ON THE GEOMETRICAL QUALITY OF PANORAMIC IMAGES

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ABSTRACT:

Creating of panoramic images is a common technique nowadays. The needed components are a sequence of overlapping digital images and a suitable stitching software. There are several software available for combining single images together just by few mouse clicks. They can also take care of the image distortions and adjust the radiometric differences so that the final image looks very consistent. In addition to the commercial software there are also free ones, which can be downloaded from Internet. Panoramic images are used in many different contexts. Real estate agents have on their web pages 360 degrees panoramic views of interiors of the houses for sale. Panoramic views can be found in many virtual reality and multimedia presentations, advertisements, work of arts, etc. Depending on the usage there are different requirements for the panoramic images. For a real estate agent it might be enough that the panorama is seamless and gives impressive presentation of the interior of the house. The most important thing is that the image looks impressive. But this is not always the case. If the images are used for measurement purposes the geometrical quality of the panoramic images is important. Even though panoramic images are not very often used in measurement tasks there are some cases where they might be advantageous. Sometimes, for example, the image must be taken quite far away from the object in order to see enough control points. This might reduce visible details. But using panoramic images taken closer to the object might give both enough control points and visible details. This paper concentrates on the geometrical quality of the panoramic images created from concentric image sequences. The main goal is to understand the suitability of panoramic images for photogrammetric measurements.

1. INTRODUCTION

Developments in imaging technology have increased the production and use of panoramic imagery. Panoramic images can be found in advertisements, artworks, virtual reality and multimedia presentations, etc. In the Internet numerous impressive panoramic images can be found. One interesting way to utilize panoramic images is to combine them with laser scanner data for modelling and visualization purposes (Haala et al., 2004; Reulke et al., 2003; Rönnholm et al., 2003; Scheibe et al., 2004)

There are two main streams in digital panoramic image capturing (Luhmann et al., 2003). First, the panoramic image can be constructed from a concentric image sequence or second, captured using rotating line scanner. In the first case there is no need for a special camera. Instead, an image sequence taken with a digital frame camera or scanned from analog photographs can be stitched to a panoramic image with proper software. There are more than 30 commercial stitching software on the market (Remondino et al., 2004) and some software can be downloaded for free from Internet. Stitching can be based on corresponding points of adjacent images (Luhmann et al., 2004) or on the whole overlapping area (Szeliski, 1996; Pöntinen, 1999). The projection centre of the camera should be stable during the camera rotation, but if the object is far away from the camera or approximately planar, small deviation from the concentricity does not prevent the stitching. To make the image sequence better concentric, a special camera adapter can be used (see Figure 1). This concept is widely in use because of its low costs.

The other concept, rotating line scanner, requires more investments but produces directly panoramic output with very high resolution. There are some commercial devices available, like EyeScan from KST Dresden GmbH and German Aerospace Centre (DLR), or SpheroCam from Spheron VR AG.

Panoramic images can be used also for photogrammetric measurements (Antipov et al., 1984; Hartley, 1993; Luhmann et al., 2004). Some possible applications concerning construction machines and building sites are listed in (Hoske et al., 2004). In the case of exact measurements the geometrical consistency of the panoramic image becomes important. In order to maximize the consistency the used instrument, either a rotating line scanner or a frame camera with panorama adapter, must be calibrated. The calibration of the instrument includes the determination of the camera parameters (camera constant and principal point), lens distortions and the eccentricity of the projection centre from the rotation centre. In the case of a rotating line scanner also the tilt and inclination of the imaging sensors with respect to the rotation axis, resolution of rotation and so called tumbling must be solved (Amiri Parian et al., 2003; Amiri Parian et al., 2004). The geometrical modelling and calibration of an EYESCAN M3 panoramic camera can be found in (Schneider et al., 2003).

This paper concentrates on the geometric consistency of stitched image sequences. The more time, money and effort is spend for creating the panoramic image mosaic, the better is the result. But if someone buys a digital camera, a panoramic adapter and a stitching software from a shop, captures the image sequences, creates panoramic images and imports them to a close range photogrammetric software, what kind of results he or she can expect? It is impossible to give a complete answer to this question, but some indicative remarks can be done.

