NON-METRIC CAMERA CALIBRATION AND DOCUMENTATION OF HISTORICAL BUILDINGS

R. Bosch[a], S. Külür[b], E. Gülch[a]
[a] HfT Stuttgart, University of Applied Science, Schellingstr. 24, 70174 Stuttgart, GERMANY, - rbosch2@yahoo.com
[b] ITÜ, Istanbul Technical University, Ayazağa Kampüsü, Inşaat Fakultesi, Istanbul/Maslak, TURKEY, - skulur@srv.ins.itu.edu.tr

KEY WORDS: Photogrammetry, Close-Range, Digital Camera, Calibration, Cultural Heritage.

ABSTRACT

The market of digital amateur cameras is growing rapidly. It turned out, that these cameras could change the field of close range photogrammetry almost revolutionary: Inconvenient in handling and expensive metric cameras could be replaced by “off-the-shelf” cameras if these had the same stability qualities and high enough resolution. Especially the documentation of (historical) buildings would profit from that development, if it was proved that this kind of cameras were good enough for photogrammetric purposes. The proposed paper describes the investigation on the digital non-metric “off-the-shelf” camera *Olympus C-5050 Zoom*. After a short introduction, the problem is outlined. A brief literature review gives the reader some general ideas of researches, already done in that field. The main section describes the single steps how the camera was investigated together with the results. First, a test field calibration in the laboratory of the technical University of Istanbul was done. Second, an “on-the-job” calibration on a historical building (German fountain in Istanbul) was carried out and the results were compared with step 1. The final step was to create a 3D model of the object from step 2 and include it in an already existing database system. The conclusion consists of results, limitations to this research and recommendations for using this camera. For the investigation analysis the software package "Pictran" from Technet GmbH was used. For the 3D modeling Autodesks AutoCAD was chosen. As an overall result it can be said, that this particular camera can be used under certain conditions for photogrammetric purposes for documentation of historical buildings.

1. INTRODUCTION

Turkey has a huge cultural heritage of historical buildings. For documentation of these objects, various methods are possible. Terrestrial photogrammetry is used for most architecture applications. Until some few years ago, special film camera equipment was necessary for this purpose. With the invention of the first digital cameras, new potentials are uprising. Nowadays it is possible to work on terrestrial photogrammetry without expensive software and hardware, because of an extraordinary fast development in the field of digital camera and digital photogrammetry. In the last few years, the market was flooded with digital cameras and still up today almost every month, a new model is introduced to the market. The quality of these cameras might be considered high; nevertheless, the usage of these cameras for photogrammetric purposes is limited since they are not calibrated. The question is what minimum requirements a camera has to meet, in order to be used for close range photogrammetry.

The purpose of this research is to find out whether the “off-the-shelf” amateur camera Olympus C-5050 Zoom (fig. 1) can be used for photogrammetric purposes, especially on the field of documentation of historical buildings and what criteria have to be applied. For that, the camera was calibrated under changing conditions in a test field as well as an “on-the-job” calibration on a historical building was done. The results of both calibrations were compared. Afterwards a 3D-model of a historical building (German Fountain in Istanbul) was created. This model will be supplied to the Technical University of Istanbul (ITU), that has been doing research for a long time in the area of documentation of historical buildings, and can now be embedded into the already existing GIS system of the photogrammetry department. However, the embedding process was not part of this research.

For photogrammetric processing the software package "Pictran" from Technet GmbH was used. Pictran is module based: Module "Pictran D/E", version 3.2, was used for interior orientation and point measuring. Module "Pictran B" version 4.1, was used for calculating the exterior orientation (bundle block adjustment).

Pictran is not capable of stereo viewing and measurements. Each picture is to be measured monoscopically.

The paper is structured in the following manner:

- Chapter 2 describes the principle of camera calibration in general.
- The main investigation process together with the results can be found in chapter 3 to 5. They are containing the topics: camera calibration on a testfield, on-the-job calibration and 3D modeling.
- A small conclusion is given in chapter 6.

2. THEORETICAL BACKGROUND ON CAMERA CALIBRATION

A brief overview on camera calibration will be presented to give the reader a theoretical background of the main research area in this study.

