Prospects of Close Range Digital Photogrammetry in large physics installations

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1. INTRODUCTION

The requirements in techniques of digital photogrammetry specially have continuously increased since the LHC project, machine and detectors, has been approved.

The modern 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 orientation parameters of the network and the object coordinates are estimated simultaneously in a common process called bundle adjustment.

The CERN Positioning Metrology Group has been using a DCS 460 non metric digital camera and the Rollei DPA / CDW software package. The main features of the system are described, geometrical results of tests validation and measurements performed in industrial conditions are presented and analyzed towards the intensive applying to the LHC needs.

2. MAIN FEATURES OF THE CERN EQUIPMENT

2.1 The image recording system

Fig.1 DCS 460 recording system

Lens system, camera body and imaging sensor build the image recording system [1]. The Kodak professional DCS 460 camera is a portable system that takes and stores high-resolution digital images. The camera back is attached to an unmodified Nikon N90 camera body that has its film back removed and it incorporates a CCD full-frame imager collecting light resulting in a file which contains 6.0 megabytes of data. The imager is 18.4 mm * 27.6 mm (2036 pixels * 3060 pixels) and it does not need any expedient for flattening as the elements are arranged very precisely. The system is pixel-synchronized and radiometric effects are minimized by individual illumination control.

The data for one image, converted from analog to digital form, are stored in the dynamic random access memory (DRAM - 16 megabytes) and transferred to the PCMCIA card. The camera is ready within 0.25 seconds after the shutter release is depressed and it can shoot a 'burst' of two images; the second image is captured in approximately 1.6 seconds, subsequent images can be taken at intervals of approximately 8 seconds.

The resolution of the image recording system and the image sizes affect the accuracy of the system. When a strong network and a good redundancy are established, the relation between the measurement accuracy of image points and the image size states a relative accuracy which can be compared to the relation between object accuracy and object size.

The DCS 460 offers image sizes up to a few centimeters and the image measurement accuracy is about 1/40 pixel, better under laboratory conditions: this leads to a relative accuracy of about 1/100000 which may be reduced due to stability reasons of the camera and the camera mount.

The calibration of the image recording system relies on how accurate the camera geometry is known. The main parameters of the camera geometry are the principal point (intersection of the image plane and the principal ray normal to the image plane) and the principal distance (distance between the principal point and the perspective center-exit pupil of the lens).

These parameters are estimated simultaneously with the orientation parameters of the network and the object coordinates by the bundle adjustment: an appropriate procedure using control information in object space (geometric constraints between object points) and photogrammetric information (self-calibration with simultaneous multi-image triangulation in a network of high convergent overlapping images) is usually developed. Systematic image errors like radial symmetric/asymmetric and tangential lens distortion as well as the affine parameters of the sensor (scale and direction) are also estimated in the same process.

2.2 The image analysis

The measured variables are the two-dimensional image coordinates of the projected object points. The image analysis is based on the detection of imaged object structures such as discrete and unique points and edges. Retro-reflecting targets reflect the light best towards the ring-light around the camera lens. Exposure time and aperture are optimized for best possible point imaging for a suitable contrast while the object image is suppressed.

A point, e.g. a well contrasted plane circle in object space, is imaged as an ellipse. The center is found with thresholding techniques and the knowledge of the structure can be used for this estimation. Analyzing the gray value variation along directions perpendicular to the borders give the edge points. A low-pass filter minimizes the sensor noise, a high-pass filter amplifies the edge to optimize the analysis. The ellipse parameters derive from an adjustment process taking the measured edges as input data.

Automated detection and identification specially by using coded patterns, realized by concentric black and white segments surrounding the retro-reflective part, speed up the digital image analysis and improve the productivity of the whole process. Special rings with only the code stuck on surround usual retro targets so that those are imaged as coded targets. It is well known that the diameter of the target in the digital image should cover at least 3 pixels (picture elements) to achieve image coordinates with subpixel accuracy. For practical use it is preferred to have a diameter of about 5 pixels or more.

