Direct Wire Offset Measurements by Photogrammetry Including a Gravity Link

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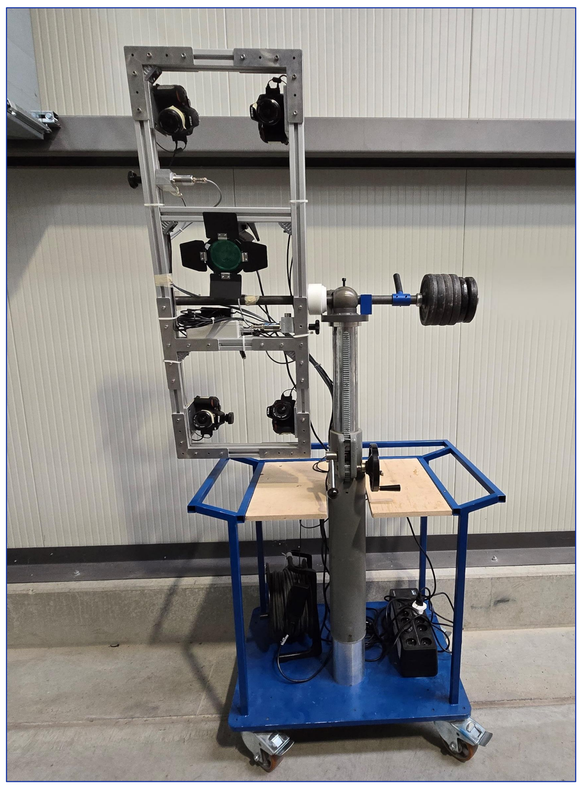
Introduction

This project addresses the critical need for precise alignment of the LHC components, particularly in the context of the HL-LHC upgrade. Given the stringent requirements for radial measurement (accuracy of 0.15 mm (1σ) in a sliding windows of 120 m in the LHC), a new automated measurement system is necessary to replace the traditional ecartometry, a labor-intensive method, which gets impractical due to increased radiation levels. The project involved the development of a prototype based on photogrammetry, integrated with inclinometers, laying the foundation for future automation. This poster details the technical methodology, including camera calibration, target detection and measurement, inclinometer calibration, and 3D reconstruction, showcasing significant advancements in precision and efficiency for wire offset measurements in the HL-LHC.



Current prototype with 4 high-resolution cameras and 4 inclinometers mounted on a 300 mm × 800 mm aluminium frame

Methodology

Step 1 — **Train camera calibration**
Interior and exterior calibration of the prototype cameras

Step 2 — **Inclinometers calibration**
Definition of rotation matrices between inclinometers and cameras

Step 3 — **Data acquisition**
Acquisition of 4 images and 4 inclination values

Step 4 — **2D Target and Wire measurement**
Computer vision method for detection and measurement in images

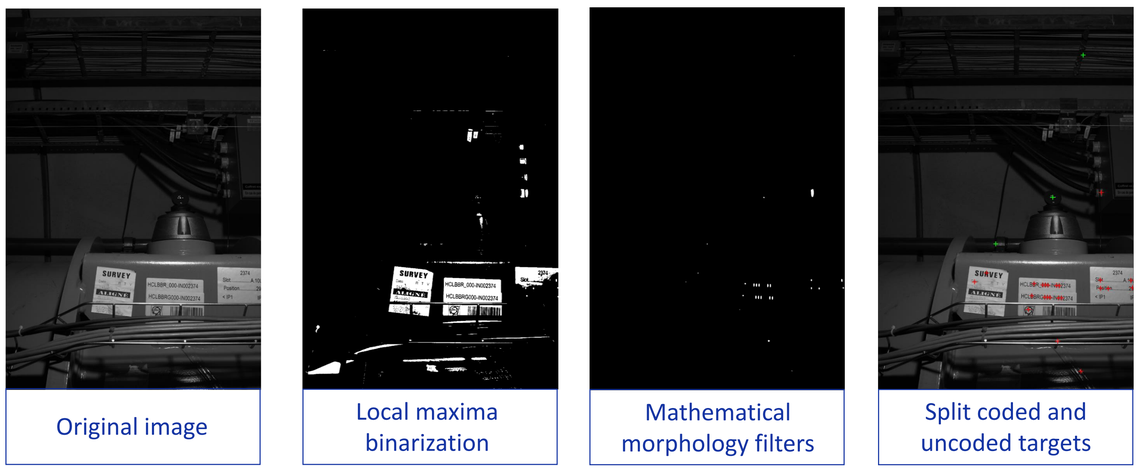
Step 5 — **3D offset calculation**
Conversion of 2D measurement to LGC's observations and 3D adjustment

