A next generation survey train for future accelerators

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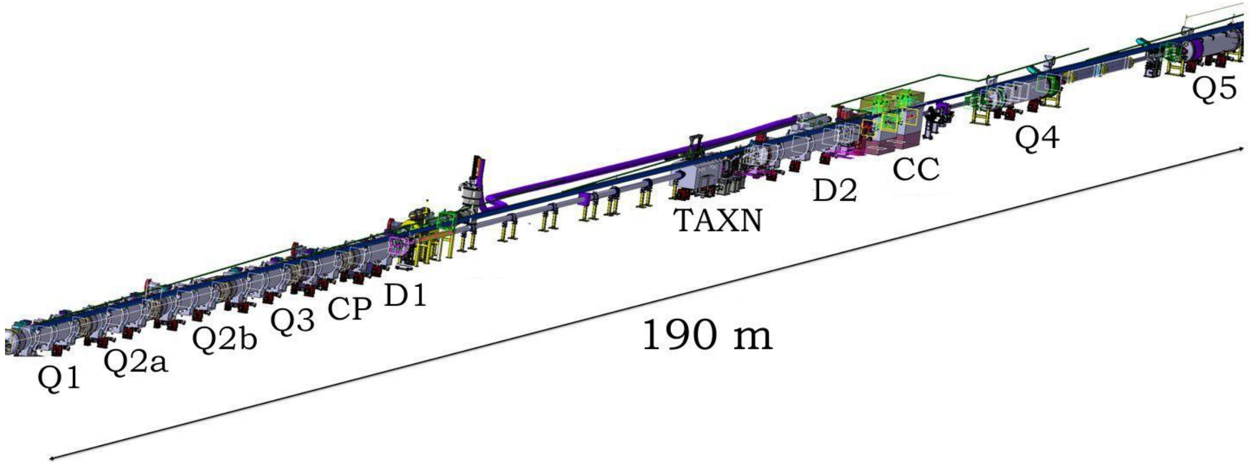
10/10/2024

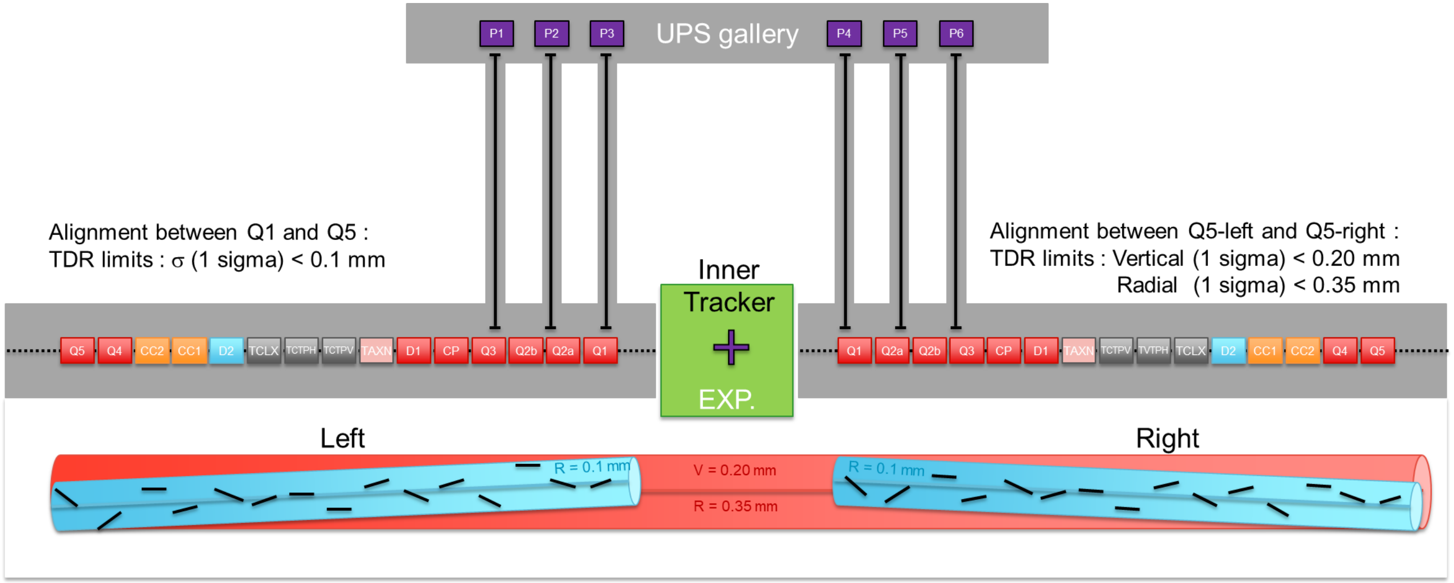
Outline

- **Introduction of the prototype for photogrammetric ecartometry**
- **Survey train process**
  - Camera and inclinometers calibration
  - Acquisition and measurement
  - Calculation and output
- **Results and analysis**
  - Comparison with laser tracker
  - Repeatability tests
- **Outlook and Conclusion**

