

SUPPLEMENTING LASERSCANNER GEOMETRIC DATA WITH PHOTOGRAMMETRIC IMAGES FOR MODELING

Fredie Kern

Institute for Geodesy and Photogrammetry, Technical University of Braunschweig, Germany
Gaußstraße 22, D-38106 Braunschweig
f.kern@tu-bs.de

KEY WORDS: laserscanner, camera calibration, texture mapping

ABSTRACT

The laser scanner take just a few minutes time to scan millions of points with arbitrary resolution. These can be compared to results achieved from measurements done using photogrammetric standard. Although photogrammetric methods produce both geometric and color information while scanner can up to now not capture color. Furthermore, one can determine easily interpret and analyse photos thus being able to extract further details like the object material or supplementing the geometry of areas in the shadow of the objects. The paper should explain how laserscanning can be used to fill up the photometric shortfalls in the use of two pictures for 3D geometric measurements. The combination of photogrammetric and laser scanner systems compliments one another perfectly for a complete object modelling. The main function of the combined system is to create textures for the surface model derived from a cloud of points. Therefore it is necessary to examine the mathematical function for the geometric relation between the images and the cloud of points. A calibration method for this problem will be described. An example for an automated generated 3D model is given.

1 OBJECT MODELING

Measurements are necessary to create a model of the reality. Models are used in documenting a fixed condition of the reality. By analyzing the model one can get some new knowledge about the object. Two different forms of information can be separated in modelling processes. There is on one hand, geometric information which is very important for object description, the geometry then forms the foundation of documenting further thematic information on the another hand. The thematic information could be data of physical, chemical, historic or legal properties. There exists a lot of technical solutions for the determination of these physical parameters, eg. kinds or strength of material. Photogrammetry is a well known technique for measurement of geometric information and physical properties which are influenced by light. With photos you can determine the object color perfectly. Despite all modern technology, a human expert has to finally survey all facts to examine the important object features like building epoch or construction details.

2 PHOTOGRAMMETRY AND LASERSCANNING

2.1 THE ESSENCE OF PHOTOGRAMMETRY

When we confine object modelling only to the geometric modelling, photogrammetry is an elegant measurement method. One is able to remotely capture a lot of images by occupying an object location for a short time period. Each image is a model of an object part in the form of an array of pixels, with the pixel values being a function of the object color and the lighting exposure of the object surface at the moment of photography. The image is a miniature model of the reality based on optical laws. In architectural photogrammetry, image scales range from 1:50 to 1:200 which implies that one pixel represents many object details. The image scale and the geometric pixel size define the object resolution. A big advantage of the photogrammetric method is that the central perspective is a simulation of the human seeing process thus making image interpretation by a viewer easy. On the contrary, it requires in theory two images to extract 3D information whereby relative strong restrictions must be fulfilled by the two images. They must be taken from different positions, cover same object parts and the rays to homologous points must intersect at a good angle. Usually more than two, typically more than a dozen images are used to reconstruct an object in 3D co-ordinates. Subsequent from the point information higher geometric primitives like lines or planes are modelled. This point by point evaluation results in a wireframe model or an boundary representation which can used to create ground plans, cuttings or views.

2.2 THE ESSENCE OF LASERSCANNING

Laserscanners work in a similar manner like robotic tacheometer with reflectorless distance measurement capability (Fig. 1). A laser beam is sent out in all directions within a equidistant grid. The laser light is reflected back to the laserscanner by the object surface. By measurement of the time of flight the distance in a fixed direction can be

determined. Two fast rotating mirror deflects the laser light in vertical and horizontal directions. Some laserscanner systems however deflect only in horizontal or vertical directions and realize the second component of direction (vertical resp. horizontal) with the help of a servo. The deflection mirror and servo system in a laserscanner correspond to the readings (horizontal and vertical angles) of the pitch circles in a theodolite. With the distance measurement and the corresponding horizontal and vertical angle the 3D position of the object can be derived. The angle of the laserscanner beam radiation defines the resolution of the scan. The scanning is an automatic process where the whole sphere around the scanner is measured resulting in a cloud of points.

