EVALUATION OF STRETCHED WIRE MEASUREMENT BASED ON PHOTOGRAMMETRY IN THE CONTEXT OF CERN

A. Behrens, D. Mergelkuhl, CERN, Geneva, Switzerland
C. Vendeuvre, INSA, Strasbourg, France

Abstract

Offset Measurements with respect to stretched wires are traditionally used for accelerator alignments at CERN i.e. for the SPS and the LHC, the position of the wire being measured either by an optical sensor or by a capacitive sensor. In recent years the resolution of digital cameras increased so that wires of few tenth of millimetres get visible in images at limited distances of 1-2 m. A method based on photogrammetry is able to measure the reference (wire) and the magnet fiducials simultaneously using the same measurement system. As an optical non-contact method it offers easier possibilities of automation in comparison to the manual procedure employed in the SPS and LHC so far. At the same time other uses of wire measurements like the calibration of wire chambers and detectors seem interesting.

The presented photogrammetric measurements are based on the feature measurement of the commercial software from AICON 3D Systems. An evaluation has been done of the wire axis measurement without special signalisation and the magnets fiducials at distances of 1-2 m as for the LHC. For this different hardware components and parameters have been tested like lenses, light conditions or different wires. An estimation of the reachable precision is verified on a dedicated test bench and a scale 1:1 mock-up with respect to the classical offset measurements. The aim is to understand the capacities and constraints of the system that reaches precisions of few hundreds of millimetres in the tested setups.

INTRODUCTION

In the accelerators at CERN, offsets measurements are the main method for the radial alignment of the components. For the measurement, mechanical ecartometers are commonly used. They are installed in one of the fiducials on the magnets and measure the perpendicular distance to a stretched wire. See figure 1 for a measurement scheme for ecartometry with overlapping wires [1].

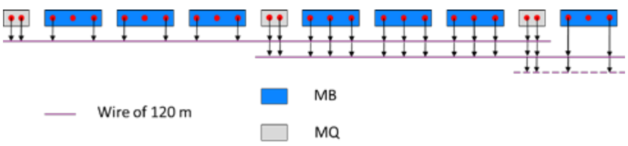

Figure 1: Scheme for ecartometry in LHC

The method has been chosen due to the favourable precision in comparison to other methods. For the LHC, alignment precisions of 0.05 mm are achieved within a sliding window of 150 m. This corresponds to an angular precision for a theodolite of 0.04 mgon, which is nearly 4x better than the specification of common instrumentation. It's even more difficult to achieve the specifications in the tunnel because of the influence of refraction.

In this context a study concerning the use of laser tracker for the radial alignment measurements of the LHC has been done in 2012 [2].

But the manual handling of the instrumentation is time consuming. With the traditional equipment, a two person team can treat approximately 500 m of accelerator per day. For the future a method with a high potential for automatization has to be developed to avoid manual installation of equipment and measurement in order to gain manpower and time.

At CERN digital photogrammetry is used for nearly 20 years [3] and has proven its efficiency during the construction of the LHC experiments with high precision and flexibility. A more recent application is the dedicated system for the collimator train. In that case the stretched wire is measured by an optical micrometre as the configuration and resolution of the cameras has not been adapted to measure the wires and fiducials by the same system [4].

AICON 3D STUDIO / DPA

CERN uses the AICON photogrammetric software since 1997 but in recent years the integrated feature measurement attracted interest. In addition to the standard photogrammetric projects with signalized target measurement, orientation and calibration up to the calculation of 3D coordinates, the software gives the possibility to measure curved lines if seen in different images.

As individual points are measured on curved lines the problem of homologous points on the homogenous lines has been solved by an algorithm based on multiple epipolar geometry that creates dense points. A point spacing of 0.25 mm to several mm distance can be defined by the user. It is recommended to have a line thickness of 3-5 pixel. Due to the increased camera resolution in the last years it is possible to measure stretched wires of 0.3 mm diameter at limited distances of 1-2 m.