Introduction : Why Precise Alignment is Critical

- **Alignment directly impacts the performance of particle accelerators.**
- **For the HL-LHC, alignment precision is required to be within 0.20 mm vertically and 0.35 mm radially over 420 meters.**
- **The ongoing upgrades present new challenges, particularly in maintaining alignment under increased radiation levels.**
- **A permanent system called the FRAS monitors this area.**





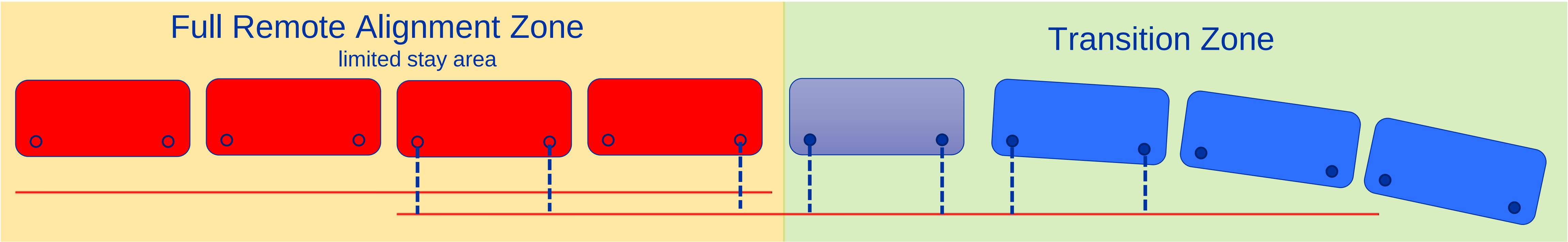
Limitations of Traditional Alignment Methods

- **Wire measurements are necessary for accelerator alignment :**

  laser tracker : angular precision of 3 µrad.

  120 m stretched wire : precision of 50 µm for an offset = angular accuracy of 0.8 µrad

- **Manual wire offset measurements are labor-intensive, time-consuming, and excluded due to high radiation levels.**
- **To maintain a continuous and smooth alignment, a link must be made between the LHC arcs and the FRAS.**
- **Given the increased radiation in these areas, traditional manual measurements are no longer feasible.**