2.3 The multi-photo orientation and the bundle adjustment programs

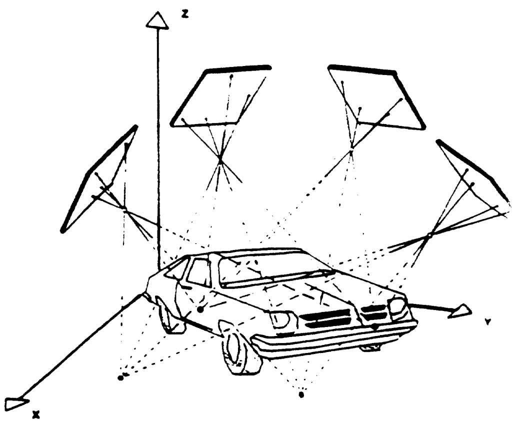


Fig.2 Multi-image triangulation

These two programs are the base for 3D object reconstruction out of the 2D image information; they allow the reconstruction in an oriented image block by ray intersection in space for single points. In addition to image point measurements, non-photogrammetric measurements such as known distances and heights and/or given control point coordinates (additional observations) are also used.

The shape of the object is derived from pure photogrammetric information, its size and location are obtained from the additional observations information given into the object space.

The Rollei CDW (Close Range Digital Workstation) bundle package under Windows 95 and NT comprises the module NAWE_OPT computing the initial values of object coordinates and parameters of exterior orientation and the proper bundle adjustment module PROMPT.

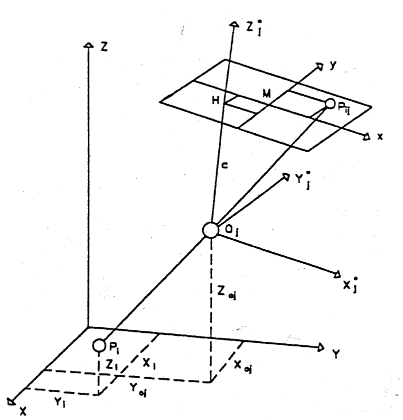


Fig.3 Geometry of the central projection

The functional relation of the bundle adjustment is the central projection where the parameters of the camera data (the interior orientation in the image co-ordinate system: the calibrated focal length c, xH, yH the coordinates of the principal point and dx, dy the systematic image errors), the camera stations (the exterior orientation in the object co-ordinate system: Xoj, Yoj, Zoj the coordinates of the perspective center and the angles axis, tilt and swing of camera; that is the relationship between the image co-ordinate system and the object co-ordinate system) and the three coordinates Xi, Yi, Zi of the object points are included.

$$\begin{bmatrix} x_{ij}-x_H-dx \\ y_{ij}-y_H-dy \end{bmatrix} = \frac{-c}{Z^*_{ij}} \cdot \begin{bmatrix} X^*_{ij} \\ Y^*_{ij} \end{bmatrix}$$

$$\begin{bmatrix} X^*_{ij} \\ Y^*_{ij} \\ Z^*_{ij} \end{bmatrix} = D(\omega_j, \varphi_j, \kappa_j) \begin{bmatrix} X_i - X_{oj} \\ Y_i - Y_{oj} \\ Z_i - Z_{oj} \end{bmatrix}$$

Fig.4 Functional relation

With xij, yij being coordinates of the image point Pi in the image co-ordinate system, X*ij, Y*ij, Z*ij coordinates of Pi in the auxiliary co-ordinate system parallel to the image co-ordinate system, Xi, Yi, Zi coordinates of Pi in the object co-ordinate system, D(ωj, φj, κj) the rotation matrix to transfer the object co-ordinate system into a position parallel to the auxiliary co-ordinate system.

A robust error detection method [2] based on the minimization of the total absolute sums of residuals is introduced in NAWE_OPT to trace the gross errors such as false measurements and point identifications, miscalculated object coordinates due to a bad ray intersection geometry. The method relies on the fact that the smearing effect of peak values in the residuals as known from the least squares is largely eliminated. In case of a single unknown it leads to the ‘ideal situation’ of the median but, in the case of several unknowns, that situation is sometimes not true due to the differing influences of individual observations.

