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# A GEOMETRIC MODEL FOR LINEAR-ARRAY-BASED TERRESTRIAL PANORAMIC CAMERAS

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## *Abstract*

*Digital panoramic cameras represent a powerful tool for generating high resolution images of scenes. They generate images of up to 100 000 × 10 000 pixels and are especially suited for 360° recording of objects such as indoor scenes or city squares. The paper describes the development of a strict geometric model for rotating linear array panoramic cameras and the extension of the model by additional parameters adapting the camera model to the physical reality. The camera model has been implemented in a spatial resection and a bundle solution. The bundle solution also allows for the combined handling of panoramic and central perspective images. In several practical tests a potential accuracy of around ¼ pixel was demonstrated.*

Keywords: bundle block adjustment, calibration, high-accuracy geometric model, panorama, rotating line camera, 3D modelling

## INTRODUCTION

Digital terrestrial panoramic cameras extend the field of view of photogrammetric object recording and may provide an interesting tool for a number of photogrammetric applications. They allow the capture of a 360° horizontal field of view in a single image at a very high spatial resolution. This can be very useful in recording landscapes, indoor scenes or city squares for architectural or industrial tasks such as cultural heritage documentation (Fig. 1), as-built documentation or data capture for virtual reality applications (Luhmann, 2004). Panoramic images can in principle be obtained from any amateur digital camera by applying shareware image stitching tools. Beyond this, high resolution digital terrestrial panoramic cameras are offered by several manufacturers. These cameras are based on a rotating linear array sensor recording an image with cylindrical geometry. The vertical resolution of the cameras is given by the number of pixels of the sensor, which may exceed 10 000. The horizontal resolution is determined by the focal length of the lens and may reach up to 100 000 pixels.

Panoramic cameras have been used for visualisation purposes for a long time. However, photogrammetric data processing requires a geometric model of the camera. In the case of rotating linear array panoramic cameras, this model does not conform to conventional central perspective geometry. Geometric models for the use of digital terrestrial panoramic cameras in photogrammetric measurement tasks have been presented by Lisowski and Wiedemann (1998), Amiri Parian and Gruen (2003), and Schneider and Maas (2003). These models include additional parameters for a geometric calibration of panoramic cameras.

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FIG. 1. Panoramic camera image of the Dresden Zwinger.

The geometric panoramic camera model described in the following was first published as a resection–intersection tool in Schneider and Maas (2003). An extension towards handling the panoramic camera model in a multi-image bundle adjustment was shown in Luhmann and Tecklenburg (2004) and in Schneider and Maas (2004). The additional integration of central perspective images in a combined bundle adjustment package was shown in Schneider and Maas (2005). The present paper combines these developments and shows results from several tests and practical applications. The next section introduces the EYESCAN M3 digital panoramic camera, which was used for practical testing of the model. The basic geometric model describing the image formation of rotating linear array sensor panoramic cameras is then presented, followed by the introduction of additional parameters for modelling systematic deviations from the ideal model. Results obtained from a testfield calibration applying the extended model in a spatial resection are then shown. The basic geometric model is integrated into a self-calibration bundle adjustment. Results from test measurements and practical applications follow. The use of the models and techniques in practical applications is then described. The final section shows the extension to a combined bundle adjustment package handling both panoramic and central perspective images, both with their sets of additional parameters modelling the physical reality of the cameras. This integration of multiple image geometries may significantly enhance the flexibility of photogrammetric data capture in complex scenes.

## EYESCAN M3 ROTATING LINEAR ARRAY CAMERA

The mathematical model described in the paper was extensively tested with data from the EYESCAN M3 camera made by KST (Kamera & System Technik, Dresden) in a joint venture with the German Aerospace Center (DLR, Berlin). Detailed technical information about the EYESCAN camera can be found in Scheibe et al. (2001). Like four or five other terrestrial digital panoramic cameras, the EYESCAN is based on a rotating linear array three-line RGB sensor. The image acquisition mode of the camera is shown in Fig. 2 (left): a tri-linear charge-coupled device (CCD) sensor rotates about a vertical axis and records an image onto a virtual cylinder. The camera is constructed with the projection centre of the lens lying on the axis of the cylinder.

