SELF-CALIBRATING NETWORK ANALYSIS FOR PANORAMIC CAMERAS BY HEURISTIC SIMULATION

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ABSTRACT:

Linear array CCD-based panoramic cameras have a high potential for measurement applications due to their design in acquiring 360 degree field of views and high information content with up to a Giga-pixel image data in one scan. The best possible accuracy of such a system can be obtained by a suitable sensor model and by establishing an optimal network following the concept of network design. The influence of different network configurations on the object point coordinates precision was shown in our previous studies with networks of panoramic cameras and panoramic and matrix array CCD cameras. In this paper, the influence of different network configurations onto the determination of Additional Parameters (APs) for self-calibration is demonstrated. The accuracy and precision values of object points and the correlations of APs with respect to the object point coordinates and the exterior orientation parameters are analyzed. By computer simulation and some sensor assumptions, networks of leveled and tilted panoramic camera stations, at the same and at different heights, are analyzed. The datum choice in all network cases is the "free network", based on the concept of inner constraints. We show that by increasing the tilt of camera stations the correlations of parameters are decreasing, especially the correlations of APs with object space coordinates. Based on these results we suggest tilted panoramic camera stations for the purpose of self-calibration.

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 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 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 Giga-pixel format. This restricts the camera system to be used for static sceneries. However, high information content, format size and color depth increase the applications of panoramic cameras for object reconstruction and texture mapping, e.g. in cultural heritage and landscape recording.

The first step towards establishing a photogrammetric network is the network design. Conceptually, the purpose of the network design is to design an optimal network configuration and an optimal 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 (Grafarend, 1974; Cross, 1985; Schmitt, 1985; Schaffrin, 1985). 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, 1974 is:

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

Research on this topic in close-range photogrammetry was done by Fraser, 1984, 1992, 1996 who discussed the network design problem in close-range photogrammetry. Fritsch and Crosilla, 1990, performed first order design with an analytical method. Mason, 1994 used expert systems and Olague, 2002 used a genetic algorithm for the placement of matrix array cameras using heuristic computer simulations. Visibility analysis by a fuzzy inference system for the camera placement was done by Saadatseresht et al., 2004. Precision and reliability considerations in close-range photogrammetry, as a part of the network quality requirements, have been addressed by Gruen, 1978, 1980 and Torlegard, 1980. Considerations on camera placement for the determination of the additional parameters of the camera by using control points were addressed by Gruen and Beyer, 2001. Amiri Parian and Gruen, 2005, showed the influence of different networks of panoramic camera and panoramic and frame-array CCD cameras on the precision of object coordinates.

Network design in our previous study was based on the assumption that the panoramic camera was calibrated in advance, with known APs. This assumption is accepted for metric cameras which maintain constant interior parameters. In the case that self-calibration parameters are present, the network should be designed in order to reduce the influence of the APs on the network quality requirements, which are usually precision and reliability values of the object point coordinates. The influence of the APs was studied in two ways:

1) The effect of individual APs on object point coordinates precision
2) The effect of the presence of one AP on other parameters in the solution vector which can be shown by correlation analysis

The first case was already addressed in Gruen and Beyer, 2001 and can be extended for every sensor. The second case was studied for frame array CCD cameras by Fraser, 1984 and Gruen and Beyer, 2001. As a general rule for recovering the interior orientation APs in self-calibration, an orthogonal kappa rotation between each camera station was suggested by Fraser, 1984.

Because of different characteristics of panoramic cameras with respect to the frame array CCD cameras and some restrictions in the design, the previous rules for frame array CCD cameras cannot be applied here.

Different self-calibrating networks were generated by heuristic simulation. The results of correlation analysis of unknowns and an accuracy test are reported in this paper. A general rule is suggested for the self-calibrating network of panoramic cameras.

2. COORDINATE SYSTEMS AND EXTERIOR ORIENTATION PARAMETERS

The exterior orientation parameters of panoramic cameras are defined based on the coordinate systems of the sensor model. The following coordinate systems were defined for the sensor model (Amiri Parian and Gruen, 2003):

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

Figure 1 shows the pixel coordinate (i, j) system. The original image observations are saved in this system. Figure 2 shows the other coordinate systems: linear array (0, y, z), auxiliary (X', Y', Z') and object space (X, Y, Z) coordinate systems. The object space coordinate system is used as a reference for determining the exterior orientation parameters of the sensor. The orientation and location of the auxiliary (X', Y', Z') with respect to the object space (X, Y, Z) coordinate system is defined as Exterior Orientation Parameters (EOPs) of the panoramic cameras ($\omega, \varphi, \kappa, X_0, Y_0, Z_0$).

