NEW DEVELOPMENTS IN CLOSE RANGE PHOTOGRAMMETRY APPLIED TO LARGE PHYSICS DETECTORS

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Abstract

One of the main tools for the measurement of the different detectors of the four large LHC experiments is a digital photogrammetric system. It consists of non-metric DCS460 and DCS660 cameras, other of the shelf products and the AICON software packages DPA-Win and 3D Studio. The system is used to measure objects from various sizes and dimension up to 20 m high since the beginning of the assemblies.

The question of stability of the camera and its interior orientation is of great importance since the image acquisition, consisting of up to 300 photos, may last 8 hours for some large sized projects. A correction model for effects of movement has been established by the Institute of Applied Photogrammetry - University of Oldenburg (Germany) in a common project with AICON and CERN. The different mathematical model has been investigated via an example of the CMS assembly.

1. INTRODUCTION

The close-range photogrammetry relies on the reconstruction of the object simultaneously from several images from different and best possible perspective to ensure a suitable geometry of intersecting rays. The images are stationed free in object space as the photogrammetric network is reconstructed from the bundle of rays: the object coordinates, the exterior orientations and the interior orientation of the camera are estimated simultaneously in a common process called bundle adjustment.

The equipment presently used at CERN by the Large Scale Metrology group consists of non-metric DCS460 and DCS660 cameras, other of the shelf products and the software packages AICON DPA-Win and 3D Studio.

Photogrammetric measurements are mainly needed for deformation analysis, geometrical calibrations and for the crucial dimensional quality controls. Measurements take place in field and often the conditions for measuring especially large objects of up to 15 m diameter are rough. Images have to be taken from a scaffolding or a lifting platform and under this constraint the question of stability of the camera and its interior orientation is a crucial point.

A check to analyse the variation of the principle point is described, an extended mathematical model for the interior orientation of the camera is presented and as example this model has been applied to a geometrical control of the CMS Yoke End Cap.

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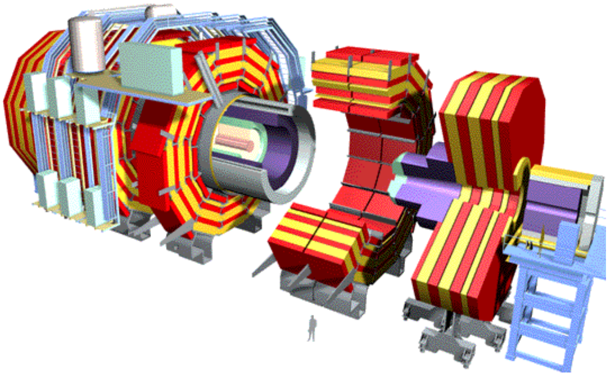
2. CERN - LHC - CMS

The LHC (Large Hadron Collider) is the new particle accelerator project at CERN (European Laboratory for Particle Physics) in Geneva. It will be a 27 km long accelerator made of super-conducting magnets. Four big physics detectors, called ALICE, ATLAS, CMS and LHC-B will be installed at four interaction points.

Compact Muon Solenoid (CMS) is one of the four experiments to operate at the LHC. CMS aims to study very high energy collisions of proton beams with the best precision possible. The experiment is built by many structures from the Central Tracker to the End Caps closing both detector heads. This typical onion layout of detectors is shown in figure 1.



Diameter: 14.60 m
Length: 21.60 m
Total Weight: ~ 14 600 tonnes

Figure 1: Experiment Compact Muon Solenoid

The performance of the particle tracks reconstruction depends on the intrinsic precision of sub-detectors and of their positioning. The requirements of the new LHC experiments for the object coordinates precision vary from 0.05 mm for medium size objects up to some tenths of a millimetre for large size objects.

3. VARIATION OF INTERIOR ORIENTATION – CONVENTIONAL MODEL

3.1. Detection of movements

The equipment like the non-metric camera DCS460 and Nikon lenses are of the shelf products and the question of stability of the camera and its interior orientation is of great importance since the image acquisition for some large size projects, consisting of up to 300 photos, may last 8 hours.