The EYESCAN M3 (Fig. 2, right) has a $3 \times 10\,200$ pixel CCD sensor. A similar type of sensor is also used in the Leica ADS40 airborne linear array digital camera. Some technical data are summarised in Table I. The horizontal field of view of the camera is 360°. The vertical field of view is determined by the focal length of the camera lens and the length of the linear array sensor. It will usually be 40° to 90°, but may also reach 180° when using a fisheye lens on a panoramic camera (Bonnet, 2004). Thanks to the three-line sensor, true RGB information is recorded. Depending on exposure time and resolution settings, recording of a scene may take from about a minute to half an hour. Obviously, the camera principle is only suited for recording static objects.

The size of a 360° panorama image depends linearly on the focal length. The image column acquisition timing is usually programmed in such a way that the cylindrical image will have square pixels. With these settings, the size of one panoramic image will be between 300

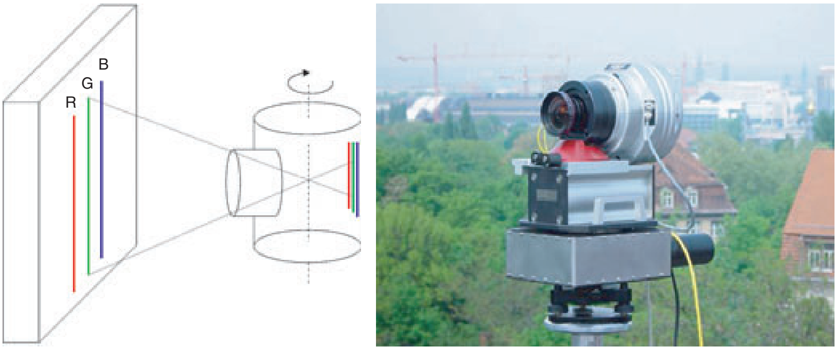


FIG. 2. RGB array sensor panoramic acquisition principle (left).
EYESCAN M3 terrestrial digital panoramic camera (right).

TABLE I. Basic parameters of EYESCAN M3.

| *Lens (focal length)* | *35 mm* | *45 mm* | *60 mm* | *100 mm* |
|---|---|---|---|---|
| Sensor | Linear array RGB CCD with 10 200 pixels per colour channel, length 72 mm, radiometric resolution 16 bit per colour channel | | | |
| Number of image columns (360° image) | 31 400 | 40 400 | 53 800 | 89 700 |
| Vertical opening angle (field of view) | 90° | 80° | 60° | 40° |
| Data volume (360°, 3 × 16 bit) | 1·7 GB | 2·3 GB | 3·1 GB | 5·1 GB |
| Recording time (360°, 8 ms per column exposure) | 3 min | 4·5 min | 6 min | 9 min |

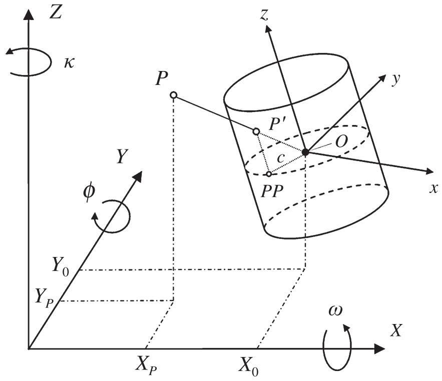
and 900 megapixels, depending on the focal length. With 16-bit RGB image information, the uncompressed data volume of one 89 700 × 10 200 pixel image recorded with a 100 mm lens will be 5·1 GB. The camera is also referred to as a "gigapixel camera" (Maas and Schneider, 2004). Further details of the camera configuration are shown in Schneider and Maas (2003).