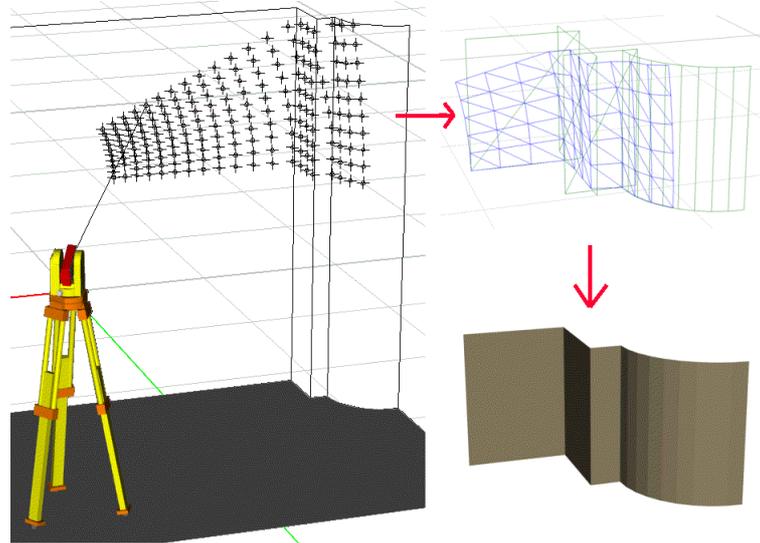


Figure 1: Scanning a cloud of points → boundary representation → extract elementary features

Table 1: Laserscanner

	LARA 25200	CYRAX 2500	SOISIC	LMS-Z210	Callidus V1.1
manufacturer	Zoller+Fröhlich GmbH	Cyra Technologies, Inc.	MENSI	RIEGL Laser Measurement Systems GmbH	Callidus Precision Systems GmbH
type	panoramic view	camera view	camera view	camera view	panoramic view
technique	phase measurement	time of flight	triangulation	time of flight	time of flight
resolution					
[mm/10m]	7.8	0.1	1.0	-	44.0
range					
Distance	< 12.6m or < 25.2m	< 100m	2,5-25m	2-150m	< 32m
speed					
[mill. points/h]	2250	1	0.36	10	4
accuracy					
Distance	3mm+2mm/10m	4mm	-	25-100mm	5mm
co-ordinate	-	6mm/50m	0.3mm (2m) 0.6mm (5m)	> 25mm	3mm/10m

Tab. 1 outlines properties of some laserscanner systems available in the market. It is possible to classify different kinds of laserscanners. The first is referred to as *camera view* laserscanner, which has a view that is similar to that of a photo camera. The second is referred to as *panoramic view* laserscanner because of its capability to scan the whole hemisphere like a panoramic camera. Camera view laserscanner are specially used to scan solid objects like sculptures while panoramic view scanners are used to scan the interior of objects as they cover the entire environment within the object. Using a panoramic laserscanner for scanning rooms of a building, it takes a minimal number of scans from different positions as compare to a camera view scanner or a photogrammetric camera. The resolution, period of scan and accuracy varies broadly between the different laserscanners. The system from MENSI works with high accuracy (0.3mm) for a point measurement but required a longer period to scan compared with the Callidus, 5mm accuracy and 1 millions points/h. This is as a result of the special construction of this scanner. The MENSI systems works according to

the triangulation principle. The laserscanner systems LARA 25200, Cyrax 2500 and Callidus can measure with an accuracy of approx. 5mm. With the Cyrax cloud of points can be done with a fine angle increment of 0.3mgon while the Callidus only works with a minimal angle increment of 278mgon.

It is possible to capture the geometry of any kind of object by using laserscanning. Nevertheless there are known limitations similar to those in photogrammetry for objects which are self-covered (concave). Laserscanning has the advantage that the measurement process is fully automatic. Furthermore the cloud of points is a 1:1 scaled 3d geometric model of the object compared to the miniature primary model produced by photogrammetry. The cloud of points contains unstructured information just like a photogrammetric image contains pixels without topological information. Both the cloud of points and the photogrammetric image have to be processed in order to get useful information. After the scanning the cloud of points is reduced into geometric primitives thereby it is important to know that no discrete corner (vertex) of the object was measured by the laserscanner. Therefore the vertices for a wireframe model have to be constructed by intersecting planes or other primitives. The approximation of planes or surfaces is easy and without risk because one feature may be represented by a lot of scanned points. On the other hand the evaluation of a cloud of points requires a surface oriented philosophy. One point of the cloud alone represents no object geometry. Three (triangle) or more points represent a part of object surface.

3 COMBINATION OF PHOTOGRAMMETRY AND LASERSCANNING

Table 2: The combination of photogrammetry and laserscanning complements one another perfectly.

