

Panoramic Mapping using CCD-Line Camera and Laser Scanner with Integrated Position and Orientation System

Ralf Reulke*
Institute for Photogrammetry
Stuttgart University

Aloysius Wehr†
Institute for Navigation
Stuttgart University

Reinhard Klette‡
CITR, Computer Science Department
The University of Auckland

Martin Scheele, and Karsten Scheibe§
German Aerospace Center DLR
Competence center

Abstract

The fusing of panoramic camera data with laser scanner data will be discussed on measurement results obtained during verification tests using the Digital 360° Panoramic camera (M2) developed by German Aerospace Center (DLR) in cooperation with Kamera und System Technik GmbH (KST) and the imaging laser scanner (3D-LS) developed by Institute of Navigation University Stuttgart (INS). First the measurement setup will be presented. Here M2 and 3D-LS are used as independent individual sensors surveying the same target. Then the data sampling and preprocessing for each sensor will be explained and the problem of transforming both independent data sets into one common coordinate system will be addressed by discussing the results of the verification tests.

Keywords: Digital panoramic camera, laser scanner, inertial measurement unit, data fusion

1 Introduction

Generation of city models offering a high realistic impression requires three-dimensional imaging sensors with high 3D resolution and high image quality. Today surfaces can be surveyed very precisely in a reasonable short time with laser scanners. However, these systems very often sample only depth data. Some of them offer monochrome intensity images of poor quality in the spectral range of the laser beam (e.g. NIR). Today some commercial laser scanners use additional imaging color sensors for obtaining colored 3D images. However, with regard to building surveying and setting up Cultural Heritage Archives the resolution must be improved. This can be achieved by combining a high-resolution digital 360° panoramic camera with a laser scanner. The panoramic camera uses triple CCD line array sensors each comprising about 10000 pixels. This sensor head samples vertical image lines. By turning the optical sensor about the azimuth angle with 360°, it delivers very high resolved panoramic color images showing the surface texture in detail. Fusing these image data with 3D information of laser scanning surveys very precise 3D models with detailed texture information will be obtained. This approach is related to 360° geometry. Linear structures can be acquired only from different standpoints with variable resolution. To overcome this problem, laser-scanner and panoramic camera should be linearly moved along e.g. a building facade.

*e-mail: Ralf.Reulke@ifp.uni-stuttgart.de

†e-mail: Aloysius.Wehr@nav.uni-stuttgart.de

‡e-mail: r.klette@auckland.ac.nz

§e-mail: fi rstname.lastname@dlr.de

Table 1: Technical parameter of the digital panoramic camera

| | |
|---------------------------------|--------------------|
| Number of Pixel | 3*10200 (RGB) |
| Radiometric dynamic/resolution | 4ms up to infinite |
| Data rate | 15 Mbytes / s |
| Data volume 360 (optics f=60mm) | 3GBytes |
| Acquisition time | 4 min |
| Power supply | 12 V |

Applying this technique the main problem is georeferencing and fusing the two data sets of the panoramic camera and the laser scanner respectively. The experimental results shown in the following will deal with this problem and will lead to an optimum surveying setup comprising a panoramic camera, laser scanner, a position and orientation system. This surveying and documentation system will be called POSLAS-PANCAM (POS supported laser scanner panoramic camera).

Verification experiments were carried out with the Digital 360° Panoramic camera (M2), the 3D-Laserscanner (3D-LS) and a Position and Orientation System (POS).

2 SYSTEM OVERVIEW

The following section describes the hardware.

2.1 Digital 360 Panoramic Camera (M2)

The digital panoramic camera EYESCAN will be preliminary used as a measurement system to create high-resolution 360 panoramic images for photogrammetry and computer vision [Scheibe et al. 2001; Klette et al. 2001; Klette et al. 2003]. The sensor principle is based on a CCD line, which is mounted on a turntable parallel to the rotation direction. Moving the turntable generates the second image direction. To reach highest resolution and a large field of view a CCD-line with more than 10,000 pixels is used. This CCD is a RGB triplet and allows acquiring true colour images. A high SNR electronic design allows a short capture time for a 360° scan.