Step 6 — **Offset adjustment**
Adjustment of wire offsets on overlapping wires

Flow chart for direct wire offset measurement by photogrammetry

Target detection and measurement

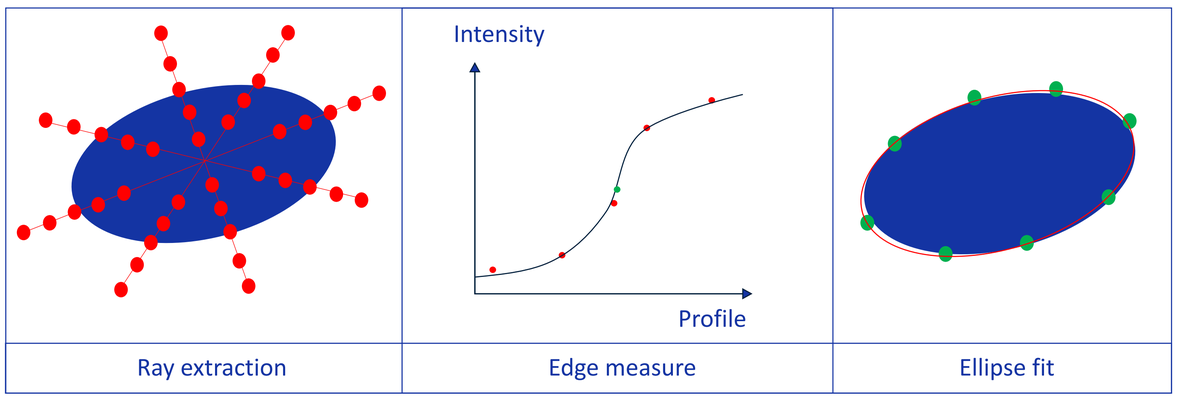
The calibrated prototype starts the ecartometry calculation with **detecting coded targets** installed on the magnet fiducials in images with the following procedure :



Original image | Local maxima binarization | Mathematical morphology filters | Split coded and uncoded targets

Computer vision process for target detection

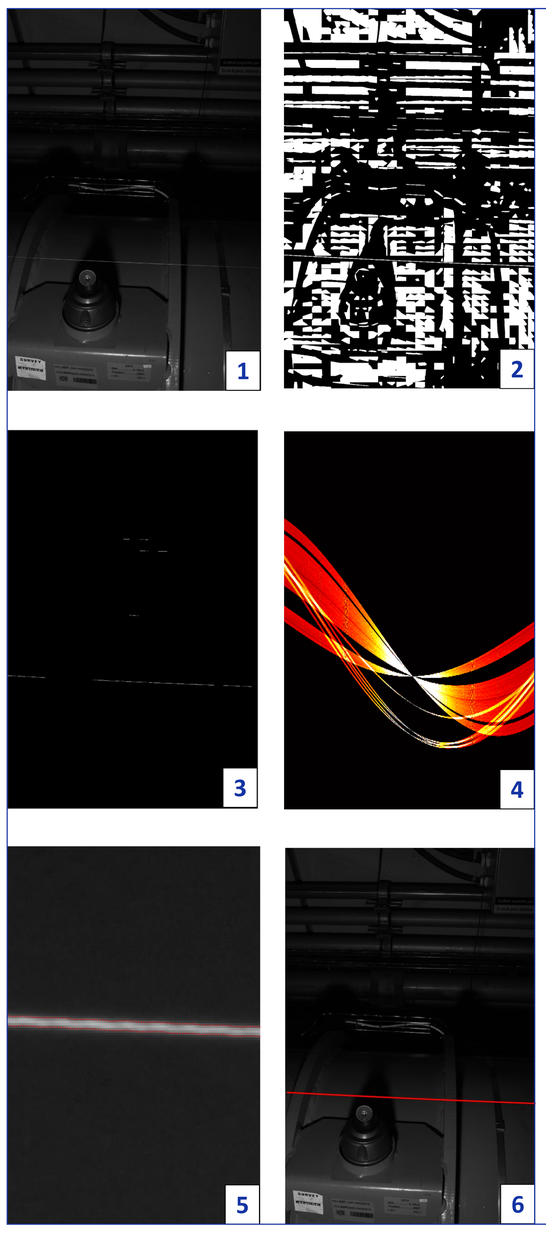
Once the targets are detected, the next step is edge measurement, using **profile** of points. Polynomial functions are fitted to **detect the edge**, and a least square adjustment estimates the **ellipse** centre, half-axes, and rotation angle.



Ray extraction | Edge measure | Ellipse fit

Target measurement process

Wire detection and measurement



Procedure :

1 : **Contrast-limited Adaptive Histogram Equalization** (CLAHE) is applied to enhance the visibility of the wire against a non-homogeneous background.

2 : The image is divided into small **patches**, and a **local thresholding** method (local maxima) is used to identify regions of interest within each patch.