	Photogrammetry	Laserscanning
advantages	<ul style="list-style-type: none"> ⊕ images are easy to read; common medium ⊕ realtime ⊕ measure the reflected light from object (color), one lightsource (ambient light) is required 	<ul style="list-style-type: none"> ⊕ 3d geometry scaled 1:1 ⊕ quick measurement, only few minutes ⊕ independent from ambient light; illumination by the laser beam; the lot of light is known ⇒ estimate of reflectance is possible
disadvantages	<ul style="list-style-type: none"> ∅ for 3d geometry two images with corresponding contents are required ∅ two phase process; 1st takes the images 2nd examine geometry by merging the images 	<ul style="list-style-type: none"> ∅ no details about color, texture, material etc. ∅ difficult to interpret

A look at the summary in Tab. 2 highlights the advantages and disadvantages of both photogrammetry and laserscanning, one can realize that the two techniques could complement one another perfectly. Photogrammetry is a quick measurement technique that produces easy to interpret models by using color (light) information. Laserscanning on the other hand can perfectly capture 3d geometry from any (not applicable to reflective and transparent objects) object in high resolution automatically, hence a combination of the two techniques would be more fruitful. The Callidus system which has an integrated video camera to take picture simultaneously during scanning embraces this idea. Presented here are some potential aspects of the Callidus system which supplements scanner data with video images. The technique differs from the combination which is described in [8] where 3d scanner data is used to create ortho images by differential rectification. The goal of supplementation is a textured 3d model for post-processing like virtual reality.

3.1 CALLIDUS SYSTEM WITH AN INTEGRATED VIDEO CAMERA

The integrated video camera of the Callidus system is used to take still images at predefined positions distributed regularly over a 360° arc. The video camera and the lasersensor rotate horizontally together during the scanning process. In addition to the horizontal motion an extra tilting in the vertical direction is possible for the camera (Fig. 2a) resulting in a mosaic of overlapping images.

The video camera provides images with a format of 576×720 pixel. This low resolution, the autofocus and the automatic gain control yield poor quality images. Subsequent photogrammetric computation will then result in low accuracy. In addition high effects of lens distortion are to be expected too because the internal image processing of the video camera destroys the geometric relationship between the CCD and the image signal [3,p. 173].

A standard scanning with Callidus results in a 1×11 mosaic covering the whole horizon by zooming or changing the focal length of the camera and using the tilting option one can capture 2×11 mosaic of images with different sidelap and overlap (Fig. 3).

