RECENT DEVELOPMENTS FOR A PHOTOGRAMMETRIC SYSTEM TO MEASURE OFFSETS TO STRETCHED WIRES AT CERN

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Abstract

Manual offset measurements, with respect to stretched wires, are used since decades for accelerator alignments at CERN, e.g. for the SPS and the LHC. A measurement system based on photogrammetry offers appreciated possibilities of automation in comparison to the manual method used so far for the radial offset measurement. Such a system built with pre-calibrated cameras is under development for different possible applications e.g. measurements in the LHC arcs or the upgrade of the LHC collimator measurement train.

The article deals with the use of image processing techniques like morphological operators and the Hough transformation for the identification and precise sub-pixel edge measurement of the stretched wire in the 2D images. The magnet fiducials are measured by means of an ellipse operator in the images. In addition, the calculation process to get the positions of the straight wire and the fiducials in 3D with CERN's compensation software LGC is described. The related algorithms have been evaluated based on image data acquired in the LHC accelerator. The attained precision is typically of a few hundredths of millimetres.

INTRODUCTION

Wire offset measurements are in combination with digital optical levels, which are the standard equipment for the alignment of accelerators at CERN. The demanded precision for the radial and vertical alignment is 0.15 mm over a sliding window of 150 m [1]. The typical accuracy of the manual ecartometry is of 0.05 mm with a repeatability of 0.02 mm, which is a tough demand for any alternative system as it corresponds to an angular accuracy over ±75 m of ±0.04 mgon, which is well beyond the accuracy of theodolites and laser trackers. In recent years, with the on-going technical developments, tests have been done using modern laser trackers [2]. In figure 1, the measurement scheme in the LHC arc is explained. For each fiducial, the horizontal and perpendicular distance to the wire is measured. The stretched wires are overlapping to ensure continuity and control.

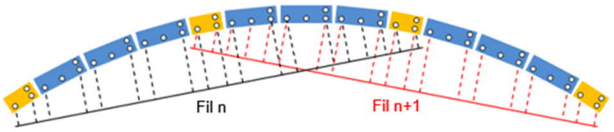

Figure 1: Measurement scheme for LHC arc (top view)

In this context, a photogrammetric approach for the radial offset measurement is one of the most promising ideas. A procedure that is based on the intersection of multiple planes to measure the position of the stretched wire has been presented in [3] with a potential precision of 10-20 µm. The analysis has been done based on the AICON DPA-Pro software. The main inconvenience of the software is the necessity of the user's manual input, which makes an automation of the measurement approach practically impossible. Due to this, an independent solution for an automation is under development at CERN where the human intervention would be expected only for the initial configuration and calibration. The measurement of a fiducial can be executed remote controlled. An advantage for the automation is the rather repetitive configuration and the measurement range that is limited to 0.8-1.6 m due to the dimension of the LHC tunnel. For these distances, the wire with a diameter of 0.3 mm can be identified and measured in the image, if high-resolution cameras are used. In addition, an automatic system reduces the human factor that is still present in the manual ecartometry.

MEASUREMENT CONCEPT

The proposed measurement system is based on a rigid frame as support for four high-resolution cameras. The inner orientation and the relative orientation of the system is calibrated in advance. In addition, two bi-directional inclinometers are installed on the frame to allow a controlled orientation to the gravity of the frame. During the calibration process, scale bars introduce the correct scale in the relative orientation. The calibration of the four cameras and their relative orientation is based on the AICON software and the used distortion model is accessible and described in [4].

The frame with the multi-sensor system can be attached as a dedicated trailer to an existing inspection train that can travel remotely controlled in the LHC accelerator.

The identification and precise measurement of the stretched wire and the targets as well as the identification of coded targets is done by a CERN development that is illustrated in detail in this paper. For convenience, the software MATLAB® has been chosen as a development environment. The least-square calculation of points and wire in 3D is done by CERN's general compensation software LGC2 [5]. In figure 2, the chain of data treatment is detailed.

For the development and diverse tests, the CERN's photogrammetric equipment has been used with a single Nikon D3X camera in combination with a 28 mm AICON metric lens and a top mounted Nikon SB-700 flash. Carbon fibre scale bars have been calibrated on CERN's Coordinate Measurement Machine with a precision of 3 µm. A conventional fishing line has been used as a stretched wire and mainly white dot targets have been used, as measurement for the stretched wire is incompatible with retro-reflective targets.