EYESCAN is designed for rugged everyday field use as well as for the laboratory measurement. Combined with a robust and powerful portable PC it becomes easy to capture seamless digital panoramic pictures. The sensor system consists of the camera head, the optical part (optics, depth dependencies) and the high precision turntable with DC-gear-system motor.

Table 1 summarises the principle features and fig. 1 shows an image of the camera: The camera head is connected to the PC with a bidirectional fibre link for data transmission and camera control.

The camera head is mounted on a tilt unit for vertical tilt of $\pm 30^\circ$ with 15 stops. Axis of tilt and rotation are in the needlepoint.

The preprocessing of the data consists of data correction (PRNU, DSNU, offsets) and a (non linear) radiometric normalisation to cast the data from 16 to 8 bit. All this procedures can be run in real time or off line. Additional software parts are responsible for real-time visualisation of image data, a fast preview for scene selection and a quick look during data recording.

Typical commercial image processing programs are not able to handle the huge raw data amount for one 360° panoramic scan of about 3 GByte. In addition some routines must be implemented for spatial coregistration of the RGB channels to correct the effect of the triplet view

- 90° rotation of the whole image,
- Visualisation of selected image parts,
- Histogram and contrast equalisation,
- Correction of the panoramic effect.

The last processing step is necessary for visualization and transforms image parts from the cylindrical panorama into a classical plane view.

2.2 3D-LS

In the experiments M2 was supported by the 3D-LS. This imaging laser scanner carries out the depth measurement by side-tone ranging [Wehr 1999]. This means, the optical signal emitted from a semiconductor laser is modulated by high frequency signals. As the laser emits light continuously such laser system are called continuous wave (cw) laser system. The phase difference between the transmitted and received signal is proportional to the two-way slant range. Using high modulation frequencies, e.g. 314 MHz, resolutions down to the tenth of a millimeter are possible. Besides depth information these scanners sample for each measurement point the backscattered laser light with a 13 bit resolution. Therefore, the user obtains 3D surface images. The functioning of the laser scanner is explained in ([Wehr 1999]. fig. 2 shows 3D-LS. The technical parameter are compiled in tab. 2

3 Fusion of M2 and 3d-LS Data

3.1 Surveying setup

In order to study the problems arising by fusion of data sets of the panoramic camera and the 3D-LS, both instruments took an image of a special prepared scene, which were covered with well-defined control points in a laboratory (s. fig. 3). The camera M2 was mounted on a tripod (like in fig. 1). After completion of the camera



Figure 1: M2 on Tripod

Table 2: Technical parameter of the digital panoramic camera

| | |
|----------------------------|---|
| laser power | 0.5 mW |
| optical wavelength | 670 nm |
| inst. field of view IFOV | 0.1 |
| total field of view FOV | 30 x 30 |
| scanning pattern | 2-dimensional line (standard)vertical line scanfree programmable pattern |
| number of pixels per image | max. 32768 x 32768 pixels |
| range | < 10 m |
| ranging accuracy | 0.1 mm (for diffuse reflecting targets with $\rho = 60\%$ in 1m distance) |
| side tone frequencies | 10 MHz, 314 MHz |
| measurement rate | 2 kHz (using on side tone) 600 Hz (using two side tones) |

recording M2 were dismantled and 3D-LS were mounted on the tripod without changing the tripod's position. 3D-LS were used in the imaging mode scanning a field of view (FOV) of $30^\circ \times 30^\circ$ comprising 800 x 800 pixels. Each pixel is described by the quadruple Cartesian coordinates plus intensity (x, y, z, I). The M2 image covers a FOV of approximately $30^\circ \times 60^\circ$ with 5000 x 10000 pixels. fig. 3 shows a part of the image from the panorama camera. The curved line e.g. from the desk is a typical effect of the panorama geometry.



