DEVELOPMENT AND APPLICATION OF AN EXTENDED GEOMETRIC MODEL FOR HIGH RESOLUTION PANORAMIC CAMERAS

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ABSTRACT:

Digital panoramic photography has become a popular tool to record landscapes, city squares or indoor scenes in a single image with a full 360° view. In photogrammetric applications, a digital panoramic camera may present an interesting alternative to conventional image acquisition techniques such as large format film or plate based cameras. Advantages of such a camera are their very high resolution, which allows the recognition of fine object detail, and the possibility of recording panorama-like object geometries such as city squares or indoor scenes by taking only a few images.

This paper describes and investigates a strict mathematical model for rotating line panoramic cameras, developed at the Institute of Photogrammetry and Remote Sensing of the Dresden University of Technology. The model accuracy was improved considerably through additional parameters, which describe deviations from the basic geometric model of cylinder projection. Furthermore the mathematical model was successfully implemented in different photogrammetric data processing routines, such as a self-calibrating bundle adjustment of panoramic image data. Based on this work, the combination of rotating line panoramic cameras and the mathematical model depict a very suitable tool for precise 3D modelling of indoor scenes, city squares or long façades in combination with the analysis of very high resolution texture information.

The paper concentrates on results of a self-calibrating bundle adjustment using the developed geometric model of panoramic image data. Furthermore some examples of high resolution 3D-models generated with the panoramic camera EYESCAN M3 will be presented as well as other applications which are derived from the geometric model such as epipolar line geometry for stereo or multi-image matching.

Fig. 1: Panorama of Theaterplatz, Dresden (camera: KST EYESCAN M3, Image format: 53,800 × 10,200 Pixel; further panoramas in (Schneider, 2004))

1. INTRODUCTION

Stereoscopic image acquisition of indoor scenes or city squares with conventional cameras may be rather laborious, since many images must been captured to achieve sufficient overlap for the following analysis. Therefore rotating line cameras (digital panoramic cameras) may present an interesting alternative to conventional methods, because panorama-like object geometries can be completely captured by taking only a few images, which concurrently offer a very high resolution (Tecklenburg & Luhmann, 2003). Analogue panoramic cameras exist a fairly long time, but they were primarily used for purely photographic purposes.

Most photogrammetric imaging techniques are based on the central perspective principle. The geometry of panoramic images deviates from the central perspective, as the image data is projected onto a cylinder. To use this kind of imagery, it was necessary to establish a generic geometric model for digital panoramic cameras (Schneider & Maas, 2003a). Based on knowledge of the mechanical and optical properties of the camera, the model was successively extended by additional parameters. The mathematical model was initially implemented in a spatial resection and tested with the camera EYESCAN M3, made by KST (Kamera & System Technik, Dresden) in a joint venture with the German Aerospace Centre (DLR). Information about the EYESCAN camera can also be found in (Scheibe et al. 2001).

Based on the geometric model, a self-calibrating bundle adjustment was developed, and other photogrammetric methods were adapted to panoramic geometry. Thus a detailed and accurate 3D reconstruction of objects such as indoor scenes, city squares or long façades based on digital panoramic imagery is possible.

2. ROTATING LINE CAMERA

2.1 Principle of image acquisition

The principle of image acquisition of a digital panoramic camera is similar to the one of a flat bed scanner, where a RGB-CCD linear array sensor moves linearly over an object. In the case of a digital panoramic camera, the sensor moves around a fix rotation axis and describes a cylindrical surface. Therefore this kind of camera is also called rotating line camera.
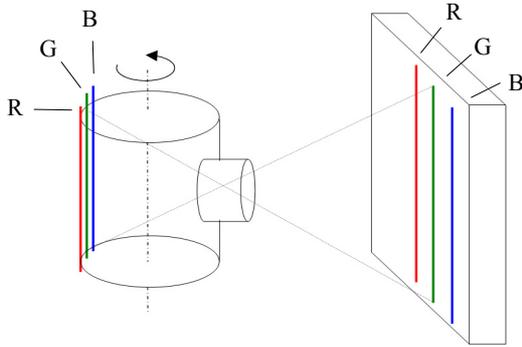

Fig. 2: Principle of digital panoramic image acquisition

Fig. 3: Digital panoramic camera EYESCAN M3

In this manner the room around the camera can be scanned with a horizontal angle up to 360°. The vertical opening angle depends on the sensor length as well as on the focal distance of the lens. As the sensor consists of one CCD line for each colour channel, true RGB information is recorded without using colour filter patterns and interpolation techniques. A disadvantage of this imaging principle is the long recording time compared to CCD arrays. Therefore moving objects are not correct represented on the image.