Permanent monitoring wire

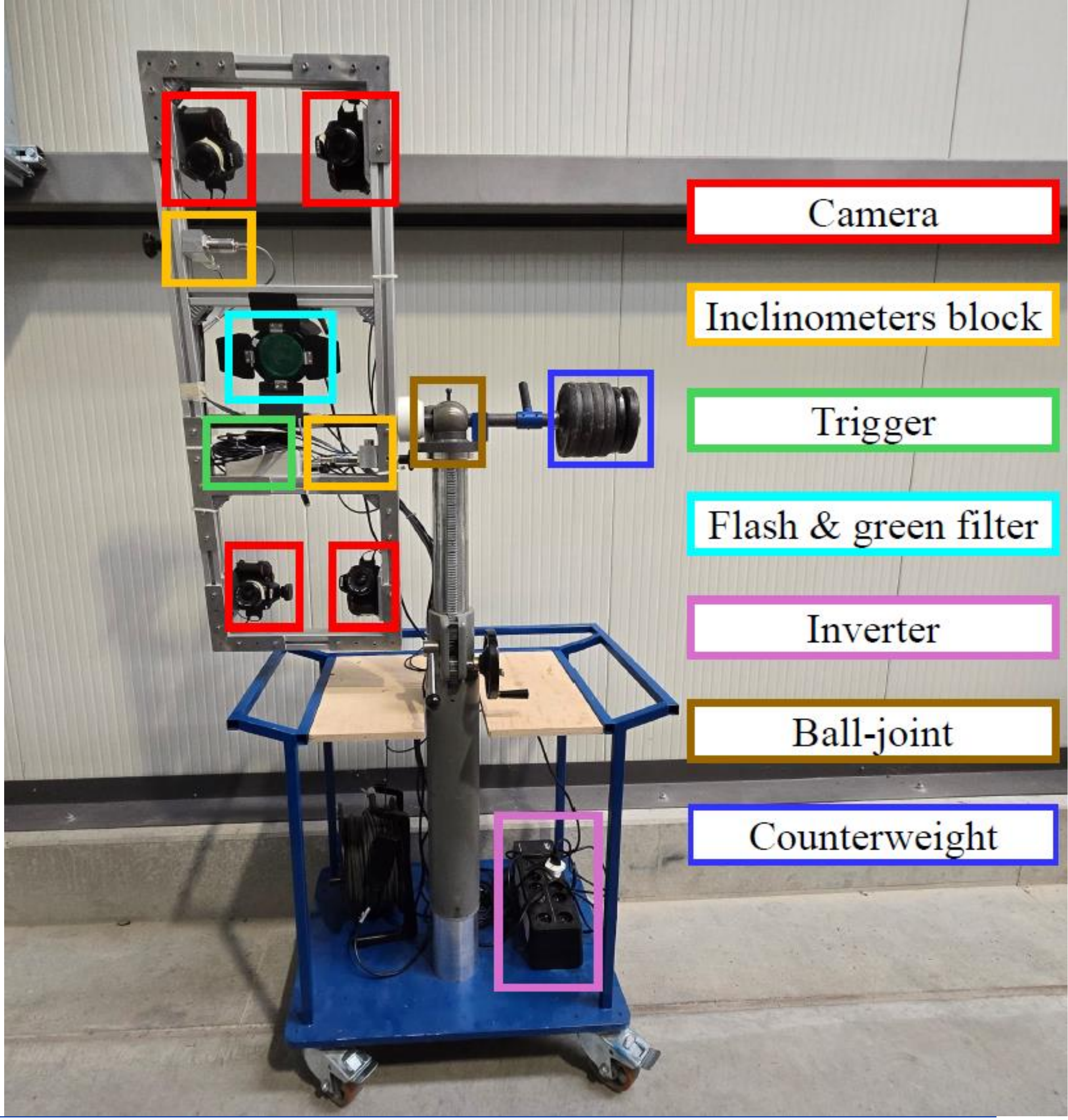
Train extension wire

Hardware and Software Innovations

- Photogrammetry provides a non-contact method for high-precision measurements.

- The key to the process is the identification and measurement of targets and the stretched wire using advanced machine vision techniques.

- Integration with gravity through inclinometer calibration ensures accuracy.



Process

Flow chart for direct wire offset measurement by photogrammetry

Step 1

Train camera calibration
Interior and exterior calibration of the prototype cameras

Step 2

Inclinometers calibration
Definition of 3D 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