In order to achieve the best results possible in photogrammetry the Interior Orientation Parameters (IOPs) of a camera needs to be known. The parameter set describes the principle distance (c), the principle point of autocollimation (x0, y0) and the radial and decentring distortion of the lens.

The photogrammetric process is a perspective projection and consists of two main principles known as colinearity and coplanearity principles. Based on these two principles, object coordinates can be derived by measuring image coordinates in multiple images of certain points.

The IOPs of "off-the-shelf" cameras are usually not known. The method to determine the IOPs is called camera calibration.

Camera calibration can be seen as the inverse of the photogrammetric process: Known object points are measured in the image and used to determine the unknown IOPs. This is done by setting up a mathematical model containing a set of colinearity equations. To solve the equation system with its unknown parameters and to minimize the residuals bundle block adjustment is used. This method is known as the most flexible and accurate technique for this purpose.

Fryer (1989), Luhmann (2000) and Atkinson (1996) are describing different calibration methods. Most important for this research are test field calibration, on-the-job calibration and self calibration method.

The result of a calibration is documented in a calibration protocol. It consists of the date of calibration, focus settings, IOPs of the camera and distortion parameters. R0 describes the point on the x-axis where the curve of the radial distortion crosses the x-axis. During the whole investigation in this project R0 was set to 0.

3. CALIBRATION ON TESTFIELD

3.1 Test field

For this research the test field of the Technical University of Istanbul was used (fig. 1). This test field consists of 37 well marked control points, which are mounted on a stable iron frame and which were clearly locatable and precisely measurable.

Figure 1. Test field of ITU

3.2 Calibration

To find out about the stability of the camera, different investigations were done. Four tests were carried out:

- Long term sturdiness
- Disturbances on camera

3.2.1 Long term stability: To see if the calibration results of a camera stay the same over a certain time, the camera was put under a long term research. Every month the camera was calibrated on the test field under same conditions. The results were compared with the first calibration taken at end of October 2004. In table 1 the results from particular calibrations are listed, which were used for the long term research

Table 1. Long term investigation

	Oct 04	**Nov 04**	**Dec 04**	**Jan 05**
Date of calibration	24.10.04	03.12.04	31.12.04	24.01.05
C [mm]	7,156	7,172	7,172	7,154
X0 [mm]	-0,012	-0,003	0,001	0,001
Y0 [mm]	0,060	0,006	0,006	0,002
Radial dist. [mm](at max. distance to PP)	-0,234	-0,237	-0,235	-0,235

The outcome in table 3 shows stability in the principle point in the period of November ´04 to January ´05. The change in Y0 from October ´04 to November ´04 happened not in a period of a whole month, but in one day. An explanation for this phenomenon will be presented in the chapter "on-the-job" calibration.

For the calibrated focal length also a significant change can be observed, but it has not such a big impact. Over the three month period a maximum difference of about 20 µm was surveyed. The impact of a change of 20 µ m on the focal length with recording distance of 5 meter (avg. dist. to test field) in one image can be calculated with the following equation: mb = h/c, where mb is image scale, h is recording distance and c the calibrated focal length. With h = 5 m and c = 7,150 mm leads to a images scale of mb1 = 1:699. A distance of 4 meters (size of test field) becomes 5,722 mm in the image. Using the same equation with c = 7,170 mm leads to mb2 = 1:697. A distance of 5,772 mm in the image becomes now 3,989 m in object space. The difference of 11 mm can be even reduced when using not only a single stereo model for 3D point measurement, but more than two images and using bundle block adjustment.

The figures of the radial lens distortion are calculated for the maximum distance (4,5 mm, R0=0) to the principle point (PP). These values have no major change during the investigation period and stay stable.

