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CLOSE RANGE PHOTOGRAMMETRIC NETWORK DESIGN FOR PANORAMIC CAMERAS BY HEURISTIC SIMULATION

Jafar Amiri Parian, Armin Gruen
Institute of Geodesy and Photogrammetry
Swiss Federal Institute of Technology (ETH) Zurich
(parian, agruen)@geod.baug.ethz.ch

Abstract: Linear array CCD-based panoramic cameras are being used also in measurement applications. The elegant image acquisition mode and the high information content of those images make them suitable candidates for quantitative image analysis. The best possible accuracy is acquired by a suitable sensor model and following the concept of network design. In our previous investigations we designed a sensor model for linear array CCD-based rotating panoramic cameras, which models substantial deviations from the pinhole model using additional parameters. The additional parameters are related to the camera itself, the configuration of camera and turntable, and mechanical errors of the camera system during rotation (i.e. tumbling). We showed a subpixel level accuracy after modeling the mentioned systematic errors, included tumbling errors. In terrestrial panoramic cameras the camera system is designed to have a leveled turntable which reduces the mechanical errors of the camera system during rotation. However, this leads to restrictions in network design. Since the optical axis is always horizontal we cannot realize convergent concepts in vertical direction. This loss in network flexibility must be compensated by other measures. In this paper, by using the results of camera calibration and the characteristics of panoramic cameras, we analyze the panoramic camera networks. Joint networks consisting of matrix array CCD and panoramic cameras are also compared with network of panoramic camera stations alone.

1. Introduction

With the development of technology, a new generation of terrestrial panoramic cameras came into the market. The camera principle consists of a linear array which is mounted on a high precision turntable and is parallel to the rotation axis. By rotation of the turntable, the linear array sensor captures the scenery as a continuous set of vertical scan lines. SpheroCam from SpheronVR AG and EYESCAN from KST Dresden GmbH (Figure 1) are two typical linear array-based rotating panoramic cameras. Both systems are designed to capture a 360 degree horizontal field of view. The vertical field of view of the camera system depends on the size of the linear array and the focal length. A precise rotating motor rotates the linear array and the lens (camera head). The horizontal angle size of each step of the rotation is computed by the camera system with respect to the focal length. Since the acquisition time depends on the mechanical part of the rotating camera head and exposure time, it takes usually a long time, e.g. half an hour for capturing a full panoramic image of a room with Neon lights. Dynamic capturing provides a large image format, for example 100’000 x 5’300 pixels with 48 bits color depth per pixel (16 bits per R, G and B channels), which corresponds to a half a Gigapixel format. Dynamic imaging restricts the camera system to be used for static sceneries. However, high information content, format size and color depth, increase the applications of the panoramic cameras for object reconstruction, cultural heritage, landscape recording and texture mapping.

Figure 1. Digital terrestrial panoramic cameras. EYESCAN (left) and SpheroCam (right).

The first step towards establishing a photogrammetric network is the network design. Conceptually, the purpose of the network design is to design an optimum network configuration and an optimum observation plan that will satisfy the pre-set quality with minimum effort. In other words, after the definition of the network quality requirements (precision and reliability) the technique of network optimization allows for finding such an optimal network configuration and an optimal set of observations that will satisfy these requirements [11, 5, 18, 17]. In the past, it was very difficult, if not impossible, to solve all aspects of the network optimization in a single mathematical step. Instead, the problem of geodetic network design was divided into sub-problems in each of which some progress could be made. The accepted classification proposed by Grafarend was [11]:

- Zero-Order Design (ZOD): the datum problem (reference system)
- First-Order Design (FOD): the configuration problem
- Second-Order Design (SOD): the weight problem
- Third-Order Design (TOD): the densification problem

In close range photogrammetry Fritsch and Crosilla [10] performed first order design with an analytical method. Fraser [7, 8, 9] discussed the network design problem in close-range photogrammetry. The datum problem was discussed in [6] and especially the basic principles of the free network adjustment in close range photogrammetry were given in [16]. Mason [14] used expert systems and Olague [15] used a genetic algorithm for the placement of matrix array cameras using heuristic computer simulations. Precision and reliability considerations in close-range photogrammetry as a part of network quality requirements have been addressed by Gruen [12, 13] and Torlegard [21].

Due to the characteristics of panoramic cameras (cylindrical image geometry) new considerations should be taken into account. Our main focus is on a panoramic camera network analysis based on heuristic computer simulations. A matrix array camera is also used jointly with panoramic camera for enhancing the precision of the object point coordinates.

After reviewing the ideal sensor model that was used in simulations, we report the results of heuristic computer simulations.