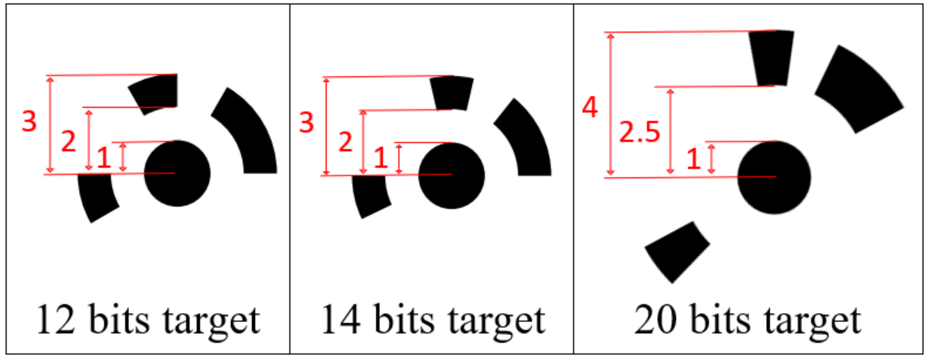
Step 6

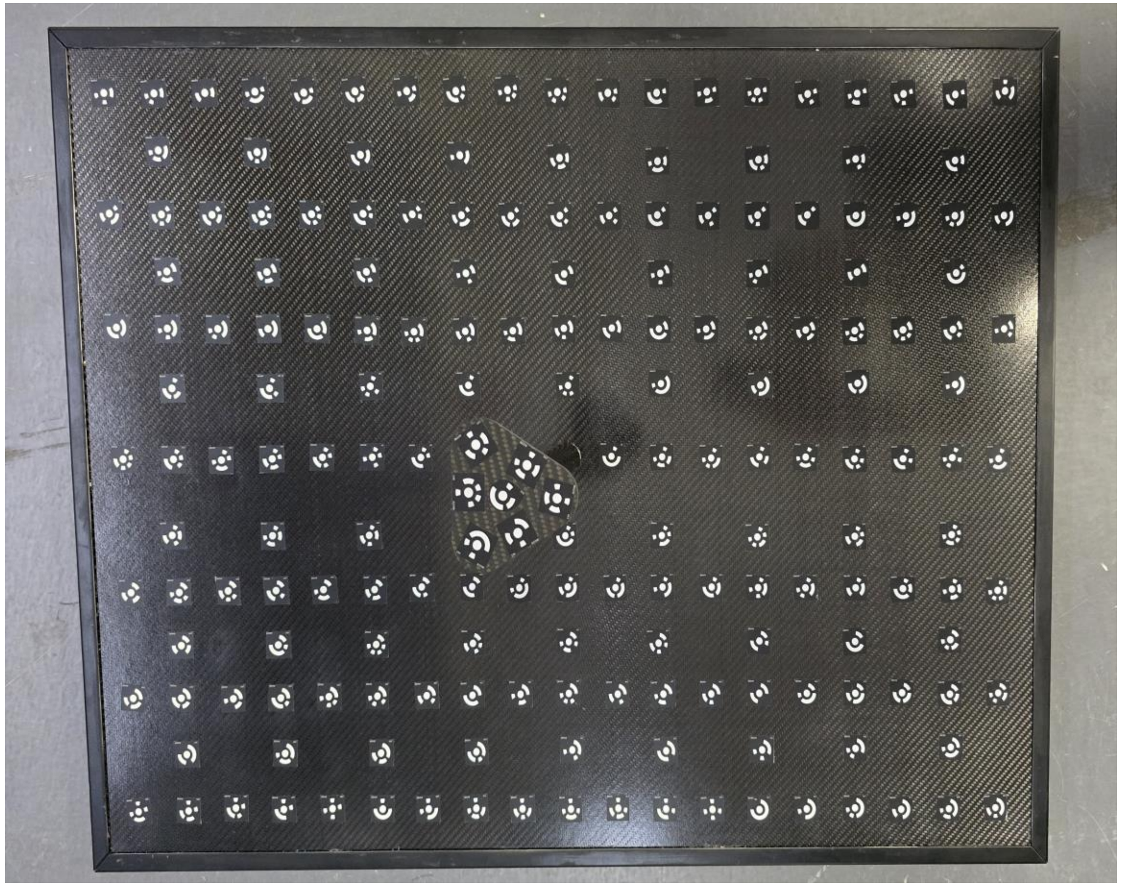
Offset adjustment
Adjustment of wire offsets on overlapping wires

- **Calibration involves defining the interior and exterior orientation of the cameras. This can be performed by DPA-Studio (Hexagon) or MicMac (IGN)**

- **The carbon sandwich panel consists of a 700 mm × 500 mm with 200 encoded targets glued on it.**

- **Regular calibration is essential for maintaining accuracy over time.**



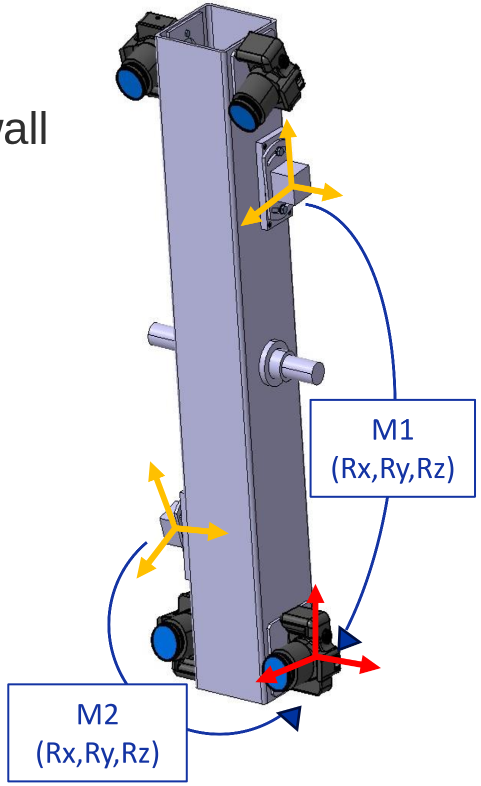


The inclinometers are calibrated to link the photogrammetric system to gravity, enabling precise vertical and horizontal measurements.

This new procedure followed these steps:

- Installation of a dozen drift-nests for 1.5 inch SMRs on a wall
- Measurement by laser tracker.
- The train setup positioned in front of the network
- Acquisition of 15 frames positions in multiple orientations
- Constraint adjustment in LGC
- Extraction of two rotation matrices

