APPLICATION AND ACCURACY POTENTIAL OF A STRICT GEOMETRIC MODEL FOR ROTATING LINE CAMERAS

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ABSTRACT:

This paper describes and investigates a strict mathematical model for rotating line cameras, developed at the Institute of Photogrammetry and Remote Sensing of the Dresden University of Technology. The model accuracy was improved through considering additional parameters, which describe deviations from the basic model approach. Furthermore the mathematical model was successful implemented in different photogrammetric analysis methods, such as a self-calibrating bundle adjustment of panoramic image data. Therefore rotating line cameras and the mathematical model are particularly suitable for precise 3D modelling of indoor scenes, city squares or long façades in combination with the analysis of very high resolution texture information.

Fig. 1: Panorama of Theaterplatz, Dresden (camera: EYESCAN MM1)

1. INTRODUCTION

Stereoscopic image acquisition of rooms or city squares with conventional cameras makes often difficulties, since many images must been captured to achieve enough 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 together with a very high resolution (Tecklenburg & Luhmann, 2003). Analogue panoramic cameras exist a fairly long time, but they were primarily only used for photographic purposes.

Fig. 2: Panorama of the ruin of Trinitatis church, Dresden
(camera: EYESCAN M3)

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 knwoldege 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 analysed 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 and applications can also be found in Scheibe et al. 2001.

Based on the geometric model a self-calibrating bundle adjustment was developed as well as other photogrammetric methods were adapted to the special panoramic geometry. Thus a precise 3-D reconstruction of objects such as indoor scenes, city squares or long façades is possible by the use of high resolution RGB information.

2. ROTATING LINE CAMERA

2.1 Principle of image acquisition

The principle of image acquisition of a digital panoramic camera is similar to those of a flat bed scanner, where a RGB-CCD line sensor moves linear 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.
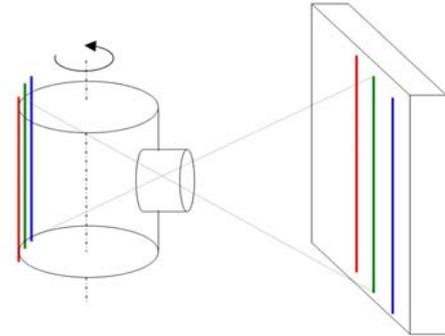

Fig. 3: Principle of digital panoramic image aqcuisition

Fig. 4: 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 aperture angle depends on the sensor length as well as on the focal distance of the used lens. As the sensor consists of a CCD line for each colour channel, the true RGB information is recorded without using any colour filter or digital interpolation. Disadvantageous 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 used rotating line camera "EYESCAN M3" is produced by KST (Kamera & System Technik, Dresden) in a joint venture with the German Aerospace Centre (DLR). The camera contains a CCD sensor with $3 \times 10,200$ pixel. Similar sensors are also used in cameras on airborne platforms such as the ADS40 (Airborne Digital Sensor). The image size of a 360° panorama depends on the used lens and can reach values between 300 and 900 mega pixel (uncompressed, 16 Bit per colour). Further details to the general camera configuration are already published (Schneider & Maas, 2003b). Some technical data are summarised in the following table (Tab. 1).

Lens	35 mm	45 mm	60 mm	100 mm
Sensor: linear RGB CCD with 10,200 pixel per colour channel, Length 72 mm, Radiometric Resolution: 16 per colour channel				
Number of image columns (360°)	31400	40400	53800	89700
Vertical aperture 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

Optional it is possible to mount an illumination system on the camera head, 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. For capturing retro-reflecting targets, as applied e.g. for calibration purposes, such an illumination system is necessary.

3. MATHEMATICAL MODEL

3.1 Basic model approach

The mapping of object points onto the 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 special cylindrical geometry of digital panoramic cameras. For this modelling different coordinate systems were used. 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 model in terms of 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 if necessary additional parameters.
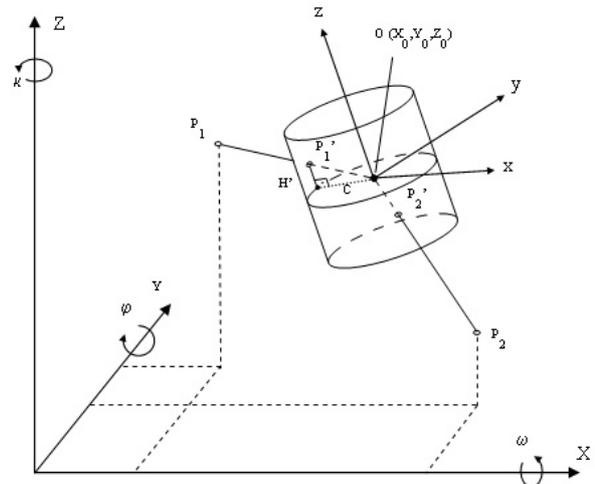