The ‘ideal situation’ is achieved when every observation receives exactly the share of the total degrees of freedom as it is achieved for the arithmetic mean where each observation receives exactly the same contribution rl = 1- nbr unknowns / nbr observations. The value of rl, similar to the internal reliability factor, is sized with the coefficient matrix A and the matrix of weights P whose shape changes when the reliability is optimized: every observation has the same share and the combination of minimization of absolute values of the residuals under the consideration of the geometry. This method is signified by the reduced sensibility of leverage points and called the L1-norm with balanced observations.

PROMPT, based on the L2-norm (normal equation formulations from least squares techniques), applies different numerical strategies for the computations of the parameters and carries out some important checks.

For the adjustment with rank deficiency design matrices and considering n the number of observations, u the number of parameters to determine, r the rank deficiency of the (n,u) size design matrix A, the r equality constraints being formulated within the (r,u) size matrix $\underline{E}$ derived from the condition $\underline{A}\ \underline{E}^T = \underline{0}$, the numerical check $\underline{E}\ \underline{x} = \underline{0}$ is displayed ($\underline{0}$ is a (n,r) size zero matrix).

The Ansermet test is carried out to determine the accuracy of the computations of the least squares adjustment including the inversion of the normal equations. The value of the test must be equal to the number of unknown parameters.

These numerical checks are important to control the computer’s processor and to decide whether to add some iterations and increase the accuracy.

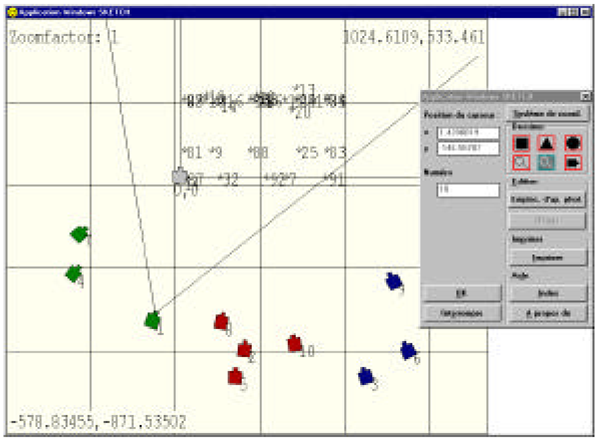


Fig.5 Sketch menu

A sketch function, as graphical tool for the judgment of the network configuration and the results, generates a computer-aided shooting on the monitor. It gives the camera stations in red if not computed yet but inserted with position, aperture orientation, height, tilt and swing manually input, green if single or multi-photo orientation computed, blue if computed by the bundle. Any computed station can be activated and position, axis, tilt and swing are edited. If a photo assembly has first been computed for only available photos, the camera stations of additional photos can be added on the basis of these results. Figures identifying the type of object can be added to the sketch to make it more descriptive.

2.4 The basic procedure for processing a photogrammetric project

The CDW package [3], running on a portable PC Siemens 166 MHz, is project-oriented: once a project is started, it creates a file *project*.PRJ where all the data involved are filed.

The camera data are checked in the *project*.IOR file where the good parameters are activated.

Additional observations are input in the *project*.AOB file; they include points coordinates measured, spatial distances measured, information about camera stations and specific additional data concerning the camera. Each observation is introduced with its own standard accuracy or errorfree or marked as ignored during the computation. The additional observations are generally entered after a first computation of the bundle because that makes a more systematic error analysis if any of the data is faulty.

When the project images are loaded, images or groups of images can be selected by marking them and existing images may be added. They are converted in the Windows Bitmap format as the DCS 460 gives the image data in TIFF, and then initialised, that is assigning the image number and the camera system used. The project images to be processed can be previewed on the screen (Windows screen) and one can be selected so that an image detail is shown on an additional window (working window).

The *Measurement* menu includes all the basic settings and functions for manual and automatic measurement of image points such as measurement of natural non-signalised or signalised points, operators for automatic point and coded targets measurement using centre and/or ellipse operator (coded targets), size of detail in image in which a signalised point is to be found and minimum contrast.