In chapter 2 the importance of the camera calibration is discussed. The next chapter describes the effect of the non-concentricity based on some examples and in chapter 4 the stitching procedure itself is discussed. In chapter 5 a small measurement example is given.

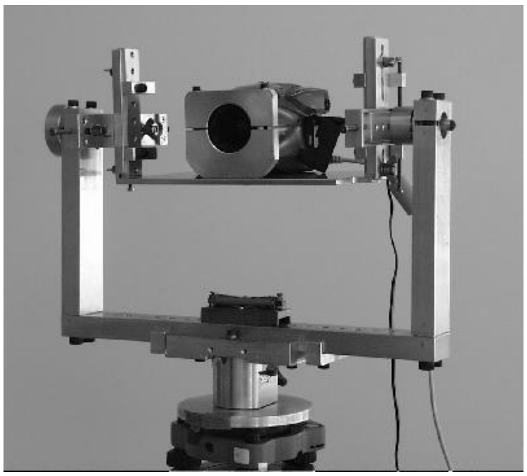

Figure 1. A camera adapter for panoramic image acquisition.

2. CAMERA CALIBRATION

Depending on the digital camera the magnitude of the lens distortions on the image edges varies from tens of pixels to hundreds of pixels. So it is clear that the whole image area cannot be used to a panoramic image mosaic if the lens distortions are not compensated.

Calibration can be done separately using for example the test field method, or alternatively it can be derived from the captured image sequence. Several papers considering the single station camera calibration can be found. Duane Browns single station camera calibration concepts are presented in (Fryer, 1996). In (Wester-Ebbinghaus, 1982) the image rotations, camera and additional parameters and the non-concentricity of the sequence are solved based on point correspondences. In (Hartley 1994) the camera calibration is based on the 2-D projective correspondence, which occurs between the images taken from one point. In (Pöntinen, 2002) the mathematical formulation of the problem follows the one presented in (Wester-Ebbinghaus, 1982), but the non-concentricity is neglected. In (Remondino, 2004) is presented the calibration of generally rotating cameras without any special adapters to remove the non-concentricity of the image sequence.

While selecting the additional parameter set the strong correlation between the additional and camera parameters must be taken into account (Grün, 1981). In the case of simple lenses there is usually no need for many radial and decentering correction terms. In (Remondino, 2004) some procedures are listed to analyse the determinability of the additional parameters.

For the examples presented later in this paper a thorough calibration of the Olympus E10 camera was carried out. The image size of the camera was 2240x1680. A representative set of 13 test field images was taken and 846 image points were measured. The so-called physical set was chosen to the additional parameter set. Even the relatively large amount of measured points was not enough to define more than two radial distortion parameters and the scale of the coordinate axes reliably in addition to the principal point coordinates and camera constant. The RMS error of the image residuals was 0.16 pixels. Based on the calculated parameters the used images were resampled to distortion-free ones.

3. CONCENTRICITY

There are adapters, or panoramic heads as they are called in some contexts, for several commercial camera and lens combinations. Some of them allow both horizontal and vertical rotations which make it possible to create a full spherical panoramic image. The camera position on the adapter is either fixed or then it can be adjusted. The possibility to adjust the camera position gives more possibilities to the camera and lens selection. Correct position on the adjustable adapter for the camera is found when the rotation of the camera does not change the perspective of the images. This indicates that the projection centre of the camera coincides with the rotation axis of the adapter.

In order to find out how close to the correct place the camera can be adjusted with reasonable effort, some tests were carried out. For the tests the adapter shown in Figure 1 and the targets shown in Figure 2 were manufactured. The adapter has two intersecting rotation axes and allows both horizontal and vertical rotations.

With the help of a theodolite and a levelling instrument two lines were constructed so, that they intersected on the rotation axes. The front targets were approximately at two meters distance from the camera and the distances to the rear targets were about 12 meters. It was found that even very small movements of the camera could be recognized on the images. Changes in the relative position of the front and rear targets on the image could be distinguished even for the movements of few tenths of a millimetre. This is of course due to the big depth difference of the targets. The cautious conclusion made based on this experiment was that the eccentricity of a carefully adjusted camera is less than one millimetre.

