Digital Photogrammetry Applied to Large Physics Detectors

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Key words: large physics detectors, specific tooling for photogrammetry, camera calibration, interior orientation.

SUMMARY

The new particle accelerator project LHC at CERN in Geneva and the 4 large physics detectors require new spatial constraints in conjunction with the best precision.
A digital photogrammetry system consisting of several DCS460 and DCS660 cameras and the Rollei-CDW software has become the main tool for measuring objects from 15 m to 20 m high. Specific aspects such as image acquisition over a long period of time are studied, also a correction model for effects of movement has been established with the Institute of Applied Photogrammetry - University of Oldenburg.

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1. INTRODUCTION

The LHC (Large Hadron Collider) is the new 27 km long particle accelerator project at CERN (European Laboratory for Particle Physics) in Geneva. Large physics detectors, ALICE, ATLAS, CMS, LHC-B, will be installed at the four interaction points and new survey requirements are apparent together with new spatial and time scale constraints.
These detectors aim to study very high energy collisions of proton beams with the best precision possible and will be built from many separate pieces of structure, from central tracking units, to end caps closing the magnetic system and both detector heads. The typical onion layout for the CMS (Compact Muon Solenoid) is shown in figure 1.

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 co-ordinate's precision vary from 0.05 mm for medium size objects up to some tenths of a millimetre for large size objects.

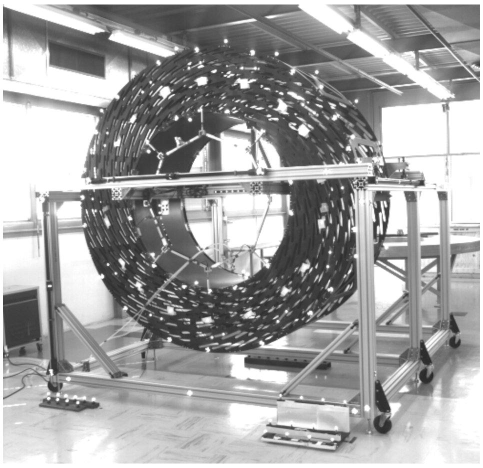
Figure 1 CMS – diameter : 14.60 m, length : 21.60 m, weight : 14600 tons.

At CERN, a digital photogrammetry system consisting of several DCS460 cameras and the Rollei-CDW software has become the main tool for solving the geometrical positioning demands, the dimensional quality and the deformation analysis controls. It provides similar and repetitive accuracy measurements when done with a regular frequency on the same object during a short period.
The interventions of a skilled but reduced team interfere as little as possible with the schedule and can be easily adapted to the environmental constraints. Large objects, from 15 m to 20 m high, must be measured in their entirety at distance of only a few meters because free and available space is generally small and cramped, with multiple obstacles.

2. SOME EXAMPLES, SPECIFIC TOOLING AND APPROACHES

2.1 Some Examples

After performing acceptance measurements, training tests and validation of specific procedures, photogrammetric operations in laboratories and factories have shown clearly that these techniques could satisfy all the constraints.



The deformation measurements on medium size prototypes of detector parts were requested early on in order to validate the finite element models of the mechanical design structures.

Figure 2 the carbon fibre structure of the 1/3 scale model of the CMS central tracker during deformation measurements – 2.5 m diameter

The five rings of the CMS Barrel Yoke, whose dimensions are 15 m in diameter and 2.5 m in thickness have been regularly measured during their construction in DWG factory – Deggendorf, Germany. After the photogrammetric validation and the delivery of the acceptance certificate, each ring is dismounted, transported to CERN, remounted and remeasured with the sub detectors inside. The blank spots on the figure are the retro targets specifically for long distance recording.