2.2 Panoramic line camera EYESCAN M3

The EYESCAN M3 is equipped with a CCD sensor with $3 \times 10,200$ pixel. Similar sensors are also used in cameras on airborne platforms such as the ADS40. The size of a 360° panorama image depends also on the focal length and can reach values between 300 and 900 mega pixel (uncompressed, 16 Bit per colour). Further details to the camera configuration are shown (Schneider & Maas, 2003b). Some technical data are summarised in the following table.

Lens	35 mm	45 mm	60 mm	100 mm
Sensor: Linear array RGB CCD with 10,200 pixel per colour channel, Length 72 mm, Radiometric Resolution: 16 bit per colour channel				
Number of image columns (360°)	31400	40400	53800	89700
Vertical opening angle	90°	80°	60°	40°
Data volume (360°, 48 Bit)	1.7 GB	2.3 GB	3.1 GB	5.1 GB
Recording time (360°, 8 ms per column)	3 min	4,5 min	6 min	10 min

Tab. 1: Basic parameters of EYESCAN M3

The resolution potential of the camera is illustrated by Fig. 4, where a small part of a panorama of the *Zwinger Dresden* is shown in 4 zoom steps.

Fig. 4: Resolution potential of the camera EYESCAN M3 illustrated through 4 zoom steps

Optionally it is possible to mount an illumination system on the camera head (see Fig. 5), which projects a light line onto the object. This system consists of a light source and an optical fibre cable, which transmits the light to 3 light profile adapters. This illumination system can be very useful for capturing retro-reflecting targets, e.g. for camera calibration purposes. .

Fig. 5: Camera EYESCAN M3 with glassfibre
illumination system

3. MATHEMATICAL MODEL

3.1 Basic model approach

The mapping of object points onto a cylindrical surface, described by the rotation of the linear array sensor, complies only in one image direction with the known central perspective principle. Therefore, it was necessary to develop a geometric model for the geometry of digital panoramic cameras. This model is based on transformations between four coordinate systems. As also described in (Lisowski & Wiedemann, 1998), an object coordinate system, a Cartesian and a cylindrical camera system as well as the pixel coordinate system were defined. Through the transformation between these coordinate systems we achieve the basic observation equations (equations 1 and 2) in analogy to the collinearity equations, which describe the observations (image coordinates) as a function of object coordinates, camera orientation and possibly additional parameters.
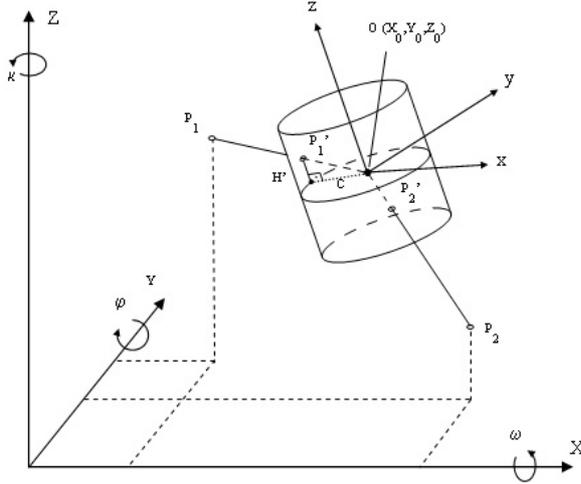

Fig. 6: Geometrical model (Definition of used variables in
Schneider & Maas 2003b)

$$m = \frac{1}{A_h} \cdot \arctan\left(\frac{-y}{x}\right) + \frac{\xi_0}{A_h} + dm$$

$$n = \frac{N}{2} - \frac{c \cdot z}{A_v \cdot \sqrt{x^2 + y^2}} + \frac{\eta_0}{A_v} + dn \tag{1}$$

where:

$$x = r_{11} \cdot (X - X_0) + r_{21} \cdot (Y - Y_0) + r_{31} \cdot (Z - Z_0)$$
$$y = r_{12} \cdot (X - X_0) + r_{22} \cdot (Y - Y_0) + r_{32} \cdot (Z - Z_0) \tag{2}$$
$$z = r_{13} \cdot (X - X_0) + r_{23} \cdot (Y - Y_0) + r_{33} \cdot (Z - Z_0)$$