2. Sensor model

We developed a sensor model for a linear array based rotating panoramic camera [1]. The sensor model as a mapping function is based on a projective transformation in the form of bundle equations, which maps the 3D object space information into the 2D image space. The sensor model uses the following coordinate systems [1]:

- Pixel coordinate system
- Linear array coordinate system
- 3D auxiliary coordinate system
- 3D object coordinate system

The functional model for an ideal sensor [1], which shows principally the relation of the four coordinate systems to each other, becomes:

$$\begin{pmatrix} c \\ 0 \\ y \end{pmatrix} = \lambda\, R_z^t(j\,P_x)\; M_{w,\varphi,k} \begin{pmatrix} X - X_O \\ Y - Y_O \\ Z - Z_O \end{pmatrix} \quad \text{with} \quad y = (i - \frac{N}{2})\, P_y \qquad (1)$$

where,

P_x……………..	The resolution of the rotation angle of the turntable
P_y……………...	The pixel size of the linear array
c……………….	Camera constant
N………………	The number of rows or number of pixels in the linear array
R_z……………...	3D rotation matrix around Z axis
(i, j)……………	Image point coordinates in the pixel coordinate system
λ ……………...	Scale factor for each ray
$M_{w,\varphi,k}$ ………...	Rotation matrix
(X, Y, Z)…….....	Object point coordinates in object space coordinate system
(X_0, Y_0, Z_0) ……	Location of the origin of the auxiliary coordinate system in the object space coordinate system

Systematic errors will disturb the ideal sensor model. For the linear array-based panoramic cameras the most important ones with a distinct physical meaning are:

1. Lens distortion (2 parameters)
2. Shift of principal point (1 parameter)
3. Camera constant (1 parameter)
4. Angular orientation of the linear array with respect to the rotation axis (3 parameters)
5. Eccentricity of the projection center from the origin of the auxiliary coordinate system (1 parameter)
6. Correction to the resolution of the rotation angle of the turntable (1 parameter)

7. Mechanical errors of turntable during rotation, including tumbling (6 parameters)

We formulated additional parameters for the modeling of the systematic errors and added them to the sensor model. Our camera calibration, procedure and results have been reported in [1, 2, 3, 4].

3. Results

In this section we report the results of simulations. We start the simulations with a network consisting of a panoramic camera and we show how a joint network consisting of matrix array and panoramic camera improve the precision of the network.

The simulated panoramic camera parameters are approximately equal to the parameters of the SpheroCam. A rectilinear lens with focal length of 50 mm is used. The radius of the cylinder, the distance of the linear array from the rotation axis, is 100 mm. The eccentricity of the projection center is 50 mm (Table 1). The measurement environment consists of 81 control points and the dimension is 15 x 12 x 3 meters (Figure 2).

Table 1. Simulated panoramic camera parameters

Focal length	50 mm
Number of pixels in linear array	5’300
Number of columns	39’269
Radius of cylinder	100 mm
Pixel size	8 microns

The simulation was performed based on Equation (1) and also considering the eccentricity of the projection center from the rotation axis. We supposed that the mean internal accuracy of the camera system is better than 0.25 pixel. This is based on the practical results of the camera calibration for a metric panoramic camera [19]. The bundle adjustment is based on free network adjustment using all object points.

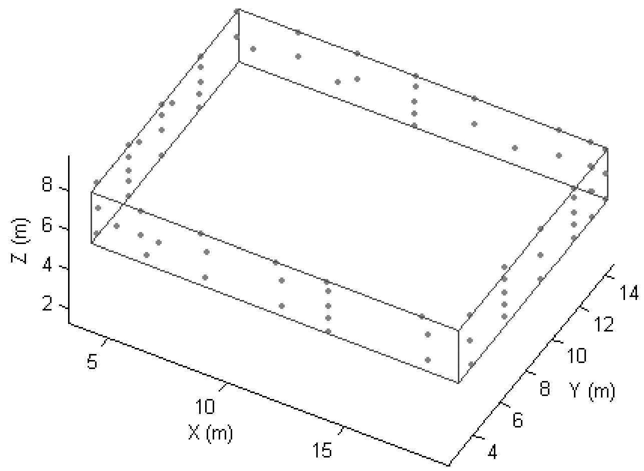


Figure 2. The 3D testfield environment for the simulation.

At the first step a network consists of two panoramic stations. The cameras are mounted on top of each other. The base line is vertical and its length is 1.5 meters. Figure 3a shows the top view of the absolute error ellipsoids of the object points. The mean of the estimated standard deviation of object points’ coordinates is 2.6 mm. Depth and lateral precisions are 2.56 and 0.38 mm (Table 2).

In the second case the network consists of 4 panoramic camera stations. The base lines are horizontal and the base length is 3.5 meters in X direction and 3 meters in Y direction. The camera stations are at the height of 1.5 meters from the workspace floor. Figure 3b shows the configuration of the panoramic camera stations and also the absolute error ellipsoids. In this network the mean of the estimated standard deviation of object points' coordinates is 0.48 mm. Depth and lateral precisions are 0.46 and 0.15 mm (Table 2). The precision is enhanced with respect to the previous network due to the increase of the image scale. In addition, due to 4-ray intersections this network is more reliable.