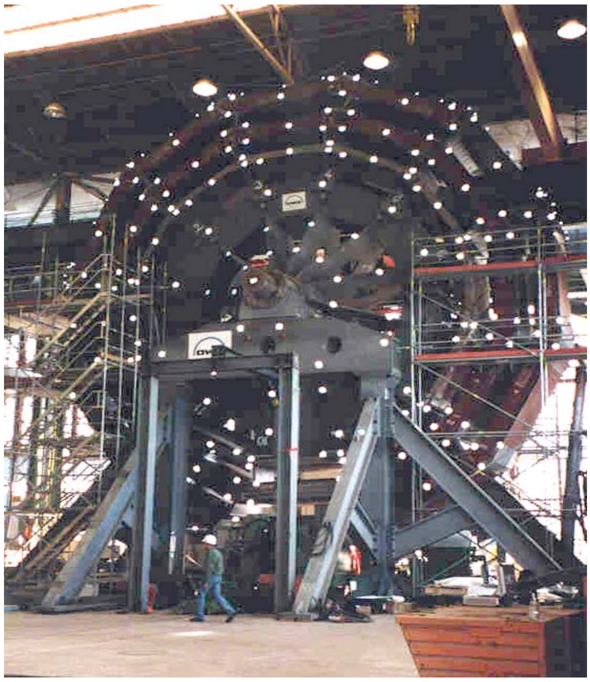


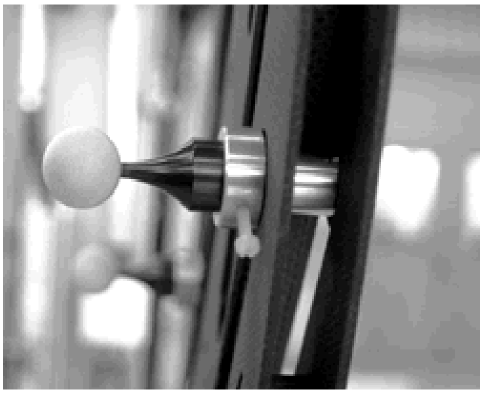
Figure 3 one full Barrel Yoke ring in factory

2.2 Adapted tooling

2.2.1 <u>Spherical targets</u>

A spherical target ensures the best possible convergence angles in case of a poor geometrical configuration and its image is independent of the viewing angle and is always a circle. In

contrast a flat target reduces the total convergence view angle to between 60° and 90° with the risk of an elliptic image too “flat” for reliable detection.
Using spherical targets allows a significant improvement of the configuration since they can be viewed by a greater number of camera stations and the connections between the different faces of an object can be ensured with a reasonable number of pictures.



Two types of spherical targets are used. A 30 mm diameter target, mounted on a magnetic foot, is used to equipping extra or connection points. A 20 mm diameter target may be mounted and centred on the 8 mm diameter axis with a precision better than 30 microns, the distance between the target and reference socket has a precision of 20 microns. These characteristics have been confirmed by the CERN Metrology service.

Figure 4 20 mm spherical target mounted on the Model of the CMS central tracker.

The 2.5 m diameter disk shown in figure 2 was equipped with 20 mm diameter spherical targets; the image co-ordinates were detected with a precision of 0.3 microns and the object co-ordinates of the sphere centre points with an overall precision of 40 microns.

2.2.2 <u>40 mm diameter button targets</u>

Large diameter targets provide a good image of sufficient pixels such that precise image co-ordinates of the target centre can be obtained over long recording distances. 250 40 mm diameter targets were fabricated for the CMS Barrel Yoke measurements and using a DCS 460 and a 20 mm lens, the images are 5 pixels and 9 pixels in diameter respectively at the operating distances of 10 m and 6 m.

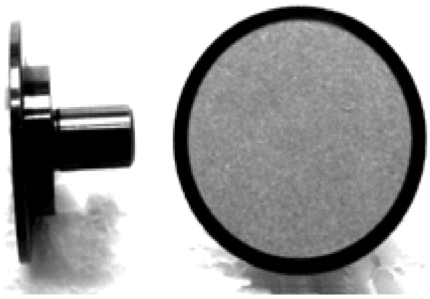


Figure 5 40 mm button target.

