DIRECT WIRE OFFSET MEASUREMENTS BY PHOTOGRAMMETRY INCLUDING A GRAVITY LINK

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Abstract

This paper presents a novel method for direct wire offset measurements using photogrammetry, with a focus on integrating a link to gravity. This development is motivated by the High Luminosity Large Hadron Collider (HL-LHC) project, where increased radiation in the Long Straight Section (LSS) necessitates automating the wire measurement within a Full Remote Alignment System (FRAS). To integrate this system with the rest of the machine, a new process had to be developed.

A prototype has been tested based on a support frame on which four high-resolution cameras and four inclinometers are mounted. Although the prototype currently operates manually, it was designed with future automation in mind, particularly for integration into CERN's Monorail Inspection Train (TIM).

The methodology for the measurement begins with an acquisition interface that defines trigger parameters for synchronized data capture, enhancing accuracy and reliability. The key to the process is the identification and measurement of targets and the stretched wire using advanced machine vision techniques. The relative orientation of each camera is calculated using specialized software tools, such as Hexagon DPA-studio and MicMac. Additionally, a custom calibration process of the inclinometer block is performed, to link the photogrammetry measurements to gravity. The acquired data is then processed to calculate the horizontal and vertical offsets.

The comprehensive integration of all these components results in a robust and precise method for wire offset measurements, with an accuracy expected to meet the stringent requirements of particle accelerator applications. Initial results are extremely promising, showing that the prototype reaches the demanded precision of less than 50 µm, making it an excellent solution for the HL-LHC's challenging environment.

INTRODUCTION

In the field of particle physics and accelerator technology, the precision and accuracy of survey and alignment measurement systems are paramount. The Large Hadron Collider (LHC) consists of two main regions: the arcs and the LSS that include the experiments. Each of these regions is measured with its unique requirements, constraints, and challenges. The alignment requirements for the LSS magnets on each side of the experiments is extremely stringent, with a vertical accuracy of 0.2 mm (1σ) and a radial accuracy of 0.35 mm (1σ) required over a length of 420 m for the HL-LHC. This is why these areas will be continuously monitored by a system known as the FRAS [1]. This is based on stretched-wire measurements with a Wire Position System (WPS) for planimetry and hydrostatic measurements with a Hydrostatic Levelling System (HLS) for altimetry.

These systems are well suited due to their high precision, but their installation is limited to these short regions by cost constraints. To ensure continuous and smooth alignment, it is essential to integrate the arcs with the FRAS. Leaving altimetry aside, CERN still relies on a traditional method for planimetric alignment known as ecartometry, which involves manual measurements with an overlapping wire stretched in front of multiple magnets. This method is labor-intensive and time-consuming. With the advent of the HL-LHC project at CERN, the increase in radiation in the LSS will make this measurement method impossible due to its lengthy procedure. Therefore, a fully automatised measurement approach must be developed to minimize radiation exposure in critical areas.

Given these constraints, the aim of this project was to research and develop a prototype capable of meeting these requirements. Various studies were carried out to address these needs. [2] [3] [4] [5]. These efforts led to the development of a measurement tool based on photogrammetry, linked with gravity through inclinometers. The current prototype features four 24 MP cameras, mounted on a 300 mm by 800 mm aluminium frame with 4 inclinometers (Fig. 1). Although it is manually operated, this prototype sets the foundation for future automation and seamless integration into CERN's TIM.

This paper focuses on the technical details of the methodology, with the general workflow and procedures shown in (Fig. 2).

It will detail the internal and external relative calibration of cameras, using mathematical processes and tools, as well as the techniques for 2D target measurement and number decoding. Furthermore, it covers the calibration process of the inclinometer sensors with respect to the camera frame, and the calculation within CERN's least-squared adjustment software, Logiciel General de Compensation (LGC). The paper also outlines the standard acquisition procedure, detailing methods for 2D wire detection and measurement, as well as the final 3D reconstruction process in LGC. Additionally, it presents statistical results of actual measurements in the LHC tunnel and provides a comparison with a laser tracker system, evaluating its precision.