3.2.2 Disturbances on camera during calibration: To check the stability of the camera, the impact of several factors during calibration were checked. The main concern in non-metric cameras is the optical zoom. This feature maybe very convenient for the user, but might be a big disadvantage for photogrammetric purposes. A calibration on a test field can only be of use if the sturdiness of the IOPs can be guaranteed. Especially the focal length of a camera is affected by the optical zoom. The purpose of this experiment is to find out whether the IOPs stay stable when using the zoom feature. Therefore different kinds of disturbances were forced onto the camera:

- The zoom was set to the other extreme position and back to see, whether the lens moves back to the prior position.
- The camera was turned off and on between picture takings.
- The camera was shaken before picture taking on every station. The shaking was done carefully, not to harm the camera.

Table 2. Influence of disturbances on calibration For analyzing the IOPs out of this test, they were compared Table 3: Extreme calibration results

Type of disturbance	IOPs	Calibration data (with disturbance)	Regular calibration	Diff. [mm]
Zoom in and out between picture taking	c [mm] x0 [mm] y0 [mm] rad. dist. [mm]	25.10.2004 7,156 -0,012 0,063 -0,234	24.10.2004 7,156 -0,012 0,060 -0,235	0,000 0,000 -0,003 -0,001
Turn on and off camera several times during photography	c [mm] x0 [mm] y0 [mm] rad. dist. [mm]	17.11.2004 7,162 -0,014 0,066 -0,235	18.11.2004 7.154 - 0.012 0.064 - 0,237	0,008 -0,002 0,001 -0,002
Gentle shake camera after every third picture	c [mm] x0 [mm] y0 [mm] rad. dist. [mm]	26.01.2005 7,150 -0,002 0,009 0,236	25.01.2005 7,156 0,002 0,001 - 0,235	0,006 0,003 -0,008 0,001

For analyzing the IOPs out of this test, they were compared with the results of a regular calibration, dated closest to it. The figures of the radial lens distortion (rad. dist.) are calculated for the maximum distance (4,5 mm, R0=0) to the principle point. It can be seen in table 4, that the overall effect of distortions is rather small.

Turning on and off the camera does not have a significant impact on the IOPs. This can also be seen in the other calibration results. The camera had to be turned on for each

calibration. The camera was often in use in between the different calibrations. If there had been a significant impact, it would have been visible on every calibration protocol. It is also a positive sign, for the assumption that there is no significant impact of the zooming. When the camera is turned on the lens has to be moved in the correct position, i.e. when the camera is turned off the lens moves automatically in the "turned-off" position.
For all tests the radial lens distortion stays stable. For the other values the highest differences can be seen in the last test (shaking). But they cannot be considered as being significant.

3.3 Accuracy of calibration results

Point measurement on the test field was done with the automated point measurement feature of Pictran. Külür (1996) proved that there is no significant difference when measuring points manually or automated. In the average a $\sigma_0 = \pm 0{,}0006$ mm (a posteriori) for image coordinates could be achieved. This result may be surprising, but when looking at the pixel size (2,751 µm) it becomes feasible. It leads to a sub-pixel accuracy of 0,22. Külür (1996) came to similar results with values in the range of 0,11 to 0,16 pixels, when investigating the camera system Kodak DCS200 on the same test field.
The SD deviations for the calibrated focal length c were in the range of ±1,8 µm and for the principle point in the range of ±1,5 µm. For the two parameters A1 and A2 for radial distortion the standard deviation was about a factor of 100 better than the value itself.
This accurate result is an indication for the good configuration of the camera setup points. However, the camera seems not to be stable enough to keep this accurate calibration results,. e.g. in all calibrations done during the research period, the focal length varies in a range of 20 µm.
Pictran calculated an average standard deviation of about ±0,6 mm (±0,4 mm in each direction X,Y and Z) a posteriori for the control points.

3.4 Accuracy in object space

To find out about the accuracy, new camera files were created. The investigation was done with four most extreme calibration results (table 3). Calibration results with largest focal length c, smallest c, highest radial distortion and lowest radial distortion. The figures of the radial lens distortion are calculated for the maximum distance (4,5 mm, R0=0) to the principle point. I.e. four additional camera files can be found now in the camera folder of "Pictran".

