

COMBINED BUNDLE ADJUSTMENT OF PANORAMIC AND CENTRAL PERSPECTIVE IMAGES

D. Schneider, H.-G. Maas

Dresden University of Technology
Institute of Photogrammetry and Remote Sensing
Mommssenstr. 13, 01062 Dresden, Germany
(danilo.schneider@mailbox, hmaas@rcs.urz).tu-dresden.de

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ABSTRACT:

Based on a strict mathematical model for rotating line cameras developed at the Institute of Photogrammetry and Remote Sensing of the Dresden University of Technology, a self-calibrating bundle adjustment of panoramic image data was implemented. This model has been extended by the option to involve central perspective images of a conventional camera.

A panoramic bundle adjustment is a suitable tool for precise 3D modelling of indoor scenes or city squares in combination with the analysis of very high resolution texture information, as only a few panoramas are necessary for stereo capture of 360° scenes. When recording an object with a complex structure, some parts of the object may not be captured with these panoramic images. In this case it may be desirable to take additional central perspective images using a conventional digital camera in order to avoid such “hidden” object areas. These additional images shall be integrated in the panoramic bundle adjustment in order to warrant full stereoscopic coverage and at the same time stabilize the bundle geometry. For this purpose it was necessary to combine two different sets of observation equations, one for panoramic and one for central perspective images, in a single adjustment calculation.

In this paper the combined adjustment will be presented as well as results based on a 360° test field consisting of ca. 120 retro-reflective targets.



Fig. 1: 360°-Panorama of test field (courtyard within the campus of Dresden University of Technology)

1. INTRODUCTION

Digital panoramic cameras provide an interesting tool for a large number of photogrammetric applications, as a 360° field of view can be captured in one single image with a very high resolution (Maas & Schneider, 2004). This may be useful to record landscapes as well as rooms or city squares for architectural or industrial tasks, e.g. cultural heritage documentation, as-built documentation or virtual reality (Luhmann, 2004). Using a camera in photogrammetric data processing requires a geometric model, which – in case of a panoramic camera – does not comply with the central perspective geometry. For this reason a geometric model for panoramic cameras (rotating linear array cameras) was developed and successfully extended by additional parameters,

which allows calibrating such cameras and precise photogrammetric processing of panoramic imagery (Schneider & Maas, 2003). The model was finally implemented in a self-calibrating bundle block adjustment, allowing for the simultaneous determination of the orientation parameters of multiple panoramic images of a scene and the 3-D coordinates of an arbitrary number of points (Schneider & Maas, 2004). In order to calculate 3-D object point coordinates in a 360° surrounding via bundle block adjustment it is necessary to record at least 3 panoramas. Recording more than this minimum number of panoramas, which could be inevitable in complex 360° geometries to avoid “hidden” object areas, may be not desired due to the long image acquisition time of linear array panoramic cameras. The advantage of high resolution and accuracy is in contrast to the disadvantage of a limited

flexibility here. Considering conventional central perspective images within the bundle block adjustment may solve this discrepancy. On the one hand it is possible to record the whole 360° field of view by taking only a few panoramic images and on the other hand it would be possible to record some complex object details using a hand-held digital camera. Combining both in one calculation step allows combining the advantages of both sensor types.

2. ROTATING LINE CAMERA

Digital panoramic cameras consist of a linear sensor and a conventional lens, which move together around a fix rotation axis. Such a rotating line camera is able to scan the 360° surrounding into one panoramic image. This principle and its advantages and disadvantages are explained in more detail in [Schneider & Maas \(2004\)](#). Figure 2 shows four different panoramic cameras which are currently available on the market.



Fig. 2: Digital panoramic cameras (KST Eyescan M3, Sasta digital DRS 5000, Spheron PanoCam, Dr. Claus Karl line)

2.1 Geometric model

In photogrammetric applications a panoramic camera is an interesting alternative to conventional image acquisition methods because of its 360° field of view and its high resolution potential. The requirement for camera calibration and photogrammetric image analysis is a geometric model, which – in case of a panoramic camera – deviates from the central perspective geometry. Approaches for the derivation of the model are described in [Lisowski & Wiedemann \(1998\)](#), [Amiri Parian & Grün \(2004a\)](#) and [Schneider & Maas \(2003\)](#).

The model was extended by additional parameters in order to compensate systematic errors such as errors caused by the lens distortion as well as special parameters such as non-parallelism of the linear sensor with respect to the rotation axis. By using these parameters the accuracy potential of the geometric model could be improved from ca. 10 pixel to 0.2 pixel in a dataset captured by an Eyescan M3 panoramic camera in a calibration

room consisting of ca. 200 object points ([Amiri Parian, J., Grün, A., 2004b](#); [Schneider & Maas, 2004](#)).

2.2 Panoramic bundle block adjustment principle

Panoramic bundle block adjustment allows precise 3-D modelling of panorama-like objects such as indoor scenes or city squares in combination with the analysis of very high resolution texture information, as only a few panoramas are necessary (Fig. 3).