By integrating these advanced techniques, the proposed method is expected to significantly improve the precision and efficiency of wire offset measurements in the HL-LHC, paving the way for enhanced alignment processes in future particle accelerators.

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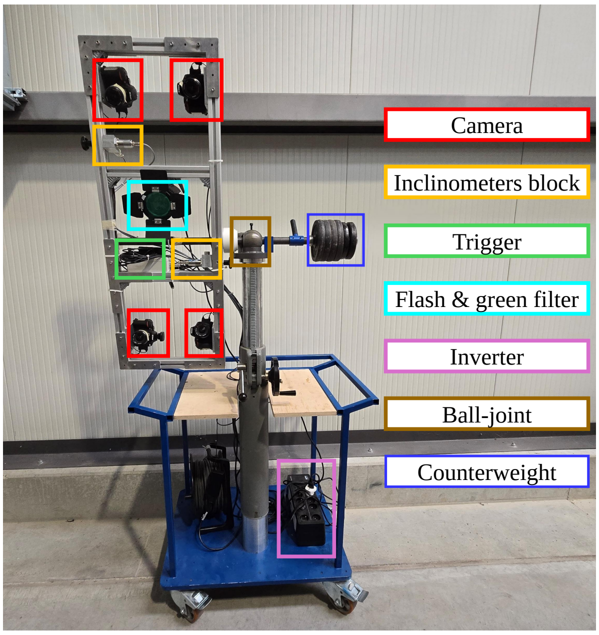

Figure 1: The prototype with 4 high-resolution cameras and 4 inclinometers mounted on a 300 × 800 mm aluminium frame.

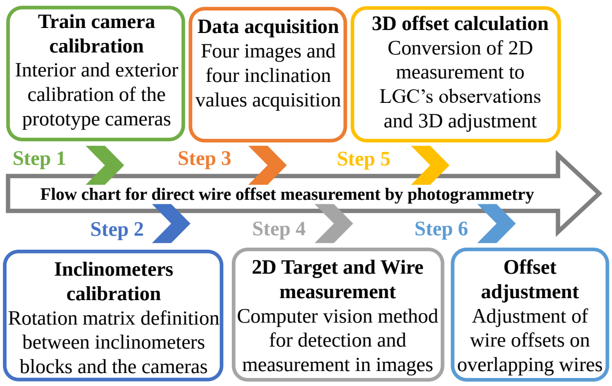

Figure 2: Flow chart for direct wire offset measurements by photogrammetry including a gravity link

CAMERA CALIBRATION

This section will describe the camera calibration process for the survey train. It outlines how the scale is transferred from the scale bar to a special calibration panel in order to define the relative position of the cameras. Additionally, it explains how the targets are measured in 2D with an in-house software.

Panel calibration

The panel consists of a 700 mm by 500 mm carbon plate, with a carbon pole fixed in the middle to create a 3D object, and to which 193 encoded Schneider targets [6] are glued. The first phase of the calibration process requires the determination of the precise 3D target coordinates of the carbon panel. This initial calibration of the panel is carried out using several carbon scale bars, whose lengths are known by Coordinate Measuring Machine (CMM) measurements. The geometry transfer from the scale bar to the panel is done using classical close range photogrammetric measurement with a Nikon D3X camera.
The interior orientation of the camera is defined by ten parameters: the principal distance (c), principal point offsets (x'_0, y'_0), radial-symmetric distortion coefficients (A_1, A_2, A_3), tangential distortion coefficients (B_1, B_2), and affinity and shear coefficients (C_1, C_2). This detailed characterization of internal parameters is crucial for correcting lens distortions and ensuring measurement accuracy. The X, Y, Z coordinates of each target are then determined. Once this calibration is done, the panel coordinates can be used as fixed references for several months to calibrate our prototype.