Figure 2: Laserscanner 3D-LS

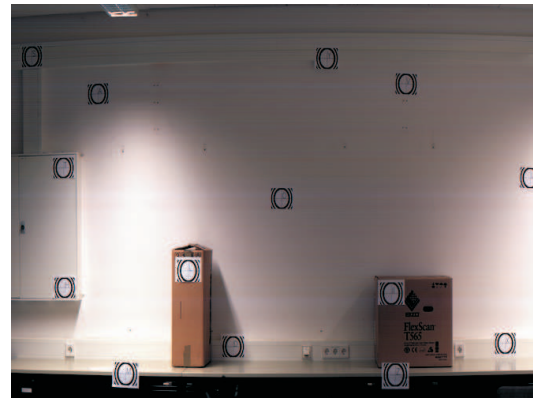


Figure 3: Measurement scene with control points

3.2 Modeling and Calibration

Laser scanner and panoramic camera work with different coordinate systems and must be adjusted one to each other. The laser scanner delivers Cartesian coordinates; where as M2 puts out data in a typical photo image projection. Although, both devices were mounted on the same tripod one had to regard that the projection center of both instruments were not located exactly in the same position. This section describes the geometrical relation between the digital surface data of the laser scanner and the image data from the camera, or the relation between object points and position of image pixel. This task needs a model of panoramic imaging and a calibration with known target data.

The imaging geometry of the panoramic camera is characterized by the rotating CCD-line, assembled perpendicular to the x-y plane and forming an image by rotation around the z-axis. The modeling and calibration of panoramic cameras was investigated and published recently [Klette et al. 2001; Klette et al. 2003; Schneider and Maas 2002; Schneider 2003].

For camera description and calibration we use the following approach (see fig. 4). The CCD-line is placed in the focal plate perpendicular to the z'-axis and shifted with respect to the x'-y' coordinate origin by (x'_0, y'_0). The focal plate is mounted in the camera at a distance, which is appropriate to the object geometry. If the object is far from the camera the CCD is placed in the focal plate of the optics at z' = -c (the focal length) on the z'-axis behind the optics (lower left coordinate system). To form an image, the camera is rotated around the origin of a (x, z) coordinate system (upper right coordinate system).

To derive the relation between object point and a pixel in an image the colinearity equation can be applied.

$$\underline{X} - \underline{X}_0 = \lambda \cdot (\underline{x} - \underline{x}_0) \quad (1)$$

To see this object point with a pixel of the CCD-line on the focal plate, the camera has to be rotated by an angle of κ around z-axis. For the simplest case (y_0 = 0) the result is

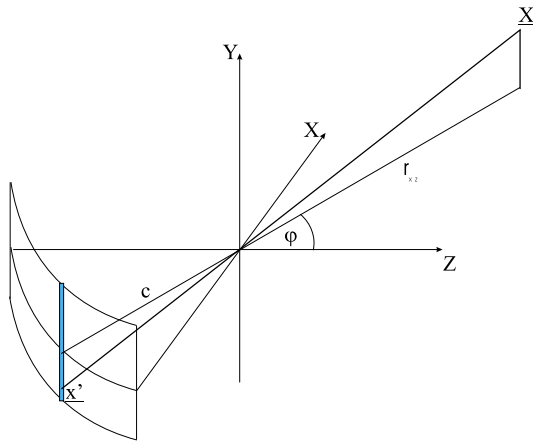


Figure 4: Panoramic imaging (see text)

$$(\underline{X} - \underline{X}_0) = \lambda \cdot \underline{R}^T \cdot (\underline{x}' - \underline{x}'_0)$$

$$(\underline{X} - \underline{X}_0) = \lambda \cdot \begin{bmatrix} \cos \chi & -\sin \chi & 0 \\ \sin \chi & \cos \chi & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} c \\ 0 \\ z' - z'_0 \end{bmatrix} \quad (2)$$

$$(\underline{X} - \underline{X}_0) = \lambda \cdot \begin{bmatrix} c \cdot \cos \chi \\ c \cdot \sin \chi \\ z' - z'_0 \end{bmatrix}$$

