin \theta \\ z &= r \cos \varphi \cos \theta \end{aligned} \quad (11)$$

#### 5. REAL EXPERIMENTS

The panoramic measure system was used to obtain the distance between feature points and one experiment is shown in Figure 4. The real length of newspaper is 380mm, our measurement distance is 386.54 mm, therefore the relative error is 1.72%. The accuracy of calculated distance depends on two

fundamentally different factors: calibration accuracy of the lens, accuracy of feature identification by pointing and clicking with the mouse.



Figure 4. Real experiment on 3D measurement

#### 6. CONCLUSIONS

To satisfy the request for high information content (both horizontally and vertically) and high precision measurement in photogrammetric applications, we designed a line-CCD-scanning panoramic measurement system. This device can capture a full spherical image in one scan (horizontal FOV: 360°, vertical FOV: 180°). An effective self-calibrating method was used to correct the panorama, thus enabling the high precision measurement of distance between two space points. Experiment results showed the high-precision metric positioning and measuring capability of digital line-CCD-based panoramic system. This is an ongoing project, the navigation and reconstruction will be completed in the next months.

#### REFERENCES

- F. Devernay, O. Faugeras, 2001. Straight Lines Have to Be Straight: Automatic Calibration and Removal of Distortion from Scenes of Structured Environments. Machine Vision and Applications, vol.1, pp. 14-24
- Amiri Parian, J. and Gruen, A., 2003. A Sensor Model for Panoramic Cameras. In: Gruen/Kahmen (Eds.), 6th Conference on Optical 3D Measurement Techniques, Zurich, Switzerland, Vol. 2, pp. 130-141.
- Xianghua Ying, Zhangyi Hu, and Hongbin Zha, 2006. Fisheye Lenses Calibration Using Straight-Line Spherical Perspective Projection Constraint. ACCV, LNCS 3852, pp.61-70.
- Schneider, D., Maas, H.-G., 2003b. Geometric modelling and calibration of a high resolution panoramic camera.
- Grün/Kahmen (Eds.): Optical 3-D Measurement Techniques VI, Volume II, pp. 122-129.