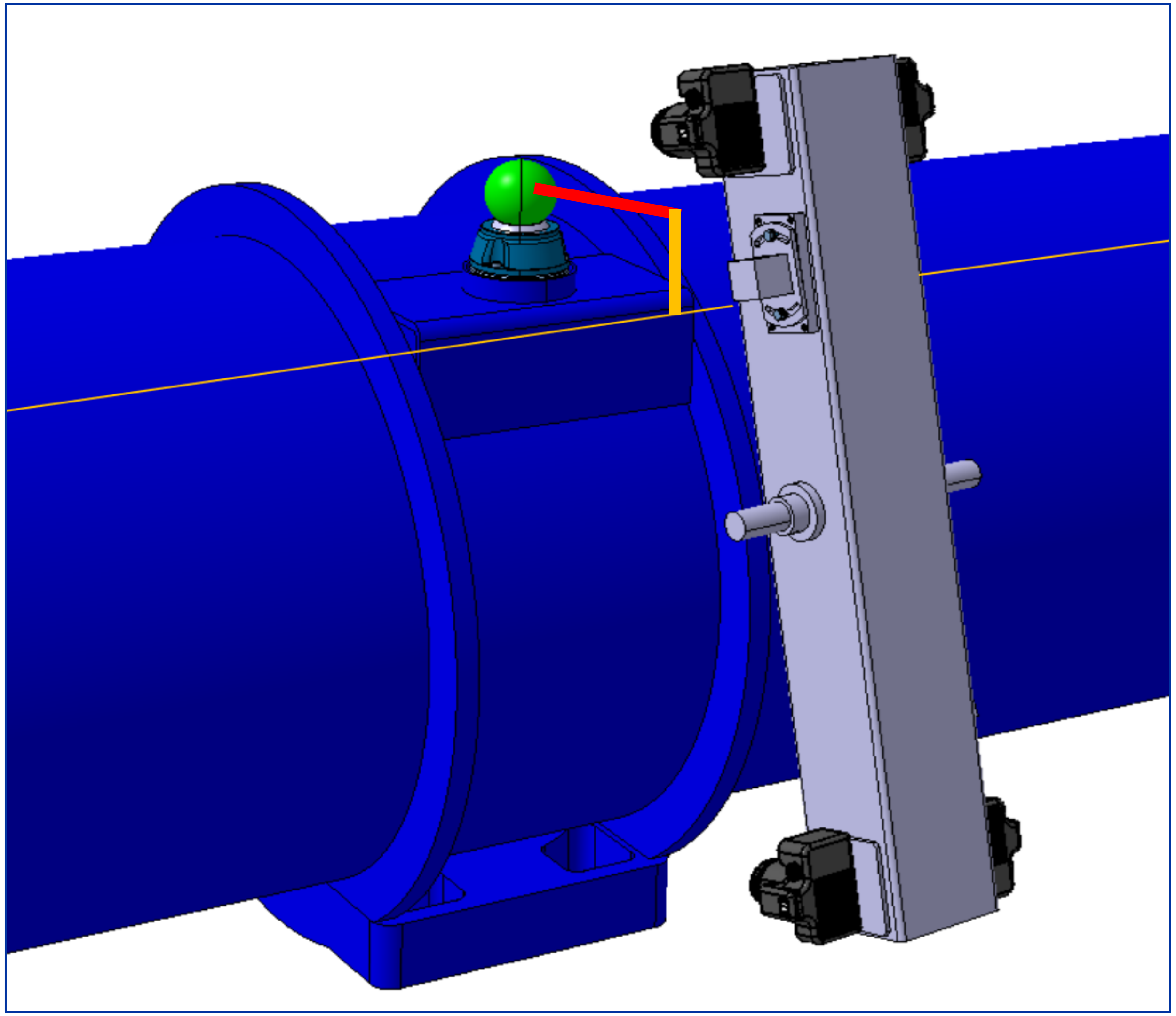
Wylerag.com



Wire stretching

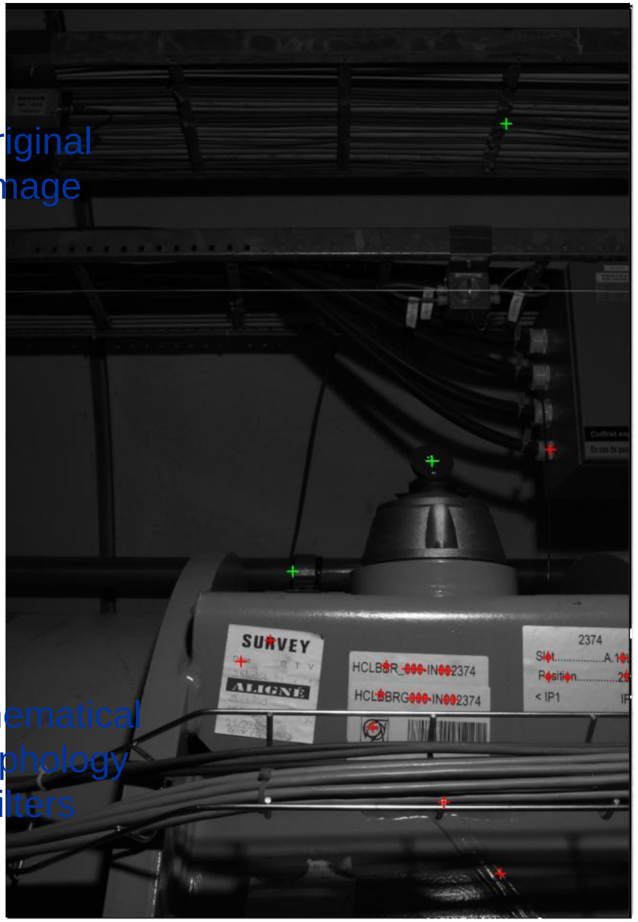
Target installation on the fiducials

Multiple sets of 4 images taken in front of each fiducials



Target :