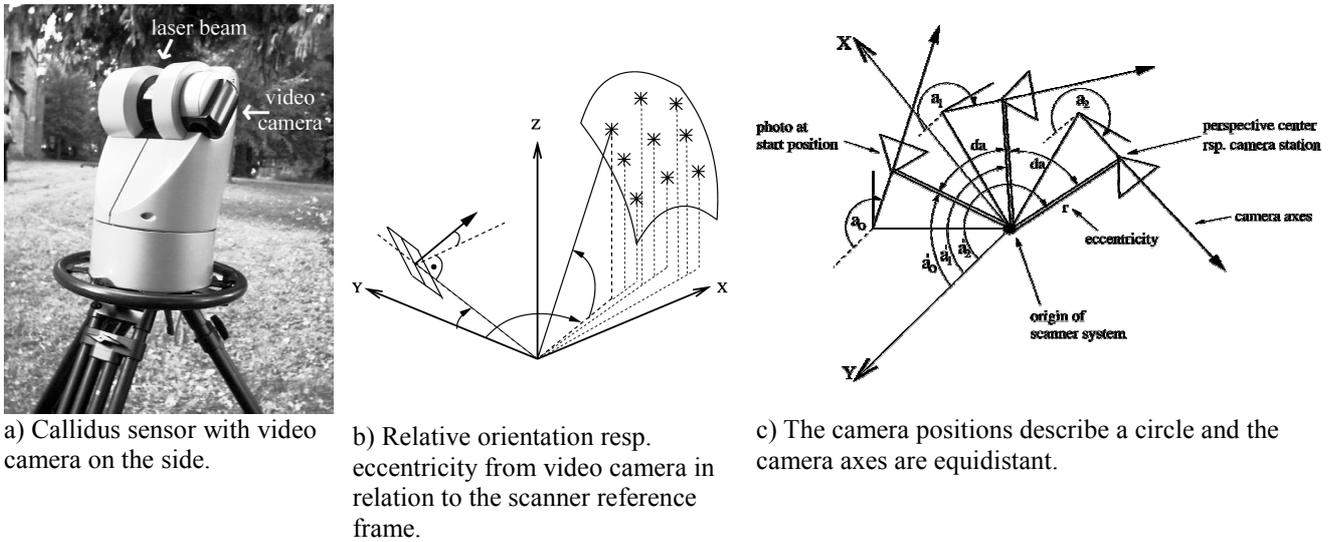


Figure 2: The Callidus has an integrated video camera, which is mounted at an eccentric position based on the rotation center of the scanner. The Goal of calibration is to determine the radius of the running circle r and the unknown direction at start position a_0 .



Figure 3: Example for a 2×11 mosaic of images (courtyard of the gothic Cistercian abbey in Walkenried)

3.2 Calibration the Video Camera

The co-coordinates of the cloud of points are related to the local reference frame of the scanner sensor. The origin of the scanner reference frame is the point of intersection of the horizontal and vertical rotation axes. The zero of the X-direction is only roughly defined by an electronic compass, the Z-direction runs parallel to vertical rotation axis of the laser unit. The Z-direction need not necessarily correspond to the zenith because no levelling of the instrument is necessary to operate the scanner.

To determine the geometric relationship between the cloud of points and images, the camera positions, the camera axes (azimuth, tilt and swing), the inner orientation and lens distortion of the camera have to be examined. The effect of the eccentricity to the camera axes is illustrated in Fig. 2c. A constant angle error will not effect the azimuth interval but the start angle a_0 . The same applies to the tilt t_0 . t_0 and a_0 are unknown variables. The camera axes (a_i, s_i) of the i^{th} image is calculated as follows;

$$a_i = a_0 + i da \quad i = 0 \dots N_{\text{photos per row}} \quad (1)$$

$$s_i = s_0 + i ds \quad i = 0 \dots M_{\text{photos per column}} \quad (2)$$

The eccentricity of the video camera is determined from the exterior orientation parameters of the images. The mathematical relationship between the camera reference frame (X^C, Y^C, Z^C) and the scanner reference frame (X, Y, Z) is as follows:

The derivation of the eccentricity radius r are is achieved by using the equation:

$$\mathbf{X}_j^C = \mathbf{R} (\mathbf{X}_j - \mathbf{X}_{0,j})$$

where

$$\mathbf{R} = \begin{bmatrix} -\cos a_i \cos s_i - \sin a_i \cos t_i \sin s_i & \cos a_i \sin s_i - \sin a_i \cos t_i \cos s_i & -\sin a_i \sin t_i \\ \sin a_i \cos s_i - \cos a_i \cos t_i \sin s_i & -\sin a_i \sin s_i - \cos a_i \cos t_i \cos s_i & -\cos a_i \sin t_i \\ -\sin t_i \sin s_i & -\sin t_i \cos s_i & \cos t_i \end{bmatrix} \quad (3)$$

a_i : azimuth, t_i : tilt, s_i : swing

$\mathbf{X}_{0,j}$: position of perspective center of image i

$$r = \sqrt{X_{0,j}^2 + Y_{0,j}^2 + Z_{0,j}^2} \quad (4)$$

Applying the Eq. 1 and 2 as constraints yields the parameters a_0 , da , s_0 and ds . For the calibration process it is necessary to have enough control points ($j \dots N_p$) which have co-ordinates in both reference frames. The scanning process delivers a lot of points but their identity is not given because a laserscanner aims blindly. For this problem special control panels (Fig. 4) were designed with the goal of having both photogrammetric and scanner control points at once.

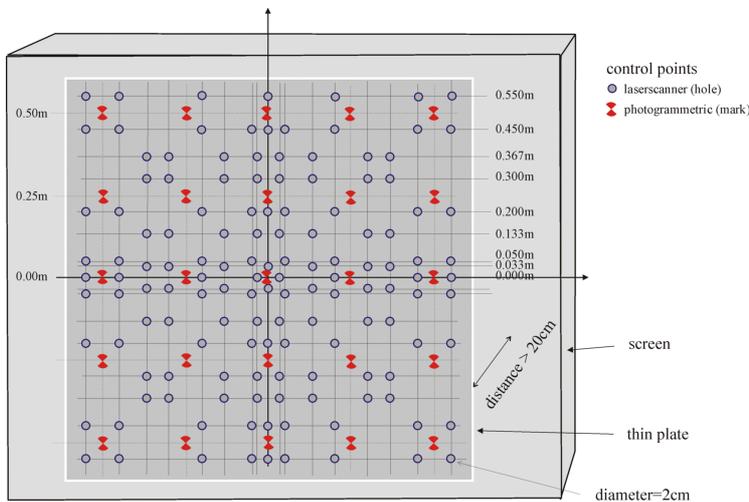


Figure 4: Details of construction of the control panels.

