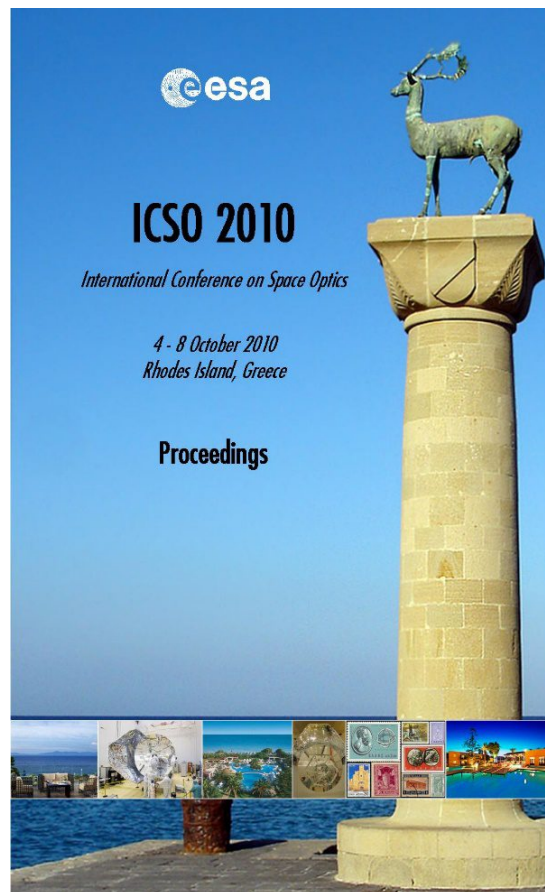


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RESEARCHES ON HAZARD AVOIDANCE CAMERAS CALIBRATION OF LUNAR ROVER

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I. INTRODUCTION

Lunar Lander and Rover of China will be launched in 2013. It will finish the mission targets of lunar soft landing and patrol exploration. Lunar Rover has forward facing stereo camera pair (Hazcams) for hazard avoidance. Hazcams calibration is essential for stereo vision. The Hazcam optics are f-theta fish-eye lenses with a $120^\circ \times 120^\circ$ horizontal/vertical field of view (FOV) and a 170° diagonal FOV. They introduce significant distortion in images and the acquired images are quite warped, which makes conventional camera calibration algorithms no longer work well.

A photogrammetric calibration method of geometric model for the type of optical fish-eye constructions is investigated in this paper. In the method, Hazcams model is represented by collinearity equations with interior orientation and exterior orientation parameters [1] [2]. For high-precision applications, the accurate calibration model is formulated with the radial symmetric distortion and the decentering distortion as well as parameters to model affinity and shear based on the fisheye deformation model [3] [4]. The proposed method has been applied to the stereo camera calibration system for Lunar Rover.

II. GEOMETRIC MODEL FOR HAZCAM LENSES

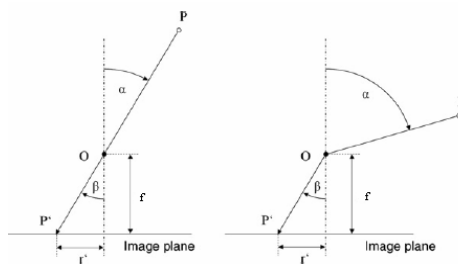


Fig.1. Undistorted central perspective geometry (left) vs. fisheye projection geometry (right)

The Hazcam optics is f-theta fish-eye lenses. Fig.1 shows a typical fisheye projection in comparison to the central perspective projection [3]. The rays are refracted in the direction of the optical axis. In the following, the f-theta type of fisheye projection is equidistant projection:

$$\alpha \neq \beta \quad r' = f \cdot \alpha \quad (1)$$

where α is the incidence angle, β the reflection angle, r' the image radius and f the principal distance.

To describe the projection of an object point into a fisheye lens image, three coordinate systems are used: The superordinated Cartesian object coordinate system (X, Y, Z) and the camera coordinate system (x, y, z) (see Fig.2). The image coordinate system (x', y') is defined as usual in photogrammetric applications, which means the origin is the image center, and the x' - and y' -axes are parallel with the x - and y -axes of the camera coordinate system.