Cameras calibration

The second phase involves calibration of the interior and relative orientation of the cameras on the train. To achieve this, images are captured synchronously every 5 seconds. The panel is manually held and moved between each capture to ensure comprehensive coverage of the camera chip with targets, allowing for accurate determination of distortion parameters. The cameras used are four Nikon D5600 models, each with 24 MP resolution. They are configured with a shutter speed of less than 1/125s, an ISO of 100, and an aperture of F11 or F16. The flash is intensity adjusted to obtain greyscale pixel values for the white targets between 100 and 200. For each of the four cameras, the ten interior orientation parameters are calculated, resulting in a total of 40 parameters across all cameras. The position and rotation of the first camera are fixed, serving as a reference point. The relative exterior orientation of the remaining three cameras requires six parameters each. Thus, the calibration requires a total of 58 parameters for both the interior and relative orientation of the cameras.
The calibration data are processed using two software packages for check and validation: the commercial DPA Pro from Hexagon and the open-source Micmac V2 from National Institute for Geographic and Forestry Information (IGN). Both software solutions aim to derive the relative exterior orientation and internal camera calibration parameters. Micmac V2 is still under development, but the goal is to analyse and compare the performance of each software in terms of accuracy and consistency of the calibration results. The comparison also provides insights into the efficiency of commercial and open-source software in handling complex photogrammetric calibrations.

2D Target measurement

To carry out these calibrations, an important step is to detect and measure the targets in the images. The coded Schneider targets consist of a circular center and a surrounding binary code of 12, 14 or 20 bits (Fig. 3).

For the 2D measurement, each software package has its own algorithms, but no existing software fully automates the measurement process. Several studies have led to the

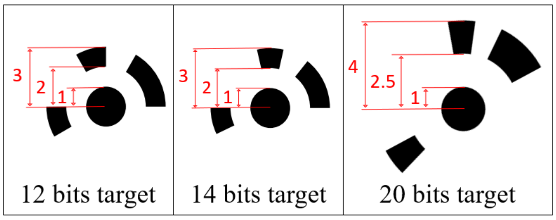

Figure 3: Schneider Coded targets used for the project

following methodology. The first step is pre-processing and detection of potential candidates in an image. Mathematical morphology operators then keep candidates corresponding to an ellipse. The final part of detection is the separation of coded and non-coded candidates. This is achieved by creating an elliptical profile just after the theoretical position of the code. On the binary image, this profile must be entirely black for the coded target. All the remaining candidates will be measured afterwards as possible uncoded targets.
Once detection is complete, the next step is the measurement of the target. This is achieved by creating a profile to precisely detect the edge, with the number of rays and points along the profile customizable by the user. By default, we are using 32 rays and 7 points (Fig. 4).

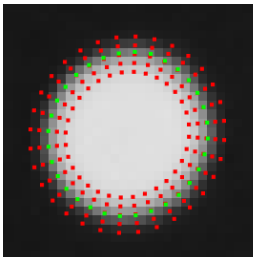

Figure 4: Target edge detection on a cropped image. Red points: a priori profile. Green points: edge points measured

The edge detection is performed by fitting a polynomial function of 3rd order on the points and finding the zero transition. This can be processed quickly, even for many ellipses and rays. Once the edge points are extracted, the least square adjustment can be done, estimating the center, the small, and large half-axis and the rotation angle θ. An error will occur when this adjustment is performed with an ellipse that is circular. In this case, a=b so the derivative of θ is 0 and the Jacobian cannot be inverted to find a solution for θ. In this case, the system has a whole range of solutions, but the pseudoinverse can help as it will choose the solution with the lowest possible norm. Theta will be zero and the other parameters will be correctly calculated. In case N is invertible, the Moore–Penrose inverse is the same as the usual inverse. From this calculation, we extract the ellipse parameters and the residuals, which allows us to define an acceptance parameter for the ellipse with a maximum sigma on the center coordinates to validate the ellipse measurement. This process is resumed in Fig. 5.