After a careful adjustment of the camera to the adapter the affect of the non-concentricity was studied. Four mosaics of nine images were created with different eccentricities. The chosen three eccentricities were 1 mm left and 1mm forward, 2 mm left and 2 mm forward, and 5 mm left and 5 mm forward. The mosaics were created so that the middle image was chosen to a base image and the rest were stitched to it. This means that all the mosaics are actually on different planes and the comparison of these mosaics becomes difficult. For this reason same centre image taken from the non-deviated set was used in all mosaics. The more the image set was deviated, the more iteration steps were needed to create the final mosaic, but finally all the calculations converged. In Figure 3 is shown the complete mosaic of the non-deviated set.

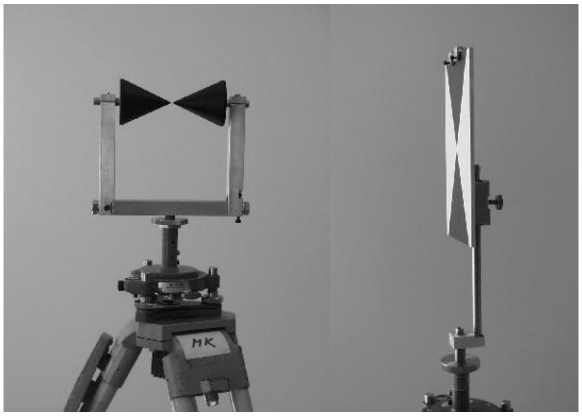

Figure 2. Targets for camera adapter adjustment.

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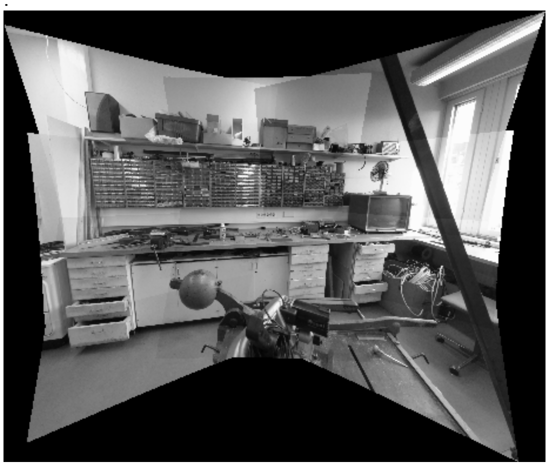

Figure 3. One of the four panoramic image mosaics. The size of the image is 7219 x 6004 pixels.

Next, the locations of 19 checkpoints were measured on all mosaics using least squares matching. In some checkpoints the signal to noise ratio was so small that they had to be measured manually. In Figures 4, 5 and 6 the differences between the non-deviated set and the 1 mm, 2 mm and 5 mm deviated sets are shown, respectively. Deformations on the image edges are bigger than in the middle of the image. The reason is clear; transforming of the concentric images to one common plane amplifies the errors of the outermost images. The average deformation of the 2 mm deviated set is slightly smaller than the deformation of 1 mm deviated set (see Table 1), but the 5 mm deviated set is clearly worse. One would expect that the 2 mm deviated image set deviates more than 1 mm deviated, but this is not always the case, because the magnitude of the eccentricity is not the only factor to be taken into account. Deviating the camera to different directions would have produced different deformations. Also the photographed objects influence the deformations. The more depth differences there are in the objects, the less deviation is allowed in concentricity (Luhmann et al., 2003). As can be seen later also the stitching order affects to the deformations. Because of the complexity of the deformation of the panoramic image mosaic the previous results are just suggestive. So even small eccentricities can cause deformations of several pixels.