The third network consists of 8 stations. Four panoramic camera stations positioned on the same level and at the top of each station one camera is mounted with the base length of 1.3 meters. The horizontal base length is 3.5 meters in X direction and 3 meters in Y direction. The mean estimated precision is 0.29 mm for object points' coordinates, which is better than the previous cases. Lateral and depth precisions are 0.27 and 0.10 mm and with respect to $\Delta\sigma$ no significant improvement was made. With respect to the previous network the precision is enhanced in this case, because of the better configuration of the camera stations. However, at the corners error ellipsoids differ more from those at the middle of each side (Figure 4a). The inhomogeneity of error ellipsoids is due to the small intersection angle and small image scale for the object points at the corners of the workspace. To resolve this problem, FOD should be applied. The weak geometrical imaging can be solved by adding more camera stations and providing a suitable geometrical configuration. One solution to this problem is to employ sub-networks, based on matrix array cameras. The possibility of combined matrix array and panoramic cameras has been addressed in [20].

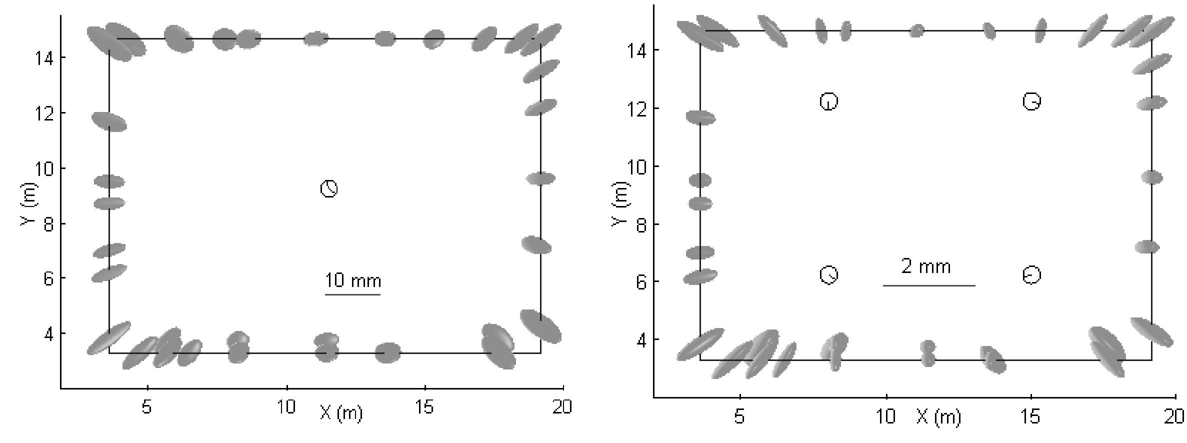
Table 2. The influence of the network configuration on the precisions of object point coordinates. The units of σ are mm.

Camera network configuration	Relative precision	$\bar{\sigma}_{XYZ}$	$\bar{\sigma}_{depth}$	$\bar{\sigma}_{lateral}$	$\Delta\sigma_{depth}$	$\Delta\sigma_{lateral}$
2 pano. stns.	1 : 20'769	2.60	2.56	0.38	2.33	0.54
4 pano. stns.	1 : 112'500	0.48	0.46	0.15	0.57	0.13
8 pano. stns.	1 : 186'206	0.29	0.27	0.10	0.32	0.07
8 pano. stns. + 12 matrix array stns.	1 : 270'000	0.20	0.18	0.07	0.18	0.06
16 pano. stns.	1 : 300'000	0.18	0.17	0.07	0.18	0.05

$\Delta\sigma$ is the difference between the maximum and minimum precision and $\bar{\sigma}$ is the mean precision.