Two different algorithms are proposed that work with the first respectively second derivative of the grey value profile to calculate the centre of the line or as in our case of a wire.

First promising tests have been done few years ago with a previous version of the software and today obsolete hardware for camera and computer. At that time a working distance of 0.5-0.8 m has been necessary to get results. An intensive study has been postponed because of sharpness issues due to limited resolution and depth of field.

A main disadvantage of the wire measurement using the AICON software is the fact that a starting point has to be given manually by the operator in two images to start the measurement. A second constraint is that a minimum of four photos is mandatory for any measurement.

BENCH DESIGN

For a detailed evaluation of the capacities of the soft- and hardware, a dedicated test bench has been fabricated. The bench is based on an aluminium base plate of 500 mm x 350 mm x 35 mm, on which two rods with steel grooves have been added using pin- and long hole to avoid constraints. In each of the grooves 26 precise ceramic balls have been glued to be in contact one to each other. The complete assembly including 16 coded and un-coded photogrammetric targets has been measured in the CERN metrology laboratory. A set of coordinates of 2 µm precision is available for the evaluation. This precision is approximately 10 times better than the repeatability of the traditional ecartometer and is considered as absolute reference for comparison.

In between the ceramic spheres wires can be stretched and fixed on the ends of the bench. Springs are used for fixation to keep the wires stretched. In figure 2 the equipped bench is shown with coded targets, non-coded targets and the wires that are inserted between the balls and fixed at the outer limit of the bench. The bench has 14 8H7 diameter reference holes that have been neglected to avoid the introduction of additional mechanical errors due to the use and change of targets. Additional coded targets are distributed around the bench for orientation and calibration.

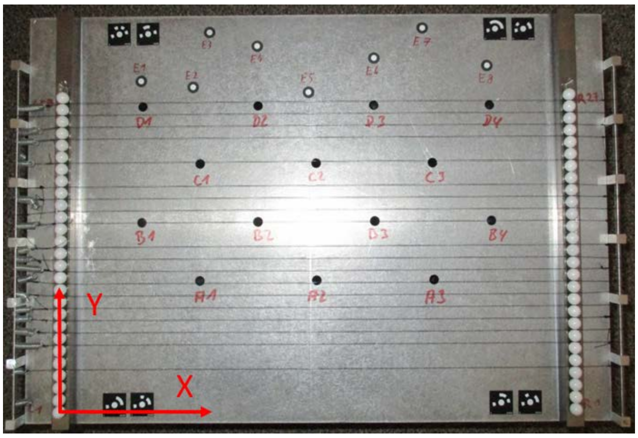

Figure 2: Test bench setup

As photogrammetric equipment a Nikon D3X in combination with AICON metric 28 mm lens and a top mounted flash has been used. Carbon fibre scale bars of ~600 mm that are calibrated at 3 µm complete the equipment.

TESTED PARAMETERS

Numerous tests have been done to evaluate different parameters of the system and the parameters have been separated in four groups:

- Wires properties: diameter, colour, material, construction.
- Camera system: lens, flash, aperture, ISO, exposure time, resolution.
- Software: line algorithm, contrast, point density.
- Configuration: number of images, intersection angle.

Wire parameters

For the wire parameters it can be summarized that the following properties increase the quality of the results. The wires should be:

- Non-reflective, as wire detection is impossible in reflective areas.
- Dark, to get a high contrast in the image.
- Monofilament, as the form of multifilament wires is less regular and creates non-uniform brightness and reflections.
- Non-metallic, as metallic wires get definitively creased during handling.
- Of adapted size. The wire diameter in the image should correspond to more than 1-2 pixels. Else the contrast is reduced, which decreases the probability to obtain reliable measurements.

The best solution that has been used for test is a black, monofilament fishing wire of 0.3 mm diameter.

Camera parameters

For the available camera system based on the D3X the following parameters can be taken as recommendation: ISO 100-600, exposure time 1/125-1/250 sec., aperture 11 or 16, top mounted flash with power 1/8 or 1/16 [5].