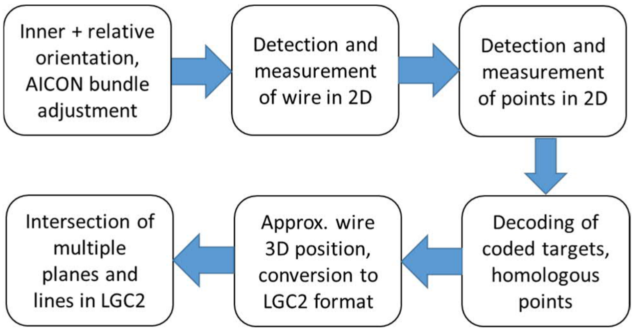

Figure 2: Measurement process

IDENTIFICATION OF WIRE

In the image, the stretched wire appears as a straight line that passes through the image. As the wire is stretched with a weight of 7 kg, the catenary formula is used to calculate the sag in a window of 2 m, which corresponds to the field of view of the camera in the LHC tunnel, and is limited to 6 micron. In this case, the additional measurement uncertainty source would be around ±3 micron, which is neglected in the current approach.

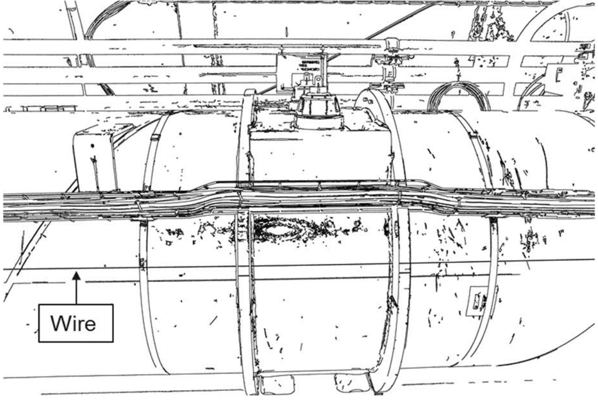

Figure 3: Image after edge detection and dilatation

A typical problem for the identification of the wire in the image is the multiple services installed in the accelerator tunnel (see figure 3) when the correct identification of the stretched wire among the numerous edges is essential for a reliable system.

The typical properties of a thin wire in a photo are:

- Continuous line that traverses the entire image
- Straight line which corresponds to a minimum curvature of the edges
- Two parallel edges with a defined distance between them
- The wire is dark in the image and the background is lighter

The identification procedure uses the above-mentioned characteristics. The property of two parallel edges is especially typical for a thin wire and can differentiate it from the services. Even the thinnest cables in the LHC are several times thicker than the 0.3 mm diameter of the wire. A pre-treatment of the acquired image is applied to enhance the image as a preparation for the line detection by the Hough transformation. After an adaptive image equalization, an edge-preserving filter is integrated as the guided filter is passed on the image to reduce the noise. In the next step, the Canny edge detector is used on the image. Once the binarized edge image is available, the morphological operators (dilatation and erosion) are applied on the image. As visible in figure 4, the dilatation joins the two parallel edges of the wire. The erosion reduces the line's thickness and erases most of the thin lines.

Figure 4: Morphological Operators

The structuring element is a disk that is slightly larger than the wire diameter for the dilatation and slightly smaller than the wire diameter for the erosion. Only edges with short distances separating each other stay clearly visible after the morphological operators. To reduce the operation time for the next steps, small objects can be eliminated as the wire passes through the image. To identify the lines in a binary image, the Hough transformation [6] is used. The Radon transformation, which is a special case of the Hough transformation, could be an interesting alternative.

The five longest line segments that are identified by the Hough transformation are stored. In the Hough transformation, the line is represented by the parameters θ and ρ, which represent the angle to the x-axis and the distance to the origin. If the parameters are identical, the line segments are merged and their lengths are added. Following this, the line segments are sorted by length and the longest segment is considered as the best candidate for the approximate wire position.