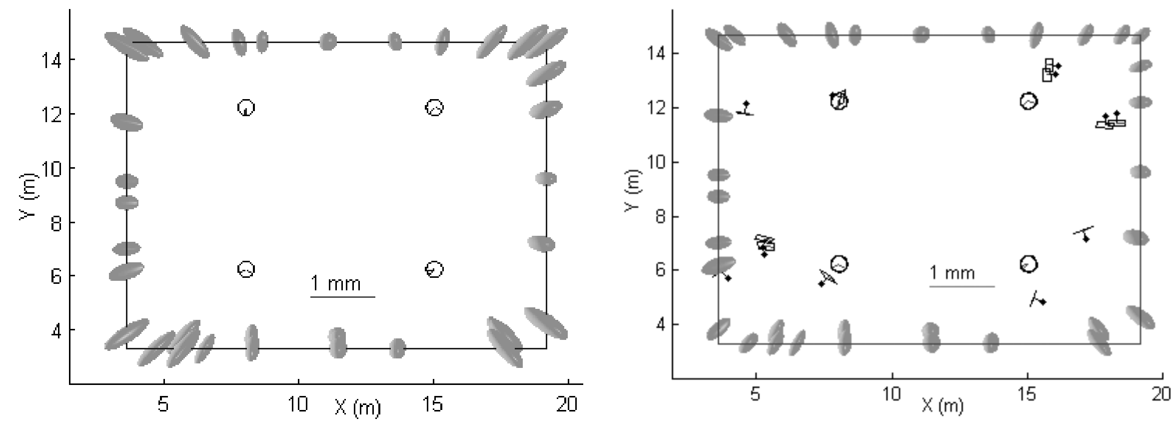
The simulation continues by adding matrix array camera stations to the previous network with the characteristics of a Sony DSC-F828. The focal length is 7.3 mm, the format size is 3264 x 2448 pixels and pixel size is 2.7 microns. We also assumed that the mean internal accuracy of the camera system is better than 0.1 pixel.

The sub-networks are used to improve the precision of those points which have worse precision than the other points (at the corner of the workspace). Because of different distribution of the object points at the corners two sub-networks were considered with two camera stations and two sub-networks were considered with four camera stations. Totally, four sub-networks with 12 matrix array stations were considered. The results of simulations are in Figure 4b and Table 2. The comparison of the precision of this network with respect to the previous network shows an improvement of a factor 1.45. In addition, this network has a better degree of isotropy with respect to previous networks. Considering the perimeter of the environment (54 meters) the relative precision is 1:270'000.



(a) (b)

Figure 3. Top view of the absolute error ellipsoids of the object points. a) The network consists of two panoramic camera stations at top of each other, b) The network consists of four panoramic camera stations of a same level.



(a) (b)

Figure 4. The absolute error ellipsoids of the object points. a) Eight panoramic camera stations and b) Eight panoramic camera and twelve matrix array camera stations. The influence of the sub-networks of matrix array camera for enhancing the object points' coordinates precision is obvious at the corners.

Another network consisted of 16 panoramic camera stations, 8 stations at the same height and on top of each one another station (Figure 5). The mean precision of object points' coordinates is almost the same as in the previous network and equal to 0.18 mm (Table 2).

The influence of 8 extra panoramic camera stations in this network is the same as the influence of using 12 matrix array camera stations. However, the shape of the error ellipsoids of the previous network is a bit more isotropic at the corners of the workspace. Shooting 12 images with matrix array camera takes much less time than taking 8 images with panoramic camera. In addition, due to the mechanical design of the panoramic camera the convergent concept is not realized in direction along the linear array axis. This lack of flexibility in geometry design of the panoramic camera network can be completed with matrix array cameras.

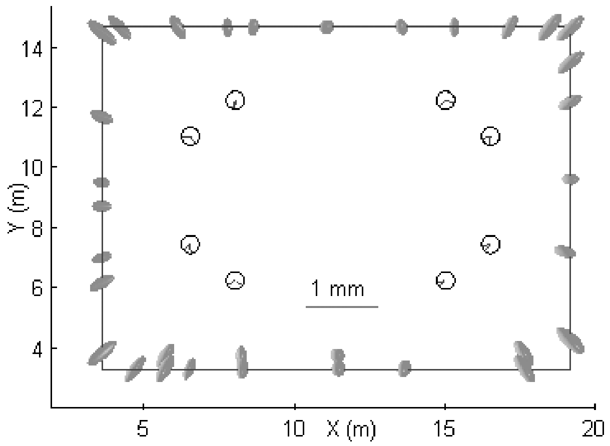


Figure 5. A network of 16 panoramic camera stations and absolute errors ellipsoids.

4. Conclusions

Considering the characteristics of the line-based rotating panoramic cameras, simulations were performed. Four networks were simulated with a panoramic camera and one with a setup of joint panoramic and matrix array cameras. The results of simulations show the good performance of a combined network consisting of matrix array and panoramic cameras. Due to the mechanical design of panoramic cameras the convergency concept cannot be realized in vertical direction (along the linear array) while this deficiency in geometry can be fully recovered by matrix array camera stations. With an example we showed that for point positioning purposes the influence of matrix array camera stations is larger than for additional panoramic camera stations.

Obviously panoramic cameras are not a suitable choice for purely point positioning purposes. However, the combination with matrix array camera can be a good solution. This solution is not economical at the moment because such precisions can be acquired with a network of matrix array cameras alone. The advantage of panoramic cameras lies, for example, in texture mapping, image-based lighting/rendering and 3D object reconstruction.

Since in real applications an online calibration is necessary, the determinability of additional parameters under different network conditions should also be investigated.

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