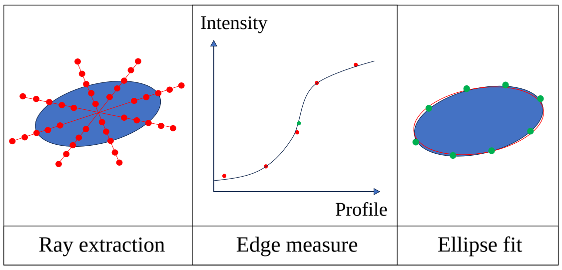

Figure 5: Ellipse measurement process

INCLINOMETER CALIBRATION

To obtain the radial alignment, it is essential to determine the shortest distance between the target and a vertical plane including the wire. In photogrammetry, without topographic data, it is impossible to measure horizontal or vertical distances because the system lacks orientation to gravity. Vertical information must therefore come from an external sensor. This sensor must be small, light, stable over time and redundant, enabling the 3D distance to be divided into horizontal and vertical components. For accurate levelling, the sensor must measure the vertical parameters to an accuracy of 30 µm, which implies a sensor and calibration accuracy better than 30 µrad. The choice was therefore to use multiple inclinometer sensors mounted on two independent support blocks fixed on the frame. The rotation matrix between the different inclinometer blocks and the cameras need to be determined through the inclinometer calibration explained in this section.

Inclinometer calibration Setup

The two inclinometer blocks are made of aluminium machined to have two perpendicular faces. On each block, we mounted two Wyler Zerotronic inclinometers with a precision of 15 µrad and 30 µrad and a measurement range of 5 and 10 degrees respectively. The more precise inclinometer is installed in the direction of the optical axis of the camera. As the acquisition range is reduced, the orientation of the blocks can be adjusted before calibration, but this orientation must remain stable afterwards.

Methodology

The experimental setup involves the installation of a dozen drift-nests for 1.5 inch SMRs on a wall with an asymmetric geometry. These nests are evenly distributed over a surface area of 1-2 m², ideally positioned as a 3D object. Measurements are conducted using two laser tracker stations, and introduced into an LGC file.
The same procedure as described for the camera calibration then allows the extraction of the relative exterior and interior orientation parameters. The prototype setup is then approximately positioned in front of the network at a distance corresponding to the acquisition and focus distance of the cameras. Data acquisition is performed using 15 positions. The prototype frame is installed on a ball joint (Fig.

1), allowing multiple orientations to cover the full range of the inclination sensors.

Calculation

Target measurements are performed using the developed algorithm, and the values from the inclinometers are extracted. These data are then integrated into LGC, using available tools, which are not optimised for photogrammetry, but allow an adjustment to be made. The principal tool used for the calculation is the frame concept [7]. A frame section in LGC is a logical block that can contain points, measurements, and additional frames, useful for grouping points that must move together and can be interpreted as a local Cartesian coordinate system. A frame is defined by three translations, three rotations, and a scale factor relative to its parent frame. The transformation into the specified frame uses a transformation matrix with homogeneous coordinates, and the rotation matrix follows the sequence $R_{xyz} = R_x \cdot R_y \cdot R_z$.
In the survey train project, frames are used to represent a pinhole camera (Fig. 6), with the origin at the optical center, the Z-axis along the optical axis, and the XY plane representing the camera chip at a constant Z-coordinate corresponding to the focal length. The relative position of the camera frame is fixed based on the exterior orientation parameters.

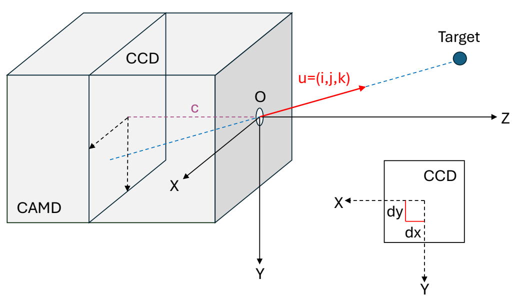

Figure 6: representation of CAMD observation

A nested frame structure allows the 3D position of the system to be calculated with photogrammetric observation of a fixed point network measured by a laser tracker. For that, the 2D measurements on the images are corrected for distortion and then integrated into LGC as a unit vector. Inclinometer measurements are also added to this geometrical structure. The rotation between the inclinometers and the camera remains constant as they are mounted on the same physical object. Therefore, the rotation matrix between the inclinometer block and the camera system can be constrained during the adjustment, as its value is constant over several positions.
From this calculation, the 3 rotations between each block and the camera system are extracted with their corresponding covariance matrix.