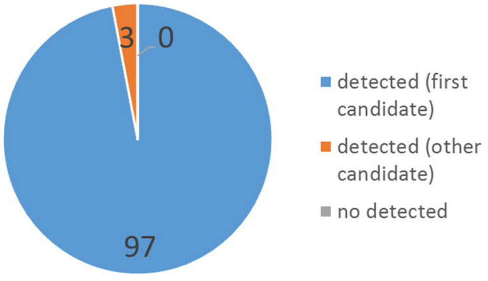

Figure 5: Reliability of the approximate wire detection

More than 150 photos have been taken in the LHC to evaluate the reliability of the wire detection algorithm in real conditions. Due to the pre-treatment, the results have been very convincing and the first candidate corresponds to the approximate wire position in 97% of the cases. Only in 3% of the cases another line than the longest line, has been identified as the approximate wire position (see figure 5). The typical contrast of the wire, with respect to its background, has been around 30 grey values. For a successful detection of the wire position in the 2D image, the contrast can go down to a minimum of ten grey values.

MEASUREMENT OF WIRE POSITION

The list of candidates for the wire position in the 2D image and the inner orientation are the entry values for the precise measurement. For performance reasons, the next steps are applied on a cropped image that contains the approximate wire position that has been extended to the image borders with an additional margin of 50 pixel in the perpendicular direction.

Edge detector

The precise edge detector, as proposed by A. Trujillo-Pino et al. [7], is applied on the cropped image. The algorithm is based on the partial area effect and provides, in addition to the sub-pixel edge coordinates for each edge point, the normal vector as well as the curvature and the maximum and minimum intensities. To determine the sub-pixel edge's position, the edge has first been approximated by a line, and in a further development, by a second order curve of the type $y = a + bx + cx^2$ in a window of 5 x 3 pixel centred on a pixel. Supposedly, each grey value depends on the area of both sides of the edge that passes through a pixel. In each window, the areas below the curve S_L, S_M and S_R are calculated, see figure 6. The resolution of the system takes into account the three integrals and the intensities to determine the parameters a, b, and c. With these parameters, the normal vector and the curvature can finally be calculated.

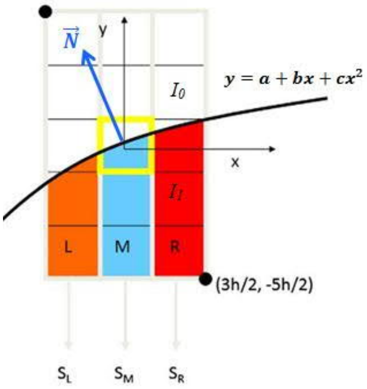

Figure 6: Edge detector (A. Trujillo Pino et al., 2013)

This additional information is valuable to separate the valid edge pixel of the stretched wire from edge points identified on the background. The following conditions are considered for the validation of edge points:

- Distance to an approximate wire position smaller than 35 pixel
- Curvature smaller than 0.2
- Normal vectors of edge points and approximate wire directions are perpendicular within 10 degrees

The normal vectors are also taken into account to separate the edge points between the two edges of the wire. An independent robust linear regression is calculated for each edge of the wire after the distortion correction, as mentioned in [8], and has been applied iteratively on the edge points. This eliminates points with residuals above a two (respectively three) sigma threshold.

The resulting two lines are verified by four different criteria with adapted thresholds that need to be fulfilled to accept the line. These are:

- The quality of the two individual lines defined by thresholds for sigma values of line parameters
- The parallelism of the two lines
- The distance between the lines has to correspond to an a priori information about line thickness in pixel
- The wire has to be dark on light background

If there is a negative response to a single one of the listed criteria, the candidate for the wire position is rejected and the precise edge measurement for the next candidate of the approximate lines starts. As a final 2D result, the parameters of the line equation with the sigma values and the percentage of the points eliminated by the blunder detection are stored.

The mean line calculation of the wire has a precision of 0.01 pixel for the position and the direction's cosine is determined with a precision of $2*10^{-06}$ in the test photos of the LHC. The extremely precise results are due to the high number of edge points per line that is typically of several thousand measurements. The residuals of the robust linear regression have a standard deviation of 0.16 pixel for an individual edge point [9].