To define the auxiliary coordinate system, an ideal panoramic camera is considered. Here, the origin of the auxiliary coordinate system coincides with the projection center O. The rotation axis passes through the projection center and coincides with Z'. X' passes through the start position of the Linear Array before rotation and Y' is defined to get a right-handed coordinate system.

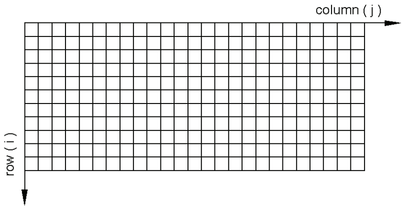


Figure 1. Pixel coordinate system (i, j).

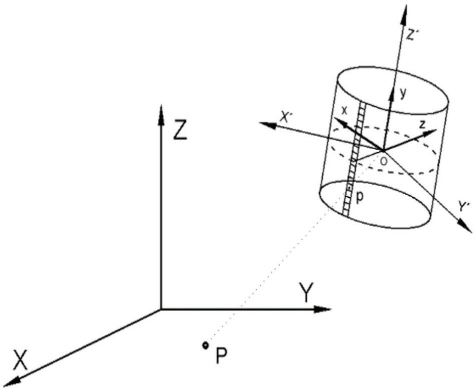


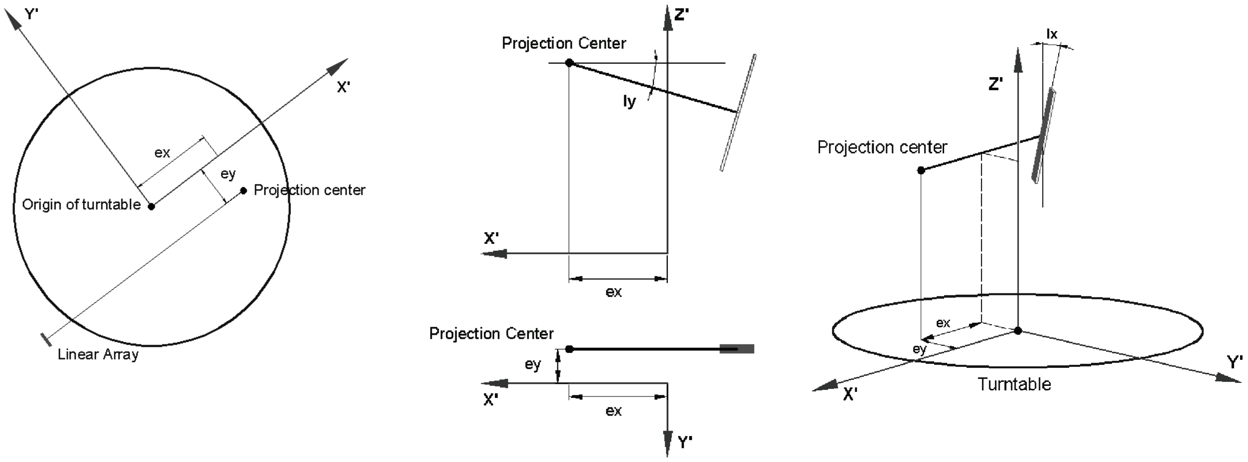
Figure 2. Object coordinate (X, Y, Z), auxiliary coordinate (X', Y', Z') and linear array (0, y, z) coordinate systems.

3. ADDITIONAL PARAMETERS

The sensor model for an ideal linear array based rotating panoramic camera was already demonstrated in Amiri Parian and Gruen, 2003. 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 2D image space. For the modeling of systematic errors which disturb the ideal sensor model, APs with a distinct physical meaning are:

1. Lens distortion: k_1 and k_2
2. Shift of principal point along linear array: dy_0
3. Shift of camera constant: *dc*
4. Angular orientation of the linear array with respect to the rotation axis: *lx* and *ly*
5. Eccentricity of the projection center from the origin of the auxiliary coordinate system: *ex* and *ey*
6. Correction to the resolution of the rotation angle of the turntable: *dPx*
7. Mechanical errors of the turntable during rotation, including tumbling: $r_1, r_2, r_3, r_4, r_5, r_6, t_1, t_2$ and t_3

The additional parameters can be divided into four different groups. The first is related to the camera head and optics (parameters of classes 1, 2 and 3). The second group of parameters (Figure 3) is related to the configuration of the camera head and the plane of the turntable (parameters of classes 4 and 5). The third group is related to the turntable itself (parameter of class 6). Finally the fourth group is related to the mechanical errors of the turntable (tumbling) which occurs while the camera rotates (parameters of class 7). Tumbling is mainly caused by an incomplete shape of ball bearings and the contacting surfaces (Matthias, 1961). For more detailed information on the mathematical modeling of tumbling see Amiri Parian and Gruen, 2004.