Fig. 5: Geometrical model (Definition of used variables in Schneider & Maas 2003b)

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

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

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 geometrical model complies only approximately with the actual physical imaging process. Most important for the accuracy of the model are therefore the correction terms dm and dn, where additional parameters for the compensation of systematic effects are considered. These parameters are already explained in Schneider & Maas (2003b). The following figures (Fig. 6 and 7) demonstrate three additional parameters.
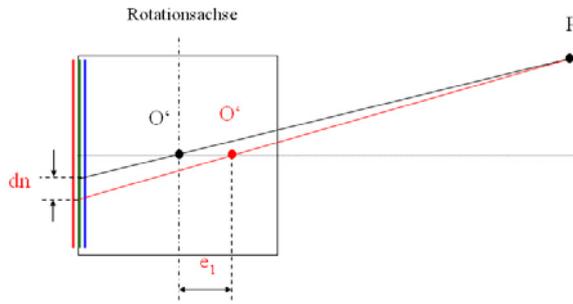

Fig. 6: Model deviations
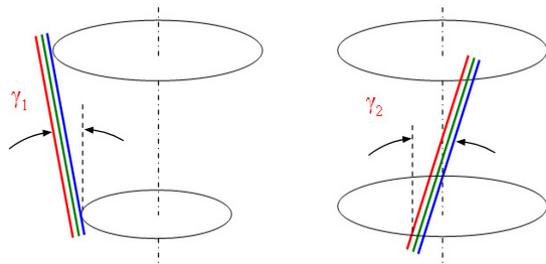(e_1: eccentricity of projection centre)

Fig. 7: 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. Among other things the resulting standard deviation of unit weight was analysed to assess the effect of every additional parameter to the model. The following table (Tab. 2) shows how $\hat{\sigma}_0$ changed by inserting additional parameters successively. 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

Through translating the resulting $\hat{\sigma}_0$ of 0.24 pixel of the spatial resection after considering all additional parameters into the object space, the outcome is a lateral point precision between 0.1 (at 2 m distance) and 0.5 mm (at 10 m distance) by 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) apart from physically defined parameters, further parameters are used for the compensation of local systematics. For this purpose the panorama is divided by means of a Wavelet analysis into partial 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, what corresponds to the order of magnitude shown here.

4. IMPLEMENTATION OF THE MODEL

4.1 Panoramic bundle adjustment

After the developed mathematical model could successfully be tested, it was implemented into different photogrammetric applications. This is above all the bundle block adjustment for panorama pictures. It is possible to determine from two or more panoramas object points, orientations and camera parameters simultaneously in one computation. In comparison to the bundle block adjustment of central perspective images it offers the advantage that interior-similar object geometries can be captured with very few pictures and a high resolution.
With the development of the bundle block adjustment above all importance was attached on user comfort, i.e. the computation should get along with as few of approximate values as possible. With only 3 object points it is therefore possible to procure approximate values for the orientation of the panoramas and from this following for all points of object. These 3 object points can be realized for example by a reference triangle placed into the object. The adjustment can be accomplished alternatively with minimum datum, a certain number of control points or as free adjustment. In Tab. 3 the results of two computations, an adjustment with minimum datum and a free adjustment are summarised. Thereby altogether 364 object points and 5 camera positions were used. Dependent on the distribution of the points used for the datum definition the RMS values of the object coordinates are crucially improved by the free adjustment and amounted to approx. 0.1 to 0.4 mm.
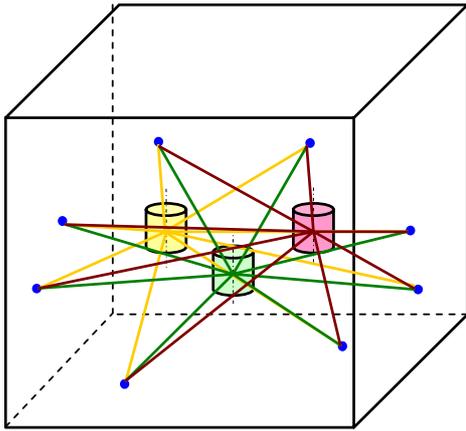
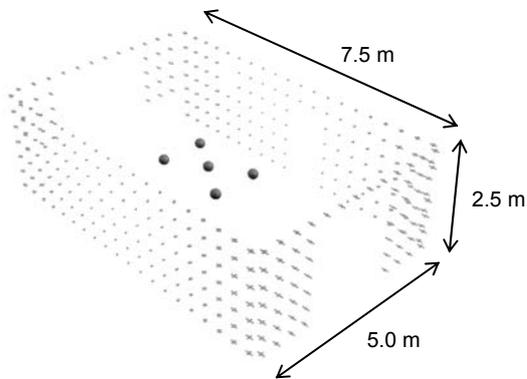Fig. 8: Principle drawing of bundle adjustment for panoramas