The *Image point measurement* function allows individual image coordinates measurement manually from the photos such as selected so-called orientation points (approximately 10 orientation points should be measured in each photo and in at least three images), automatic measurement of coded and non-coded targets in several images and automatic measurement based on object points (even approximately and provided that the camera stations and the camera data are known). For both of the last types of measurement existing image coordinates can be used and are overwritten by new ones; all these types use the parameters entered under the settings.

The *Computation* menu comprises the multi-image orientation and the bundle adjustment (NAWE_OPT and PROMPT) programs. The following data must be given for the multi-image orientation to recover the situation of a photo assembly that is determining the camera stations:

- the image coordinates of the orientation points from manual or automatic measurements: there must be 10 to 12 well identifiable points measured in every image, the image points have to be well distributed across the whole image format and not being on a straight line and every point should be measured in at least 3 images taken from different camera stations with the best possible conditions of intersection,
- the camera data input under the file *project*.IOR,
- the definition of a user co-ordinate system: the minimum specification for a system fixing is 6 coordinates of three no-colinear points (control points) plus one distance and is only used for computing the multi-image orientation to start with. The data is marked as additional observations with SYS for the bundle adjustment and is used in the computation as standard,
- the approximate camera stations: they are given either by means of a the sketch function or manual input. No starting data may be required if enough control points are known.

The order in which the images are to be computed must be specified since successive images must have at least 5 points in common measured in both images.

Different multi-image orientation computations depends on the available information:

- computation with starting values for all camera stations and object points unknown; the successful computation depends on the first two images having at least 7 common points. All successive images should have at least 3 (preferably 5 points) in common with the preceding one. The minimum specification is sufficient for the system fixing,
- computation with starting values for the first two images of the sequence and object points unknown; the successful computation depends on these first two images having at least 7 common points. All successive images should have at least 6 points in common with the preceding one. The minimum specification is sufficient for the system fixing,
- computation without starting values for the camera stations and object points unknown; the successful computation depends on the first two images having at least 7 common points. All successive images should have at least 6 points in common with the preceding one. A definition of at least 4 full control points is required for the system fixing.

The multi-image orientation is done automatically step by step by the program:

- computation of the camera stations and the object points in a local co-ordinate system defined by the first two camera stations and relative orientation for the first image pair,
- computation of the camera stations of the 3rd to nth image by spatial resection and computation of further object points by intersection,
- transformation of the object points into the defined co-ordinate system (system fixing) and multi-image orientation in the specified system: computation of the camera stations of the 1st to nth image by spatial resection and computation of improved new point coordinates by intersection.

Single-image orientation without starting values for all camera stations can be computed when the image coordinates of at least 6 points of which the object coordinates are known have been measured (spatial resection). A system fixing is not necessary.

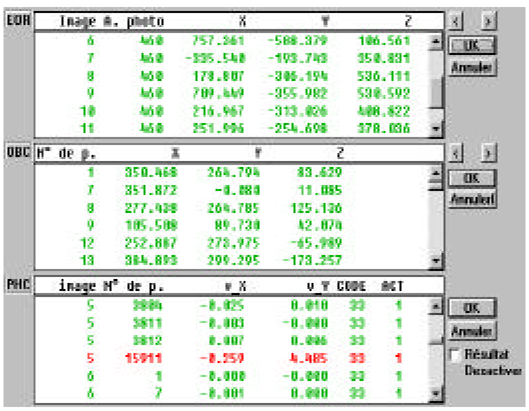


Fig.6 Multi-orientation results

A view of all the results is displayed namely the camera stations (EOR), the object coordinates(OBC) and the image coordinates(PHC) corrections v_x and v_y (deviations between a measured point co-ordinate and a point co-ordinate computed from the determined point). An important criterion for judging the results are the values v_x and v_y and robust estimation techniques detect blunders without smear effect distorting the overall result: all image corrections greater than 0.1 mm are considered as grossly erroneous.

The image measurements whose corrections are larger than the preset threshold are marked in red (the successful images are in green) and can be excluded from further computations by the function *Outlier deactivate*. Individual measurements are repeated or confusions of points corrected before any re-activation. The corrections should be on average 0.001 mm for automatic point measurement but blunders are reliably detected by the L1-norm in PROMPT so that it is sufficient to eliminate only those greater than 0.1 mm for multi-image orientation.