PHOTOGRAMMETRIC ECARTOMETRY

The aim of the survey train project is to automatically measure the horizontal orthogonal distance between a wire and a target. As explained in previous sections, the calibration parameters for cameras and inclinometers must remain stable over time, at least for a full measurement sequence. This section explains how the real acquisition takes place, and how the 2D wire is detected, measured and processed in 3D.

Procedure

The measurement procedure begins with the installation of a 120 m stretched wire, which has a diameter of 0.3-0.4 mm and is fluorescent green or yellow. The wire is braided with multifilaments that have a breaking strength of around 30 kg. To obtain a smooth surface, a coating is thermally fused all around the wire. We use a fishing reel and a locking system to tension the wire. The process starts with the installation of Hubbs photogrammetric targets on the accelerator fiducials, utilizing a universal support. A future modification will include replacing this setup with a 3.5-inch calibrated sphere that has multiple coded targets, enhancing the precision of the determination. For one fiducial, multiple sets of photos are taken to ensure the repeatability of the measurements. The following step in the acquisition process is to move the prototype to the next fiducial. A forward and return run allows capturing the necessary data to cover and control the 120 m wire.

2D wire measurement

To start the 2D detection of the wire, enhancing the contrast is crucial. Given the wire's small size, generally covering only 3 to 6 pixels, and its placement in a cluttered environment with a non-homogeneous background, contrast enhancement allows the wire to stand out from its background. To achieve this, Contrast-limited Adaptive Histogram Equalization (CLAHE) [8] is employed. This enhancement is followed by a method based on a tiles threshold. The idea is to divide the image into small images (patches) and then apply a threshold (local maxima). In each small individual patch, interesting regions are searched for using a mathematical operator, and only single linear objects with the size of the wire are kept. Finally, the Hough transform is used on the entire black and white image to detect lines, and these lines are sorted by length to isolate the wire.

Using the approximate parameters obtained with the Hough transform, the image region of the wire is extracted with a margin of 10 pixels on each side. A subpixel edge detection is then performed with a 5×3 operator (Fig. 7)

This extracts both edges of the wire and the normal vector of these edges. Next, a sorting is performed based on this normal vector to classify each edge point by type (top or bottom line). Following a distortion correction of the image coordinates, different filters are applied in this process to test the straightness, thickness, and colour of the two detected edges. Another criteria is that the number of

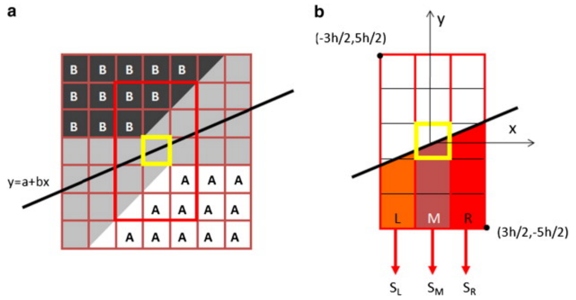

Figure 7: a) Input image with an edge b) Edge detection operator, image from [9]