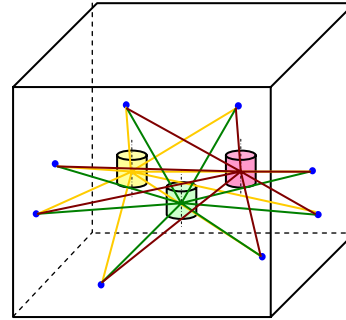


Fig. 3: Principle drawing of bundle adjustment of panoramas

A bundle block adjustment algorithm of panoramic imagery was therefore developed using the geometric model and subsequently analysed in a test room as well as at a real world project as already published in [Schneider & Maas \(2004\)](#). The bundle adjustment resulted in a standard deviation of unit weight of ca. 0.2 pixel, depending on the precision of object points. The average standard deviation of object point coordinates was about 0.5 mm in the test room (distance Ø 3 m), and about 2.5 / 4.5 mm (signalised / natural points) in a real world project (distance Ø 25 m).

3. CONSIDERATION OF CENTRAL PERSPECTIVE IMAGES

As illustrated in Fig. 3 it is necessary to capture at least 3 panoramic images to avoid singularities in the calculation of a bundle block adjustment in a 360° surrounding. This can only be circumvented by using a vertical base, at the cost of a loss of stereo viewing capabilities. If the object has a very complex structure, much more than 3 panoramas may be necessary to cover each object detail. This limits the flexibility and may take a long time. Many object details do not require taking a 360° panorama. For example there may be object areas which are not visible for a panoramic camera situated close to the center of a room (cp. [Fig. 4](#)), or areas where the 3-D geometry has to be determined very accurately and reliably, thus requiring a good intersection geometry. The idea is to integrate conventional central perspective image data into the bundle block adjustment, which could make the work flow more efficient. While recording 3 to 5 panoramas to generate a stable 360° panoramic image block, the operator could walk around with a hand-held central perspective camera taking some additional images of special object details which will be integrated into the bundle block adjustment afterwards. Combining both, panoramic and central perspective images, in one calculation step allows combining the advantages of both methods: High resolution and 360° coverage on the one hand, flexibility and reliability on the other hand.

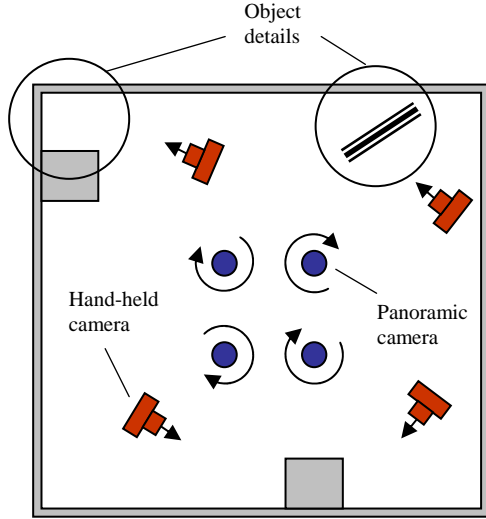


Fig. 4: Principle drawing (ground plan) of the combination of panoramic and central perspective images

3.1 Geometric model

The geometric model of central perspective images is described by the collinearity equations:

$$x'_{cp} = x_0' - \frac{c \cdot x}{z} + dx'_{cp} \quad (1)$$

$$y'_{cp} = y_0' - \frac{c \cdot y}{z} + dy'_{cp}$$

Observations in a panoramic image obey these formulas:

$$x'_{pano} = x_0' - c \cdot \arctan\left(\frac{-y}{x}\right) + dx'_{pano} \quad (2)$$

$$y'_{pano} = y_0' - \frac{c \cdot z}{\sqrt{x^2 + y^2}} + dy'_{pano}$$

- x', y' .. image coordinates
- x_0', y_0' .. principle point coordinates
- c .. principle distance
- dx', dy' .. additional parameters
- x, y, z .. object point coordinates in the camera coordinate system (see eq. 3)

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

$$\begin{aligned} x &= r_{11} \cdot (X - X_0) + r_{21} \cdot (Y - Y_0) + r_{31} \cdot (Z - Z_0) \\ y &= r_{12} \cdot (X - X_0) + r_{22} \cdot (Y - Y_0) + r_{32} \cdot (Z - Z_0) \\ z &= r_{13} \cdot (X - X_0) + r_{23} \cdot (Y - Y_0) + r_{33} \cdot (Z - Z_0) \end{aligned} \quad (3)$$

Additional parameters for compensating lens distortion, affinity of the sensor coordinate system or non-parallelism of the linear sensor to the rotation axis are considered by the terms dx' and dy' . During the bundle adjustment process these parameters can be calibrated.

3.2 Combined bundle block adjustment

The goal was to combine the mathematical models of central perspective and panoramic cameras in a joint bundle adjustment. For this purpose two kinds of observations – either equations (1) or equations (2) - have to be adjusted in the calculation. Every image coordinate has to be attributed by its origin – either panoramic or array based sensor camera. By this means the design matrix for the adjustment can be built. Figure 5 shows the structure of a synthetic example of a design matrix, where 9 object points, measured in 3 panoramic and 2 central perspective images, are adjusted. The unknown parameters are the coordinates of the object points, the exterior orientation of every image and the interior orientation and appropriate additional parameters for both kinds of cameras. Optionally the observations can be weighted according to their estimated precision.