Software parameters

In practical tests the method “centreline”, based on the first derivative of the grey value profile and recommended for thin lines, is considered as not robust enough for our application but the method “edge” gives satisfying results. Its mathematics is based on the determination of the second derivative of the grey value profile that is set equal to zero. For the “edge” algorithm the mean coordinates of the two inflection points of the grey value profile are considered as line centre (see figure 3). It is recommended for thick lines. The density of points along the wire can be chosen and values for the spacing from 0.25 mm to 2.0 mm have proven efficiency. If the spacing gets larger the detection algorithm has problems to follow continuously the line from the manually given starting point.

The wire measurements are based on the analysis of grey values which underlines the importance of the contrast value for the measurement. The default contrast value in the software for line measurement with respect to its background is 30 units of grey values. The different measurements have shown that values of 20-40 give acceptable results. Even below 20 a suitable measurement is still possible in several cases. It’s not recommended to use values below 10 as it’s too close to the noise level of the image.

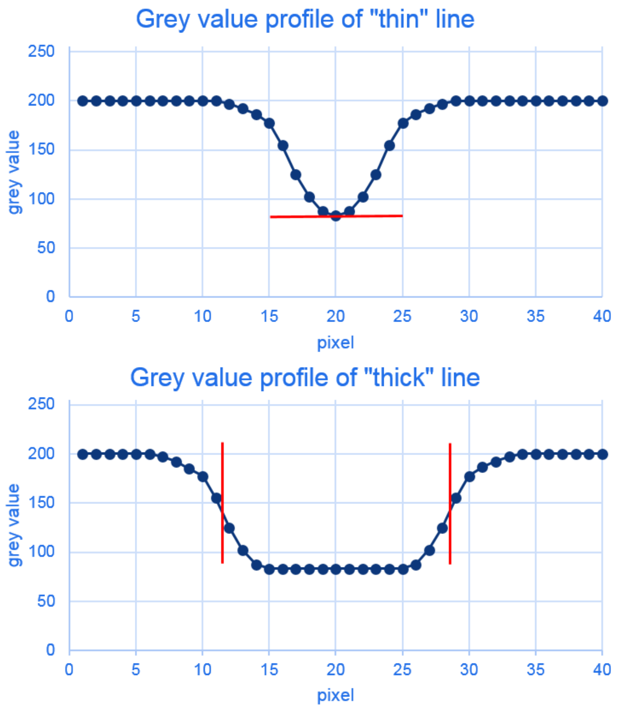

Figure 3: Algorithms for measurements

Configuration parameters

Even if the theoretical minimum configuration requires only two images, the software needs a minimum of four images to have redundancy in the adjustment of each point on the line. In practical tests a standard configuration as shown in figure 4 of 16 photos at a distance of ~1.4 m and intersection angles above 90 degree has given good results.

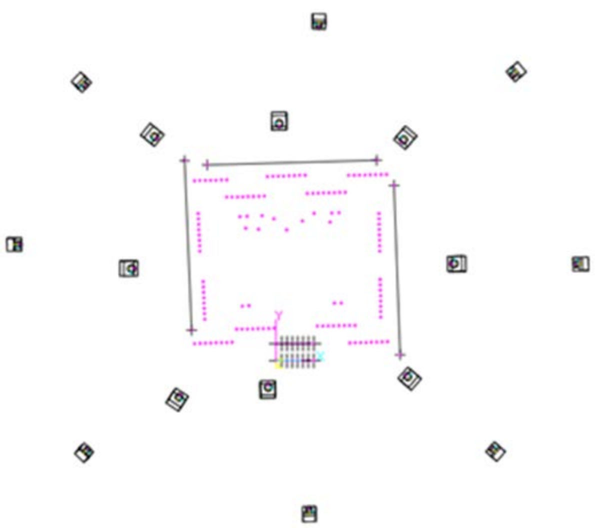

Figure 4: Configuration for photogrammetric project

At least 8-10 images and numerous points are recommended to get a robust calculation as the self-calibration of the camera parameters is done on-the-job. The time for the measurement is proportional to the number of photos and more than 30 images are not recommended as the contribution to the geometrical determination is very limited. The photos should be taken in a way that the base between photos is preferably perpendicular to the measured wire. If the base and as consequence the epipolar line is parallel to the wire a measurement is impossible due to a singularity in the configuration.