IDENTIFICATION OF TARGETS

For the detection of circular targets and their measurement, a different automatic procedure is necessary. The pre-treatment corresponds to the previous one but with an additional sharpening filter to enhance the edges and to facilitate the binarization of the image. The target detection uses the analysis of image regions that are established on connected components. For the connectivity, an 8-connected neighbourhood is considered. In addition to the centroid coordinates, further properties are provided for each image region such as the area of the region or the parameters of an ellipse that has the same second-moment as the region. The identification of targets is based on the relation between the measured area of the image region and the calculated area of the ellipse. The component is considered as a photogrammetric target if the area measured for the image region is within ± 1 % of the calculated area. For targets with a diameter smaller than 10 pixel, the value has to be gradually enlarged to ± 3 % to find targets with diameters down to a three-pixel diameter.

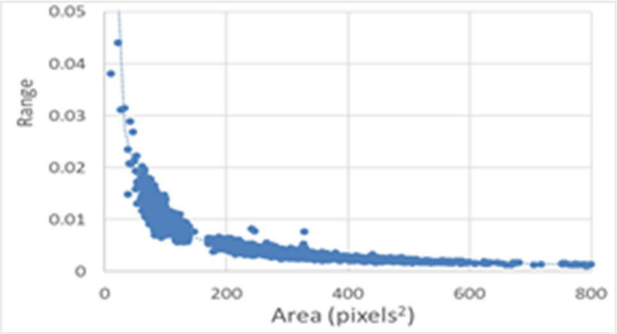

Figure 7: Difference of calculated and measured area

For the precise target measurement, an ellipse algorithm has been chosen as it provides quality parameters from the least-square adjustment that are crucial for the elimination of blunders like damaged or partly hidden targets. For our application, it is considered as superior in comparison to the algorithms based on the weighted centroid. The target identification process provides at the same time the approximate 2D coordinates for the precise measurement.

MEASUREMENT OF TARGETS

For each target, the precise measurement is performed in a cropped part of the original image that potentially includes the binary code of the target. The dimension of the cropped image is calculated as 3.5x the axes diameters to include the entire binary code of the targets.

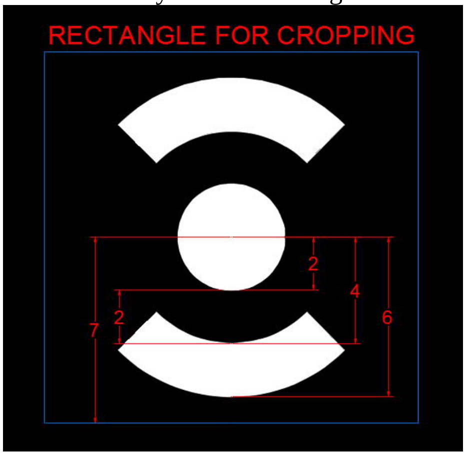

Figure 8: Rectangle for target cropping

Again, the edge detection algorithm from Trujillo-Pino is used to measure the edge points. A distance condition and the direction of normal vectors are used as a blunder detection before the least-square ellipse adjustment that considers the edge points as observations. Damaged or wrongly identified targets are eliminated based on the sigma values of the ellipse centre as well as ellipses with a ratio of the half axes a to b that is larger than three. The chosen threshold for the ellipse precision is 1/12 of a pixel.

The results of the precise image measurement algorithm have been compared, for different types of projects, to the results of the professional AICON software. The chosen projects have white or retro-reflective targets, different target diameters and different environments in order to avoid an optimisation for special conditions. An identical image material has been taken and the projects have been measured with the CERN algorithm and the AICON software as reference.

Table 1 shows that the precision of the bundle adjustment calculation is comparable and the standard deviation for the residuals in image space are nearly identical at the level of ±0.038 pixel for AICON and ±0.039 pixel for CERN algorithm for the used D3X camera.

Table 1: σ_0 values of bundle adjustment

Project	**σ_0 (AICON)**	**σ_0 (CERN)**
1	0.00020	0.00022
2	0.00021	0.00021
3	0.00027	0.00027
4	0.00025	0.00026
5	0.00027	0.00028

DECODING OF TARGETS

The AICON software uses circular targets with binary codes for the reliable identification of homologous points. As the AICON software is used for the calibration and relative orientation of the cameras, it is necessary to decode the targets and provide the correct AICON point numbers. Three different codes exist, which are based on 12, 14 or 20 code elements. An example of a 12-bit coded target is visible in figure 9. The construction of a coded target is based on the radius of the central point that is identical to the distance of the code ring, with respect to the central points, and equal to the thickness of the code ring as detailed in figure 8.