3 : A **mathematical morphology** operator filters out irrelevant objects, retaining only single linear objects that match the wire's size.

4 : The **Hough transform** is used on the entire black-and-white image to detect lines, with the longest line being selected as the wire.

5 : Using the approximate wire parameters, **subpixel edge detection** is performed to extract the wire edges and their normal vectors for classification.

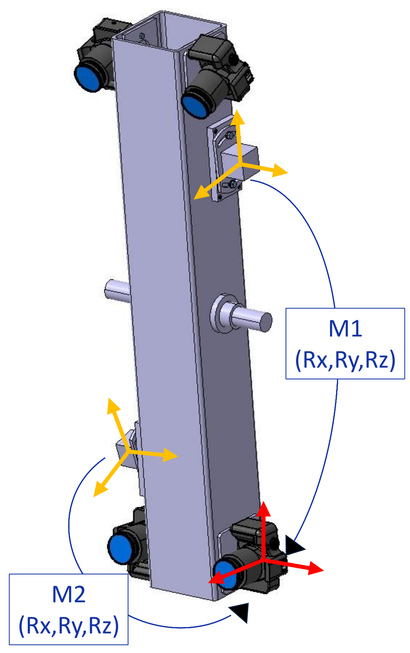
6 : A Principal Component Analysis (PCA) is applied for robust **line fitting**, iteratively removing outliers and considering only lines with a sigma below a user defined threshold.

Wire detection and measurement process

Gravity Link Integration

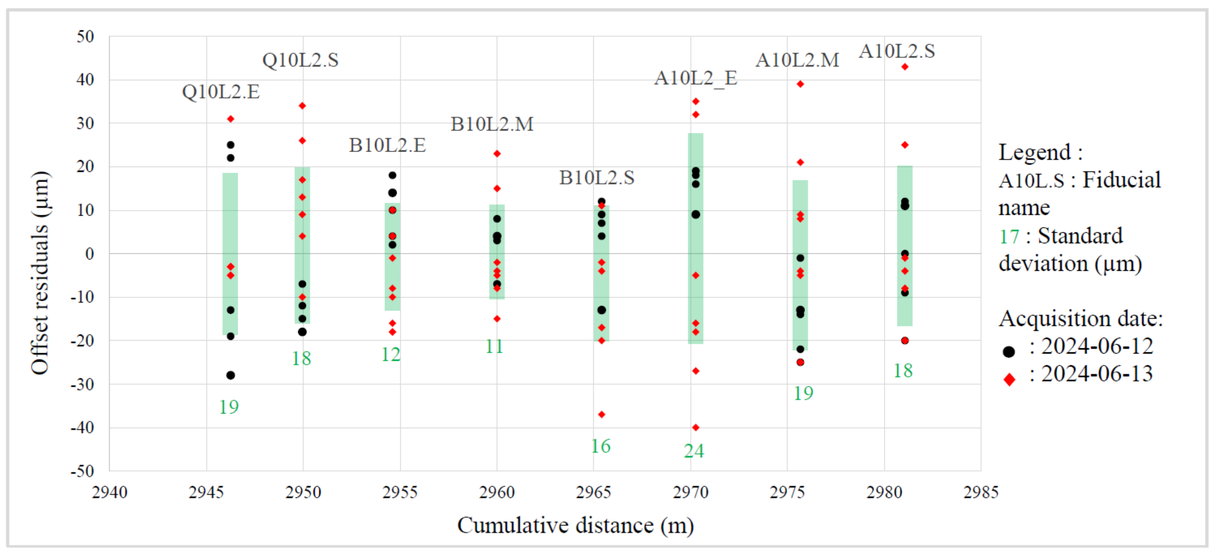
The gravity link is needed to transfer the photogrammetric measurement to a verticalized reference system. This allows to extract the horizontal distance between the wire and the target. This link is done with **two blocks** of two Wyler Zerotronic inclinometers mounted on the frame. The **rotation matrices** between the different inclinometer blocks and the cameras (M1 and M2) need to be determined by a **new procedure** referred to as **inclinometer calibration**.

The determination of these matrices is done thanks to a dozen drift-nests for 1.5 inch SMRs installed on a wall and measured by **laser tracker**. The train setup is then positioned in front of the network and data acquisition is performed using 15 positions, with a ball joint allowing **multiple orientations** to cover the full range of the inclination sensors. With a **constraint adjustment** in LGC, two rotation matrices (one for each block) can be extracted.



Future prototype frame and the transfer of rotation matrix between inclinometers block and camera

June 2024 Results



Offset residuals of two overlapping stretched wire lines adjusted with LGC

Conclusion

This poster introduces 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 achieves precision levels better than 50 µm, which is essential for the demanding environment of particle accelerators. The promising results demonstrate the potential of the system for future automation and broader application in accelerator alignment.

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