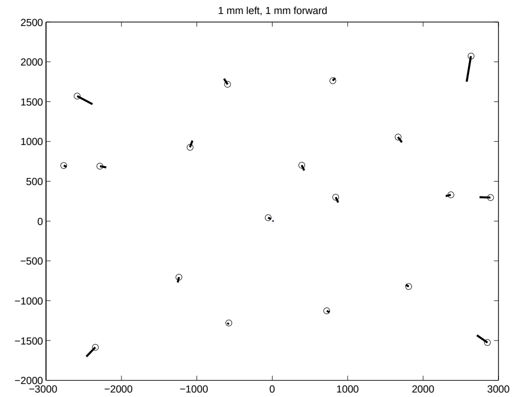

Figure 4. Deformations (x 50) of the 1 mm deviated set.

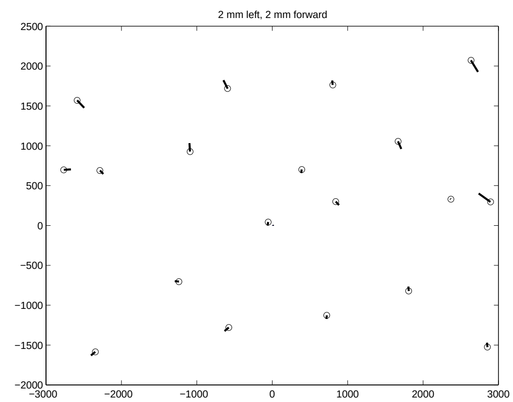

Figure 5. Deformations (x 50) of the 2 mm deviated set.

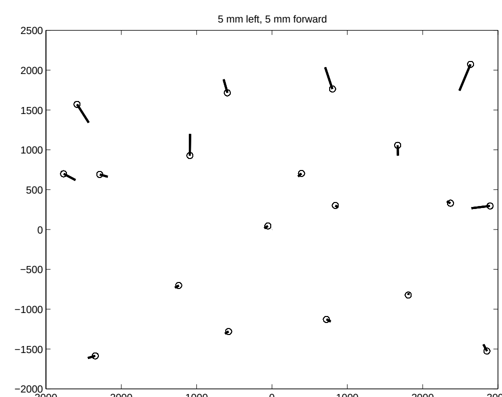

Figure 6. Deformations (x 50) of the 5 mm deviated set.

set	1 mm	2mm	5mm
mean	1.9858 pix	1.6347 pix	2.7576 pix
std.	1.5275 pix	0.9176 pix	2.0554 pix
max.	6.4973 pix	3.7748 pix	7.1805 pix

Table 1. Statistics of the deformations caused by different eccentricities.

4. STITCHING

There are two ways to combine the image sequence taken from one point to a panoramic image mosaic. The single images can be stitched together directly based on the two dimensional projective transformation

$$x_2 = \frac{a_1 x_1 + a_2 y_1 + a_3}{a_7 x_1 + a_8 y_1 + 1} \ , \quad y_2 = \frac{a_4 x_1 + a_5 y_1 + a_6}{a_7 x_1 + a_8 y_1 + 1} \ , \qquad (1)$$

or the rotations between the images can be solved and the images projected to a common surface.

The transformation parameters a_1,..., a_7 and a_8 in Equation 1 can be solved if the image coordinates of at least four corresponding points are known on both planes and if no three points lie on the same line. Instead of using a set of points, the whole overlapping area can be utilized to determine the transformation parameters. The initial transformation parameters can be solved using the coordinates of four corresponding points and then adjusted using least squares so that the sum of squared grey level differences in corresponding points will be minimized (Szeliski, 1996; Pöntinen, 1999).

In the other method the rotations of the images are solved based on image correspondences. Also in this case it is possible to use either single points or the whole overlap area. The mathematical model is

$$\frac{\mathbf{a}}{|\mathbf{a}|} = \mathbf{R}\frac{\mathbf{b}}{|\mathbf{b}|} \ , \qquad (2)$$

where **a** and **b** are the corresponding image vectors and **R** is the unknown rotation matrix. Using least squares principle the optimal rotation matrix, which minimizes the squared sum of grey values in corresponding points can be found. After the rotations have been solved, the relatively oriented images can be projected to a chosen surface. If the amount of the images is small, the chosen surface can be a plane, but the more there are images the better is to use a cylinder or a sphere.

