

GEOMETRIC MODELLING AND CALIBRATION OF A HIGH RESOLUTION PANORAMIC CAMERA

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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. As the image geometry does not obey a central perspective it was necessary to establish a geometric model for digital panoramic cameras. This model was tested using a camera prototype produced by KST (Kamera & System Technik). Several mechanical and optical characteristics of the physical camera system cause deviations from the basic model. These deviations were geometrically modeled using additional parameters. The model was implemented in a spatial resection and a spatial intersection to calculate the exterior and interior orientation, to analyse the effect of additional parameters and to verify the accuracy potential of the camera.



Lens	35 mm	45 mm	60 mm	100 mm
Image format (360°)	31,400 × 10,200	40,400 × 10,200	53,800 × 10,200	89,700 × 10,200
Data Volume (360°)	1.7 GB	2.3 GB	3.1 GB	5.1 GB
Radiometric resolution	16 bit per channel			
Pixel pitch	7 μm × 7 μm			

FIG. 1. Camera EYESCAN M3 with glass-fibre illumination system and its basic parameters

1. INTRODUCTION

Panoramic photography is a popular tool to record landscapes, rooms and squares in a single image, allowing a full 360° view. It is used for purposes such as tourism, facility management, preservation of works of art and web presentations. In photogrammetric applications, the use of a digital panoramic camera presents an interesting alternative to conventional methods. Advantages of such a camera are the possibility of recording objects such as rooms and squares by taking only a few images or even only one image, at high resolution, and with relatively low costs.

Conventional camera systems are based on a solid state array sensor. The geometric model of these systems is known, and there are several software products available for use in photogrammetric

systems, for example bundle adjustment software. The image geometry of a digital panoramic camera deviates from the central perspective, because the image data is not projected onto a plane but on a cylindrical surface using a single CCD line. Therefore, it was necessary to develop a geometric model for digital panoramic cameras.

One approach for the use of a CCD line in close range photogrammetry was developed within the scope of a research project between TU Darmstadt and Universität Stuttgart (Hovenbitzer & Schlemmer, 1997; Fritsch & Kraus, 1997). In this project an electronic total station served as the basis for the integration of the CCD line. First ideas for the geometric modelling of panoramic cameras are also described in (Lisowski & Wiedemann, 1998).

(Scheibe et al., 2001) describes the use of a panoramic camera in architectural photogrammetry, through a transformation of panoramic imagery into central perspective views. Approaches for generating 3D-models from panoramic images are already given in (Tecklenburg & Luhmann, 2002).

In the frame of the research work presented here, the geometric model for panoramic cameras was applied to the EYESCAN M3 (Fig. 1), a camera prototype provided by KST (Kamera & System Technik GmbH). This camera is a joint development between the German Aerospace Center (DLR) and KST. Based on an analysis of the results and the properties of the camera extended by additional parameters representing the physical reality of the camera, a spatial resection and a spatial intersection were implemented.

Finally, the panoramic camera can be used as a photogrammetric system to generate high-resolution 3D-models of objects, such as rooms and squares, to produce high-resolution orthophotographs, for example of facades as needed in architectural photogrammetry, as well as other different photogrammetric tasks.

2. DIGITAL PANORAMIC CAMERA EYESCAN M3

2.1 General Configuration

The configuration of the camera system is shown in the following figure.