## BASIC PANORAMIC CAMERA MODEL

The imaging process of the rotating linear array camera can be described by a projection onto a cylinder (Fig. 3). The image geometry complies with the known central perspective principle only in the vertical image coordinates. This camera model is based on transformations between four coordinate systems. As also described in Lisowski and Wiedemann (1998), an object coordinate system, a Cartesian and a cylindrical camera system and a 2D pixel coordinate system can be defined. The basic observation equations (equations (1)) express the image coordinates as a function of object coordinates and camera parameters and are obtained from transformations between these coordinate systems as described in Schneider and Maas (2003) in more detail:

$$\begin{aligned} x'_{pano} &= x'_0 - c\arctan\left(\frac{-y}{x}\right) \\ y'_{pano} &= y'_0 - \frac{cz}{\sqrt{x^2+y^2}}. \end{aligned} \tag{1}$$

As the $x, y$ and $z$ coordinates refer to each individual coordinate system of a camera position, the values have to be transformed into a global system using the following equations:



| | |
|---|---|
| $O\,(X_0,Y_0,Z_0)$ .. | Projection centre |
| $\omega,\phi,\kappa$ .. | Camera orientation in rotation matrix $\mathbf{R}(r_{ij})$ |
| $P\,(X, Y, Z)$ .. | Object point |
| $P'(x', y')$ .. | Image point |
| $x,y,z$ .. | Coordinates in camera-bound 3D coordinate system |
| $PP\,(x_0', y_0')$ .. | Principal point |
| $c$ .. | Principal distance |

FIG. 3. Basic cylindrical camera model.

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

## PANORAMIC CAMERA MODEL WITH ADDITIONAL PARAMETERS

The camera model as outlined in the previous section can be considered an ideal model, which does not pay attention to the physical reality of the camera. In the same way as for central perspective cameras, the panoramic camera model has to be extended by additional parameters, which should be determined in a calibration process. The additional parameters are contained in correction terms $\Delta x'$ and $\Delta y'$, which are added to the observation equations (1):

$$\begin{aligned} x'_{pano} &= x'_0 - c\arctan\left(\frac{-y}{x}\right) + \Delta x'_{pano} \\ y'_{pano} &= y'_0 - \frac{cz}{\sqrt{x^2 + y^2}} + \Delta y'_{pano}. \end{aligned} \tag{3}$$

*Interior orientation.* The interior orientation is given by the principal distance $c$ and the vertical component of the principal point ($y'_0$). Because of the linear array principle the horizontal component of the principal point ($x'_0$) is not relevant.

*Eccentricity.* The eccentricity of the projection centre with respect to the rotation axis is illustrated in Fig. 4. The following equation can be derived from Fig. 4 through the intercept theorem:

$$\frac{y'}{z} = \frac{c}{\sqrt{x^2 + y^2} - e}. \tag{4}$$

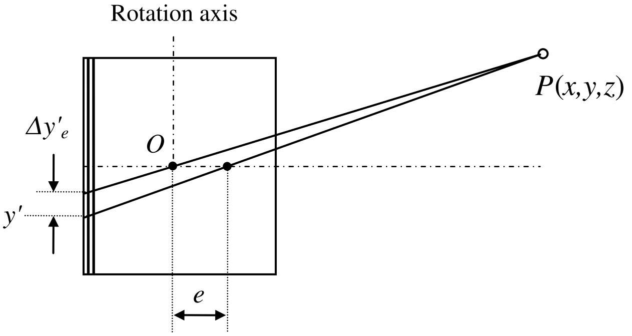


FIG. 4. Model deviations: eccentricity of projection centre ($e$).

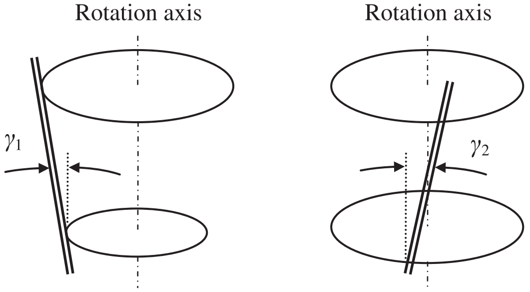


FIG. 5. Model deviations: non-parallelism of CCD line, components ($\gamma_1$, $\gamma_2$).