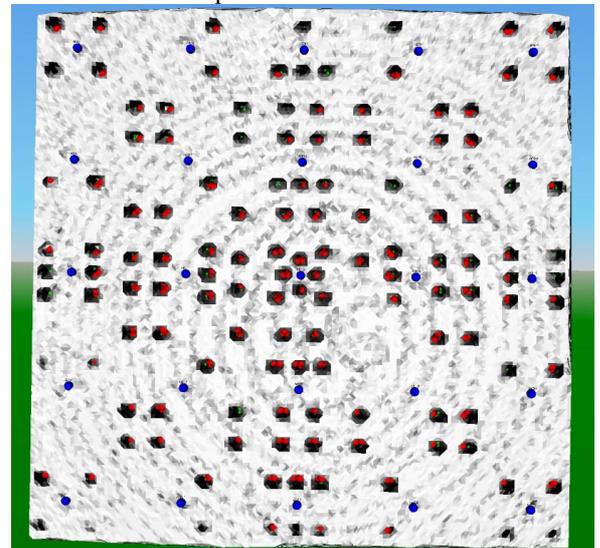


Figure 5: A part of the cloud of points shown as a surface model. Scanner measurements through a hole are marked as spheres. The successful identification process can be controlled by verifying the point numbers.

For measurements from the images the photogrammetric control points were painted in a conventional grid manner on a panel (25 per control panel). The control points for the laser scanner are simple 2cm diameter holes in the panel. If a laser measurement "flight" passes through a hole, the resulting registered distance is much longer than all other distances in the neighbourhood on the panel. The displacement of a scanner point to the plane, which represents an approximation of all other scanner points, is the criteria to select laser measurements that passed through the hole. The separation of points on and points behind the control panel is then simple to realize. To identify a measurement that passed through the hole, means to examine the correct point number of the hole. The holes were drilled using a special arrangement based on Golomb-rulers [7]. A ruler marked at 0,1,4,6 (cm) is called gracefully labeled because such a ruler can measure all integral distances from zero to the length of the ruler, namely 1, 2, 3, 4, 5, 6 (cm). In this case, all distances between pairs of marks are different and run consecutively from zero to the ruler's total length. Inverting the characteristic of Golomb-rulers a distance can identify the pair of marks. For example if one has the distance of 3 (cm) and one knows the marks are prepared by the Golomb-ruler 0,1,4,6 the used pair of marks are 1 and 4. Based on this principle, the holes in the control panel were drilled using the (not gracefully labeled) Golomb-ruler 0,1,4,9,11. During the identification process, all possible distances between the separated hole measurements are calculated and compared with the known distance between the holes. The algorithm for the identification try each possible numbering of the pairs of separated holes. The algorithm stops if a high correlation is reached; typically after 60-70%. Fig. 5 shows a result of this full automated identification process.

The position of the photogrammetric control points in relation to the holes is known therefore their co-ordinates can easily be transformed in the scanner reference frame after identifying the scanner control points. After this step the exterior orientation for all video images can be calculated. The image co-ordinates relate to the object co-ordinate by the well known central perspective formula.

$$px_j = px_0 + f_x \frac{X_j^C}{Z_j^C} - D_x(px_j, py_j, \dots)$$

$$py_j = py_0 + (f_x + df_y) \frac{Y_j^C}{Z_j^C} - D_y(px_j, py_j, \dots)$$

where

px_0, py_0 : location of principal point

f_x : focal length in x -direction of camera reference frame

df_y : bias for focal length in y -direction to correct affinity

$D_x(), D_y()$: model functions for lens distortion

The perfect modeling of the lens distortion is very important as the image quality is poor. To this end, the model function by Beyer [3,p.124] has been used to consider the many systematic effects: the radial symmetry, the radial asymmetry and the tangential lens distortion plus shearing.