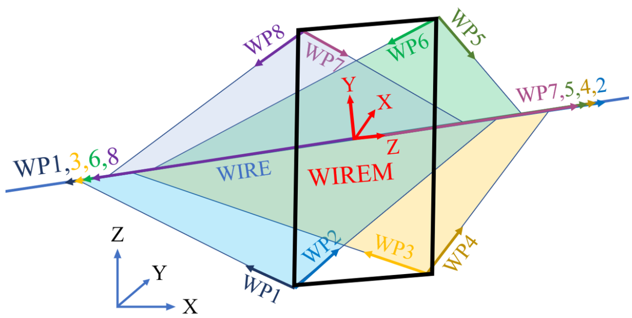

Figure 8: 3D wire calculation in LGC

considered edge points per line should differ by less than 20%. A robust fit is performed using Principal Component Analysis (PCA), iteratively removing outliers (points further than a 99% probability). After the fit, only lines with a sigma value below a user defined threshold are considered. If a measurement fulfills all these criteria, two points with their xy-coordinates belonging to the line on opposite image edges will be exported.

3D Calculation

The 3D reconstruction is done in the LGC software. According to Equation 1 [10], it is possible to define the maximum wire sag for the train configuration :

$$f = \frac{gql^2}{8T} \tag{1}$$

With:

- f the sag of the tensioned wire (m).
- g the gravitational acceleration (m.s^{-2}).
- q the linear mass of the wire (kg.m^{-1}).
- l the wire length (m).
- T the wire tension (kg.m.s^{-2})

Considering the extreme value for the project with g=9.8 $m.s^{-2}$, q=9.2e^{-5} $kg.m^{-1}$, l=1.4 m, and T=70 $kg.m.s^{-2}$, the sag is around 3 µm which can be neglected because this effect is below the measurement precision.

For the calculation, the inclinometer observations and calibration matrix are used to link the photogrammetric system to gravity. The determination of the wire position is calculated by the intersection of multiple planes in a line. The line is represented in LGC by a frame with 4 degrees of freedom : 2 translation and 2 rotations (WIREM in Fig. 8).

The previous 2D wire measurement is used, with each plane constructed using the centre of projection and the measured wire in image space. Simulated observations have been calculated to construct the orthogonal projection of the target on the wire and of the target in a vertical plane including the wire. This allows the relative precision between the wire and the target to be estimated in the same adjustment process.

MEASUREMENT

The measurements performed in the LHC machine covered a distance of 40 m. The objective of this operation was to test the new hardware in real conditions, perform comparative measurements with a laser tracker and evaluate the repeatability of the measurements.

Measurement Setup

The camera parameters are set at the beginning of the acquisition to be compatible with the environmental light. A green filter is installed on the flash as it increases the contrast of the green or yellow wire with respect to the mainly blue, grey or red magnets as background. For the inclinometer calibration, a nest network is glued on a wall over a surface of 1.5 square meters and measured with a laser tracker.

The calibration of the cameras is performed using 30 positions of the reference panel in a highly redundant configuration. Each target is measured between 30–100 times for a total of 30000 observations with 238 unknowns.

The standard deviation of the adjusted points reprojected in the image is respectively 1/10th and 1/15th of a pixel in X and Y. The relative precision of the camera position is around 3 µm in X-Y and 9 µm in Z, while the relative orientation precision is around 6 µrad in RX, RY, RZ.

For the inclinometer calibration, the precision of the 3D resection of the photogrammetric system on the network is around 20 µm for the translations and 30 µrad for the rotation. The standard deviation of the inclinometers is below 15 µrad.

A minimum of 2 positions is necessary to get a computable calibration setup, and with an increasing number of positions the estimated precision improves. With around 15 positions the setup provides a satisfactory precision and the inclusion of more positions improves the quality only slightly. The rotation matrix precision after the adjustment is less than 8 µrad for RX and RY, and less than 60 µrad for RZ. This larger RZ value can be explained because there is no direct observation for the rotation around the vertical.

Repeatability measurement

Once the calibration procedure for the cameras and the inclinometers was complete, a repeatability measurement was performed. A wire was stretched over two dipoles and one quadrupole, covering an approximate distance of 40 m (Fig. 9).