2.2.3 Extended codes on magnetic plates

Specific foils with an extended ring, coded from to 1 to 512, printed around a central hole, can be attached around the conventional button targets to provide a coded point.

Adapter foils, mounted on a magnetic plate, were fabricated for all the 40 mm diameter button targets, for the CMS Barrel Yoke measurements.

Figure 6 codes on magnetic plates for 40 mm button target.

2.2.4 Synchronisation module

This module synchronises up to five DCS460 cameras and allows, with cameras placed in fixed positions, the control of the behaviour of an object under deformation.
The synchronisation precision is a few milliseconds and the data acquisition cannot be done if the object moves with a speed greater than 10 mm/s.
The process of deformation measurement in synchronisation mode is in three stages:

1. no deformation applied and measure the object with 1 camera,
2. measure with the n synchronised cameras in fixed position and calculate their external orientations,
3. deformations applied to the object, measure with the n synchronised cameras in the same fixed position and repeat for each deformation step.

The deformations of the 1/3 scale model CMS central tracker were measured with a precision of 50 microns from 3 DCS460 cameras equipped with 24 mm lenses and placed on tripods at 2.5 m from the object.

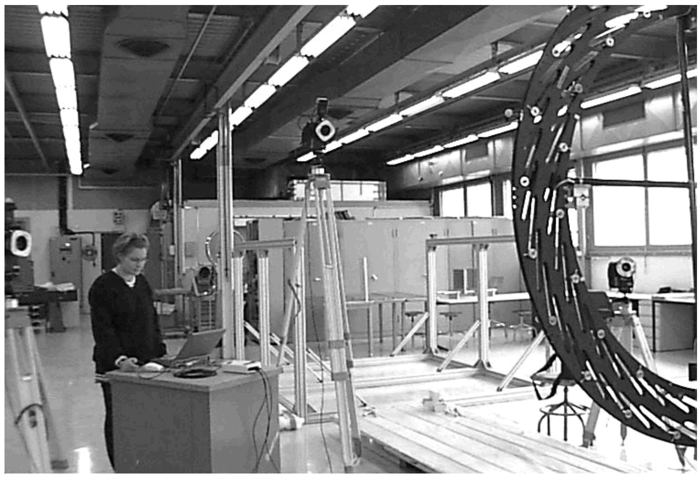
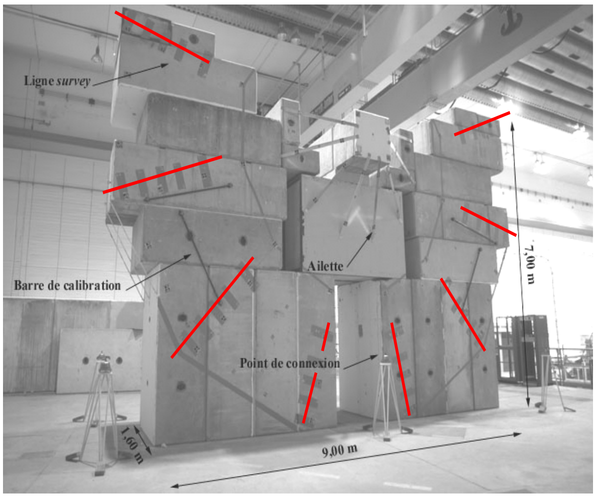


Figure 7 synchronisation module and deformation control.

2.3 Specific Approach for the CMS Barrel Yoke Rings

The validation of a method for carrying out the measurements of a large object leads to the use of models for practical simulation.



A $^{2}/_{3}$ scale model of one Barrel Yoke rings has been built in order to test a working and repeatable procedure using the Kodak® DCS460 CCD Nikkon camera box and the CDW software. The goal was to achieve the highest possible reliability in conjunction with the determination of specific needs such as the size of the targets, the number of distance measurements, and also people, time and working requirements. The connections between the faces are done around the outside and the data taking must interrupt the workshops for a minimum time.

Figure 8 the $^{2}/_{3}$ scale model of a CMS Barrel Yoke ring.