PRECISION AND ACCURACY IN LAB

The experience of the previous parameter evaluation has been used to setup a repeatability test for the bench. On the bench 10 wires have been installed in parallel and measured 10 times in a minimum time to avoid change of conditions (temperature). The 2D distances of five measured points to the ten wires have been calculated each time so that the estimation could be evaluated on a statistic of 500 measurements.

Procedure for analysis

The data of the wire measurements is analysed as calculation of a least square fitted mean line in the XZ and YZ planes. The analysis has been done on 2D distances between five measured targets and the 10 wires as the bench construction gives a reference for the radial but not the vertical component. The 2D distances of the targets to the wires on the bench are 400 mm long and the wires are stretched by springs so that the sag of the wire is not taken into account.

The ends of the lines are often populated with blunders (see figure 5). These errors are linked to the bench construction and the fact that the measurement algorithm has no defined end point.

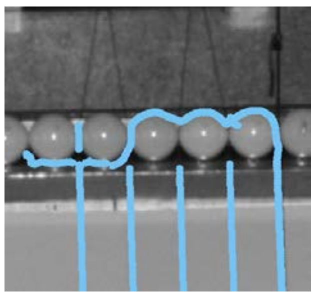

Figure 5: Blunders at line ends

To cope with this fact, different error detection methods have been implemented and an iterative error detection has been used that deactivates all points with residuals above 2.58 σ (99% probability). Due to the high number of errors on several lines, this technique has been superior in practical tests with respect to alternative blunder detection algorithm as the “Iterative Reweighted Least Square” as presented in [6]. The result after the blunder detection has been compared to the result of a manual exclusion of the line ends. Due to the high number of measurement with up to 1600 point per line the loss of 1 % can be accepted.

An analysis of the results has been done for the 3D coordinates of sticker targets as well as on the 2D distances between points and wires on the bench. For the targets the estimated precision of the bundle adjustment has been compared to the calculated precision from the repeatability test and to the metrology data. The comparison is shown in table 1. The Z-direction corresponds to the depth that is less precise but for the other direction the obtained estimations are in-line with the reference data from metrology.

Table 1: Precision and accuracy for 3D points

Sigma of points	X (µm)	Y (µm)	Z (µm)
Precision AICON	1.7	1.9	4.8
Repeatability	1.3	1.2	3.6
Accuracy	2.4	3.1	13.0

As visible in the figure 6 the precision of the measured 2D distance is 5 µm at 1 σ level and the accuracy with respect to the metrology data adds a shift of -3 µm.

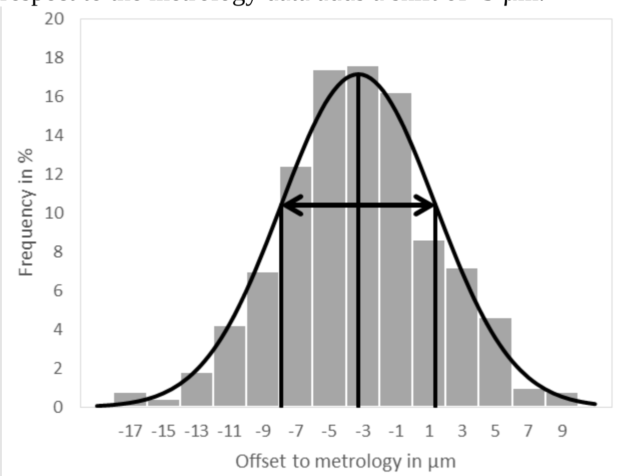

Figure 6: Precision and accuracy for 2D distances

VALIDATION IN REAL SCALE

Following the previous encouraging results, a dipole LHC mock-up has been used to validate the laboratory data in a scale one installation shown in the following figure.