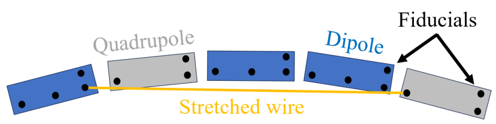

Figure 9: Stretched wire for measurement in the LHC tunnel

This setup allowed the measurement of 8 fiducials (the tilt fiducials have not been measured). The acquisition was conducted over two days, each with an independent calibration. On each day, the measurements were taken in round-trip mode, with 3 acquisitions made for each passage in front of a fiducial. This results in 12 ecartometry values for each fiducial.
The results in Fig. 10 demonstrate a high degree of repeatability, with the variations between the two sets of measurements being minimal (17 µm). Notably, the repeatability is within 40 µm, underscoring the robustness of the calibration process and the reliability of the measurement system across different days. This consistency in the normed offset across the fiducials indicates that the calibration is valid for periods of half a day, providing confidence in the system's precision for similar setups.

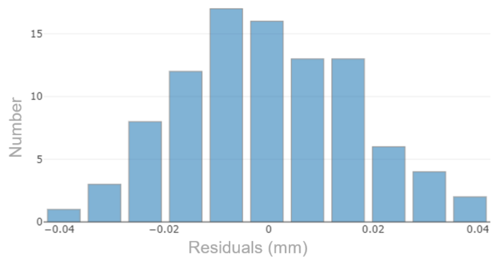

Figure 10: Histogram of 95 offsets residuals for an LGC adjustment

The extraction of the relative precision between the target and the wire from the photogrammetric system is possible thanks to LGC. The comparison between this precision (a priori precision) and the precision after the adjustment (a posteriori precision) is shown in Table 1. The result reveals the same order of magnitude for both values, which confirms that the stochastic model is consistent.

Comparison with Laser Tracker Measurements

Two comparisons with laser tracker measurements were performed. The first is an adjustment in LGC with photogrammetric offset and Laser tracker measurements. The result is shown in Figure 12. The standard deviation is similar to that obtained for the repeatability test (17 µm), which means that the Laser tracker and the photogrammetric setup are consistent.
To verify the exact offset and to control if a systematic error exists for the prototype measurements, a system was

Table 1: A priori and a posteriori precision (1σ)

Point name	**A priori precision from train (µm)**	**A posteriori precision after adjustment (µm)**
A10L2.E	21	24
A10L2.M	17	19
A10L2.S	15	18
B10L2.E	18	12
B10L2.M	22	11
B10L2.S	22	16
Q10L2.E	13	19
Q10L2.S	24	18

developed to measure the wire position with a laser tracker (Fig. 11). This consisted of two prism supports placed on

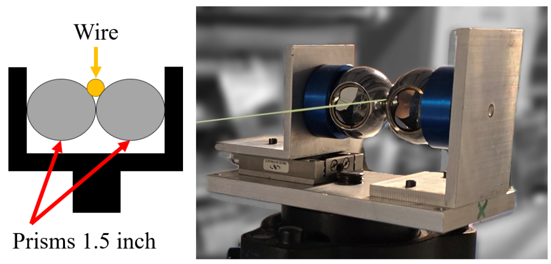

Figure 11: Setup for wire measurement with Laser tracker

removable brackets. In this way, two prisms can be inserted and touch each other. By adjusting the prism support to be horizontal, and then passing the wire through the middle, it is possible to determine the horizontal position of the wire by calculating the average of the prisms.

This comparison was done using the mean value over 12 offset measurements per fiducial. Table 2 shows the difference between the two methods with a systematic offset of approximately −36 µm, probably due to a horizontal force applied during the wire stretching at its attachment points. This systematic is transparent for the relative alignment of the fiducials with respect to the wire. The standard deviation of the difference is around 22 µm. The preliminary results of the prototype are very encouraging, as the specification of an automated system below 50 µm for horizontal offset measurement seems reachable.