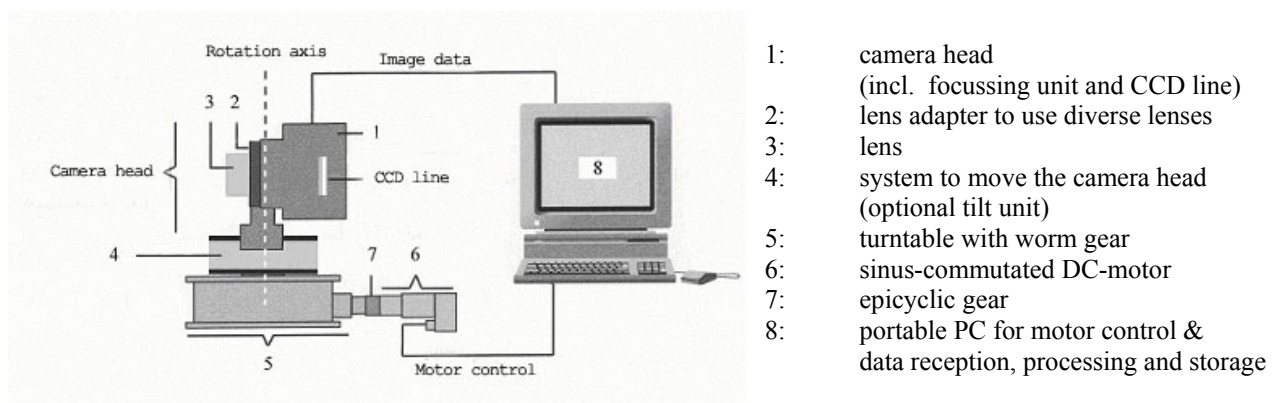


FIG. 2. Structure of the panoramic camera EYESCAN M3

2.2 Operating Mode

Camera head and turntable module constitute one unit with a plug adapter on the bottom side to mount the camera on a geodetic tripod. The camera consists of a RGB-CCD-line with about 10.200 sensor elements for each colour. The CCD line is parallel to the rotation axis and describes therefore a cylinder while the camera operates. With a focussing unit in 5 fix steps the distance between lens and sensor can be set to focus the camera.

Currently the use of 4 different high performance Rodenstock lenses is possible (focal length/opening angle: 35mm/90°, 45mm/80°, 60mm/60°, 100mm/40°). Other lenses can be used by applying special adjustment rings. A special system allows movement of the camera head with respect to the rotation axis. Thus the projection center can be positioned on the rotation axis if lenses with different focal lengths are used.

The camera works with a high precision turntable. It consists of a sinus-commutated DC-motor which is directly controlled by a PC, and a gearsystem to reduce the motor revolution speed. The camera rotational speed is calculated by the assumption that the horizontal pixel spacing is used without gaps or overlap. For this calculation the sensor integration time and the cylinder radius (determined by the focal length) are needed.

3. GEOMETRIC MODELLING

3.1 Coordinate Systems

The basis for the derivation of the model is the definition of necessary coordinate systems. This definition is similar to the coordinate systems already described in (Lisowski & Wiedemann, 1998), which were implemented to investigate a panoramic camera of Innotech GmbH. These systems are not only a Cartesian object and camera coordinate system, but also a cylindrical system adapted to describe the special camera geometry. The z-axis of the camera coordinate system is equal to the rotation axis, and the x-axis defines the direction of the first column in the image. Finally it is necessary to use an image coordinate system, consisting of columns (m) and rows (n).

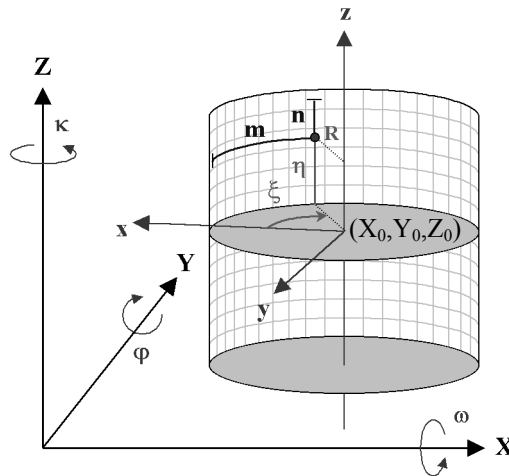


FIG. 3. Used coordinate systems

3.2 Transformation equations

Object points are mapped on a cylindrical surface through straight lines, which intersect in the projection center. In order to describe this mapping mathematically, transformation equations between the coordinate systems must be developed.

Transformation between object coordinates (X, Y, Z) and Cartesian camera coordinates (x, y, z):

$$\underline{X} = \underline{X}_0 + \underline{R} \cdot \underline{x} \quad (1)$$

Transformation between Cartesian camera coordinates (x, y, z) and cylindrical camera coordinates (r, ξ, z) :

$$x = r \cdot \cos \xi \quad y = -r \cdot \sin \xi \quad z = z \quad (2)$$

The radius r describes the distance between an object point and the rotation axis, z the height of an object point above the xy -plane. In the cylindrical coordinate system it is relatively easy to describe image points and thus to express the proper mapping of object points into the image:

$$x' = R \cdot \cos \xi \quad y' = -R \cdot \sin \xi \quad z' = \eta \quad (3)$$

The rotation angle ξ is identical for an object point and its image. The distance r is substituted by the radius of the image cylinder R , which is in the ideal case equal to the principle distance c , and z is substituted by the height η of an image point above the xy -plane using an intercept theorem.