Table 3. Extreme calibration results

	biggest focal length	**smallest focal length**	**biggest radial dist.**	**smallest radial dist.**
Name of camera file	"Big_c"	"Small_c"	"Big_r"	"Small_r"
Date of calibration	3.12.04	26.01.05	18.11.04	24.01.05
Disturbance	no	gentle shaking	no	no
Focal length c [mm]	**7,173**	**7,150**	7,153	7,157
X0 [mm]	-0,003	-0,002	-0,011	0,012
Y0 [mm]	0,006	0,009	0,064	0,064
Radial distortion [mm]	-0,235	-0,236	**-0,238**	**-0,233**

For a statement about the accuracy of the 3D evaluation, with the achieved calibration results, a sequence of 15 pictures was taken (18.11.2004) and the exterior orientation was repeated with the new camera files. After completion of the exterior orientation the points on the test field were measured and 3D coordinates evaluated. This coordinates were then compared with the coordinates acquired with the total station. For getting comparable results the point measurements were stored in a pixel coordinate system file. For all four "cameras" the same pixel coordinates were used and transformed to image coordinate system. The test is not independent, because all 37 points were used for exterior orientation already and the same 37 points are now used for acquiring check points. But this test still can give a tendency of what accuracy can be expected, when recording a object in the same distance, under same conditions, number of images.

Table 4. Accuracy in object space

Camera Name	**mdX [mm]**	**mdY [mm]**	**mdZ [mm]**	**mdR [mm] (dR= 222 *dZ dY dX* ++)**
Big_c	0,0 ± 0,3	0,0 ± 0,5	0,0 ± 0,3	0,5 ± 0,4
Small_c	0,0 ± 0,4	0,0 ± 0,3	0,0 ± 0,4	0,5 ± 0,3
Big_r	-0,2 ± 0,9	1,0 ± 0,5	-0,6 ± 0,5	1,5 ± 0,5
Small_r	0,1 ± 0,5	-0,5 ± 0,4	0,3 ± 0,4	0,9 ± 0,5

Parameters mdX, mdY and mdZ in table 4 are the average (mean) shifts of the 37 points plus standard deviations in X,Y and Z directions in object space. Parameter mdR is the average shift (3-dimensional) plus standard deviation from coordinates evaluated by means of photogrammetry to coordinates acquired with a total station. The sub-millimeter accuracy looks quite astonishing, but looking at the over sampling rate (15 pictures for same scenery), short recording distance and well marked points the result becomes feasible.

4. ON-THE-JOB CALIBRATION

Figure 2. German Fountain in Istanbul

For testing the camera on a "real" object and to check whether this camera can be used for documentation of buildings the German Fountain in Istanbul was chosen (fig. 2).
As control points prominent natural points on the object were chosen. The 26 points were pre-coordinated by a Pentax total station with an angle accuracy of 2" in a local system.

4.1 Configuration setup

Figure 3 shows the configuration set up of the camera. For each facade two frontal pictures in landscape format were taken; one in a distance of about 15 meters the other in a shorter distance of about 7 meters to the object. In between every two facades a picture in portrait format -facing the corner -was taken. With this settings a collection of 24 pictures was taken. Every facade

is covered by four pictures
.

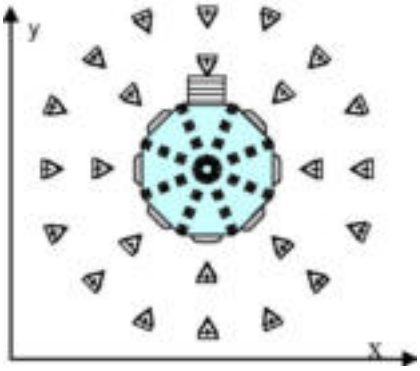


Figure 3. Configuration setup for camera

4.2 Evaluation

For evaluation of both calibrations the approximate values for x0 and y0 were set to zero. For the focal length an approximate figure of 7,150 mm was chosen. Pictran calculates all other necessary estimated values.
With a σ_0 = ±2,5 µm (≈ 1 Pixel) a posteriori for image coordinates the result is acceptable. Especially because of the fact, that natural control points were used. The accuracy of image coordinates does not only depend on the fact how accurate a point can be measured by hardware and user; with natural control points it depends also very much on the fact how good the points are identifiable. This was already the problem when pre-coordinating the points by a total station.
For the coordinates of the object points a σ_0 = ±6 mm a posteriori was calculated during the bundle block adjustment.