Table 2: Comparison of Offset and Laser Tracker Measurements

Point name	**Train Offset (m)**	**Laser tracker offset (m)**	**Difference (µm)**
A10L2.E	0.084532	0.084493	-39
A10L2.M	0.064628	0.064617	-11
A10L2.S	0.044289	0.044286	-3
B10L2.E	0.075662	0.075603	-59
B10L2.M	0.082559	0.082537	-22
B10L2.S	0.090198	0.090138	-60
Q10L2.E	0.050277	0.050221	-56
Q10L2.S	0.063226	0.063185	-41

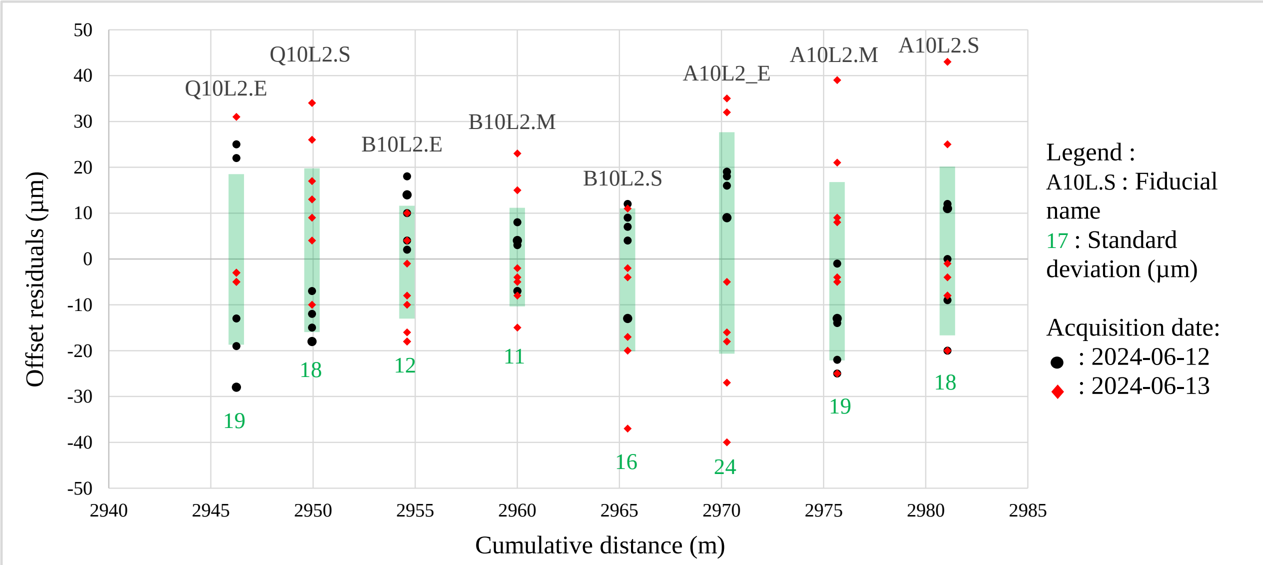

Figure 12: Offset residuals of two stretched wire lines adjusted with LGC

CONCLUSION

This paper introduced a novel tool for direct wire offset measurements through photogrammetry, incorporating a gravity link via inclinometer calibration. Developed as part of the HL-LHC project at CERN, the prototype system, comprising high-resolution cameras and inclinometers, achieves precision levels under 50 µm, essential for the demanding environment of particle accelerators. The integration of photogrammetry with advanced image processing and custom algorithms significantly enhances the accuracy and efficiency of wire alignment measurements, offering a promising solution for the precise alignment needed in high-radiation areas. The promising results demonstrate the potential for future automation and its broader application.

The survey train prototype will soon be further tested during the HL-LHC String Test setup [11] to validate the process. Additionally, a new carbon frame is currently being developed to ensure stability over time. Industrial cameras can also be purchased to reduce weight, volume, and guarantee stability. Efforts will also continue to adapt MicMac to the needs of the Survey train project. This will ensure that the software is robust, efficient, and maintainable over time. These combined efforts aim to deliver a highly reliable and optimized system for future alignment needs.

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