3.2 Additional parameters and accuracy potential

The geometric model complies only approximately with the actual physical reality of the image forming process. Therefore the correction terms dm and dn, where additional parameters for the compensation of systematic effects are considered, are crucial for the accuracy potential of the model. These parameters are explained in more detail in Schneider & Maas (2003b). The following figures (Fig. 7 and 8) illustrate three of the additional parameters.
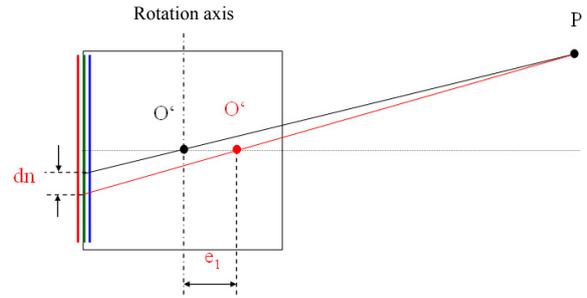

Fig. 7: Model deviations
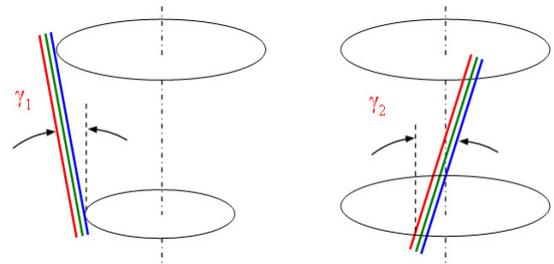(e_1: eccentricity of projection centre)

Fig. 8: Model deviations
(γ_1, γ_2: Non-parallelism of CCD line, 2 components)

As a fist step, the geometrical model was implemented in a spatial resection. The resulting standard deviation of unit weight and other output parameters of the resection were analysed to assess the effect of every additional parameter individually. The following table (Tab. 2) shows how $\hat{\sigma}_0$ changed by successively inserting additional parameters. The spatial resection is based on approx. 360 reference points around the camera position of a calibration room courtesy of AICON 3D Systems GmbH.

Parameter	$\hat{\sigma}_0$ [Pixel]
Exterior orientation	25.20
Interior orientation	5.88
Eccentricity of projection centre	5.63
Non-parallelism of CCD line (2 components)	1.15
Lens distortion	0.60
Affinity	0.45
Non-uniform rotation (periodical deviations)	0.24

Tab. 2: $\hat{\sigma}_0$ of spatial resection

Translating the resulting $\hat{\sigma}_0$ of 0.24 pixel into object space, we receive a lateral point precision between 0.1 (at 2 m distance) and 0.5 mm (at 10 m distance) when using a 35 mm lens. According to the length of the CCD line of 10,200 pixel, this value corresponds with a relative precision 1 : 42,000.

In (Amiri Parian & Grün, 2003) further parameters in addition to physically defined parameters are used for the compensation of local systematics. For this purpose the panorama is divided into pieces, in which a polynomial approach is then used for the compensation of local remaining systematics. Thus $\hat{\sigma}_0$ = 0.23 pixels was reached, which corresponds to the order of magnitude shown here.

4. IMPLEMENTATION OF THE MODEL

The mathematical model was implemented into different photogrammetric applications, with primary focus on a bundle block adjustment for panoramic images.

4.1 Panoramic bundle adjustment

Using the bundle adjustment, it is possible to determine object points, orientations and camera parameters simultaneously from two or more panoramas. An important goal during the development of the panoramic image bundle block adjustment was user friendliness, which means among other things that the computation should get along with as few as possible approximate values. The implemented solution requires only three object points to procure approximate values for the orientation of the panoramas and successively for all object points. These three object points can be realized for example by a small reference triangle placed into the object. The adjustment can be accomplished alternatively with a minimum datum solution, a certain number of control points or as free network adjustment. In Tab. 3 the results of two computations, an adjustment with minimum datum and a free network adjustment, both with 364 object points and 5 camera positions, are summarised. As expected, the standard deviations of the object coordinates are better in the free network adjustment. This effect can be explained by the datum point distribution.
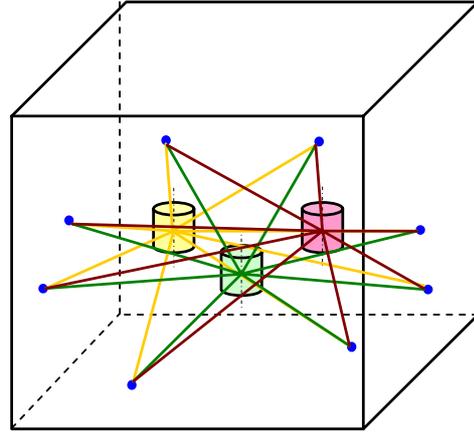