4.3 Analysis

For analyzing the quality of the outcomes of the on-the-job calibration the two calibrations are compared to their next "neighbors" in the test field investigation. I.e. the closest test field calibrations (before and after on-the-job calibration) will be taken for comparison.

Table 5. Comparison test field calibration to on-the-job calibration

	Test field calibration 18.11.2004	On the job calibration 19.11.2004	Diff
Focal length c [mm]	7,154	7,160	- 0,006
X0 [mm]	-0,012	-0,025	0,013
Y0 [mm]	0,064	0,004	0,060
Radial distortion [mm]	-0,237	-0,236	- 0,001

Table 6. Comparison test field calibration to on-the-job calibration

	Test field calibration 3.12.2004	On the job calibration 19.11.2004	Diff
Focal length c [mm]	7,168	7,160	0,008
X0 [mm]	0,000	-0,025	0,025
Y0 [mm]	0,004	0,004	0,000
Radial distortion [mm]	-0,236	-0,236	0,000

In table 5 and 6 the comparison of the on-the-job calibration to test field calibrations is shown. No significant difference can be observed in the values of the focal length. The value is surprisingly in the middle of the two test field calibrations. The different focus setting had no major impact on the focal length. Also no significant difference can be found in the radial distortion. For the principle point a rather large difference can be observed. The on-the-job calibration is dated on the 19.11.2004, only a day after the test field calibration from 18.11.2004. The difference of $\Delta x_0 + y_0$ = 61 µm in the principle point is considered as being significant. During the whole period of the investigation (4 months) no such big change in a value can be observed. Since the camera was not in use in between the two tests, no significant change was expected. When looking for reasons only one fact seems reasonable and this is that during the transportation the stability of the camera was harmed. Another possibility would be the camera configuration setup of the camera: Maybe not enough "rotated" pictures were taken. But due to the fact, that all pictures are tilted towards each other, which stabilizes determination of the principle point, the calculated figures are seen as feasible. The comparison with the calibration from the 3.12.2004 (table 6) are proving the results from the on-the-job calibration as well. The impact of a shift in the principle point can be neglected if only stereo pairs of pictures are used, which are laying in the same plane. As it can be seen later in the accuracy section of the 3D model, the impact of the change in the principle point is small.

4.4 Accuracy

For image coordinates an accuracy of σ_0 = ±2,5 µm (a posteriori) was determined, which is a factor of 5 worse than in the test field. The standard deviation for the focal length and principle point is in the range of ±4 to ±6 µ m. That is about three times worse than in the test field. The same factor can be seen for the accuracy of the radial lens distortion lens parameters. But when taking the input values into consideration it is a very good result. The accuracy of object coordinates on the fountain is even a factor of 10 worse then the ones in the test field. This is again due to the fact that natural control points were used, which can not be measured with the same accuracy as well marked points.
The subject leading to a nevertheless good result for the error in the unknowns could be because of the high over-sampling rate. For 1397 unknowns a number of 2614 observations and 24 constraint equations leads to a redundancy of 1241.
For the additional vertical and horizontal distances put into the adjustment a reasonable standard deviation of ±2,5 mm a posteriori was determined.