Transformation between cylindrical camera coordinates (r, ξ, z) and pixel coordinates (m, n) :

$$m = \frac{\xi + \xi_0}{A_h} \quad n = \frac{N}{2} - \frac{\eta + \eta_0}{A_v} \quad (4)$$

- N: number of rows in the image
 η_0 : vertical component of the principal point
 ξ_0 : horizontal component of the principal point
 A_v : vertical pixel pitch
 A_h : horizontal resolution (rotation angle per column)

After some transformations of equations (1) - (4) (Schneider, 2002) we achieve the following equations, which are suitable to describe the transformation of object points onto the image:

$$m = \frac{1}{A_h} \cdot \arctan\left(\frac{-y}{x}\right) + \frac{\xi_0}{A_h} + dm \quad n = \frac{N}{2} - \frac{c \cdot z}{A_v \cdot \sqrt{x^2 + y^2}} - \frac{\eta_0}{A_v} + dn \quad (5)$$

with

$$\begin{aligned} x &= r_{11} \cdot (X - X_0) + r_{21} \cdot (Y - Y_0) + r_{31} \cdot (Z - Z_0) \\ y &= r_{12} \cdot (X - X_0) + r_{22} \cdot (Y - Y_0) + r_{32} \cdot (Z - Z_0) \\ z &= r_{13} \cdot (X - X_0) + r_{23} \cdot (Y - Y_0) + r_{33} \cdot (Z - Z_0) \end{aligned} \quad (6)$$

r_{ij} : elements of the rotation matrix \underline{R}

These equations are extended by the correction terms dm and dn , which contain additional parameters in order to compensate remaining systematics as specified later in this paper. They are comparable with the collinearity equations known from the central perspective, because they express the observations (image coordinates) as a function of the camera orientation and object point coordinates. Therefore the developed equations are the basic for diverse adjustment calculations of image data of a panoramic camera.

4. SPATIAL RESECTION

4.1 Calibration Room

At first the geometrical model was implemented in a spatial resection, which means calculation of the camera orientation and, if necessary, additional parameters from reference points and their measured images. For this purpose a calibration room was set up with more than 200 retro-reflecting targets around the camera position. The coordinates of the targets were determined by taking images with a camera Kodak DCS 660 and calculating a bundle adjustment. The precision of the control points averaged between 0.05 and 1 mm. Fig. 4 shows an image of the calibration room, captured with the panoramic camera. The targets are highlighted by a bright circle.

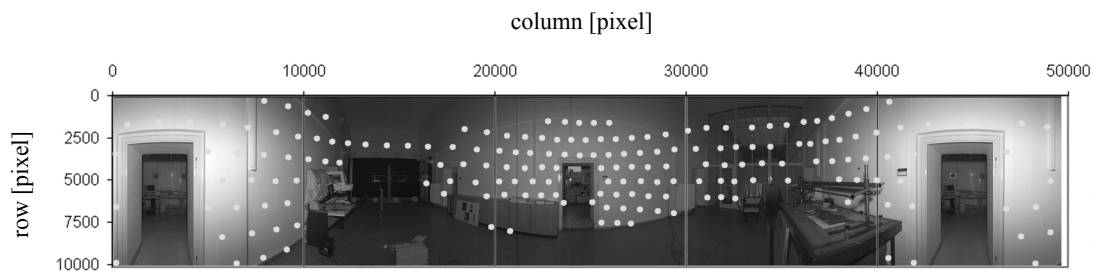


FIG. 4. Panorama image of the calibration room (ca. 395°)

To determine the orientation and additional parameters by adjustment iteratively, software for calculating the resection was developed. Statistical parameters to assess the precision and significance of the determined values were also calculated, allowing investigation of the functional model.

4.1 Additional Parameters

The geometrical model complies only approximately with the actual physical imaging process. Deviations from the model have diverse reasons, which are caused by mechanical and optical characteristics of the physical camera system. Most of these deviations can be compensated by additional parameters in the basic model (Schneider, 2002). Such deviations are:

- Non-parallelism of the CCD line w.r.t. the rotation axis (2 components)
- Eccentricity of the CCD line w.r.t. the optical axis
- Eccentricity of the projection centre w.r.t. the rotation axis (2 components)
- Radial-symmetric lens distortion
- Radial-asymmetric and tangential lens distortion
- Angular deviations of the turntable movement
- Deviations in the number of revolutions of the motor per full 360° cycle
- Gear reduction ratio errors

These parameters were added to the functional model successively, and the effect to the model was assessed by analyzing significance of the parameters and the standard deviation of the unit weight. Furthermore the residuals of the image coordinates were analyzed for remaining systematics. In this way the precision of the adjustment model could be increased step by step.