An important task was to evaluate the variations of the camera calibration and the influence of the long operating distance measurements on the final results.

2.3.1 Camera calibration

The coordinates of the principal point, the focal length, the affinity and non-orthogonality of the pixel and the radial symmetrical, asymmetrical and tangential distortions, are generally estimated simultaneously with autocalibration during the calculations. The use of the camera parameters from a separate calibration was considered an important preliminary stage to the work.

A movable, and easily stored, calibration bench, 1.6 m x 1.8 m x 1.28 m, was built with three pieces of 8 mm wide vetronit and has 310 photogrammetric targets. Adapted fixings allow the use up to eight carbon-fibre scale-bars. Measurements with different optics proved that a 20 mm lens was the most stable and could be used for the Barrel Yoke ring. Measurements of the calibration bench were performed before and after each measurement of the model and the real ring.

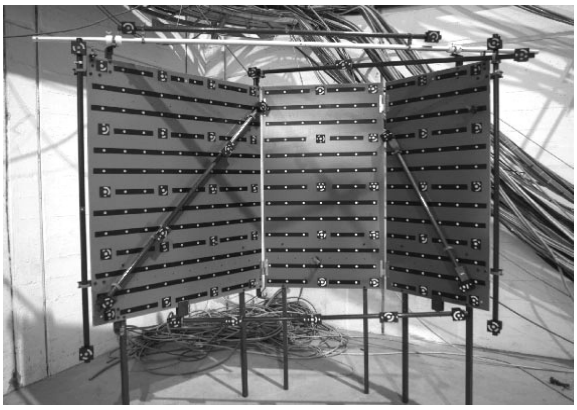


Figure 9 the portable calibration bench

2.3.2 Connection between two planes

The distance between the two faces is 2.5 m and the available space above the yoke is only 4 m. The different test measurements show that numerous targets and scale bars have to be used to achieve the connection between the two faces. 30 mm diameter spherical targets on magnetic supports were used since they gave a wide viewing angle, essential when supporting structures and access scaffolding might block the view for the operations and connections.

2.3.3 Long distance measurements

The 1.5 m carbon fibre scale bars are not sufficient as the only distance observations and some longer distances of the highest possible precision are necessary over the full extent of the object being measured in all directions.
These long distances are measured within an accuracy of 0.3 mm, using calibrated tapes between the reference holes where the photogrammetric targets were centred. A special measurement tool based upon calibrated tapes, with a compressed spring device to ensure that the tension was repetitive and accurately achieved, was used. The distances were compared to those calculated from the photogrammetric coordinates and were a control of the error propagation and the quality of the final results.

2.3.4 Summary of the tests

Magnetic coded targets of 40 mm and sphere targets proved to be efficient for the connections using a 20 mm lens which turned out to have the best and most stable optics.
The minimum number of photos needed for one Barrel was estimated to be 200 and the approximate time for the photographing to be about four hours. The design positions of 20 1.5 m long scale bars - precision 0.05 mm - and 14 long distances - 0.3 mm – on the object were determined to provide reliable controls for reaching the required results.
The estimated precision of the coordinates turned out to be 0.7 mm after the practical test.

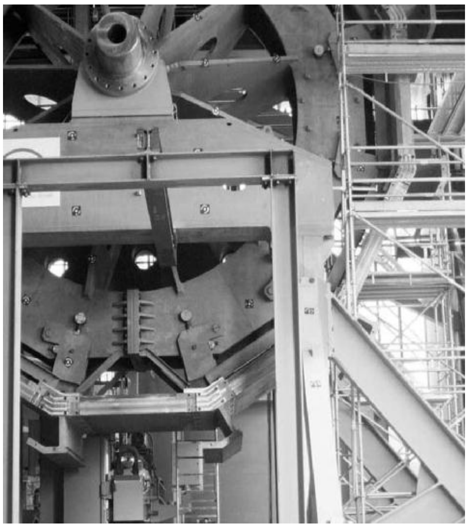
3. THE MEASUREMENTS OF THE CMS BARREL YOKE AND THE RESULTS

3.1 Installation

240 targets centred in the precise reference holes and surrounded by a coded plate and 300 connecting magnetic coded points and spheres arranged on the perimeter were the points measured on the real ring. Twelve 1.5 m scale bars on each face were installed and 6 temperature sensors were placed at three different heights to record the temperature gradients.