$$D_x(px, py, \dots) = DK_x(\dots) + DP_x(\dots) + DC_x(\dots)$$

$$D_y(px, py, \dots) = DK_y(\dots) + DP_y(\dots) + DC_y(\dots)$$

where

$$DK_x(\dots) = px' (K_1 r^1 + K_2 r^2 + K_3 r^3 + K_4 r^4)$$

$$DK_y(\dots) = py' (K_1 r^1 + K_2 r^2 + K_3 r^3 + K_4 r^4)$$

$$DP_x(\dots) = P_1 (r^2 + 2 x'^2) + P_2 x' y'$$

$$DP_y(\dots) = 2 P_1 x' y' + P_1 (r^2 + 2 y'^2)$$

$$DC_x(\dots) = C_2 py'$$

$$DC_y(\dots) = C_2 px'$$

$$r = \sqrt{(px - px_0)^2 + (py - py_0)^2}$$

$$px' = px - px_0$$

$$py' = py - py_0$$

K_1, K_2, K_3, K_4 : radial symmetric lens distortion parameter

P_1, P_2 : radial asymmetric and tangential lens distortion parameter

C_2 : shearing

3.3 CALIBRATION RESULTS

Since the video camera is mounted on the Callidus system, it is not possible to separately determine the eccentricity, the interior orientation and exterior orientation parameters. Therefore ten control panels were arranged around the scanner covering the whole horizon. One calibration scene achieved by capturing a 1×14 mosaic with 60° side lap. It was necessary to extent the free available adjustment program called Xdesy [2] to enable the bundle block adjustment with the special constraints given in Eq. 1, 2 and 4. Some typical calibration results are summarized in Tab. 3.

Comparing these results with the values given from the manufacturer one realizes an good agreement. The theoretical values of focal length $f_x=862$ pixel resp. $df_y=-52$ pixel are given by the manufacturer. The determined focal length varies significantly from theoretical values since autofocus is used and big values of the principal point are significant. Only a radial symmetric (K_2) and an little bit of tangential lens distortion (P_2) are detected. The eccentricity radius ($r=0.1376$ m) is nearly the same as the one given by manufacturer (difference is 0.8 mm). The *a posteriori* standard error for the image measurements is $s_{px,py}=0.4$ pixel.

Looking at Tab. 3 one can observe a high scatter of the camera axis values. The mean distance between scanner and control panel are only 3m thus a small displacement of the scanner control points (diameter of hole 2cm!) results in an increased change of up to 1° in the horizontal direction.

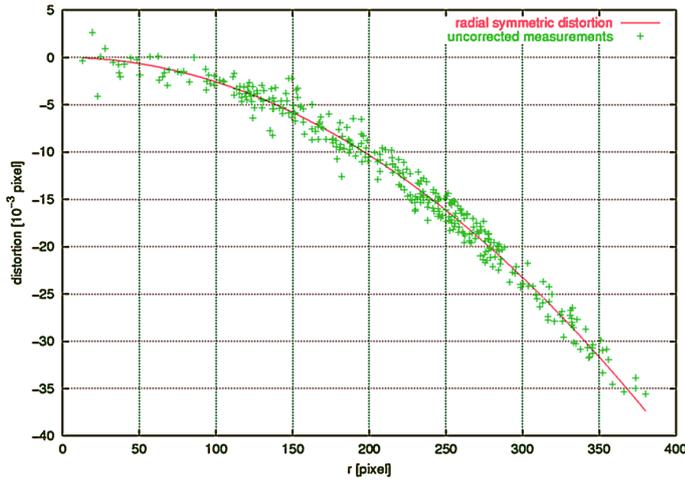


Figure 6: Radial symmetric distortion of video camera resulting from calibration

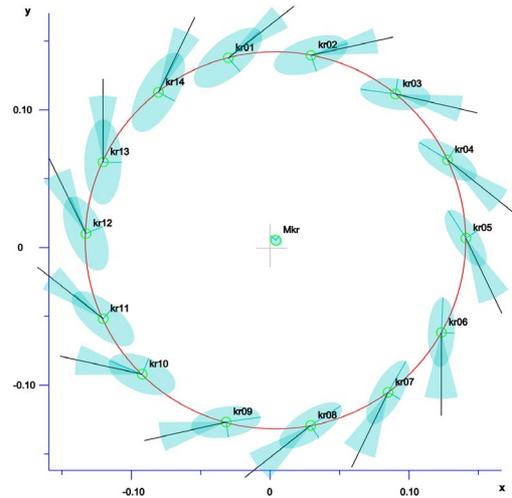


Figure 7: The resulting eccentricity, the camera positions and axes with confidence areas.