The impact on image coordinates caused by the eccentricity is described by the following equations which can be added as correction terms to the basic observation equations (1) directly:

$$\Delta x'_e = 0 \quad \Delta y'_e = e\frac{z + y'}{\sqrt{x^2 + y^2}}. \tag{5}$$

*Non-parallelism.* Two small angles ($\gamma_1$, $\gamma_2$) describe the non-parallelism of the linear sensor with respect to the rotation axis, with the orientation of $\gamma_1$ perpendicular to $\gamma_2$. Fig. 5 illustrates these parameters, and the following equations define the deviations of image coordinates in case of non-parallelism between sensor line and rotation axis:

$$\Delta x'_{\gamma_1} = 0, \qquad \Delta y'_{\gamma_1} = \frac{y' \cos\left(\arctan\frac{y'}{c}\right)}{\cos\left(\arctan\frac{y'}{c} + \gamma_1\right)} - y' \tag{6}$$

$$\Delta x'_{\gamma_2} = y' \tan\gamma_2, \qquad \Delta y'_{\gamma_2} = y'\left(\frac{1}{\cos\gamma_2} - 1\right). \tag{7}$$

*Radial symmetric lens distortion.* Lens distortion is described by a polynomial approach which is well known for conventional cameras. In a panoramic image it affects the image coordinates only in the vertical coordinate direction (equation (8)). The parameter $r_0$, the second zero-crossing of the distortion curve, is introduced to avoid numerical correlations between distortion parameters and the principal distance:

$$\Delta x'_{distortion} = 0, \qquad \Delta y'_{distortion} = A_1 y'(y'^2 - r_0^2) + A_2 y'(y'^4 - r_0^4). \tag{8}$$

*Affinity.* The consideration of an affinity parameter (unequal scale between horizontal and vertical image directions) is of fundamental importance in a panoramic camera model since exact synchronisation of the rotation speed with the integration frequency of the sensor is difficult or impossible. The affinity parameter $C_1$ (equation (9)) can simply be transformed into the horizontal resolution (angle per column):

$$\Delta x'_{affinity} = C_1 x', \qquad \Delta y'_{affinity} = 0. \tag{9}$$

*Rotation non-uniformities.* Non-uniform rotation of the camera head caused by the camera gear has been modelled by parameters of a Fourier transformation:

$$\Delta x'_{rotation} = S_1 \sin(2\xi + S_2) + S_3 \sin(4\xi + S_4) \tag{10}$$

where

$$\xi = \arctan\frac{-y}{x}.$$

## RESULTS OF CAMERA CALIBRATION AND ACCURACY TESTS

The model as outlined here has first been implemented in a spatial resection in order to verify the model and to test the accuracy potential of the camera by processing panoramic images recorded in 3D calibration fields at Dresden University of Technology and at Aicon 3D Systems. Both calibration rooms are equipped with a large number of signalised points. The 3D coordinates of the points are known from reference measurements; the 2D image coordinates were measured by applying sub-pixel accuracy image measurement techniques.

Table II shows the standard deviation of unit weight from a spatial resection without additional parameters (25·20 pixels) and the improvement obtained by successively introducing additional parameters into the geometric model. The results refer to a 35 mm focal length lens. The strong influence of the interior orientation and the sensor non-parallelism is obvious from the table. A total improvement of the camera precision potential of two orders of magnitude could be achieved.

Translating the resulting standard deviation of unit weight of 0·24 pixel into object space, a lateral point precision of 0·5 mm can be achieved at 10 m distance when using a 35 mm lens. Related to the length of the CCD line, this value corresponds to a relative precision of 1:42 000.