(a) (b) (c)

Figure 3. Additional parameters of the configuration of the camera head on the turntable. (a) Eccentricity (*ex*, *ey*), (b) tilt of the linear array (*ly*), (c) inclination of the linear array with respect to the rotation axis (*lx*).

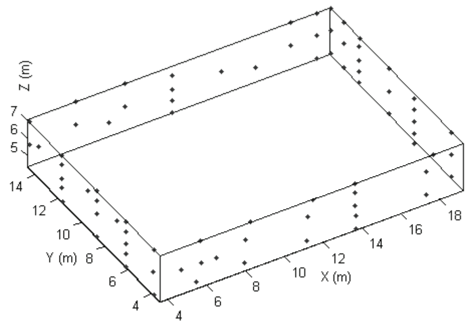


Figure 4. The monitoring environment with control points used in the simulation.

4. ASSUMPTION OF THE SIMULATION

Assumptions in the simulation are related to the sensor characteristics, monitoring object (points) and APs of the sensor which will be given in the following sections.

4.1. Sensor

The panoramic camera parameters in the simulation are approximately equal to the parameters of the SpheroCam. The lens is a rectilinear lens with a focal length of 50 mm. The radius of the cylinder, the distance of the linear array from the rotation axis, is 100 mm. Therefore the eccentricity of the projection center is 50 mm (Table 1). We modified the synthetic true pixel coordinates by introducing random errors of the normal distribution $N(0, \sigma; \sigma = 0.25$ pixel). This is based on practical results of the camera calibration for a metric panoramic camera (Schneider and Maas, 2004).

Table 1. Panoramic camera parameters for the simulation

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

4.2. Monitoring object

The measurement environment consists of 81 control points and the dimension is 15 x 12 x 3 meters (Figure 4).

4.3. Additional parameters

The parameters of the first three groups (classes 1, 2, 3, 4, 5 and 6) which can be assumed as block invariant parameters are considered in the simulation. The values of the APs are approximately equal to the APs of the SpheroCam which was already calibrated by use of a testfield (Amiri Parian and Gruen, 2004). All APs were treated as free parameters in the simulation.

5. SIMULATION RESULTS

Because of the design structure of panoramic cameras, the camera stations are leveled in practice. This is not only caused by mechanical restrictions of the panoramic cameras but also by the visibility requirements of the surroundings. However, these kinds of networks have problems in self-calibrating networks.

We have studied six different network cases by heuristic simulation. In all cases, the datum choice was inner constraints (free network) based on all control points. All control points were also used as checkpoints for the accuracy test. In four network cases (cases 4-6) we have introduced non-leveled camera stations, with omega (rotation around X-axis) and phi (rotation around Y-axis) different from zero.

5.1. Case 1 - 2 stations

The first network consists of 2 stations. The stations have a vertical base of 1.5 meters and the horizontal base is zero. Both stations are leveled (omega and phi are 0). This is the simplest and optimal configuration which could be established for the measurement of a 360 degrees environment.

Self-calibration with all APs of the first three groups is not possible in such a network because of very high correlations among APs, EOPs and the coordinates of the object points.

Increasing the vertical and horizontal bases does not improve the situation.

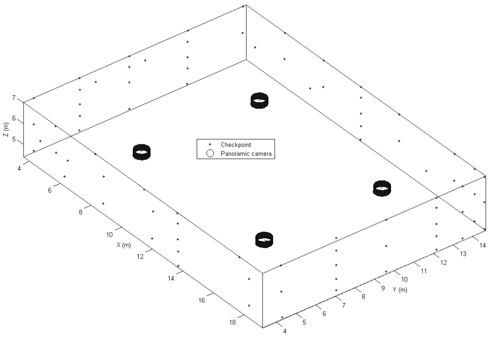


Figure 5. The configuration of four panoramic camera stations network.