Figure 7: Real scale mock-up

The mock-up is a wooden tunnel with the diameter of the LHC where a cryostat with fiducials as well as some services have been installed. Three wires have been put in place along the mock-up and numerous photogrammetry targets have been glued for the orientation and measurement. A plumb line measured in the same way as the wires has been used to orient the photogrammetry measurement to gravity. Altogether ten photogrammetric measurements have been performed with the following configuration.

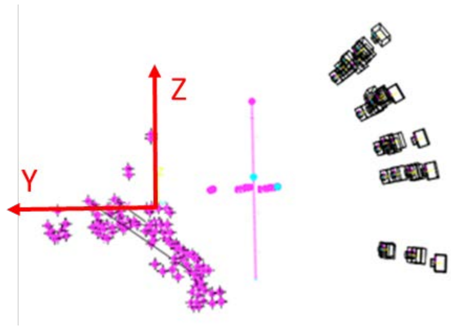

Figure 8: Configuration for real scale project – side view

The precision for 3D coordinates of the targets measured by photogrammetry is shown in table 2. Again the 2D distances between some measured targets and the different wires are analysed. The precision is given in table 3.

Table 2: Precision for 3D points – real scale project

Sigma of points	X (µm)	Y (µm)	Z (µm)
Precision AICON	4.2	7.7	4.2
Repeatability	4.0	7.0	4.3

Table 3: Precision for 2D distances – real scale project

	σ (µm)	min (µm)	max (µm)
Wire 1 nylon	8.0	-29.4	28.9
Wire 2 vectran	6.3	-20.8	22.0
Wire 3 nylon	7.9	-24.4	26.3

As reference for comparison a manual theodolite, Wild T3000, with a specification of 0.15 mgon has measured a part of the targets and arbitrary points on the three wires. The optical theodolite is able to measure by intersection the same targets and arbitrary points on the stretched wires without any mechanical change of supports that could introduce errors that are difficult to estimate and to discover. Each wire has been measured at five positions from four theodolite stations. A conservative simulation expects precisions for the 3D points in this volume (2 m x 1.5 m x 1.5 m) of 10-20 µm. The precision for the 3D coordinates has been confirmed by the adjustment using the software LGC [7].

For each wire that has been measured from a theodolite station a mean plane calculation has been done. The rotation centre of the theodolite has been taken as point and the five directions measured to the same wire define the plane.

As analysis the distance calculation of the wire measured by photogrammetry with respect to each of the theodolite measured mean planes has been considered. The theodolite stations have been chosen in different heights to obtain optimal intersection angles on the three wires.

Differences for the measurement of 3D coordinates by photogrammetry and theodolite shown in table 4 are within the expected precision of both systems.

Table 4: Comparison photogrammetry to theodolite

Differences for 3D points			
	σ (µm)	**min (µm)**	**max (µm)**
Quadratic mean	8.1	15.2	13.3

Differences for the measurement of 2D distances between targets and the different wires by photogrammetry and theodolite are shown in table 5.

Table 5: Comparison photogrammetry to theodolite

Differences for 2D distances			
	Wire 1 nylon	**Wire 2 vectran**	**Wire 3 nylon**
Quadratic mean	19.9	34.2	15.0

ALTERNATIVE APPROACH

The AICON software cannot be automatized for the measurement of the wires and the algorithms are not published. In addition CERN would be dependent on a supplier for a long term project with the associated risks. In consequence an alternative method for the wire measurement based on public algorithms is proposed. The advantages of this solution include the detailed knowledge of the mathematics behind the measurements, the reduced costs of the operator due to possible automation and maintenance of license.