Object coordinates are transformed into the camera coordinate system using Eq. (2), where \vec{X} is the coordinate vector in the object coordinate system, \vec{x} the coordinate vector in the camera coordinate system, \vec{R} the rotation matrix and \vec{X}_0 the translation between object and camera coordinate system:

$$\vec{x} = \vec{R}^{-1}(\vec{X} - \vec{X}_0) \quad (2)$$

The incidence angle α in the camera coordinate system is defined as follows:

$$\tan \alpha = \frac{\sqrt{x^2 + y^2}}{z} \quad (3)$$

For the equations for fisheye projection as described above, the image radius r' is defined as a function of the incidence angle α and the principle distance. Instead of functions for the image radius r' , functions for the image coordinates x' and y' are required. For this purpose Eq. (4) is applied:

$$r' = \sqrt{x'^2 + y'^2} \quad (4)$$

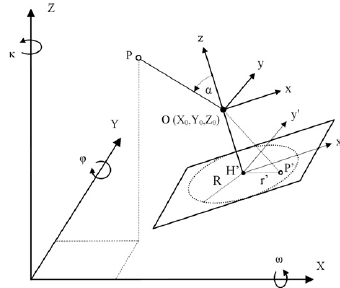


Fig.2. Geometrical model of the Hazcam

To describe the image coordinates x' and y' as a function of the object point coordinates in the camera coordinate system x and y Eq. (5) has to be introduced. This equation is set up applying the theorem on intersecting lines in the plane which is defined by the z -axis, the image point and the object point [3] [5] [6].

$$\frac{x'}{y'} = \frac{x}{y} \quad (5)$$

After transforming equations (4) and (5), the projection equations become:

$$x' = \frac{r'}{\sqrt{\left(\frac{y}{x}\right)^2 + 1}} \quad y' = \frac{r'}{\sqrt{\left(\frac{x}{y}\right)^2 + 1}} \quad (6)$$

The insertion of these equations into the type of projection (Eqs.(1)) leads to the respective geometric models of with fisheye lens cameras. The coordinates of the particular object point in the camera coordinate system x , y and z still have to be transformed into the object coordinate system using Eq.(3). The model equations are finally extended by the coordinates of the principle point x'_0 and y'_0 and the correction terms $\Delta x'$ and $\Delta y'$ which contain distortion parameters to compensate for systematic effects [3] [5].

Equidistant projection:

$$x' = f \cdot \frac{\arctan \frac{\sqrt{x^2 + y^2}}{z}}{\sqrt{\left(\frac{y}{x}\right)^2 + 1}} + x'_0 + \Delta x' \quad (7)$$

$$y' = f \cdot \frac{\arctan \frac{\sqrt{x^2 + y^2}}{z}}{\sqrt{\left(\frac{x}{y}\right)^2 + 1}} + y'_0 + \Delta y' \quad (8)$$

As distortion parameters to compensate for deviations of the geometric fisheye model from the physical reality the same parameters are applied as they are in common use for central perspective lenses (Eq. (9) and (10)). These are parameters to describe the radial symmetric distortion and the decentering distortion as well as parameters to model affinity and shear [3] [7] [8].

$$\Delta x' = x' \cdot (A_1 r'^2 + A_2 r'^4 + A_3 r'^6) + B_1 \cdot (r'^2 + 2x'^2) + 2B_2 x' y' + C_1 \cdot x' + C_2 \cdot y' \quad (9)$$

$$\Delta y' = y' \cdot (A_1 r'^2 + A_2 r'^4 + A_3 r'^6) + 2B_1 x' y' + B_2 \cdot (r'^2 + 2y'^2) \quad (10)$$

where

A_1, A_2, A_3 = radial distortion parameters

B_1, B_2 = decentering distortion parameters

C_1, C_2 = horizontal scale factor, shear factor.