3.2 Measurements

Initially a set of photos were taken on the calibration bench before photographing the ring.
16 long distances were measured on each face between the reference holes following the test scheme and the precision of the compressed spring device was 0.4 mm/10 m. The temperature gradients were less than 4.6°C during the measurement. The second set of photos were taken on the calibration bench at the end of the measurements of the ring.



It took 4 h 30 to photography at up to height meters distance. The image configuration had to be adapted because of the huge feet and scaffoldings and the photos for the connections of the two faces were taken from the top and the bottom only. At a final count 260 photos were taken altogether, which was more than expected from the simulation conclusions.

Figure 10 bottom mounting structure and scaffolding

3.3 Results

As a consequence of the good connections, the calculations were finally processed with a self-calibration procedure and gave the three dimensional co-ordinates of 500 points with an average RMS (one sigma) of 0.5 mm, proved by the long distances information.
The practical test with the study of adapted tools and procedures was helpful for the real measurements and the analysis of the results and, the other constraints having been met fully, the procedure was qualified for the 4 other rings and the re-measurement of all 5 at CERN.

4. DETECTION OF MOVEMENTS OF THE INTERIOR ORIENTATION

4.1 Justifications

The aim is to find a realistic standard deviation for the final measurement since, in some cases, internal accuracy seems to be optimistic in light of the external information.
The equipment like the non-metric camera DCS460 camera 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, consisting of 300 photos, may last 5 hours for some large sized projects. The problem appeared with consecutive projects treated on the same day: the interior orientation of each block of more than 80 images was calculated in a different self-calibration and the comparisons of the various interior orientations were greater than 10 times the standard deviation of a single block.
Considering the instability of the DCS when using a different interior orientation for each image, two solutions have been proposed. Maas has fixed the distortion parameters and constrained the values of principal point and focal length to be within their standard deviations, and Beyer has fixed the distortion parameters and the focal length, the principal point being free.

4.2 Tests of possible movements in the interior orientation

Our approach is to evaluate the movements of the interior orientation with the software by attaching one camera per image, such that the principal point and the focal length can be left free for each image, with the distortion being invariant for the block.
Tests on the 1/3 scale model CMS Central Tracker measurements show that the focal length and the principal point are not stable throughout the whole period of image acquisition and vary within 30-40 microns in both directions except during the initial phase. The values for the principal point confirm the results obtained by Mass and Beyer.