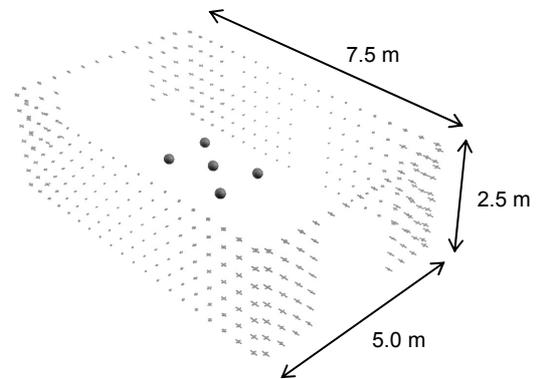Fig. 9: Principle drawing of bundle adjustment for panoramas

Fig. 10: Object points of calibration room of AICON 3D Systems GmbH incl. camera positions

	Minimum datum	Free network adjustment
$\hat{\sigma}_0$ [pixel]	0.22	
$\overline{\sigma}_X$ [mm]	0.48	0.33
$\overline{\sigma}_Y$ [mm]	0.45	0.27
$\overline{\sigma}_Z$ [mm]	1.01	0.15

Tab. 3: Results of panoramic bundle block adjustment of points in the calibration room

Remaining systematic errors of the camera might result in object point coordinate errors and not show up in the results of the bundle adjustment. Therefore the computed object coordinates were compared with the reference coordinates of the calibration room. For the stabilization of the block geometry four well-distributed control points were used. From Tab. 4 it becomes obvious that the average value of the deviations amounts to ca. 0.5 mm for all three coordinate directions. It is not sure, however, whether the small discrepancy between bundle results and checkpoint deviations can be interpreted as a limitation of the accuracy potential of the camera, or whether the deviations are caused by the limited precision of the reference coordinates.

$\overline{\Delta X}$	0.58 mm
$\overline{\Delta Y}$	0.44 mm
$\overline{\Delta Z}$	0.36 mm

Tab. 4: Average deviations between calculated object points and reference points

Further bundle adjustments were calculated using panorama imagery of an inner courtyard within the campus of the Dresden University. Fig. 11 shows one of 4 panoramas. This courtyard has a dimension of approximately 45 x 45 m in the ground view and the building height is ca. 20 m.

Fig. 11: Panorama of an inner courtyard within the campus of Dresden University

A first calculation was carried out using image coordinates of 120 signalized points, which could be measured semi-automatically with subpixel precision. The free network adjustment resulted in $\hat{\sigma}_0$ = 0.24 Pixel. The mean standard deviation of object points is summarized in the following table.

	Signalized points
$\hat{\sigma}_0$ [pixel] (120 sign. points)	0.24
$\overline{\sigma}_X$ [mm] (120 sign. points)	2.6
$\overline{\sigma}_Y$ [mm] (120 sign. points)	2.5
$\overline{\sigma}_Z$ [mm] (120 sign. points)	2.8

Tab. 5: Results of panoramic bundle block adjustment of signalized points of a real-word object

The same dataset was processed with 48 additional natural object points, which were measured manually. Table 6 shows the mean standard deviations of these natural points.

	Natural points
$\hat{\sigma}_0$ [pixel] (all 168 points)	0.41
$\overline{\sigma}_X$ [mm] (48 natural points)	4.2
$\overline{\sigma}_Y$ [mm] (48 natural points)	4.7
$\overline{\sigma}_Z$ [mm] (48 natural points)	5.3

Tab. 6: Results of panoramic bundle block adjustment of natural points of a real-word object