The decoding of 12-bit codes takes place in the binarized image. The measured ellipse is scaled up by a factor of 2.5 to pass in the centre of the code ring. Five points are measured per code element to identify the binary code. Five points are necessary to be robust if points fall on the edge between two code elements. Once all elements are identified, a stepwise rotation is performed and every time, the binary code is converted in the decimal system. To solve the ambiguity the smallest decimal number out of the 12 values is used and finally a point number is given thanks to a look-up table. If the smallest decimal number is not part of the look-up table the target is considered as non-coded. On real image data of the five test projects, more than 16 000 coded targets have been measured, and the assignment of codes is identical for 98% of the coded targets with the AICON software. An explanation for the slight difference could be lower detection rate on smaller targets as the algorithm works so far with a binarized image instead of a subpixel edge detection to identify the code elements.

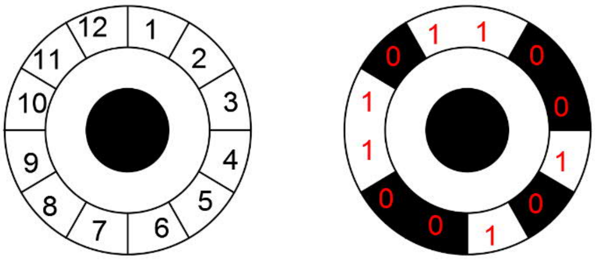

Figure 9: Binary code of circular target

3D CALCULATION WITH LGC2

The adjustment software LGC2 has recently been extended to the use of additional observation types. Each sensor position can be expressed as a local coordinate system that is characterised by six degrees of freedom and a scaling factor. The 7DOF can be set fix or free individually. Among the new observation types, a simplified camera model is available. The observations are represented as unity vectors with the projection centre as the local origin. The observation data is converted from the measured image coordinates in the corresponding format based on unity vectors and the image distortion needs to be applied in parallel, as the parameters of the inner orientation are not yet integrated in the mathematical model of LCG2.

A virtual camera with all observations on its optical axis simulates the stretched wire. For the exterior orientation, a single rotation and translation are fixed during the adjustment in order to avoid singularities. A function extracts automatically the camera orientations from the calibration file and converts them in the LGC2 format. In this case, LGC2 calculates the fiducial positions by intersection of lines and the wire position by intersection of multiple planes in a line. For an example at 1 m distance in the LHC tunnel, the typical residuals for the points and the wire are smaller than 10 µm in object space. This value is below the precision of the manual ecartometer and confirms the precision previously tested in laboratory conditions with the AICON software [10]. The estimation of the measurement uncertainty trough the uncertainty propagation law applied to the different measurement algorithm steps is problematic, as the entire variance/co-variance matrices are not available for export respectively import. The precision for the 3D offsets determination has been estimated by repeatability tests and is 10-20 µm for a project based on 35 images. Different configurations with three to six cameras have been tested and the four-camera solution is considered as the best compromise that provides a reliable measurement with a precision better than 30 µm for the 3D offset determination.

High precision bi-directional inclinometers have to be added to calculate the link to gravity for the photogrammetric results. This is mandatory to obtain horizontal and vertical offsets with respect to the stretched wire.

CONCLUSION AND OUTLOOK

The different developments are part of a larger feasibility study of Survey Trains for the CERN accelerators such as the LHC. The various modules for the identification and the measurement of wires, as well as target, exist as separated features for testing and for an evaluation of the precision. The data transfer between the modules, including the 3D calculation with LGC2, is still manual and the initial camera calibration remains an operation with the AICON 3D Studio software. In a future tool for production, the integration into a common architecture with the train and an optimization for computation time is mandatory.

The conceptual idea stays closely to the proven concept with a rigid frame such as a camera support as it is used for the Survey Collimator Train [11]. The precision of the measurement system would increase due to the upgrade of the wire measurement to a photogrammetric. At the same time, the handling would be less risky as the number of moving pieces is reduced.

The next steps to be undertaken would be the definition of the final configuration and the choice of the camera system on the hardware side. For a complete automation of the system, a robotic installation and transport of the stretched wire coupled with photogrammetric targets should be investigated in detail.

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