5.2. Case 2 - 4 leveled stations at the same height

In order to improve the network geometry, a new network with 4 camera stations was considered (Figure 5). The geometry of this network is better than the network of two stations in the first case (Amiri Parian and Gruen, 2005).

Simulation and self-calibration was performed. Very high correlations (almost close to 1) were observed between (Table 2):

1. *dc*, k_1 and k_2 and object point coordinates
2. EOPs and object point coordinates
3. APs and EOPs

The mean precision of this network, which is 0.5 mm in depth and 5.4 mm in lateral axes, is much worse than the RMSE from checkpoints, which turned out to be 76.5 mm for depth and 930.2 for lateral axes. From this type of network configuration (Amiri Parian and Gruen, 2005) we expect better lateral precision and RMSE than depth precision and RMSE. The reason of such degradation is the high correlation of object point coordinates with EOPs and APs. In addition, this degradation is not only seen in the estimation of the object point coordinates but also influences the estimation of those APs which show very high correlation with other parameters. In this example, *dc*, k_1 and k_2 could not be estimated and are far from the true value of the simulation.

Table 2. Results summary of the simulated networks (units are mm. RMSE and standard deviations are from checkpoints). For the estimation of the standard deviations, $\hat{\sigma}_0$ (around 0.2) of each version were used.

#	Network configuration (4 stations)	[1] High correlations	RMSE of *X, Y, Z*	[2] $\overline{\sigma}_X, \overline{\sigma}_Y, \overline{\sigma}_Z$
2	omega and phi are 0 degree stations are at the same height	*dc* …… all (X,Y,Z) (>0.95) k_1 ……. all (X,Y,Z) (>0.95) k_2 ……. all (X,Y,Z) (>0.95) EOPs ... all (X,Y,Z) (>0.95) APs ......EOPs (>0.95)	89.5, 63.5, 930.2	0.6, 0.5, 5.4
3	omega and phi are 0 degree stations are at different heights	dy_0 ……all (X,Y,Z) (>0.95) *dc* …… all (X,Y,Z) (>0.95) k_1 ……. all (X,Y,Z) (>0.95) k_2 ……. all (X,Y,Z) (>0.95) *ly* ……. all (X,Y,Z) (>0.85, >0.85, >0.90) EOPs ... all (X,Y,Z) (>0.95) APs ..... EOPs (>0.95)	89.5, 63.5, 929.6	0.6, 0.4, 4.8
4	omega and phi are 3 degrees stations are at the same height	*dc* ……. Z-coordinate (>0.95 for 67 points) EOPs … Z-coordinate (>0.95) APs ….. some EOPs (>0.95)	0.5, 0.4, 2.0	0.4, 0.3, 1.2
5	omega and phi are 9 degrees stations are at the same height	*dc* …….. Z-coordinate (>0.75 and <0.85 for 29 points) EOPs … Z-coordinate (>0.80 and <0.95 for 15 points) APs ….. some EOPs (>0.75 and <0.95)	0.3, 0.3, 0.2	0.3, 0.3, 0.3
	omega and phi are 9 degrees stations are at different heights	*dc* ……. Z-coordinate (>0.75 and <0.85 for 34 points) EOPs … Z-coordinate (>0.80 and <0.95 for 24 points) APs ….. some EOPs (>0.75 and <0.95)	0.3, 0.3, 0.3	0.3, 0.3, 0.3
6	omega, phi are 14 degrees stations are at the same height	———————————	0.3, 0.3, 0.2	0.3, 0.3, 0.2

[1] High correlation for APs-EOPs, APs-XYZ object points and EOPs-XYZ object points.

[2] $\overline{\sigma}$ is mean standard deviation

5.3. Case 3 - 4 leveled stations at different heights

Case 3 investigates the influence of different heights of stations. The results are similar to the results of case 2. High correlations still exist and the determination of the object point coordinates is not accurately possible (Table 2). The APs with high correlations with object point coordinates cannot be determined. The height difference of stations in this network did not de-correlate parameters.