4.2 Object model generation

After the calculation of coordinates of points representing the object geometry such as edges or corners via bundle block adjustment or spatial intersection, it is possible to generate 3D-models of the 360°-surrounding. After creating surfaces using these discrete points, the model can be filled with high-resolution texture from the panoramic images. This texture mapping can be achieved by projecting image data of an orientated and calibrated panorama onto the object surface planes using the accurate mathematical model as described in chapter 3. Fig. 12 illustrates the principle of this projection.
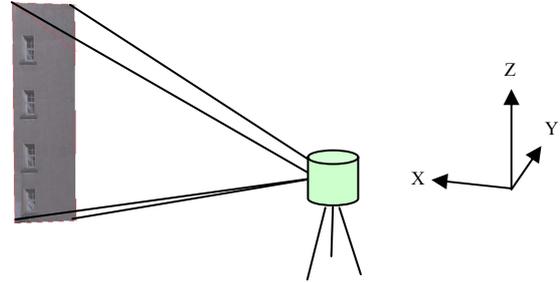

Fig. 12: Principle of the projection of panoramic texture into a 3D-Model

Using the 3D object geometry as outcome of the geometric processing of panoramic imagery it is then possible to generate precise photo-realistic 3D-models of objects such as city squares, rooms or courtyards, e.g. with CAD-software (Fig. 13). Some virtual reality models (VRML) can be found in (Schneider, 2004).
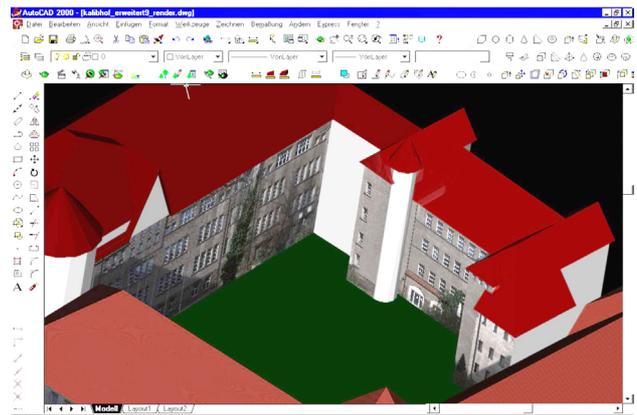

Fig. 13: 3D-modelling with AutoCAD using object geometry and texture from panoramic imagery

4.3 Epipolar line geometry

The developed mathematical model was further used to describe the epipolar line geometry for panoramic images. As evident from Fig. 14, in most cases the epipolar lines are actually no straight lines but rather epipolar curves in the image.
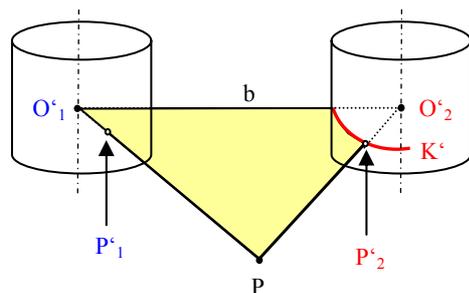

Fig. 14: Epipolar line geometry of panoramas

The epipolar line geometry can be computed from the orientation parameters of a set of panoramic images, taking into consideration the additional parameters. It may be used to support the search of corresponding points during interactive stereo mapping, and is indispensable for semi or fully automatic processing of panoramic image data. Proceeding from a point in one panorama, the homologous point a second panorama can be searched for along the epipolar curve. The same point a third panorama can be found at the intersection point of two epipolar curves.

4.4 Tangential projection

The RGB information of the panoramic cylindrical surface of a panoramic image can be projected onto a tangential plane by a tangential projection. In this process, the panoramic image is converted into a central perspective view using the developed geometrical model, allowing to use it in conventional photogrammetric software tools. With this method only panorama sectors can be converted, whose panoramic angle is significantly smaller than 180°. The procedure can for example be used in architectural applications such as capturing façades (Fig. 15).

Fig. 15: Panorama sector of a façade and tangential projection

Fig. 16: Rectified image

The panoramic image projected on the tangential plane was rectified by means of a projective transformation (Fig. 16). The advantage of this procedure over the use of area sensor cameras is a very high resolution of rotating line panoramic cameras, which allows for the recognition and mapping of very fine object detail in the image. The original image of the panoramic sector shown in Fig. 15 has ca. 64 million pixel.

5. FUTURE PROSPECTS

The presented algorithms for the photogrammetric processing of panorama pictures were programmed in the form of functions and already partly integrated in a user software package of the company fokus GmbH Leipzig. This integration will be completed in the next months, so that comprehensive software will finally be available for highly exact three-dimensional processing of panoramic images.

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