Table 3: Exterior orientation of video images and the eccentricity after bundle block adjustment

image <i>i</i>	<i>a</i>	<i>t</i>	<i>s</i>	<i>da</i>	<i>dt</i>	<i>ds</i>	<i>da</i> - \overline{da}	<i>dt</i> - \overline{dt}	<i>ds</i> - \overline{ds}
	[°]			[°]			[°/1000]		
1	51.5873	92.2700	359.8322	25.9064	0.5624	-0.0199	192.1	562.4	-113.8
2	77.4140	92.4958	359.6445	25.8267	0.2258	-0.1876	112.4	225.8	-281.5
3	103.0962	92.2642	359.4694	25.6821	-0.2316	-0.1751	-32.1	-231.6	-268.9
4	128.8452	92.3378	359.3965	25.7490	0.0735	-0.0728	34.7	73.5	-166.7
5	154.6195	91.3692	359.4618	25.7742	-0.9685	0.0652	59.9	-968.5	-28.5
6	180.1058	92.2819	359.6180	25.4863	0.9127	0.1562	-227.9	912.7	62.3
7	205.7677	91.7325	359.6194	25.6619	-0.5494	0.0013	-52.3	-549.4	-92.4
8	231.4955	90.6688	359.9532	25.7277	-1.0637	0.3337	13.4	-1063.7	239.9
9	257.0618	91.4949	0.3696	25.5663	0.8260	0.4164	-147.9	826.0	322.6
10	282.5109	92.2365	0.4202	25.4491	0.7416	0.0505	-265.1	741.6	-43.3
11	308.4141	91.6330	359.9582	25.9031	-0.6034	0.4620	188.8	-603.4	368.1
12	334.0687	92.0065	0.0848	25.6546	0.3734	0.1266	-59.6	373.4	32.8
13	359.9090	92.7504	359.8899	25.8403	0.7439	0.1949	126.0	743.9	101.0
14	25.6808	91.7075	359.8522	25.7718	-1.0428	-0.0377	57.5	-1042.8	-131.6
	$\overline{da}, \overline{dt}, \overline{ds} =$			25.7143	0.0000	0.0938			
	$r = 0.1368 \text{ m}$			$a_0 = a_1 - \overline{da}/2 = 218.7302^\circ$					

	value	std. dev.
f_x	855.861 pixel	4.8 pixel
df_y	-48.656 pixel	0.6 pixel
px_0	8.069 pixel	3.2 pixel
py_0	9.175 pixel	4.9 pixel
K_2	$-2.584 \cdot 10^{-7}$	$3.8 \cdot 10^{-9}$
P_2	$-1.609 \cdot 10^{-6}$	$7.2 \cdot 10^{-7}$

4 TEXTURE MAPPING USING CALIBRATION RESULTS

The cloud of points can be textured by using the simultaneously taken images with the help of calibration parameters. First, the cloud of points had to be triangulated to get a boundary representation of the object. Then the vertices of each triangle were mapped to each image by using Eqn. 5 and 6. This equation realizes the relationship between the object and the image (pixel) co-ordinates. The three pixel co-ordinates of a triangle cuts out an area of the image which is then used to texture the corresponding triangle in the object. Some triangles refer to two or more images because they overlap one another. Unfortunately, corresponding areas of adjacent images are often taken with very different exposures (Fig. 3) an intelligent mean value operation is thus necessary to find the image with the correct exposure. The Fig. 8c is a first result from the application of supplementing scanner and photogrammetric data.