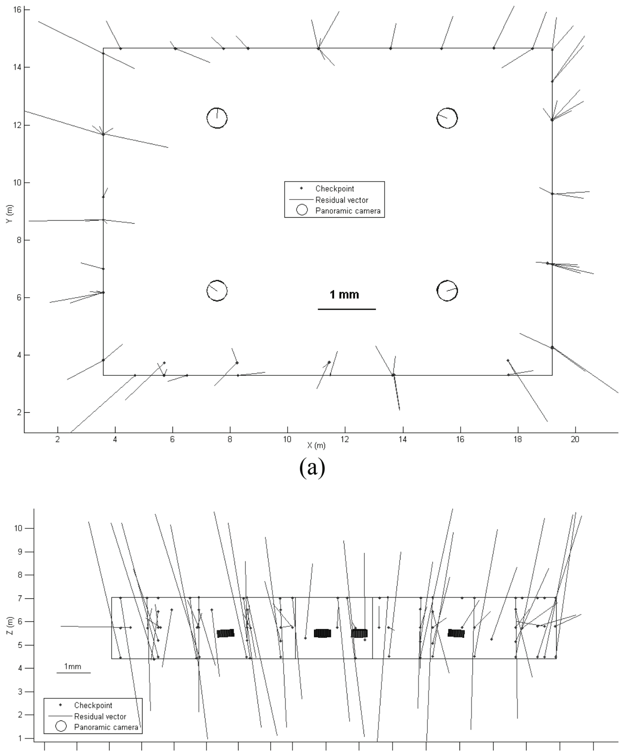
5.4. Case 4 - 4 unleveled stations at the same height

In this network case, the influence of a convergent network is investigated. The network convergency of panoramic cameras along the rotation axis (vertical axis) is weak and usually cannot be realized because of the design structure of the turntable which optimally and with less mechanical errors operates at leveled situations.

The network in this case consists of 4 camera stations. The stations are not leveled and omega and phi are ±3 degrees. After the self-calibration adjustment of this network high correlations (Table 2) appear between:

1. *dc* and Z-coordinate, only for some of the object point coordinates
2. EOPs and Z-axis of the object point coordinates
3. APs and some EOPs

The mean precision of checkpoints from this network is 0.4 mm for depth and 1.2 mm for the lateral axes. The RMSE of checkpoints is 0.4 mm for depth and 2 mm for lateral coordinates. Figure 6 shows the depth axes view and lateral axis view of the residuals in object space for checkpoints. From this figure it is clear that the high correlation of *dc* and Z-coordinate of the object points has degraded the estimation of the Z-coordinate. Therefore, depth precision is better than lateral precision which is unusual for this kind of geometrical network.



(a)

(b)

Figure 6. The residuals of checkpoints in object space in case 4. a) The visualization of the depth axes residuals and b) the visualization of the lateral axis.

Comparing the result of this network to the network of case 2, a significant improvement is obvious. Although it is not an ideal network, it shows the influence of convergency along the vertical axis for panoramic cameras in a self-calibrating network.

5.5. Case 5 - 4 unleveled stations

The network of this case is similar to the previous network (case 4) with the difference that the stations are not leveled and omega and phi are equal to ±9 degrees, which means more convergency along the vertical axis. The comparison of the results of this network with the network case 4 shows a substantial improvement (Table 2) of de-correlations of parameters and object point coordinates.

Networks of different station heights of this version were also simulated. The results (Table 2) are similar to the case were camera stations are at the same height. This implies that the height difference does not have an influence regarding our purpose of de-correlation of the parameters.

5.6. Case 6 - 4 unleveled stations at the same height

In continuation of the evaluation of convergent panoramic camera networks, a network of 4 stations at the same height with omega and phi equal to ±14 degrees (more convergency with respect to the previous networks) was simulated. The result of the simulation (Table 2) shows no high correlations of parameters any more. In addition, the mean standard deviation of the object point coordinates and RMSE from checkpoints are in good agreement with each other. The lateral precision is better than the depth precision which is expected from this network configuration.

In this network configuration highly correlating APs are:

- dy_0, ly with correlation of 0.98
- k_1, k_2 with correlation of 0.96

Both sets of parameters: k_1, k_2 and dy_0, ly have inherent correlations. All the parameters of this network turned out to be significant after testing. In addition, the estimated APs are in good agreement with the true APs of the simulation.

6. CONCLUSIONS

Self-calibrating networks of panoramic cameras were analyzed by heuristic simulation. Different networks consisting of leveled, unleveled, same height and different height of stations were studied. For the analysis of self-calibrating networks, the correlations of the parameters and accuracy tests were considered.

By tilting the camera we achieve a positive effect on the determinability of APs. It was shown that a tilt of around 10 degrees gives already stable results in all APs and the determination of object space coordinates. A strong self-calibrating network, for both object point positioning and APs determination, can be realized with tilted camera stations.

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