The unknown scale factor can be calculated from the square of the x-y components of this equation:

$$\lambda = \frac{r_{XY}}{c} \quad r_{XY} = \sqrt{(X - X_0)^2 + (Y - Y_0)^2} \quad (3)$$

The meaning of r_{XY} can easily be seen in fig. 4. This result is a consequence of the rotational symmetry. By dividing the first two equations and using the scale factor for the third, the following equations deliver an obvious result, which can also be geometrically derived.

$$\frac{\Delta Y}{\Delta X} = \tan \kappa \quad \text{and} \quad \Delta Z = r_{XY} \cdot \frac{\Delta z'}{c} \quad (4)$$

The image or pixel coordinates (i, j) are related to the angle κ and the z-value. Because of the limited image field for this investigation, only linear effects (with respect to the rotation and image distortions) should be taken into account:

$$i = \frac{1}{\delta \kappa} \cdot a \tan \frac{\Delta Y}{\Delta X} + i_0 \quad j = \frac{c}{\delta z} \cdot \frac{\Delta Z}{r_{XY}} + j_0 \quad (5)$$

Δz is the pixel distance, $\Delta \kappa$ the angle of one rotation step and c is the focal length.

The unknown or not exactly known parameters $\Delta \kappa$, i_0 , c and j_0 can be derived from known marks in the image field.

For calibration we used 16 signalized points randomly distributed and in different distances from the camera. Exact location and distance was measured with the laser scanner. The analyzing of the resulting errors in the object space shows, that the approach from equation (4) and (5) must be extended. Following effects should be incorporated:

- Rotation of the CCD (around x-axis)
- Tilt of the camera (rotation around y-axis))
- Off-axis rotation of the projection center (X_0, Y_0)
- Distortion effect of the optics
- Shift of the CCD in y-direction

All these effects can be described by extension of equation (2) with better interior orientation, rotations around x- and y-axis in the rotation matrix and a rotation of the projection center around an idealized rotation axis. The following table shows the different effect and here influence on the calibration result.

The result of the error analysis (tab. 3) is in relation to limited number of signalized points and the small field of view of the scene (30° × 30°). The resulting error is comparable to the size of the light spot of the laser.

Table 3: Calibration model and the influence on calibration error (distance to the objects is in X-direction)

| Model | Value | σ in Y [mm] | σ in Z [mm] |
|--|-------------|--------------------|--------------------|
| Linear Model (5) | | 13 | 33 |
| Rotation of the CCD | 1.2° | | |
| Tilt of the camera | 0.03 | 4 | 24 |
| Linear distortion | 0.97 | 4 | 5 |
| y0 | $30 \mu m$ | | |
| Off axis rotation of projection center | 10 mm | 3 | 5 |

3.3 Fusion of Panoramic and Laser Scanner Data

The calibration procedure, as shown in the last section delivers a relation between image coordinates (i,j) and object points (X,Y,Z). The classical orthophoto approach however is in the opposite direction. After defining the region, which should be orthorectified, the procedure is the following:

- Discretisation of this region with a defined object pixel distance
- For each location take the height and calculate for the object coordinates (X,Y,Z) the equivalent image point (i,j)
- Put the grey or color value in the object raster

A resulting problem of panoramic geometry is the implicit relation between the pixel coordinates i and the rotation angle κ , which is only solvable for the simplest case (5). Because of CCD-line rotation and camera tilt the pixel coordinate can be determine only in an iterative way. An additional problem results from the small object distance to height relation, which is addressed by the true ortho-rectification. Occludes areas from larger objects will be filled with wrong object texture and some objects seems to be twice.