By using a different interior orientation for each image, the instability of the DCS is considered. Shortis, Robson and Beyer [1] have proposed the solution to fix the distortion parameters and the focal length, the principal point being free for every image.

The first approach at CERN has been to evaluate the movements of the interior orientation for a DCS460 with the DPA-Win software by defining one camera per image, such that the principal point and the focal length is left free for each image, with the distortion being invariant for the block. It is not possible with the available software to free the principle point for every image independently and to keep the focal length invariant for the block, because the parameters are grouped for selection.

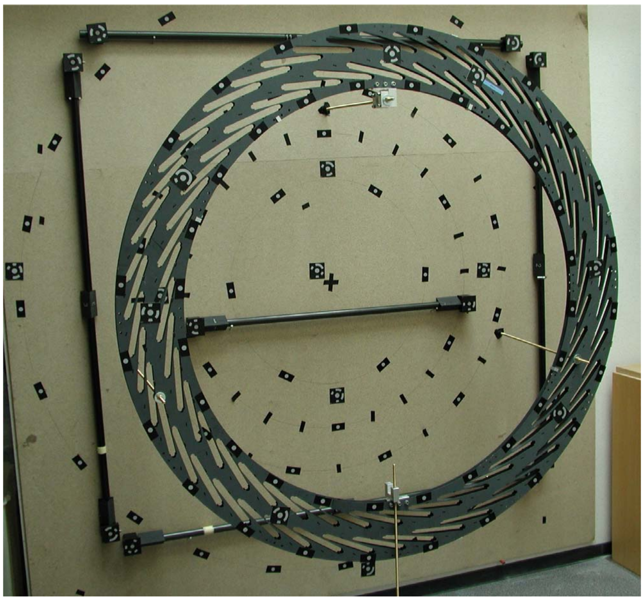
One of the tests is to evaluate the movement of the principle point due to the rotation of the camera around its optical axis. In order to have the same geometry of object points and distribution of image coordinates for every image taken, a circular object has been chosen.

A wheel is fixed vertically in front of 4 concentric circles of targets of up to 2 m diameter, with a distance of 0.5 m to provide a certain depth.

The camera is positioned in front of the wheel on the axis of circles centres, and a series of images is taken. Between the images, the camera is rotated around its optical axis by about 15 degrees, giving 24 images for a complete turn. Several cameras are used after each other and the complete procedure is repeated 4 times.

After the adjustment, the standard deviations for the coordinates of the principal point were below 1 µm for all the images. Therefore a movement of the principle point of more than 3 µm can be significantly detected. The adjusted coordinates of the principle point for one turn of one camera are presented in figure 3.

The results show, that the principal point is not stable during one turn. The movement is nearly elliptical, with amplitude of about 40 µm in x-direction and 50 µm in y-direction. Equivalent results were obtained for the three other turns of this camera [2].



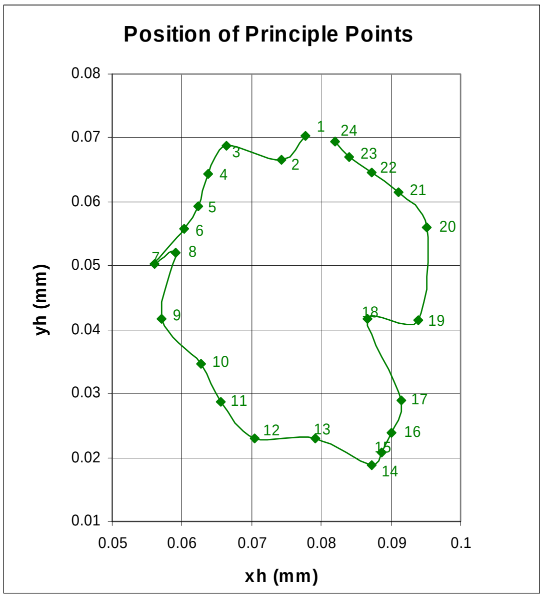


Figure 2: Carbon Fibre Wheel

Figure 3: Adjusted principle points for one turn

3.2. Conclusions

The test has shown a systematic movement of the adjusted principle point for the images of one turn. This effect seems to be due to gravity by two possible mechanical effects:

- Deformation of the camera body caused by the mass of the lens and the attached flash
- Movement of the CCD sensor, which is fixed by only one screw inside the DCS460

Clarke, Fryer and Wang [3] have shown that the variation of the principle point is partly a result of the correlation to certain parameters of the interior and exterior orientation, and not exclusively to the mechanical deformations of the CCD sensor or the lens.

Therefore the configuration of the test was chosen to minimize correlations. It can be assumed, that gravity has a certain influence on the principle point, because also other tests have shown a systematic behaviour of the principal point for tilted images [2].

Because of the mechanical instabilities influenced by gravity and by the handling, it is impossible to avoid any deformation. It is possible to calculate the principle distance and the principle point for each image, but the constraints of the object itself, as a lack of depth or the distribution and number of points in each image would lead to a weak equation system.

Another approach is the use of a different mathematical model that can compensate for slight changes of the interior orientation. The Institute of Applied Photogrammetry – University of Oldenburg (Germany) has examined an extended camera model in a research project with AICON 3D Systems GmbH, Braunschweig (Germany) and CERN as partners.

4. VARIATION OF INTERIOR ORIENTATION – EXTENDED MODEL

4.1. Extended mathematical model of FiBun

The parameters used in the conventional mathematical model for camera calibration assume a stable interior orientation over the whole period of image acquisition, which is mostly estimated simultaneously in the bundle adjustment.

But the mechanical construction of the digital of the shelf cameras is instable and during the whole period of image acquisition different parameters influence the stability of the camera and its interior orientation:

- Mechanical influence by the user; during the hand-held shots different constraints influence the camera, especially for difficult accessible objects during climbing on a scaffolding or using a lifting device
- Effects of gravity, which changes relatively to the camera with different viewing directions
- Heating of the camera during a long period of image acquisition, especially for large or difficult accessible objects

Therefore the conventional mathematical model for camera calibration has been extended by Hastedt, Lumann and Tecklenburg, in order to model instabilities and other influences [4].

The image-variant interior orientation describes the variation of the principle distance and the principle point. A possible displacement of the lens with respect to the CCD sensor during the image acquisition can be compensated.

The changes of the principle distance and the principal point can be estimated to be within some hundreds of a millimeter. In order to avoid the effect of a weak equation system caused by the lack of sufficient observations, these parameters of the interior orientation are introduced as observed unknowns, weighted by an a priori accuracy, which has to be defined a priori by the user. Smearing effects caused by the correlation to other parameters are minimized. The variation of the principal point affects the lens distortion with respect to the image plane. Consequently this can no longer be modeled as a function of image coordinates rather than a function of imaging angle.

The radial-symmetric distortion is described by the parameters A1, A2 and A3 as for the conventional model.

As an extension to the conventional model a finite elements correction grid is added, which corrects the following block invariant parameters and influences:

- Tangential-asymmetric distortion, affinity and shearing
- Sensor unflatness
- Other remaining invariant errors in sensor space
- Other remaining invariant lens effects

The raster-wise correction grid is based on anchor points, its grid-width has to be chosen a priori by the user. Corrections are calculated as plane vectors for each grid point, the correction for every image point is interpolated within the grid by bi-linear interpolation. In order to avoid the effect of a weak equation system or even singularities caused by the lack of measured image points for every grid element, curvature constraints are added as pseudo observations. These observations are weighted by an a priori accuracy, which has to be defined by the user, depending on the estimated unflatness of the CCD sensor. In addition, random measuring errors can be separated from real sensor deformations by this approach.