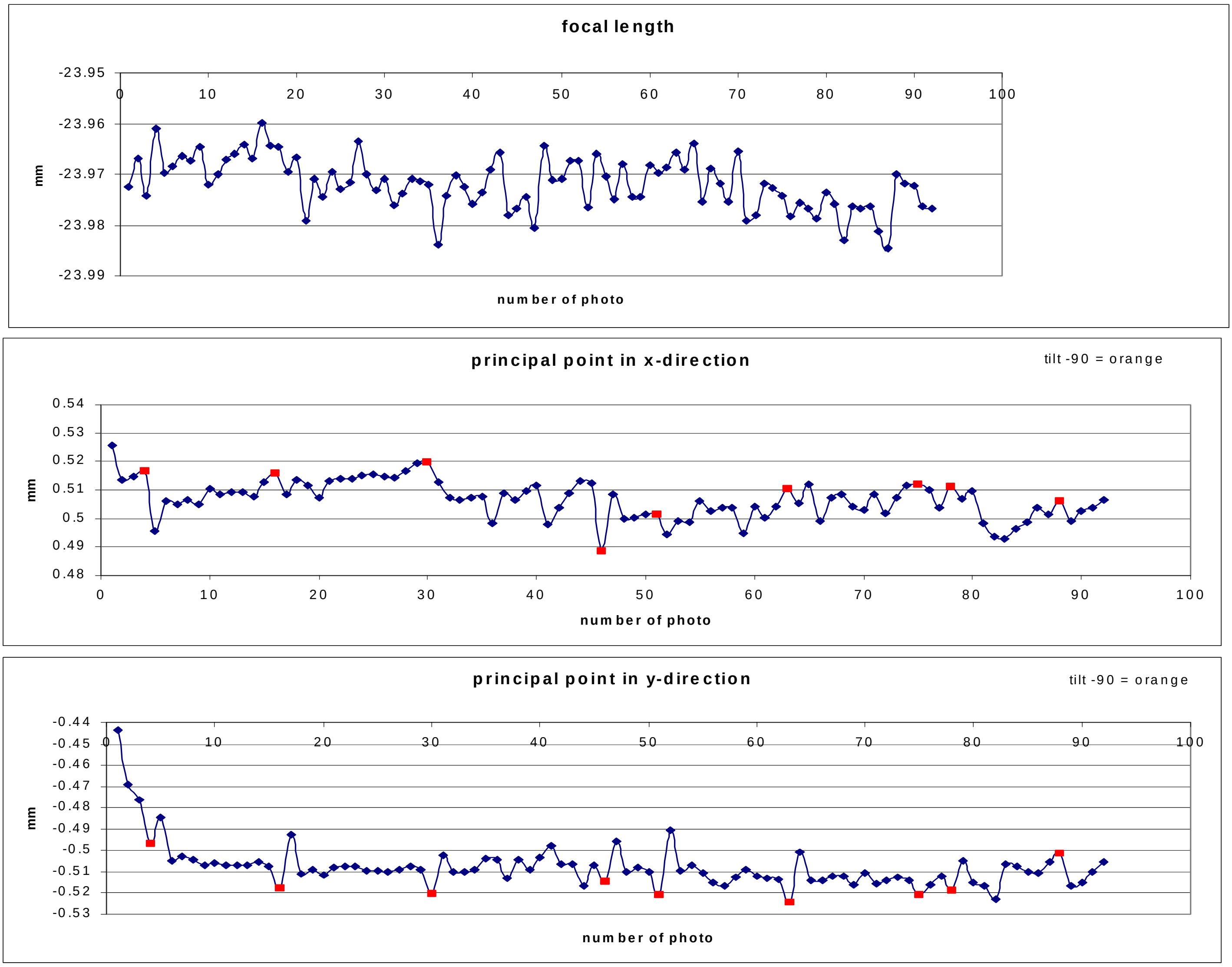


Figure 11 movements of the focal length and of principal point over 92 images acquisition time – see effect of tilted image.

A global movement of the principal point of 20 microns changes the image coordinates by up to 0.5 micron, depending on the slope of the distortion curve, and causes a difference of 0.001 for the image scale.
A significant effect up to 70 microns is noticed during the first 10 photos of the project. The cause seems to be more the way the camera is transported, upside down in the suitcase and then turned by 180 ^{0} for the operation, than an electronic or temperature effect due to the heating of the PCMCIA card which cannot be directly detected.
When taking a sequence of photos with one camera orientation at different locations it is practically impossible to keep the camera at the same tilt (charging camera, changing PCMCIA cards, climbing a ladder or using a lift). Dispersions of 13 microns were recorded between two consecutive +- 90^{0} camera positions in a same sequence of photos of the 1/3 scale model CMS Central Tracker. This may imply that specific internal orientation parameters could be related to a given handling of the camera.
A test with a fixed camera and a small but rigid moving object has been done such that any deformations of the camera and of the object are excluded.