The bundle adjustment, unlike image by image computation in multi-orientation, considers the entire photo assembly and allows all ties between image co-ordinates, camera stations, camera data and additional observations. The setting parameters are especially the *active* function if the camera calibration data are to be used or the *fix* function if these data are to be re-calibrated by the bundle and the *Free network* function if the system is positioned with object points marked as datum points.

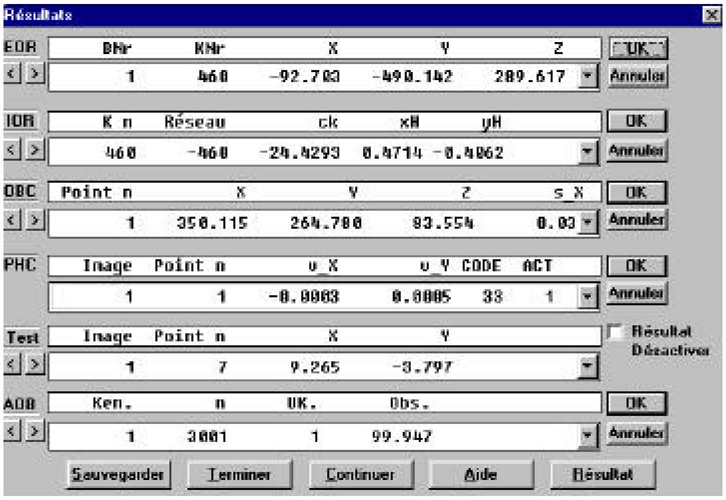


Fig.7 Bundle adjustment results

After the error detection have been processed and the blunders excluded by the *blunders deactivate* function, the L2-norm starts. The a posteriori sigma0 after the bundle should have the expected accuracy (0.0005/0.001mm) for automatic measurement of signalised points. Other criteria are the residual mismatches of individual observations and the statistical test magnitudes. The automatic blunder deactivation and the L2-norm bring the final overall result.

3. TESTS VALIDATION AND APPLICATIONS

3.1 validation benches

Two different sizes validation benches have been used for testing and learning the system.

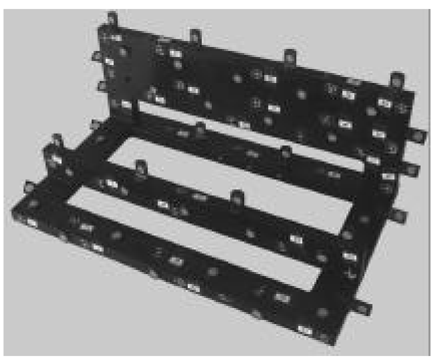


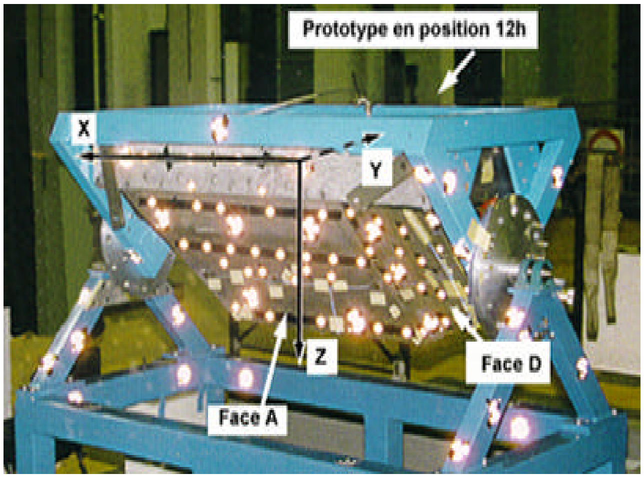
Fig.8 Portable validation bench

- a portable frame: 0.5 m*0.3m*0.2m, 5 planes in depth, various retro and coded targets fitted into 50 precise holes and sticked to the structure on every side.
  - 13 camera stations, 1533 observations,
  - 13 additional observations distances measured on a 3 CMM (accuracy 5µm),
  - Sigma0 0.3 µm, S_{XYZ} r.m.s 7µm, additional distances r.m.s. 8µm, relative accuracy $1.7*10^{-5}$,
  - reproducibility: 100 % XYZ < 2.7 sigma.