According to common sense the more images have overlap the more reliable is the joint. But on the other hand the more images are needed to cover a certain object and the stitching process is slower. Because the image sequence usually is not exactly concentric and the camera calibration parameters are not exactly correct, also the stitching order has some impact to the deformations. As an example the image shown in Figure 3 was created two more times so that in both two cases the stitching order was different than in the first case. Again the 19 checkpoints were measured on all images. The movements relative to the first image mosaic are shown in Figures 7 and 8. Both new images had the middle image of the set as a starting image and in the case presented in Figure 7 the rest eight images were combined clockwise starting from the middle left image. Figure 8 shows the deformation caused by the anticlockwise stitching order starting from the middle right image. The statistics of the deformations are presented in Table 2. It can be seen the deformation is pushed to the corners of the image mosaics. Surprisingly the stitching order causes stronger deformations than the non-concentricity. Based on authors own experiences the best way to avoid the accumulation of errors to a certain part of image is to do the combining symmetrically. For example, the middle left and middle right images are combined to the middle image, then the middle top and middle bottom images to the previous mosaic and finally the corner images. And if there are differences in the overlaps the images with the biggest overlaps should be combined first to make the structure of the mosaic stronger.

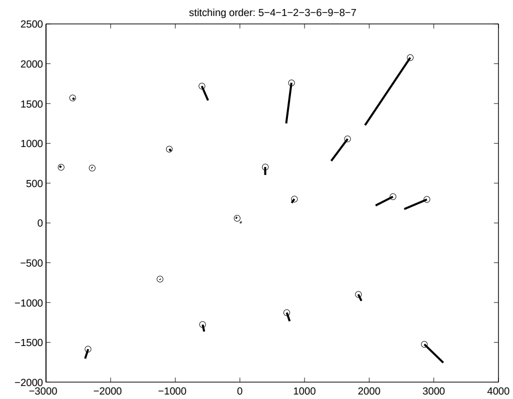

Figure 7. Clockwise stitching order causes strongest deformations to the top right part of the image mosaic (error scale 50:1).

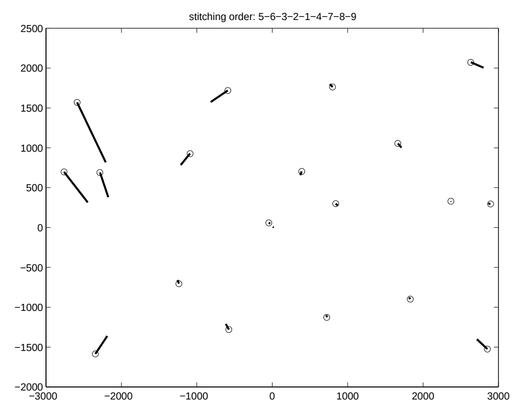

Figure 8. Anticlockwise stitching order causes strongest deformations to the top left part of the image mosaic (error scale 50:1).

set	clockwise	anticlockwise
mean	4.1688 pix	3.3928 pix
std.	5.2864 pix	4.1973 pix
max.	21.9940	16.8583

Table 2. Statistics of the deformations caused by different stitching order.

5. SMALL PANORAMIC BLOCK

To obtain some numerical values for achieved accuracies of panoramic image measurements a small panoramic block was calculated. Three panoramic images of a facade shown in Figures 9, 10 and 11 were created. Images in Figures 9 and 10 were created from 6 and image in Figure 11 from 11 single images.

Figure 9. The left image of the block (5831 x 6019 pixels).

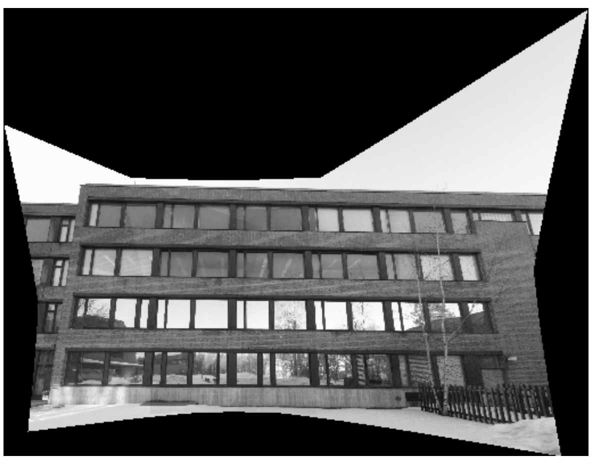

Figure 10. The middle image of the block (8238 x 6298 pixels).