Then, Equations (13) and (14) is geometric model for the Hazcams.

III. PHOTOGRAMMETRIC CALIBRATION MODEL

A photogrammetric calibration model for the Hazcams defines a set of interior orientation (IO) parameters and a set of exterior orientation (EO) parameters. The IO parameters include the focal length of the Hazcam f , the image coordinates of the principal point (x'_0, y'_0) where the optical axis intersects the image plane and the lens distortion parameters $(A_1, A_2, A_3, B_1, B_2, C_1, C_2)$. The EO parameters are coordinates of the exposure center (X_C, Y_C, Z_C) in the ground-coordinate system and three rotation angles (ω, ϕ, κ) that describe the rotations about the three principal axes needed to rotate from the object coordinate system $X - Y - Z$ to the camera coordinate system $x - y - z$ (Figure 2).

The transformation from the object coordinates (X, Y, Z) to the image coordinate system (x', y') is expressed by the following collinearity equations [4] [6]:

$$x' = f \cdot \frac{a_{11}(x - x_0) + a_{12}(y - y_0) + a_{13}(z - z_0)}{a_{31}(x - x_0) + a_{32}(y - y_0) + a_{33}(z - z_0)} + x'_0 + \Delta x' \quad (11)$$

$$y' = f \cdot \frac{a_{21}(x - x_0) + a_{22}(y - y_0) + a_{23}(z - z_0)}{a_{31}(x - x_0) + a_{32}(y - y_0) + a_{33}(z - z_0)} + y'_0 + \Delta y' \quad (12)$$

where a_{ij} are elements of a rotation matrix \bar{R} and sine and cosine functions of the three angles:

$$\bar{R} = \begin{bmatrix} \cos \phi \cos \kappa & \sin \omega \sin \phi \cos \kappa + \cos \omega \sin \kappa & -\cos \omega \sin \phi \cos \kappa + \sin \omega \sin \kappa \\ -\cos \phi \sin \kappa & -\sin \omega \sin \phi \sin \kappa + \cos \omega \cos \kappa & \cos \omega \sin \phi \sin \kappa + \sin \omega \cos \kappa \\ \sin \phi & -\sin \omega \cos \phi & \cos \omega \cos \phi \end{bmatrix}$$

According to the above equations, the interior and exterior orientation parameters of the Hazcams can be acquired.

IV. EXPERIMENT AND RESULTS

According to the above principles, a special calibration field-based stereo camera calibration method is set up (see Fig.3). In the Hazcams calibration, the 3-D frame was used for the calibration targets and several total stations were used to measure reference points on the 3-D frame for each target position. The Hazcams is moved around in front of the 3-D frame and target location relative to the fixed 3-D frame is captured using the total stations.



Fig.3. the Hazcams calibration field image

A. Hazcams Interior and Exterior Orientation Parameters

Table 3. Converted Parameters of the Photogrammetric Model

	Interior Orientation Parameters			Exterior Orientation Parameters	
	Left Hazcam	Right Hazcam		Left Hazcam	Right Hazcam
f / mm	12.267183	12.273872	X_C / mm	1354.7655	1348.0565

x'_0 / mm	0.011192	0.047829	Y_C / mm	221.3103	321.2786
y'_0 / mm	-0.282195	-0.018330	Z_C / mm	28.5753	34.2121
A_1	3.198820×10^{-5}	1.644557×10^{-5}	ω / rad	-3.05065290	-3.06353309
A_2	1.347663×10^{-8}	1.996294×10^{-7}	φ / rad	0.91277076	0.91451995
A_3	1.350535×10^{-9}	7.239769×10^{-10}	κ / rad	-0.07501764	-0.05252820
B_1	8.193353×10^{-5}	-6.253752×10^{-7}			
B_2	1.174602×10^{-4}	7.107864×10^{-5}			
C_1	3.805374×10^{-4}	3.805374×10^{-4}			
C_2	-1.023475×10^{-4}	-1.023475×10^{-4}			

B. Hazcams Rectification Results

By applying the perspective matrix, the Hazcams stereo image pair can be rectified. Using the camera models generate rectified images where the rows of one image correspond to the rows of the second image (see Fig.4). This reduces the stereo matching problem from 2D to 1D search problem.