4.5 Precision in object space

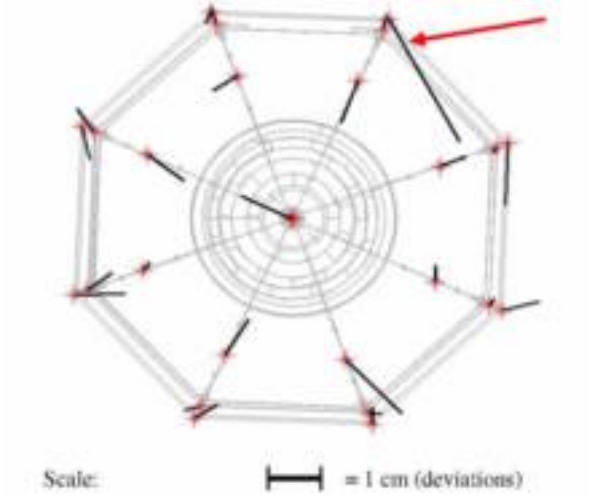
To find out about the accuracy, a new camera file "on_job_1" was created and the new achieved values were inserted. The test was done in the same way as with the test field in the chapter before. The 3D coordinates of the 26 control points measured with the total station are taken as a reference. Again, it has to be mentioned that this test is not independent, because all 26 points were used for exterior orientation already and the same 26 points are now used for acquiring check points. The image coordinates taken for this test were stored also in a pixel coordinate file, to have exact the same measurements for comparison of the different IOPs.
Average differences of coordinates evaluated photogrammetrically with on-the-job IOPs to coordinates acquired with a total station (reference) are listed in table 7:

Table 7: Differences to coordinates acquired with total station

Camera Name	mdX [mm]	mdY [mm]	mdZ [mm]	mdR [mm] (dR= 222 dZ dY dX ++)
On_job_1	-1,8 ± 5,2	1,3 ± 7,0	0,4 ± 5,6	8,3 ± 6,4

- mdX,mdY and mdZ are average shifts in direction of the coordinate axis.
- mdR is the average distance of the coordinate pairs in the two different systems.

The average shifts in a certain direction are small, because the whole object is adjusted in a way, that the plus and minus differences are almost equal. The last column with the average distance in 3D space is the most important one. The evaluated coordinates having a high precision of 8,3 mm ± 6,4 mm. Since the coordinates of the control points are having an accuracy of about +/-6mm the result is satisfying.



= 1 m (object space)

Figure 4. Plot with differences in X,Y plane

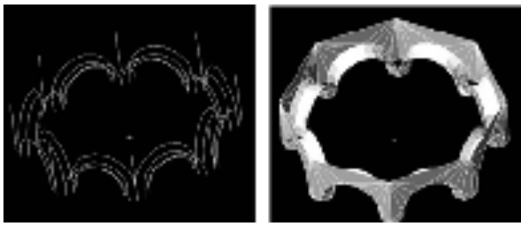
Figure 4 is showing a plot with the control points and the differences (superimposed) to the photogrammetric coordinates, using the camera file "on_job_1". A big difference can be seen in the point, which is marked with a arrow. This point belongs to one of the 8 control points on the roof circle.The difference is about 3 cm, which is rather big, but this is to the fact, that this point could not be seen on all possible images, because of a leaf of a tree nearby. This point could be measured on five images whereas the other control points were visible on the average on nine images.

5. 3D MODELING

Pictran offers the possibility to install a direct connection to the CAD-Software AutoCAD. Points as well as lines can be transferred. But it is not possible to transfer additional point information (like point number or accuracy of point). The main goal of this part was to create a 3D model of the fountain together with a statement of the accuracy. Additionally it was tried to transform the model into a VRML model.

5.1 AutoCAD model

If possible, points were measured in Pictran and transferred to AutoCAD. In some parts not enough points could be measured. These parts were then constructed by making some assumptions.



a) b)

Figure 5. Arcs (lines (a) and shaded (b))

Figure 5 shows the construction of the arcs in AutoCAD. No special construction was necessary here. All points were measured and connected with 3D polylines. For planes triangles were used.

Figure 6 Shows the final model in AutoCAD

Figure 6. Final model in AutoCAD (shaded)

5.2 VRML model

It was found that the conversion to VRML format cannot be done by AutoCAD directly. A step in between needed to be taken. First the model was exported to "3D Studio Max". The problem here was to skip the surface normals to the outside where necessary. This is very time consuming, since there is no automation for this work every surface had to be flipped manually. The whole model consists of about 3200 surfaces were about ¼ had surface normals pointing into the wrong direction.

For part of the model, the flipping was done and converted to VRML format, which can be seen in figure 7. Only the front sided faces are visible here.