Original image



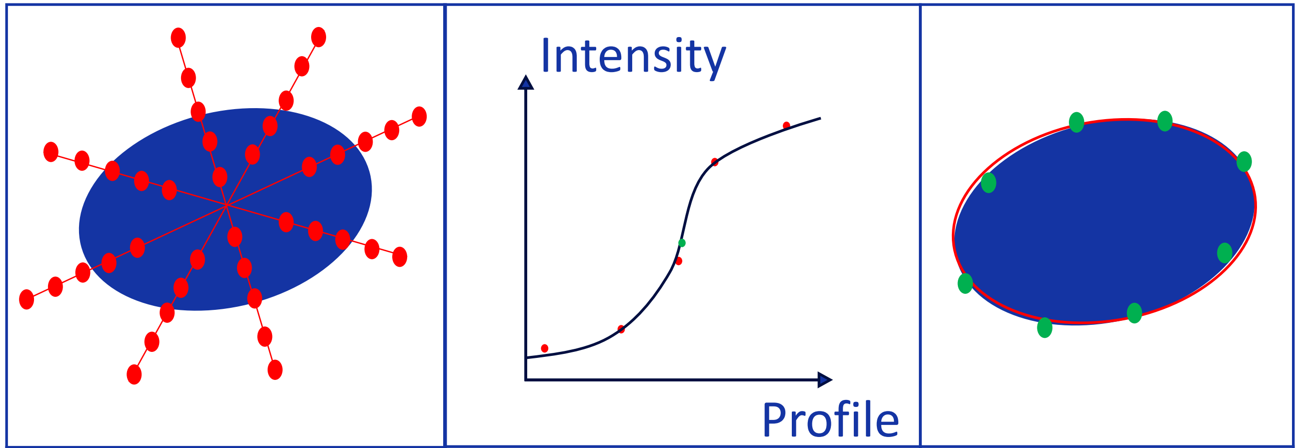
Mathematical morphology filters

Local maxima binarization

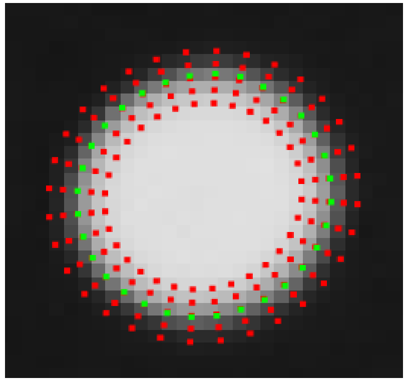
Candidates split between coded and uncoded
Mathematical morphology filters
Local maxima binarization

Candidate split between coded and uncoded

Target detection



Ray extraction	Edge measure	Ellipse fit

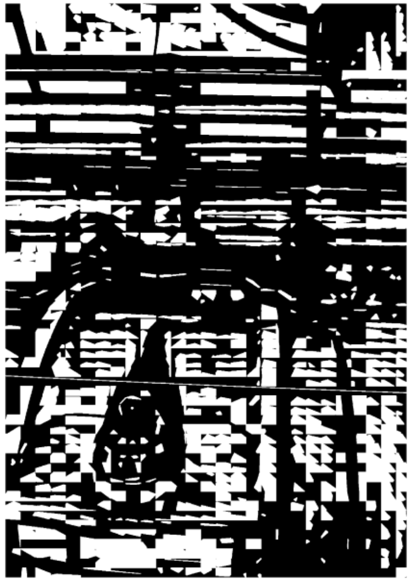


Target Measurement

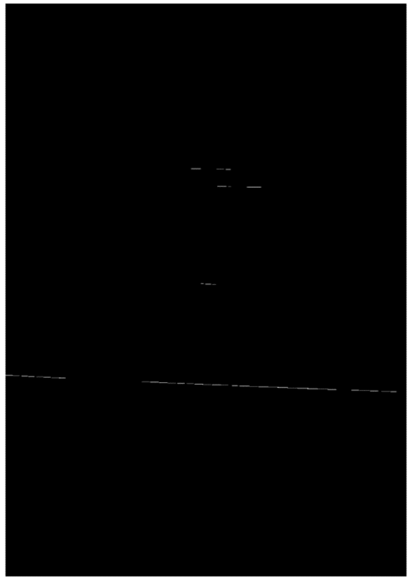
Train camera calibration | Inclinometers calibration | Data acquisition | 2D Target and Wire measurement | 3D offset calculation | Offset adjustment