The precision potential achieved in these tests compares well to the results obtained by Amiri Parian and Gruen (2003). The latter used an approach based on dividing the panoramic image into sections and defining polynomials for each image section in order to

TABLE II. Standard deviation of unit weight obtained from a spatial resection in a calibration field.

| *Parameter* | $\hat{\sigma}_0$ *(pixels)* |
|---|---|
| Exterior orientation | 25·20 |
| Interior orientation | 5·88 |
| Eccentricity of projection centre | 5·63 |
| Non-parallelism of CCD line (two components) | 1·15 |
| Lens distortion | 0·60 |
| Affinity | 0·45 |
| Non-uniform rotation (periodic deviations) | 0·24 |

compensate for local systematic effects. Furthermore, in Amiri Parian and Gruen (2004) two panoramic cameras were tested for tumbling errors of the rotation axis and subsequently a method for the mathematical modelling of the tumbling error of panoramic cameras has been introduced.

## BUNDLE ADJUSTMENT WITH PANORAMIC CAMERA IMAGES

In a next step, the panoramic camera model was implemented as a photogrammetric bundle solution, allowing for simultaneous orientation of an arbitrary number of panoramic images and 3D object point determination. The bundle facilitates self-calibration and can be parameterised to handle multiple images with different parameter values. Approximate camera station values can be derived in a user-friendly manner from a small reference triangle placed into the object (Schneider and Maas, 2004).

As can be seen in Fig. 6, a minimum of three panoramic images will usually be recorded to avoid singularities at points in extension of the baseline. An alternative to this may be given by a vertical baseline. However, a vertical baseline will often not provide satisfactory intersection geometry for practical reasons when a panoramic camera is placed on a tripod.

## PRACTICAL RESULTS

Fig. 7 shows the network configuration of a test measurement with five panoramic camera stations imaging 364 signalised object points in a camera calibration room at Aicon 3D

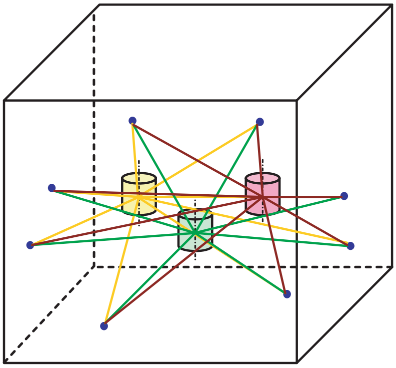


FIG. 6. Principle of panoramic image bundle adjustment.

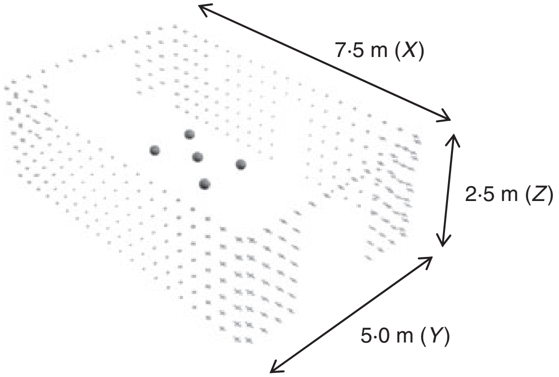


FIG. 7. Object points and panoramic camera stations in Aicon 3D Systems' calibration room.

Systems. The image coordinates of the targets were measured with sub-pixel accuracy using an industrial photogrammetry software package. All object points were treated as unknowns, with the datum either defined as a minimum datum or a free network solution. Table III shows the image space and object space precision values obtained from the bundle adjustment for the two datum definitions. As the values for the minimum datum solution are affected by an unfavourable datum point distribution, the results from the free network solution can be considered a more realistic figure for the internal geometric precision potential achieved in the test.

As these internal precision figures obtained from the bundle solution might be affected by remaining systematic effects not covered by the geometric camera model, the object point coordinates obtained from the bundle solution were compared to reference coordinates.

Table IV shows the external precision figures obtained from the comparison. It is not clear, however, whether the small discrepancy between the interior precision figures obtained from the bundle adjustment and the exterior check point deviations can be interpreted as a limitation of the accuracy potential of the camera model, or whether the deviations are caused by the limited precision of the reference coordinates themselves.