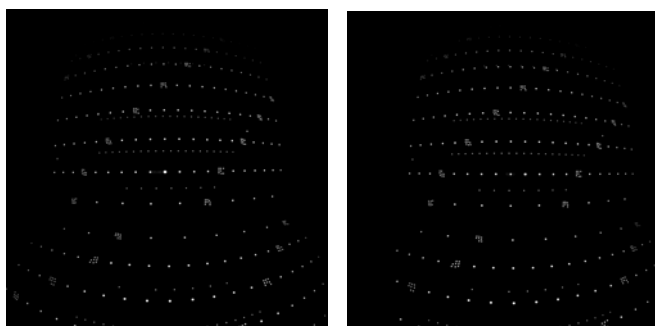


Fig.4. Original image of left Hazcam vs. original image of right Hazcam

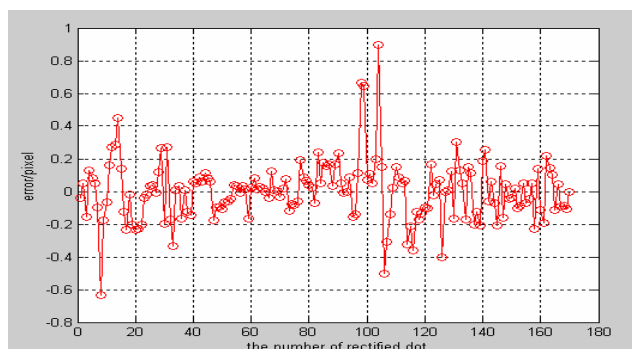


Fig.5. Rectified results for the Hazcams

Figures 5 show the rectified results for the Hazcams. The rectified error is less than 1.0 pixel. The experimental results show that the calibrated model is more perfect.

C. 3-D Reconstruction Results

Since the Hazcams calibration process produced the 3-D metrology data of the calibration dot positions and their associated 2-D image points, the 3-D localization error for each dot position can be computed by comparing the metrology-based 3-D position and the reconstructed 3-D position from the 2-D image point pair based on the stereo camera models.

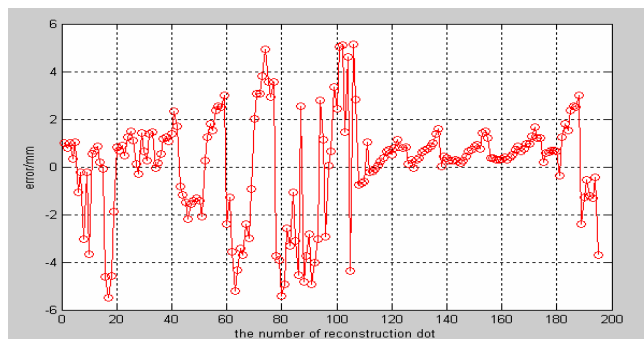


Fig.6. the 3-D reconstruction results for the Hazcams

Figures 6 are the 3-D reconstruction results for the Hazcams. The 3-D reconstruction error is less than 6.0mm. It is shown that the accuracy is improved largely after system calibration.

V. CONCLUSIONS

A photogrammetric calibration method of geometric model for the type of optical fish-eye constructions is investigated in this paper. In the method, Hazcams model is represented by collinearity equations with interior orientation and exterior orientation parameters. For high-precision applications, the accurate calibration model is formulated with radial distortion, decentering distortion, horizontal scale factor and shear factor parameters based on the fisheye deformation model. By applying the perspective matrix, the stereo image pair can be rectified. The error is less than 1.0 pixel. The experimental results show that the calibrated model is more perfect. And the 3-D reconstruction error is less than 6.0mm. The reconstruction precision can be improved greatly. The proposed method has been applied to the stereo camera calibration system for Lunar Rover.

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