Fig. 9: Object points of calibration room of AICON 3D Systems GmbH incl. camera positions

	Minimum datum	Free bundle adjustment
$\hat{\sigma}_0$ [pixel]	0.22	
RMS$_X$ [mm]	0.97	0.39
RMS$_Y$ [mm]	0.85	0.28
RMS$_Z$ [mm]	2.28	0.16

Tab. 3: Results of panoramic bundle block adjustment

If remaining systematics of the camera should be still present, these would possibly result in "wrong" object point coordinates and could not be uncovered alone by the analysis of the standard deviations. Therefore the computed object coordinates were compared with the reference coordinates of the calibration room. For the stabilization of geometry for the computation 4 well-distributed control points were considered. From Tab. 4 it becomes clear that the medial value of all deviations for each coordinate direction amounts to approx. 0.5 mm. It is not sure however whether the remaining deviations can be interpreted as possible accuracy potential of the rotating line camera or whether the deviations are caused by uncertainties of the reference coordinates. This must be examined by further test measurements, whereby it will be difficult in principle to make sufficiently exact reference coordinates available.

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

Tab. 4: Medial values of deviations between calculated object points and reference points

4.2 Epipolar line geometry

The developed mathematical model was further used to describe the epipolar line geometry for panorama pictures. As from Fig. 10 evident, in most cases there are actually no lines but rather epipolar curves in the image.
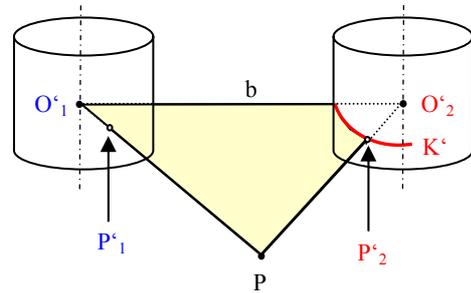

Fig. 10: Epipolar line geometry of panoramas

The epipolar line geometry supports the search of corresponding points and is indispensable for semi and/or fully automatic processing of panoramas. If to a point found in the first panorama the appropriate homologous point in the second panorama is looked for, the epipolar curve can be computed and the point finding algorithm can search along these. The same point in the third panorama can be found in the intersection range of two epipolar curves.

4.3 Tangential projection

With a tangential projection the RGB information is projected from the panoramic cylindrical surface onto a tangential plane. The panorama is thereby converted under use of the developed geometrical model into a central perspective view and can be finally used in conventional photogrammetric processing programs. With this method only panorama sectors can be converted, whose panoramic angle is clearly smaller than 180°. This procedure can be used for example in architecture for capturing façades, which is demonstrated by Fig. 11 and 12.

Fig. 11: Panorama sector of a Façade

Fig. 12: Tangential projection

Fig. 13: Rectified image

The panorama projected on the tangential plain was rectified additionally by means of a projective transformation. The advantage over the use of area array sensors is a very high resolution which allows recognition of very fine object detail in the image. The original of the panorama sector represented in Fig. 11 consists of approx. 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 user software of the company focus GmbH Leipzig. This integration will be completed in the next months further, so that comprehensive software will finally be available for highly exact three-dimensional processing of panoramic images.

ACKNOLEDGEMENT

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