An approach, which avoids both problems is based on ray tracing. The procedure starts from pixel location (i,j) and calculates the equivalent object point (see e.g. [Scheele et al. 2001]). fig. 5 shows the result of co-registration of depth and image data.

In the rectified image image errors can be observed in the box occluded regions. The white background of the DEM image represents the wall in the background of the left image (see fig. 6).



Figure 5: Orthorectified panoramic image based on the digital elevation model from laser scanner

4 POSLAS-PANCAM

The results of the preceding experiments leads to an integrated mechanical setup of the M2, 3D-LS and the Applanix POS which is called POSLAS-PANCAM (PLP-CAM). fig. 7 depicts that the center of rotation of the inertial measurement unit (IMU) of POS, the origin of 3D-LS and the phase center of the GPS antenna are aligned to a vertical line which is the axis of rotation. M2 is mounted off axis. This construction eases the computation effort with respect to data fusion, as the 3D-LS data can be precisely related to the POS data as the lever arms were minimised and are well defined by the construction. The algorithms for transforming the position and orientation data with regard to 3D-LS center which is defined in the center of the first scanning mirror fig. 7 are available in the Applanix software PROSPOC. For fusing the M2 data with the 3D-data the parallax between M2 and 3D-LS must be regarded. In a first approximation it can be derived from the construction drawings. However, for precise surveys a special calibration is required which gives the parameters for correcting manufacturing tolerances. The calibration is carried out using a sophisticated test field e.g. described in chapter 2.1 and applying photogrammetric means.

For PLP-CAM one main problem is the exact synchronization between the different devices, because each item works independently. The block chart in fig. 8 shows that this problem is solved by using two event markers. These markers are stored in POS and evaluated during post processing. The 3D-LS launches an event marker when a scanning line is started. At that instant the local time of the controlling PC is stored on this PC. M3 transmits an event marker to POS starting the readout of the CCD-line. fig. 10 depicts the setup on an experimental moving carrier and fig. 11 presents the first result of an outdoor test.

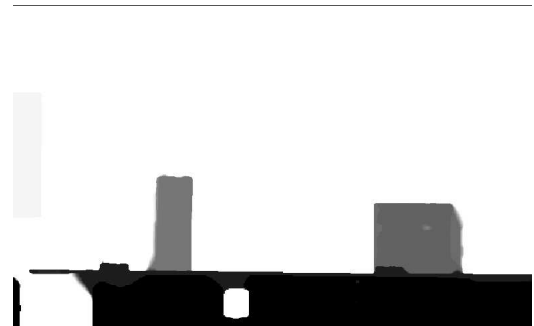


Figure 6: digital elevation model from laser scanner

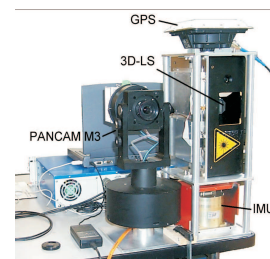


Figure 7: PLP-CAM



Figure 8: Reference Point of 3D-LS

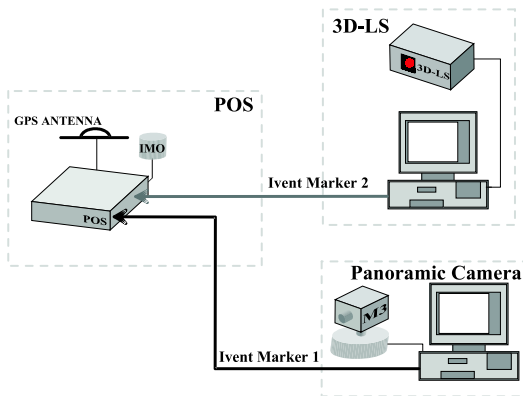


Figure 9: Synchronization



Figure 10: PLP-CAM on moving platform

5 Rectification of Line Scanner Data

First experiments were done with line scanner data from a (non-rotating) moving platform. For rectification we use attitude data from the Applanix system. The rectification was done on a plane and is equivalent to airborne data rectification [Scheele et al. 2001]. Fig. 12 shows the original data. The following fig. 13 shows the result after correction. The analysis of the attitude data shows, that the amplitude of the disturbing movements of the platform are much more larger then for the airborne application.