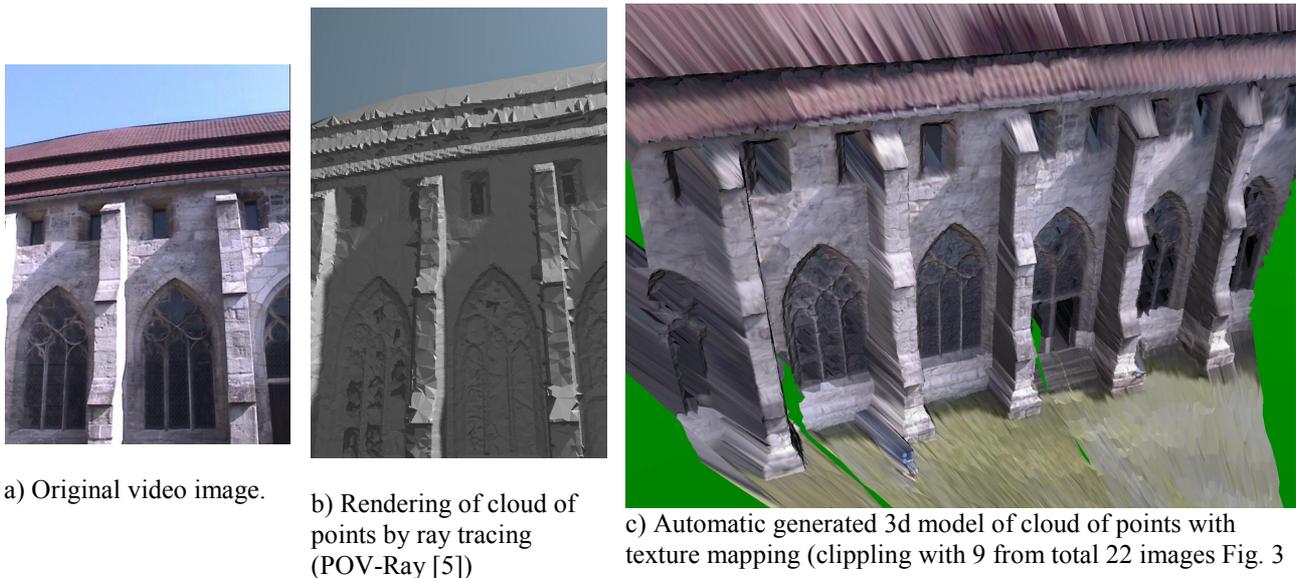


Figure 8: Texture matching with using the 3D information from point cloud

With the availability of a complete 3D geometric model of the object it is possible to reconstruct the circumstances of image exposure during scanning process. Fig. 8a shows the original video image and in Fig. 8b, a visualization of the cloud of points made by using a ray-tracing program. The shadows in both images look similar. Why not use this information to correct the original image? Textures which are independent of the actual light exposure are very valuable for computer visualization and animation because the light sources are simulated in virtual reality processes too.

The institute for geodesy and photogrammetry, technical university of Braunschweig is working on a project for virtual reconstruction of the Cistercian abbey sited in Walkenried/Harz. Up to now the first phase of the project is complete, but not all existing buildings have been reconstructed. It is planned to use the supplementing laserscanning method in the second project phase to complement the computer animation.

5 CONCLUSIONS

A calibration technique for the Callidus system, which allows supplementing geometric data from laser scanner with images, has been explained. The combination of photogrammetric and laser scanner systems compliments one another perfectly for a complete object modelling. Today only the Callidus system can capture images during the scanning process however only with poor quality and resolution. In future video cameras have to be replaced with digital cameras with minimum resolution of 2 mill. pixel in order to attain more accurate and better quality results that can be used for different purposes. The use of this technique in cultural heritage documentation has been presented.

6 ACKNOWLEDGE

I would like to thank to Dirk Mittelstädt and Olaf Gay, ÖbVI Mittelstädt&Schröder, for support, data and fruitful discussions.

References

- [1] Fellner, W., 1992. *Computergrafik*. Number 58 in Reihe Informatik. BI-Wissenschaftsverlag, Mannheim, Leipzig, Wien, Zürich, second edition.
- [2] Kern, F., 2001. *Xdesy*. www-public.tu-bs.de:8080/~fkern/.
- [3] Luhmann, T., 2000. *Nahbereichsphotogrammetrie*. Wichmann, Heidelberg.
- [4] Niemeier, W., 1995. Einsatz von Laserscannern für die Erfassung von Gebäudegeometrien. In [6], pages 155-168.
- [5] POV-Ray-Team, 1999. *Persistence of Vision™ Ray Tracer (POV-Ray™) Version 3.1*. www.povray.org.
- [6] Schrader, B., 1995. *Gebäudeinformationssystem*. Number Band 19/1995 in DVW-Schriftenreihe. Wittwer, Stuttgart.
- [7] Staiger, R., 1987. Die Anwendung von Golomb-Linealen zur Anlage von Prüfstrecken für elektronische Distanzmesser. *Allgemeine Vermessungsnachrichten*, 94:361-367.
- [8] Wiedemann, A., 2001. Kombination von Laserscanner-Systemen und photogrammetrischen Methoden im Nahbereich. *Photogrammetrie Fernerkundung Geoinformation*, Heft 4:261-270.