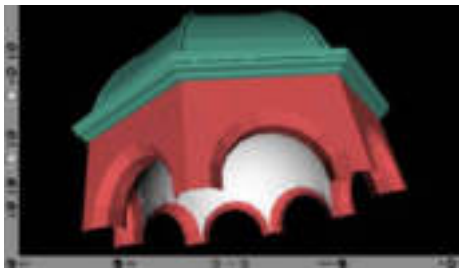


Figure 7. VRML model with artificial texture

6. SUMMARY AND PROSPECT

6.1 Résumé:

This research proved that the camera can be used for photogrammetric purposes especially for documentation of historical buildings.
The picture quality is acceptable for photogrammetric measurement. With the above mentioned settings the measurement of the points could be done without facing bigger problems.
The calibration results achieved in the test field are feasible and accurate. The overall sturdiness of the camera can be considered to be good. Nevertheless it was found, that the figures for the principle point were changing significantly. These changes were proofed to have no larger impact on the accuracy, if using the camera under the same conditions like in this research.
It was proofed, that the outcome of an on-the-job calibration is satisfactory for documentation of historical buildings. It is recommended to apply a on-the-job calibration or, if not possible, at least to measure some independent coordinated checkpoints for quality control. For overall good results a high redundancy should be mandatory.
The use of natural control points was proofed to be functional. Because of the shape of the object and enough texture on the surfaces, the points were clearly detectable and measurable.
Pictran uses stereo pairs to calculate approximate values for the bundle block adjustment. For round shaped objects the "normal stereo case" is usually not given. Therefore it is recommended to shoot enough pictures with enough overlapping area, if round shaped objects are recorded. After calculation of the approximates it is still possible to delete images not wanted for the photogrammetric process. The version used in this research lacks in graphical display of the adjustment results.
The 3D modeling in AutoCAD was not always found to be satisfactory. But that could be compensated by an operator with more experience. To convert the model into VRML AutoCAD is lacking of a tool for this. The step to be taken in between is very time consuming and the result is not satisfactory.

6.2 Outlook:

Digital "off-the-shelf" cameras are serious competitors to the so far used expensive metric cameras. For most terrestrial photogrammetric applications this cameras will replace the metric systems in near future. Traditional terrestrial photogrammetry has to share the market of object-recording to the more and more uprising terrestrial laser scanners. Newer systems are combining both systems already.
The fast internet development makes 3D visualization more and more important. But not only in cyber space, also for construction, planning and quality control, 3D visualization is getting a key issue. Digital photogrammetry seems to be the ideal instrumentation for supporting these needs.

REFERENCES

ASPRS, Editor: Karara H. M. (1989): *Non-Topographic Photogrammetry*. American Society for Photogrammetry and Remote Sensing. Second Edition. ASPRS, Falls Church, Virginia, USA.

Atkinson, K. B. (1996): *Close Range Photogrammetry and Machine Vision*. Whittles Publishing, Caithness, Scotland, UK.

Cardenal, J., Mata, E., Castro, P., Delgado, J., Hernandez,

M. A., Perez, J. L., Ramos, M., Torres, M. (2004):

Evaluation of a digital non-metric camera (Canon D30) for the photogrammetric recording of historical buildings. Retrieved October 23, 2004, from ISPRS Congress 2004 Istanbul Website http://www.isprs.org/istanbul2004/comm5/papers/617.pdf.

Fryer, J.G. (1989): *Camera Calibration In Non-Topographic Photogrammetry,* Chapter 5 out of: *Non-Topographic Photogrammetry*. American Society for Photogrammetry and Remote Sensing. Second Edition. ASPRS, Falls Church, Virginia, USA.

Külür, S. (1998): *Kalibrierung und Genauigkeitsuntersuchung eines digitalen Bildaufnahmesystems* [Electronic version]. 18. Wissenschaftlich-Technische Jahrestagung der DGPF, 15. DFD-Nutzerseminar des DLR, 14.-16. Oktober 1998, Technische Universität München, S. 63-72.

Luhmann T. (2000): *Nahbereichsphotogrammetrie; Grundlagen Methoden und Anwendungen*. Wichmann Verlag, Heidelberg, Germany.