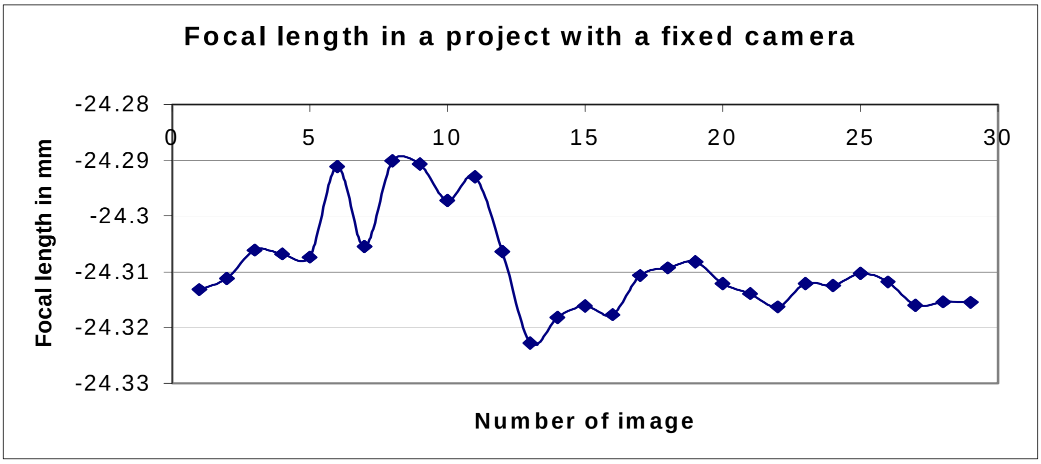


Figure 12 seeming movement of the focal length in the test with a fixed camera

The focal length varies within the same range as in the previous test and stays stable within 2 microns for photos taken at a same relative camera/object position (see positions 6, 8, 9 and 27, 28 29). At each point the correlation between the focal length and the point of view, and also between the focal length and the exterior orientation is visible.
The limitations of this approach are twofold: the lack of information in the direction of the focal length, specifically when the points are almost in a plane parallel to the image sensor, and the poor redundancy, since the calculation of the focal length and principal point for each image increases the number of unknowns.
The weak equation system and the additional unknowns may also cause the variations in the interior orientation. Deleting one image from 25 of a same project provokes changes between 8 and 10 microns and proves that the use of one interior orientation per image is not stable enough in this test.

The existence of remaining systematic errors is indicated by the significant differences between the internal and the external accuracy calculated using several scale bars as a control.
When a bundle block adjustment is calculated without considering the distortion, the whole object is deformed and residuals on external control are up to 1 mm. Any important residual on distances provided by the scale bars indicates systematic errors.

4.3 Further works

More points both in object and image space to stabilise the block and more control with additional information like scale bars to detect deformation of the network are identified as topics for a more exhaustive study.
All these parameters cannot be provided by an individual industrial project and they will be analysed in accordance with the actual future works since we have decided these studies will be based on practical operating examples and not on an object in a controlled laboratory environment.
Particular projects fulfilling specific aspects such as image acquisition over a long period of time, image acquisition in an area with large range of operating temperatures, and the measurement of an object with a large depth in relief using a limited number of camera positions are in process of being studied.

5. CONCLUSION

The correction model, for distortions and the effects of movement, for off the shelf lenses used are not as well developed as for metric cameras and photogrammetric quality lenses and they can vary from less then 10 micron up to more than 300 micron. At the same time the accuracy of the radiometric measurement of the image points has increased to 0.3 micron.
Because of this and despite some bundle adjustment applications like BINGO, using 32 parameters, offering extended models of the distortion, a more global and adapted model is needed for use in high accuracy industrial applications.
A partnership has been established with the Institut of Applied Photogrammetry - University of Oldenburg - in order to explore our present projects with a more scientific approach.

ACKNOWLEDGMENTS

The authors would like to thank especially C. Humbertclaude, J. C. Gayde and the CERN surveying students F. Fuchs, K. Nummiaro, C. Wantz, F. Fuchs and M.Daeffler. They would also like to thank N. Romman (*GMS*), C-T. Schneider (*Aicon*) and Prof. T.Luhman (Institut of Applied Photogrammetry - University of Oldenburg) for their advice and support.

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