TABLE 1. Additional parameters and their effect on the functional model

	Parameter	$\hat{\sigma}_0$ [Pixel]
Exterior orientation	$X_0, Y_0, Z_0, \omega, \varphi, \kappa$	25.20
Interior orientation	c, η_0	5.88
+ Eccentricity of the projection centre (1 st component)	e	5.63
+ Non-parallelism of the CCD line (1 st component)	γ_1	1.51
+ Non-parallelism of the CCD line (2 nd component)	γ_2	1.15
+ Radial-symmetric lens distortion	A_1, A_2	0.60
+ Deviations of the turntable concentricity and eccentricity of the projection centre (2 nd component)	$S_1, (S_2), S_3$ $S_4, (S_5), S_6$	0.35
+ Horizontal resolution (angle per column)	A_h	0.31
+ Other parameters (e.g. Deviations from a planar movement)	$S_7, (S_8), S_9$ $T_1, (T_2), T_3$ B_2	0.24

By inserting additional parameters into the model, the standard deviation of unit weight obtained from the resection was improved by about one order of magnitude from more than 5 pixels to less than 0.25 pixel (cp. Table 1). Translated into the object space, this corresponds to a lateral point precision of 0.1 mm (2 m distance) to 0.5 mm (10 m distance) by using a 35 mm lens. This is shown in the following figure. The determined accuracy reaches limitations posed by the calibration field.

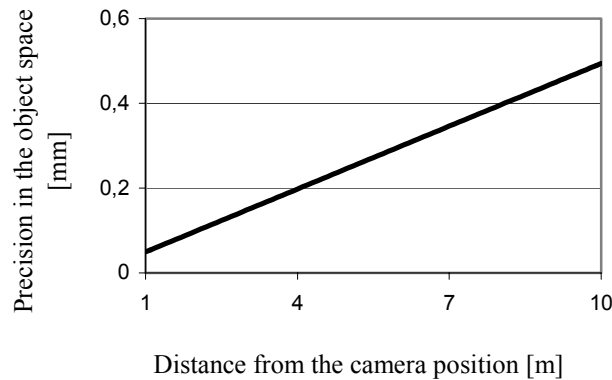


FIG. 5. Precision translated into the object space

5. SPATIAL INTERSECTION

To determine 3-D object point coordinates, a spatial intersection based on the same math model was implemented. In a next step, this sequence resection-intersection will be replaced by a bundle adjustment procedure.

The intersection was carried out using different combinations of camera positions. At first only two images with a vertical baseline (ca. 60 cm) were inserted into the calculation. This means that the rotation axis of both images were approximately the same. High precisions were achieved, as shown in table 2, but the common field of view was reduced by the limited vertical opening angle of the camera. Furthermore, two images with a horizontal baseline were taken for the calculation. It is obvious that the precision of the point coordinates depends on the angle of intersection. This angle varies for the points in the calibration room if using a horizontal baseline. If the projection

centres and the object point represent one line, the coordinates can not be determined. Therefore it is recommended to use more than two camera positions in order to avoid weak intersection geometry when using horizontal baselines. Table 2 shows the precision of the calculated object coordinates, determined by using different camera dispositions.

TABLE 2. Precision of intersected object points depending on the camera disposition

Number of Positions	Disposition	Number of calculated points	RMS _X	RMS _Y	RMS _Z
2	Vertical (2, 3)	110	2.78 mm	0.89 mm	1.01 mm
2	Horizontal (2, 7)	158	5.97 mm	1.23 mm	1.91 mm
6	Horizontal	185	1.48 mm	1.65 mm	0.54 mm
7	Horizontal + 1 Vertical	185	1.13 mm	1.35 mm	0.51 mm

Figure 6 shows the ground-plan of the calibration room, including the determined object points and their precisions in X- and Y-direction.

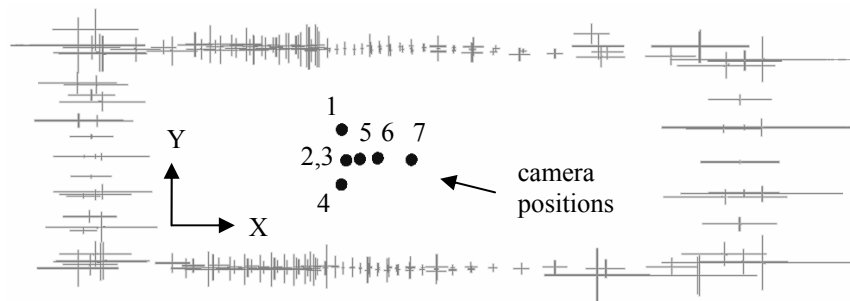


FIG. 6. Ground-plan of the calibration room incl. precision of object points

6. RESULTS AND FUTURE WORK

The spatial resection and spatial intersection were implemented and tested successfully. The accuracy potential of the panoramic camera EYESCAN M3 could not be fully exploited yet. Limitations were set by the quality of control points in the calibration room.

Future work will concentrate on the development of a self-calibrating bundle adjustment based on the introduced geometric model of panoramic images. By this means the model will be tested for accuracy again and, if necessary, the additional parameters will be amended. Further tasks are the definition of the epipolar line geometry, as this research aims to develop tools for generating precise high resolution textured 3D-models of rooms, squares or other objects from panoramic imagery.

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