Fig.9 The indoor calibration base

- an indoor calibration base: 3m*3m*2.2m, 22 Cern reference sockets, ‘corner arrangement’, minimum 82 retro and coded targets fitted into precise holes and sticked to the structure.
  - 45 camera stations, 4072 observations,
  - 20 additional distances (interferometer and precise leveling -accuracy 5 µm /20µm),
  - Sigma0 0.2 µm, S_{XYZ} r.m.s 20 µm, additional distances r.m.s. 18 µm, relative accuracy $0.6*10^{-5}$,
  - reproductiblity: 100 % XYZ < 3 sigma.

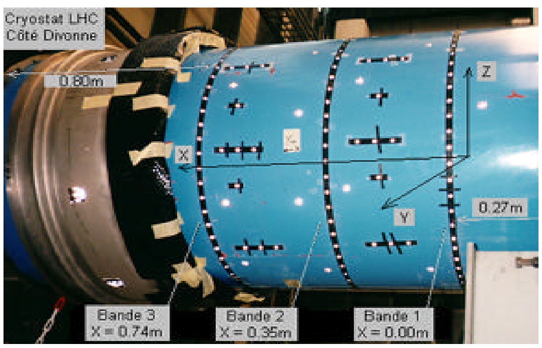
3.2 applications in industrial environment



- CMS-ECAL prototype .8m*.6m*.4m, measurements of deformations under 13 different positions, 135 retro targets sticked on the 5 faces plus 80 coded targets on the supporting structure and the prototype faces.

- 40 stations and 3500 observations per position, lenses 18 mm and 24 mm,
- system fixing attached to the mechanical link plate,
- Sigma0 0.25 µm, S_{XYZ} 30 µm, relative accuracy $4.1*10^{-5}$.

Fig.10 The CMS-ECAL prototype (position 12h)



- LHC cryostat prototype 1m diameter, measurements of ovalisation under 3 different profiles, 210 retro targets spaced and stuck regularly around the cylinder every 0.1m (reels) plus 60 coded targets.

- 23 camera stations, lens18 mm,
- system fixing attached to the cylinder,
- Sigma0 0.3 µm, S_{XYZ} 50 µm, relative accuracy $5*10^{-5}$.

Fig.11 The LHC cryostat prototype

These two examples clearly show some premium advantages of the system:

- for the CMS-ECAL prototype deformation measurement triangulating the same amount of points with theodolites would have implied setting up at specific locations regarding the various measured positions of the object; because of the difficulties in linking these stations and the likely deformations of the support while the rather long duration of theodolites data taking, the same homogeneity would not been achieved,

- for the LHC cryostat prototype the form and the setting-up of the cylinder at 1.2 m from the floor would have implied very uncomfortable high and low theodolites stations with also difficulties in linking these ad-hoc places; owing to the nearly infinite depth of field (small aperture) camera stations could be managed very close to the down parts of the cylinder.

4. TOWARDS THE PHYSICS INSTALLATIONS IN LHC ...

A Quality Assurance Plan (QAP), implemented in the machine and experiments LHC project, will govern specially all mechanical tools used to measure physical dimensional parameters during manufacture, inspection, acceptance testing and assembly. Because of the dimensions [4], the breakdown in numerous items, the various forms (rings, wheels, perspective towers, petal-shaped frames, overlapped planes, ...) and the prerequisite tight tolerances in relative positioning (from 20 µm up to 200µm), the digital system has been integrated as a major measuring device to intervene at decisive steps such as trial assemblies in factory, re-assembly in surface halls at Cern and final installation in underground.

The following considerations may be helpful for a coarse estimation of expected accuracy and for a preview of potential measuring problems on the spot.