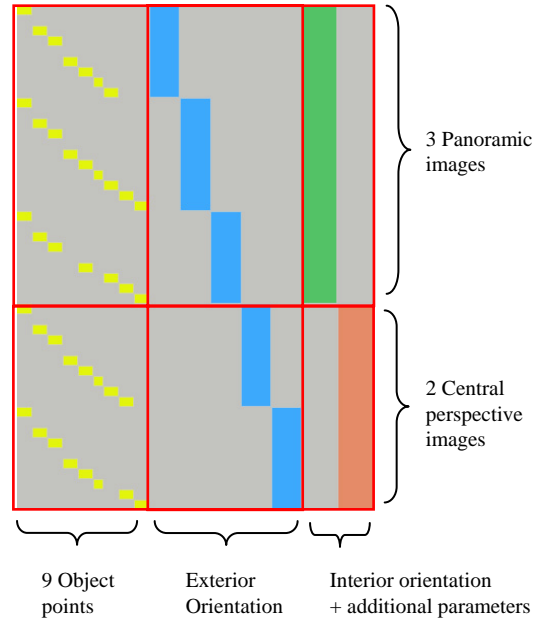


Fig. 5: Example of design matrix for combined bundle adjustment

3.3 Software implementation

The bundle block adjustment was implemented in a software package. This package allows combining different cameras in one adjustment, independent of the camera type. The user is able to define a list of cameras and to associate each image with one entry of this list. Each camera parameter as well as each object point coordinate can be set as fix or to be calculated. Object distances can also be considered as observations in the calculation. Among some other settings it is possible to choose between an adjustment with a minimum datum and a free adjustment.

The result of this bundle block adjustment is a value for each camera parameter, correlations between these parameters, position and orientation of each involved camera position, object point coordinates of points which are measured in at least 2 images and residuals of image observations. For each parameter and coordinate a standard deviation is computed.

In the frame of a joint project these software algorithms were integrated into a convenient user interface by the company [fokus GmbH Leipzig](#) (cp. Fig. 6).

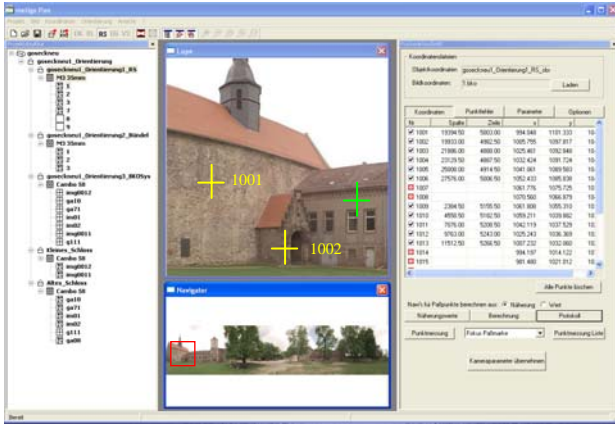


Fig. 6: Screenshot of bundle adjustment user interface

The user interface also implements modules for measuring of image coordinates in high-resolution images in a clearly arranged menu structure. As the file size of panoramic images is often larger than 1 gigabyte, this requires a refined image management system. Finally the software represents a tool for processing a photogrammetric project, where high-resolution panoramic images and conventional central perspective images can be used together to compute accurate 3-D information of panorama-like objects.

4. TEST FIELD RESULTS

4.1 360° Test field

A combined bundle adjustment was calculated using linear and array sensor based imagery of an inner courtyard within the campus of the Dresden University. Figure 1 shows one out of 4 panoramas. This courtyard has a dimension of approximately 45 x 45 m in the ground plan and the building height is ca. 20 m. There are approximately 100 signalised retroreflective markers attached at the surrounding building facades.

4.2 Results of bundle block adjustment

In order to verify the bundle block adjustment, two computations were carried out, one with 4 panoramic images of a Eyescan M3 camera and one with an additional central perspective image of a Nikon D100 digital camera. In both cases 125 points, some signalised and some natural points, were processed in a free bundle adjustment. The results are summarised in Table 1.

	4 Panoramas	4 Panoramas + 1 array sensor image
$\hat{\sigma}_0$ [pixel]	0.28	0.27
RMS _x [mm]	3.4	3.3
RMS _y [mm]	2.9	2.9
RMS _z [mm]	3.7	2.7

Tab. 1: Results of bundle block adjustment

As expected, the standard deviations are in the same magnitude. As the additional central perspective image has a lower resolution than the panoramic ones and contains only 40 object

points, the extra observations do not improve the over-all accuracy but stabilise the intersection geometry (hence the RMS_z of object coordinates was reduced), which will lead to a higher reliability of the determined point coordinates.

FUTURE WORK

Further tests involving more complex objects and many more central perspective images are planned in order to be able to better assess the efficiency and the benefits of the presented combined adjustment approach in comparison to conventional methods.

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