For the procedure the following steps have been identified for the measurement of wires:

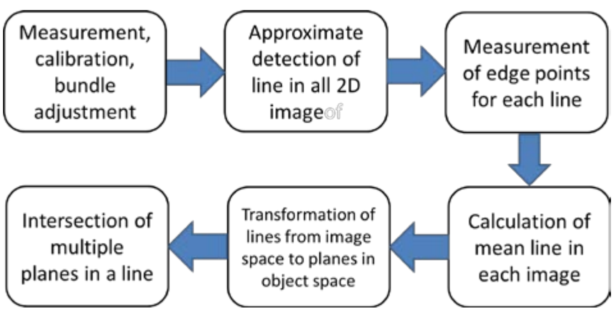

Figure 9: Measurement process

The proposed method is an ideal complement to the AICON MoveInspect that covers the target measurement, orientation and calibration.

Generation of approximate coordinates is based on algorithm like RANSAC [8] or a Hough transformation that should deliver the position of the line in each 2D image at a level of 1-3 pixels. The a priori knowledge of the wire can be a major help as multiple lines will be detected. It's known that the line is nearly horizontal; its two edges are close to each other and separated by the thickness of the wire. In addition the wire passes through the entire image and the colour of the wire could be chosen for the installation. As this task still needs to be developed, pre-defined masks have been used to identify the line at a level of few pixel using RANSAC algorithm.

The next step is the precise measurement of the edges along the line. The sub-pixel edge detector as described by Trujillo-Pino [9] has been used for a test implementation. The measured edge points need to be corrected iteratively for distortion [10] and separated in the two edges. After that a mean line calculation is done by a linear regression for each edge. The angle bisector of the edges is considered as best-fit line of the wire in the image. As next step the intersections of the line with the image borders are projected in the object space using the collinearity equations.

In the object space the intersection of the multiple planes forms a line that could be calculated by adjustment.

A test implementation has been done to prove the feasibility of the proposed approach and the following results have been obtained. The reference values for a comparison have been taken from the AICON measurement for the wire. In figure 10 the tip of each triangle represents a projection centre of a single photo and the intersection line of the triangles corresponds to the wire. For the analysis the offset of each plane with respect to the wire has been calculated at the two extremity points for all planes. For the example the calculated sigma of the difference to the AICON result is less than 8 µm.

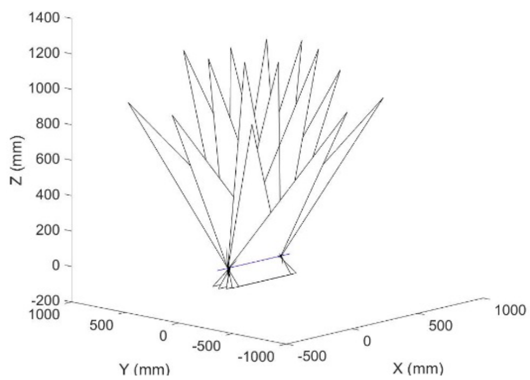

Figure 10: Configuration of plane intersection

Recommendations for this method

Even if for a mathematical solution the photos can be without overlap, it is highly recommended to avoid extrapolation that reduces significantly the precision. The portion of the wire used for the calculation should be symmetrical with respect to the projection of the point on the wire to profit from the precision of the offset and to reduce the influence of the determined direction on the distance. An eventual wire sag can be neglected for the ecartometry as the horizontal 2D distance is measured.

CONCLUSION AND OUTLOOK

The study has proven the photogrammetry as possible tool for ecartometry in laboratory conditions as a precision of less than 10 µm for the wire measurement can be reached. To improve the real scale comparison the Micro-Triangulation as developed in the framework of the PACMAN project [11] could provide reference data with higher precision. At the same time the definition of scale and the introduction of the vertical within the photogrammetric measurements has to be optimized.

The following step could be a manual measurement on a length of a complete wire of 120 m and later a complete sector of the LHC to verify the results in real conditions in comparison to the traditional ecartometry and to get a time estimation in case of manual analysis.

If this confirms the potential, a decision for the kick-off of a long term development can be taken.

In addition the detection of wires by photogrammetry could be also an interesting approach for the fiducialisation of wire chambers for particle detectors. Further studies have to confirm the potential.

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