Parameter	Modelisation DPA-Win	Modelisation FiBun
Principle distance	ck	Image-variant ck
Principle point	xh, yh	Image-variant xh, yh
Radial-symmetric lens distortion	A1, A2, A3	A1, A2, A3
Tangential and asymmetric distortion	B1, B2	Finite elements grid
Sensor properties as affinity and sheering	C1, C2	Finite elements grid
Non-planarity of the CCD sensor and other invariant errors	Non	Finite elements grid

Table 1: Comparison of the conventional and the extended calibration model

4.2. Example: CMS Yoke End Cap

It has been decided to investigate this approach via practical operating examples and not on an object in a controlled laboratory environment.

Three End Caps for each end of the detector have been fabricated in Japan. The dimensions are 14 m in diameter and 0.6 m respectively 0.25 m in thickness, weight 2300 tons. 12 half discs have been preassembled, followed by a first photogrammetric validation.

Since the production rate has been one half disc every month, one measurement had to be done every month. Two members of the personnel in Japan have been trained by CERN staff for image acquisition of this repeated measurement. Since they didn’t have any experience in photogrammetry, a precise procedure for the image positions and viewing directions has been established. The image evaluation has been done at CERN.

After a certain time the measurement results have shown a decreasing quality. The personnel in Japan has been changed, and untrained people have taken the images. One of these projects has been used to investigate the extended calibration model.

For the measurement 108 reference holes on the half disc are equipped with retro-reflective photogrammetric targets of 40 mm diameter.

In order to facilitate the connection of the two faces, spherical targets are positioned on the circumference of the disc. 90 images, 45 of each face, are taken with the Kodak DCS 460 equipped with a Nikon 20 mm lens because of limited possible distance between the camera positions and the object. 6 carbon fibre scale bars of about 1.4 m length are positioned in object space for the definition of the scale and as additional control. After the image acquisition of the first face these scale bars are repositioned on the second face, providing 12 distance observations. In addition long distance information is acquired by using a calibrated tape, providing 12 distances from 5 m up to nearly 14 m to avoid extrapolation.

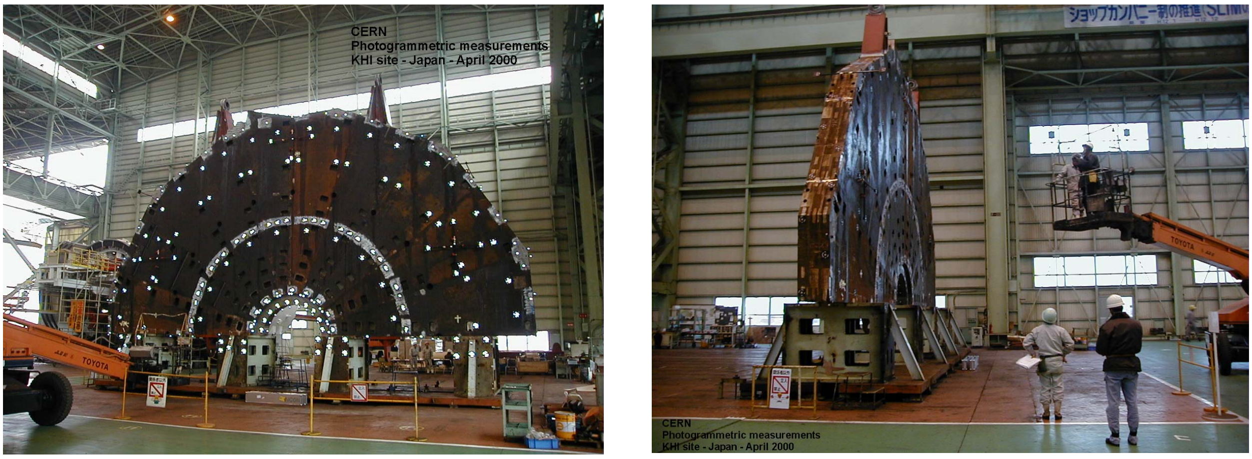


Figure 4: Yoke End Cap at Kawasaki Heavy Industry, Japan

4.3. Investigation and results

In order to compare the results of both approaches, the adjustment has been calculated as a free net with only one long distance information fixed for scale definition. The remaining distance observations are used as external control.