Another practical test was performed with four panoramic images taken in a larger calibration field with 120 signalised targets, in a courtyard measuring 45 m × 45 m × 20 m within the campus of Dresden University (Fig. 8).

Table V summarises the precision figures obtained from a free network bundle solution.

The results achieved in these two projects confirm the precision potential of the camera as obtained from a spatial resection (Table II in this paper) as well as results published in the literature (Amiri Parian and Gruen, 2004). Image space precision is consistently in the range

TABLE III. Results of panoramic bundle block adjustment of points in the calibration room.

| | *Minimum datum* | *Free network adjustment* |
|---|---|---|
| $\hat{\sigma}_0$ (pixels) | 0·22 | |
| $\text{Rms}_x$ (mm) | 0·97 | 0·39 |
| $\text{Rms}_y$ (mm) | 0·85 | 0·28 |
| $\text{Rms}_z$ (mm) | 2·28 | 0·16 |

TABLE IV. Deviations (rms) between calculated object points and reference points.

| | |
|---|---|
| $\overline{\Delta X}$ | 0·77 mm |
| $\overline{\Delta Y}$ | 0·52 mm |
| $\overline{\Delta Z}$ | 0·43 mm |

FIG. 8. Panorama of a courtyard on the campus of Dresden University.

TABLE V. Results of panoramic bundle block adjustment for Dresden University campus courtyard.

| | *Free network bundle adjustment* |
|---|---|
| $\hat{\sigma}_0$ (pixels) | 0·24 |
| $\text{Rms}_X$ (mm) | 2·9 |
| $\text{Rms}_Y$ (mm) | 2·4 |
| $\text{Rms}_Z$ (mm) | 3·1 |

⅕ to ¼ pixel. It has to be noted that this value is significantly worse than the precision figures which are usually obtained from central perspective digital cameras, where an image space precision of much better than 0·05 pixel can be achieved by self-calibrating bundle adjustment based on sub-pixel accuracy image coordinate measurements. This difference is attributed to the moving parts in the image acquisition process of panoramic cameras. Similar precision figures of approximately 0·15 pixel were also obtained in a recent test of a 94 megapixel scanner camera based on a linearly moving 8000 pixel RGB CCD sensor (Schneider et al., 2005).

## INTERACTIVE MAPPING AND RECTIFICATION BASED ON PANORAMIC IMAGES

The geometric camera model as developed and tested in earlier sections allows for the use of high resolution panoramic cameras in photogrammetric applications such as stereoscopic mapping in architectural photogrammetry. In these applications, camera calibration and multiple image orientation can be performed by the bundle adjustment tool. The 3D object coordinates can be determined by a spatial intersection based on the camera model. The use of epipolar geometry in panoramic images as a support to finding homologous points in interactive or automatic stereo measurement tools is shown in Luhmann and Tecklenburg (2004) and Schneider and Maas (2004). Epipolar lines, which can be computed from the panoramic camera model and orientation parameters, are in general not straight lines in panoramic image pairs with a horizontal baseline (Fig. 9).

Many applications in the field of architectural photogrammetry require texture mapping onto surfaces. Applying the geometric model, texture from high resolution panoramic cameras

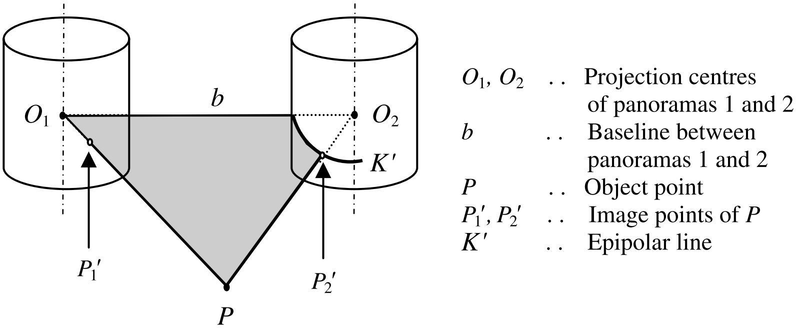


FIG. 9. Epipolar line geometry in panoramic images.

can be projected onto 3D object models obtained from stereoscopic panoramic image processing or from laser scanning. Schneider and Maas (2004) also show the generation of geometrically corrected tangential images as a basis for single panoramic image rectification. Tangential images show a good approximation to central perspective geometry (only strict if eccentricity of projection centre *e* is zero) and can be handled in standard photogrammetric software packages for applications such as interactive mapping.