Considering an image measurement where the X/Z object plane is parallel to the image plane, the object accuracy σX is the product of the photo scale mb and the image accuracy σX', σY'. A second image is to be added to determine the depth Y and the object accuracy σY depends on the ratio between the photo base b and the camera-to-object recording distance s:

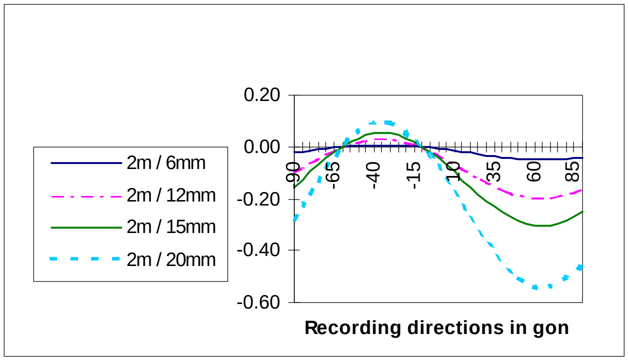
$$\sigma X = \sigma X' * mb = \sigma Y' * mb \qquad \sigma Y = \sigma X' * mb * s / b$$

Besides the usual criteria (filling the frame, good convergence of camera axes) the admissible photo scale, based on the attainable accuracy, is decisive for the selection of camera stations, the equipment and the accessibility of the object. For a rough estimation of operating conditions, the photo scale can be obtained from the ratio of an object distance to the same distance in the image: mb = object / image.

- if the desired object accuracy is 20 µm and the attainable image accuracy is 0.25 µm, mb = 20 / 0.25 = 80 (photo scale = 1/80),
- if the DCS 460 is used with a 24 mm lens c, s (camera-to-object distance) = mb * c s = 80 * 0.024 = 1.92 m,
- the maximum object size in the DCS 460 image is, 0.0184 * 80 = 1.47 m vertically (V) and 0.0276 * 80 = 2.21 m horizontally (H).
- considering a desired object accuracy of 200 µm and a 18 mm lens ... mb = 800, s = 14.4 m , (V) = 14.7 m, (H) = 22.1m ...

The minimal target diameter in object space D is estimated from the recording distance s, the focal length c and the minimal diameter in the image pn (5 pixels = 45 µm) by $D \geq pn * s / c$; the minimum target size is 3.6 mm for the '20 µm' project, 36.0 mm for the '200 µm' project.

An estimation of maximal target diameters is also necessary specially on close range measurements: oversized targets, due to the fact that the projection of a circular target will appear as an ellipse, can cause measurements errors (offset) and the true target center may be not identical to the center of the elliptical target image.



This offset has been modeled [5] for various recording distances and orientation between ± 90 gon, different target diameters and the maximum image radius (18 mm for the DCS460). Assuming an image measurement accuracy of 0.3 µm, 10 mm target diameters have no influence on recording distances between 2 m and 5 m and target diameters of more than 10 mm should not be used for these distances.

Fig.12 Offset (µm) for 24 mm lens, 2m distance
18 mm maximum image radius and various targets

Tests have revealed a systematic shift of the center of targets with painted edge masks from ± 30 µm normal to the line of sight when they are viewed from directions of ± 45 gon [6].

The optimization of the digital photogrammetry procedures for the LHC detectors is based on these considerations and that forms an important aspect of the preparatory works such as the design of the targets, the configuration of the camera stations network etc.

5. CONCLUSION

Comparing to spatial triangulation, digital photogrammetry offers valuable advantages such as a short time on-site nearly independent from the number of object points, the possibility to choose the recording stations in a very flexible way and a procedure with high measuring accuracy for voluminous objects in situ.

The rather new experience in using this system has taught us the large benefits of integrating it in our tool box. It has enabled us to treat demands that could have been achieved in very harsh conditions with the conventional triangulation methods. Owing to its portability it perfectly meets the problems of accessibility and the condition of operating (small aperture) allows to use it at very short focus. It has also been carried out in conjunction with the usual methods to ensure relative positions with high accuracy for fiducialisation of detectors. Linear geometrical correlations computed from the photogrammetry results are introduced as field observations with their own error in the spatial adjustment program.

New product like the $Q^{16}{}_{\text{Metric camera}}$ from Rollei (4096*4096 pixels) pushes the limits far ahead and we can expect that one understands the ‘conventional triangulation methods’ as the ‘high accuracy digital metric unique camera triangulation method’ in a very near future.

6. REFERENCES

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