4.3.1. Interior accuracy

The sigma 0 a posteriori is reduced from 0.8 for the bundle adjustment with the conventional approach to 0.5 for the bundle adjustment using the extended calibration model.

	DPA-Win	**FiBun**
Calibration model	conventional	image-variant parameters, finite elements correction grid
Object coordinates		
RMS X (mm)	0.083	0.062
RMS Y (mm)	0.082	0.057
RMS Z (mm)	0.136	0.088
RMS XYZ (mm)	0.179	0.122
Relative precision by interior accuracy	1 : 80 000	1 : 110 000
Accuracy of image measurements		
Sigma 0 a posteriori	0.8	0.5

Table 2: Comparison of interior accuracy

4.3.2. Image-variant interior orientation

After a first calculation, the a priori accuracy for the interior orientation has been defined as 15 µm for the final adjustment. The principle distance varies within a range of 200 µm. The principle point moves up to 140 µm in x-direction and 90 µm in y-direction.

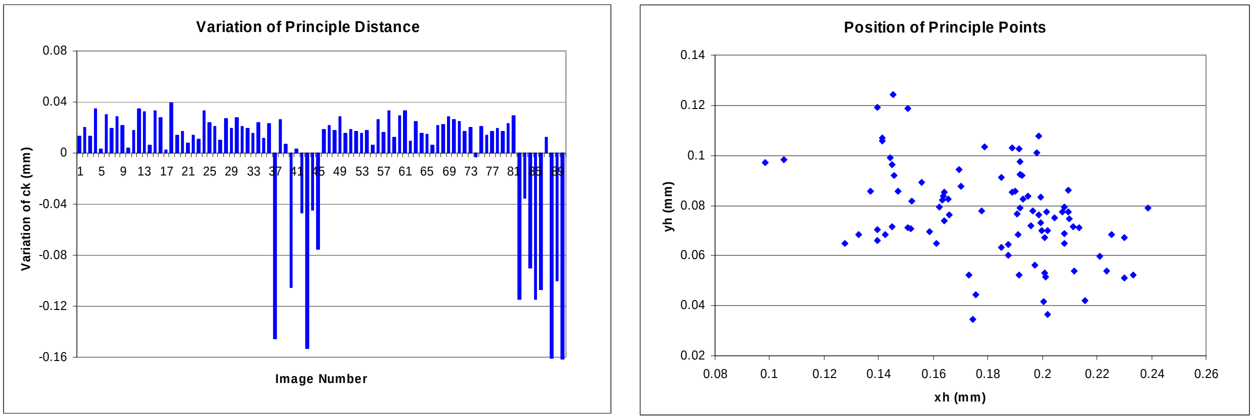


Figure 5: Variation of principle distance and position of principal point

For the finite elements correction grid a raster-width of 2.35mm resulting in a 13:9 grid has been chosen with a priori accuracy of 1 µm for the curvature constraints. The correction vectors show mainly the influence of the tangential-asymmetric distortion.

For the outer edges the corrections are extrapolated, only few image measurements are available in these regions on the sensor. The maximum length of a correction vector is 8 µm for the grid points (except edges).