## COMBINED PANORAMIC AND CENTRAL PERSPECTIVE IMAGE BUNDLE BLOCK ADJUSTMENT

Beyond the necessity of recording at least three panoramic images, hidden areas in complex scenes may necessitate the recording of many more images. This may be impractical due to the long recording times of panoramic cameras. In these cases it may be desirable to cover large parts of the scene by a limited number of high resolution panoramic images and to fill in hidden object regions by snapshots taken with a conventional medium resolution digital camera.

In order to handle panoramic and central perspective image data simultaneously, a combined bundle adjustment procedure was developed (Schneider and Maas, 2005). The combined adjustment procedure integrates observation equations for panoramic images and for central perspective images, both extended by additional parameters, into one coefficient matrix. Fig. 10 shows the structure of a coefficient matrix of a synthetic project, treating nine object points measured in three panoramic and two central perspective images. The unknown parameters are the coordinates of the object points, the exterior orientation of every image and the interior orientation and additional parameters for both cameras. Optionally the individual observations can be weighted according to their estimated precision.

In the practical handling of the bundle adjustment tool, the user has the possibility of associating each image with a camera type and a camera number. Multiple images may or may not share one set of additional parameters. Each camera parameter as well as each object point coordinate can be set as fixed or to be calculated. Object distances can also be added as observations in the calculation. The user can choose between an adjustment with a minimum datum and a free adjustment.

A practical example of integrating one single central perspective camera snapshot into a combined bundle adjustment tool is shown in Table VI. The left-hand column shows results obtained from processing four panoramic images of an EYESCAN M3 camera in the courtyard shown in Fig. 8, which contains both signalised and natural points. The right-hand column

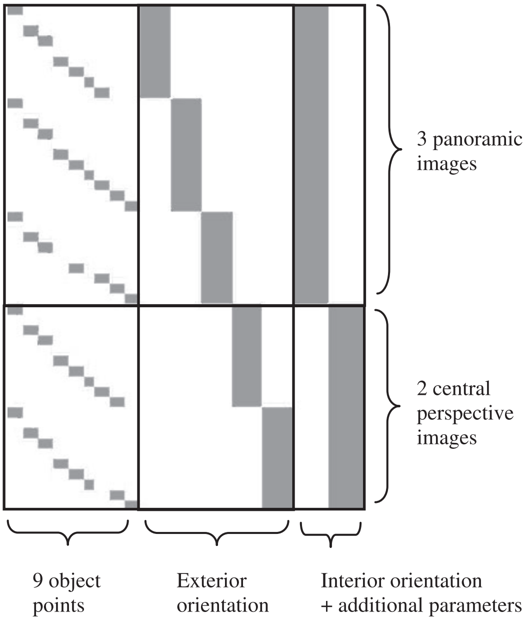


FIG. 10. Example of design matrix for combined bundle adjustment.

TABLE VI. Results of the integration of a central perspective snapshot into the bundle adjustment.

| | *Four panoramic images* | *Four panoramic images plus one snapshot* |
|---|---|---|
| $\hat{\sigma}_0$ (pixels) | 0·28 | 0·27 |
| $\mathrm{Rms}_X$ (mm) | 3·4 | 3·3 |
| $\mathrm{Rms}_Y$ (mm) | 2·9 | 2·9 |
| $\mathrm{Rms}_Z$ (mm) | 3·7 | 2·7 |

shows the results with one additional snapshot from a central perspective digital camera covering only a small part of the scene.