Figure 11. The right image of the block (10706 x 5979 pixels).

One image of each set was chosen to the base image and the rest of the set were stitched to them. The principal points of the base images were also the principal points of the final image mosaics. As can be seen the block geometry was far from ideal, but this kind of situations easily occur in practice if there are no cranes or scaffolds available. Due to the poor block geometry this experiment might give too pessimistic impression of the performance of the panoramic image mosaics.

There were 32 targets with known 3-D coordinates attached to the facade. The targets were so small that the images had to be taken close to the wall, otherwise they could not be recognized on the images. The image coordinates of the targets were measured manually and a free network adjustment was calculated. The additional parameters were not used, because the image mosaics were assumed to be distortion free. The calculated points were transformed to the correct coordinate system with 3-D similarity transform and the comparison between the known and calculated points are shown in Figures 12 and 13. Due to the imaging geometry the accuracy in depth direction is clearly better than the planar accuracy. It can be seen that there is clear systemacy in the deformations. The points in the middle deviated only few millimetres from the correct coordinates and the worst deformation on the top left point was almost 5 cm. The average length of the deformation vectors was 16.3 mm and the standard deviation was 10.9 mm.

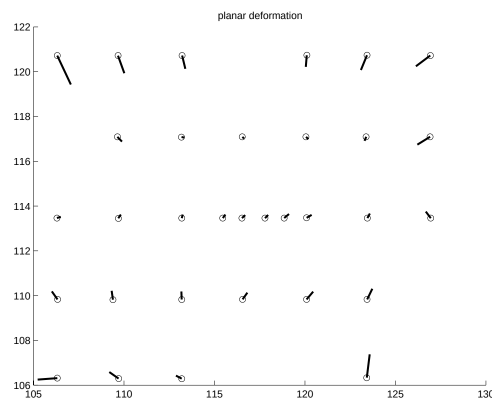

Figure 12. The planar deformations. The correct coordinates are marked with small circles. The biggest deformation vector in the top left corner of the figure is 5 cm. The units in the graph are metres.

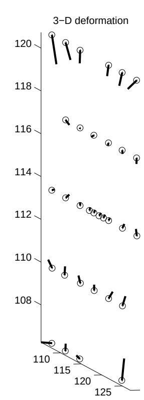

Figure 13. The accuracy in depth direction is better than the planar accuracy.

6. CONCLUSIONS

Because the lens distortions may be tens or hundreds of pixels on the edges of the images, camera calibration is essential in the creation of seamless panoramic image mosaics, especially if they are meant for measurement purposes. Deviations, like 1 mm, in the concentricity cause visible deformations to the image if the imaged object is close to the camera and not planar. Visually the camera can be adjusted to a correct place with the accuracy of some tenths of a millimetre. Also, the stitching order is important. The images should be combined symmetrically and according to the size of the overlap area to force the mosaic structure strong.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Amiri Parian J., Grün A., 2003. A Sensor Model for Panoramic Cameras, *Optical 3-D Measurement Techniques*, Vol. II, A. Grün / H. Kahmen (Eds.), pp. 130-141, Zurich, Switzerland.

Amiri Parian J., Grün A., 2004. A Refined Sensor Model for Panoramic Cameras, *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. XXXIV, Part 5/W16, H.-G. Maas and D. Schneider (Eds.).

Antipov I. T., Kivaev A. I., 1984. Panoramic Photographs in Close Range Photogrammetry, *International Archives of Photogrammetry and Remote Sensing*, Vol. XXV, Part A5, Commission V, pp. 32-38.

Brown D., 1971. Close-Range Camera Calibration, *Photogrammetric Engineering, August*, 1971, pp. 855-866.