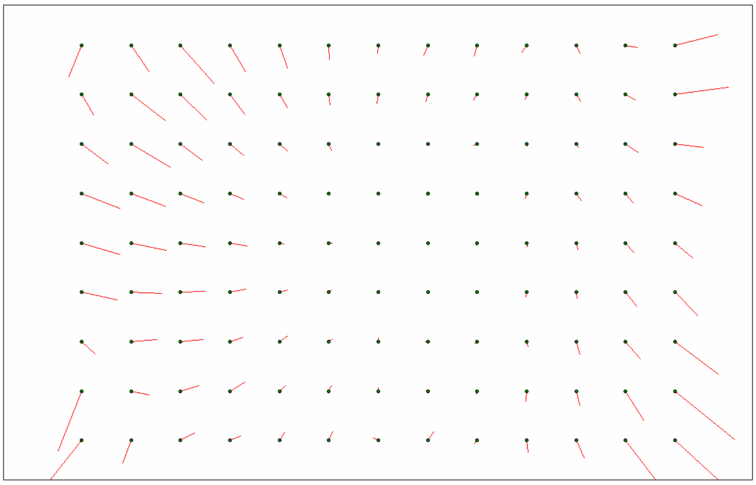
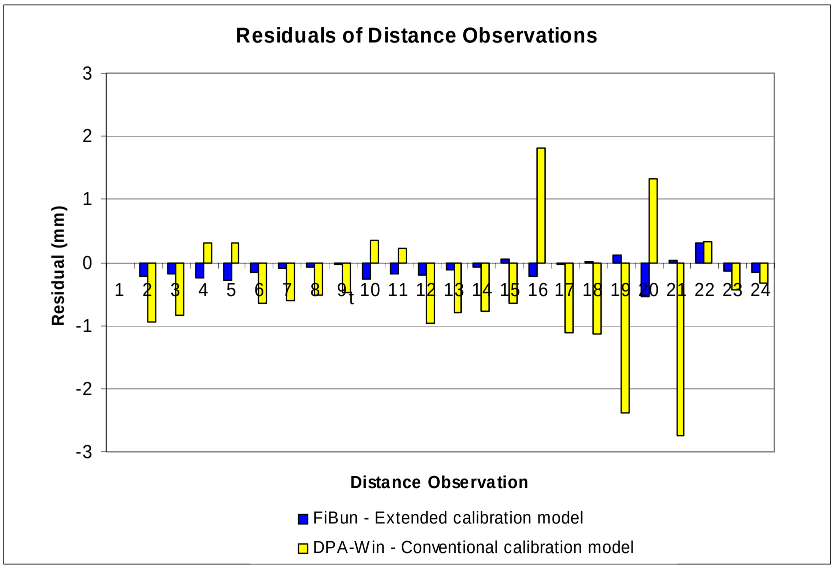


Figure 6: Finite elements correction grid after adjustment

4.3.3. Exterior accuracy

Only one long distance information was used for scale definition of the adjustment (scale 1). Scale 2 to scale 13 represent carbon fibre scales, calibrated with an accuracy of 0.02 mm (1 Sigma). Scale 14 to scale 24 represent long distance information measured within an accuracy of 0.3mm (1 Sigma). The range of the residuals is reduced by factor 5 from 4.5 mm for the conventional model to 0.9 mm for the extended calibration model.



	DPA-Win	FiBun
Range	4.56 mm	0.85 mm
Stdev	0.99 mm	0.17 mm

Figure 7: Residuals of control distances

5. CONCLUSION

The adjustment results for this Yoke End Cap measurement using the conventional calibration model have shown a decreasing quality compared to former projects. It can be assumed, that after the change of the personnel an untrained operator has handled the camera more careless during the image acquisition.

By using an extended calibration model for the adjustment the interior and exterior accuracy can be enhanced. Image-variant interior orientation combined with a finite elements correction grid models instabilities of the camera, sensor unflatness and invariant errors in sensor space.

An evaluation of this approach has also been done for different projects of medium and small size objects, where the camera has been carefully handled. For some projects the interior and exterior accuracy increases, for some projects no enhancement can be notified and for other projects the accuracy even decreases slightly.

One problem for this verification is the lack of sufficient external reference information to validate the results, because the interior accuracy seems to be too optimistic to estimate the measurement accuracy.

It has to be further investigated, under which conditions and for which object geometry this presented approach is improving the results significantly.

References

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