## CONCLUSIONS

The geometric model developed for rotating linear array sensor panoramic cameras, integrated into a self-calibrating bundle adjustment tool, enables this type of camera to be used for photogrammetric applications. Applying thorough camera modelling, an image space precision of 0·24 pixels could be achieved both in a spatial resection based on reference points and in a free network bundle adjustment, improving the precision potential of the uncalibrated camera by two orders of magnitude.

The strengths of the panoramic camera are clearly in the 360° field of view and the superior resolution, manifested by true RGB images of up to 90 000 × 10 000 pixels. The fact that the camera does not reach the image space measurement precision potential of central perspective digital cameras is irrelevant for the typical applications of these cameras in architectural photogrammetry, where interactive image measurement plays a predominant role.

The precision of 0·24 pixels achieved in the camera modelling and calibration is better than the precision obtained from manual image measurements; on the other hand, the large image format of panoramic cameras provides a high level of object detail, which is crucial for this type of application.

Beyond the work shown in this paper, the camera model has also been extended to handle full spherical images obtained by a panoramic camera equipped with a 180° fisheye lens (Schwalbe and Schneider, 2005). For this purpose, the central perspective equation for the vertical image coordinate of the panoramic camera model was replaced by the observation equation of an extended equiangular camera model for describing the geometry of 180° fisheye lenses (Schwalbe, 2005).

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## *Résumé*

*Les caméras panoramiques numériques constituent un outil puissant pour obtenir des images à haute résolution. Les images qu'elles fournissent contiennent jusqu'à 100 000 × 10 000 pixels et conviennent particulièrement bien pour saisir sur 360° des objets comme les scènes en intérieur ou les places en ville. On présente dans cet article le développement d'un modèle strictement géométrique conçu pour des caméras panoramiques pivotantes munies de capteurs à barrettes et son adaptation a la réalité physique par l'ajout de paramètres supplémentaires. La mise en œuvre de ce modèle prévoit une solution par faisceaux ou un relèvement dans l'espace. La solution par faisceaux permet de combiner l'emploi d'images panoramiques ou non panoramiques, à perspective centrale. Les essais pratiques effectués ont montré que l'on pouvait obtenir une précision d'environ ¼ de pixel.*

## *Zusammenfassung*

*Digitale Panoramakameras stellen ein leistungsfähiges Werkzeug zur Aufnahme hochauflösender Bilddaten dar. Mit einem Bildformat von bis zu 100 000 × 10 000 Bildelementen eignen sie sich insbesondere für die Aufnahme von 360°-Szenen wie Innenräumen oder Plätzen. Die Publikation beschreibt die Entwicklung eines strengen geometrischen Modells für die Handhabung von Rotationszeilenkamerabilddaten und die Erweiterung des Modells zur Berücksichtigung zusätzlicher Parameter zur Kompensation systematischer Modellabweichungen. Das Kameramodell wurde in einem räumlichen Rückwärtsschnitt und in einer Bündellösung implementiert. Letztere erlaubt zusätzlich die simultane Verwendung von Panoramabildern und zentralperspektiven Bildern. In mehreren praktischen Tests wurde ein Genauigkeitspotential von etwa ¼ Pixel nachgewiesen.*

## *Resumen*

*La cámara panorámica digital es una herramienta eficaz para generar imágenes de alta resolución de hasta 100 000 × 10 000 píxel y registrar objetos y escenas en 360° tales como interiores y plazas urbanas. El artículo describe el desarrollo de un modelo geométrico estricto para cámaras panorámicas rotatorias de detectores lineales y la extensión de dicho modelo mediante parámetros adicionales, adaptando el modelo de la cámara a la realidad física. El modelo de la cámara se ha aplicado en una resección espacial y en una solución por haces. Esta solución por haces permite manejar de forma combinada las imágenes en perspectiva central y panorámica. Los resultados de varios ensayos prácticos demuestran que se puede alcanzar una exactitud aproximada de ¼ de píxel.*