Fryer J., 1996. Single Station Self-Calibration Techniques, *International Archives of Photogrammetry and Remote Sensing*, Vienna, Vol. XXXI, Part B5, pp. 178-181.

Grün, A., 1981. Precision and Reliability Aspects in Close-Range Photogrammetry, *The Photogrammetric Journal of Finland*, Vol.8, No. 2, pp. 117-132.

Haala N., Reulke R., 2004. Tree Species Recognition by Combination of Terrestrial Laser Scanning with High Resolution Panoramic Images, *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. XXXIV, Part 5/W16, H.-G. Maas and D. Schneider (Eds.).

Hartley R., 1993. Photogrammetric Techniques for Panoramic Cameras, *Integrating Photogrammetric Techniques with Scene Analysis and Machine Vision*, SPIE Proceedings Vol. 1944, Orlando, USA.

Hartley R., 1994. Self-Calibration from Multiple Views with a Rotating Camera, *Lecture Notes in Computer Science*, Jan-Olof Eklund (Ed.), Computer Vision -ECCV '94, Springer-Verlag Berlin Heidelberg, pp. 471-478.

Hoske P., Kunze G., 2004. Possible Applications of Panoramic Photogrammetry Concerning Construction Machines and Building Sites, *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. XXXIV, Part 5/W16, H.-G. Maas and D. Schneider (Eds.).

Luhmann T., Tecklenburg W., 2003. Potential of Panoramic View Generated from High Resolution Frame Images and Rotating Line Scanner Images, *Optical 3-D Measurement Techniques*, Vol. II, A. Grün / H. Kahmen (Eds.), pp. 114-121, Zurich, Switzerland.

Luhmann T., Tecklenburg W., 2004. 3-D Object Reconstruction from Multiple-Station Panorama Imagery, *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. XXXIV, Part 5/W16, H.-G. Maas and D. Schneider (Eds.).

Pöntinen P., 1999. On the Creation of Panoramic Images from Image Sequence, *The Photogrammetric Journal of Finland*, Vol. 16, No. 2, pp. 43-67.

Pöntinen P., 2002. Camera Calibration by Rotation, *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. XXXIV, Part 5, Commission V, ISSN 1682-1750, pp. 585-589.

Remondino F., Börlin N., 2004. Photogrammetric Calibration of Image Sequences Acquired with Rotating Camera, *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. XXXIV, Part 5/W16, H.-G. Maas and D. Schneider (Eds.).

Reulke R., Wehr A., 2003. Fusion of Digital Panoramic Camera Data with Laser Scanner Data, *Optical 3-D Measurement Techniques*, Vol. II, A. Grün and H. Kahmen (Eds.), pp. 142-149, Zurich, Switzerland.

Rönnholm P., Hyyppä H., Pöntinen P., Haggrén H., 2003. Interactive Relative Orientation Between Terrestrial Images and Airborne Laser Scanning Data, Proceedings of the ISPRS working group III/3 workshop '3-D reconstruction from airborne laserscanner and InSAR data', Dresden, Germany, H.G. Maas, G. Vosselman and A. Streilein (Eds), ISSN 1682-1750 VOLUME XXXIV, PART 3/W13 .

Scheibe K., Scheele M., Klette R., 2004. Data Fusion and Visualization of Panoramic Images and Laser Scans, *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. XXXIV, Part 5/W16, H.-G. Maas and D. Schneider (Eds.).

Schneider D., Maas H.-G., 2003. Geometric Modelling and Calibration of High Resolution Panoramic Camera, *Optical 3-D Measurement Techniques*, Vol. II, A. Grün / H. Kahmen (Eds.), pp. 122-129, Zurich, Switzerland

Szeliski R., 1996. Video Mosaics for Virtual Environments, *IEEE Computer Graphics and Applications*, March, pp. 22-30.

Wester-Ebbinghaus, W., 1982. Single Station Self Calibration, Mathematical Formulation and First Experiences, *International Archives of Photogrammetry*, Commission V, Vol. 24, York, pp. 533-550.