Wire :

Contrast-limited Adaptive Histogram Equalization (CLAHE)

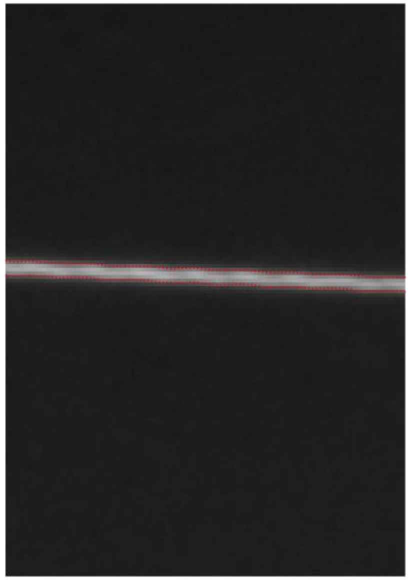


Patch threshold method



Mathematical morphology operator filters

Hough transform

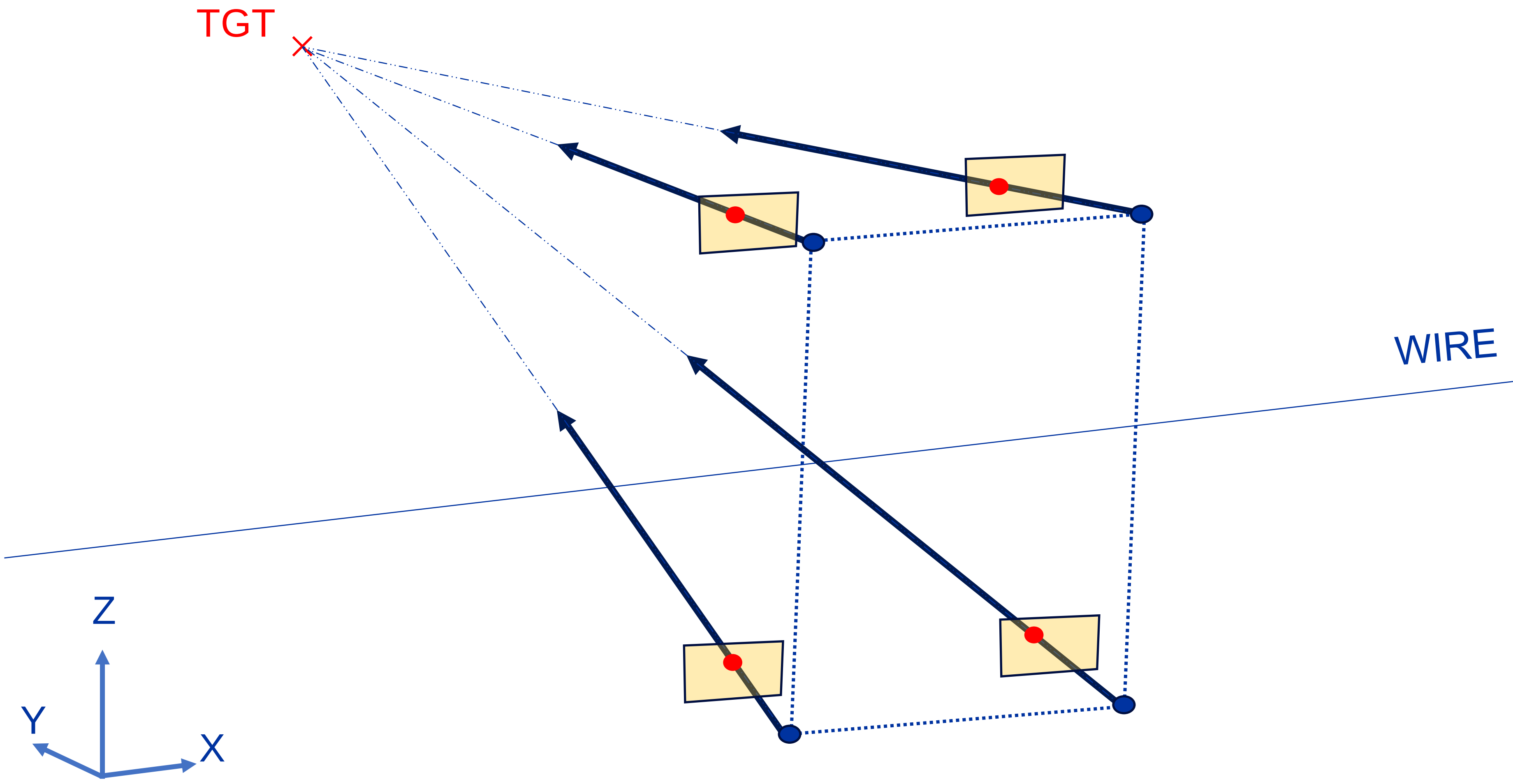


Subpixel edge detection

Line fit

Train camera calibration | Inclinometers calibration | Data acquisition | 2D Target and Wire measurement | 3D offset calculation | Offset adjustment