6 Conclusion

The laboratory experiments fusing M3 data with 3D-LS data show that using such an integrated system high resolved 3D-images can be computed. The processing of the two independent data sets make

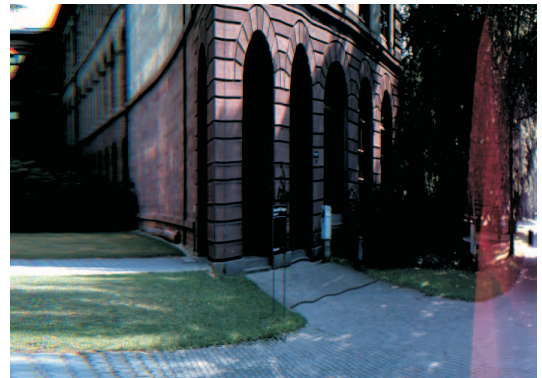


Figure 11: Result of outdoor test

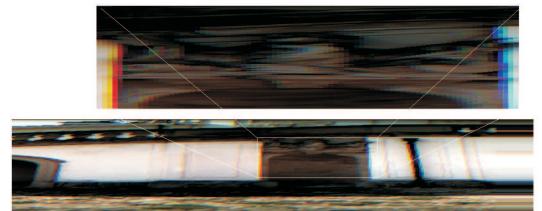


Figure 12: Original data



Figure 13: Rectified data

clear that a well defined and robust assembly is required. Such an assembly benefits from the well defined locations of the different origins and the relative orientation of the different devices with respect to each other. These parameters must be derived by using a special calibration test field. The experiments with PLP-CAM demonstrated that in courtyards and in narrow street with high buildings one has to face poor GPS signals. Here the POS-AV system of Applanix company was used. It worked very degraded, because it is designed for airborne applications, where one do not have to regard obscurations and multipath effects. For this application POS-LV system of Applanix will deliver improved results.

References

- KLETTE, R., GIMEL'FARB, G., AND REULKE, R. 2001. Wide-angle image acquisition, analysis and visualization. In *Proc. 14th Internat. Conf., Vision Interface (VI'2001)*, 114–125.
- KLETTE, R., GIMELFARB, G., HUANG, F., WEI, S.-K., SCHEELE, M., SCHEIBE, K., AND BÖRNER, A. 2003. Review on research and applications of cylindrical panoramas. Tech. Rep. CITR-TR-123, Centre for Image Technology and Robotics, The University of Auckland, New Zealand, January.
- SCHEELE, M., BÖRNER, A., REULKE, R., AND SCHEIBE, K. 2001. Geometrische korrektoren: Vom flugzeugscanner zur nahbereichskamera. *Photogrammetrie, Fernerkundung, Geoinformation*.
- SCHEIBE, K., KORSITZKY, H., AND REULKE, R. 2001. Eyescan - a high resolution digital panoramic camera. In *Proc. Robot Vision 2001*, 77–83.
- SCHNEIDER, D., AND MAAS, H.-G. 2002. Geometrische modellierung und kalibrierung einer hochauflsenden digitalen rotationszeilenkamera. In *DGPF-Tagung*.
- SCHNEIDER, D. 2003. Geometrische modellierung und kalibrierung einer hochauflsenden digitalen rotationszeilenkamera. In *2. Oldenburger 3D-Tage*.
- WEHR, A. 1999. 3d-imaging laser scanner for close range metrology. In *Proc. of SPIE, Vol. 3707*, SPIE, 381–389.