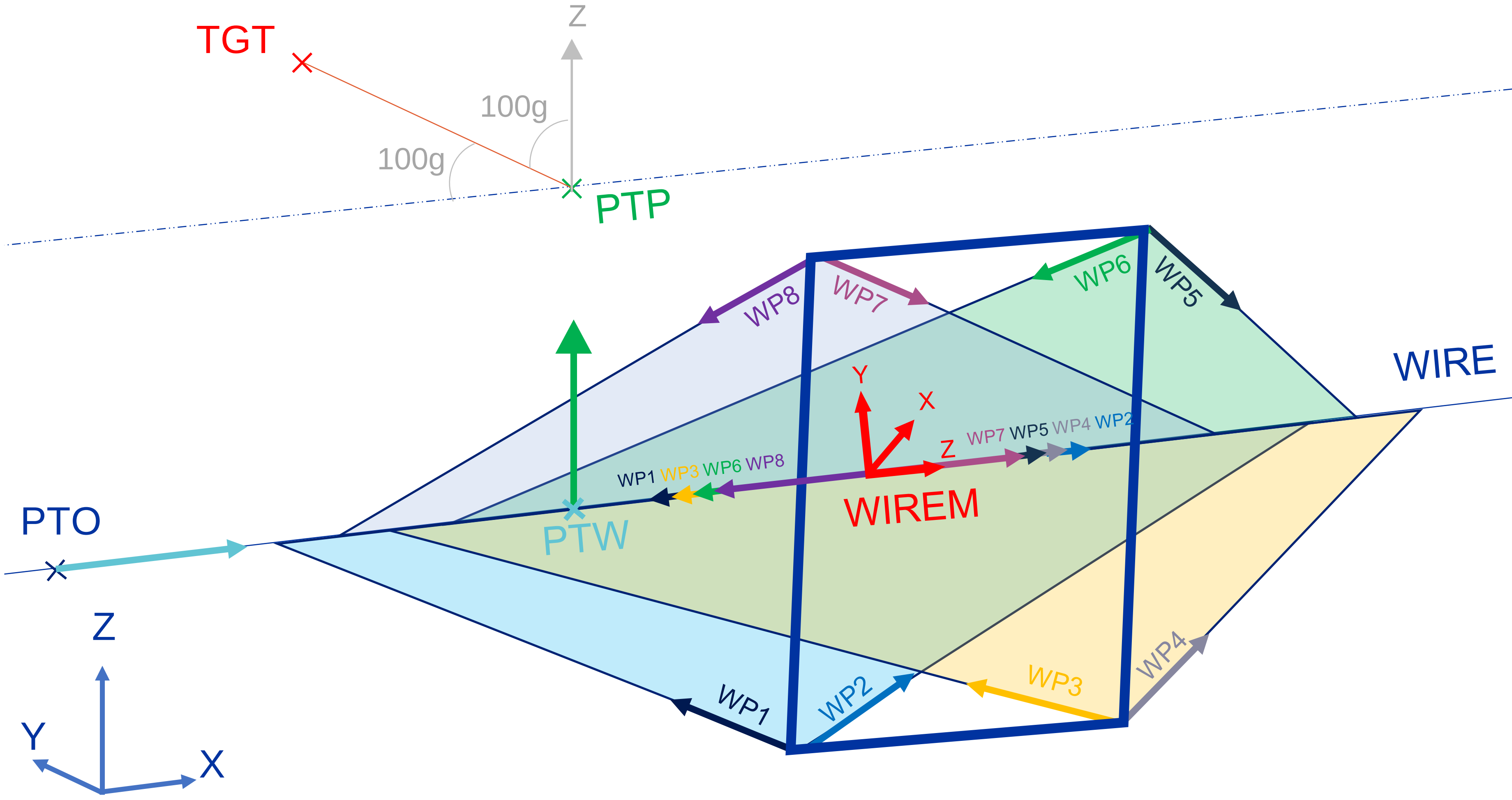
- **Geometrical calculation for each offset with LGC**



Train camera calibration | Inclinometers calibration | Data acquisition | 2D Target and Wire measurement | 3D offset calculation | Offset adjustment

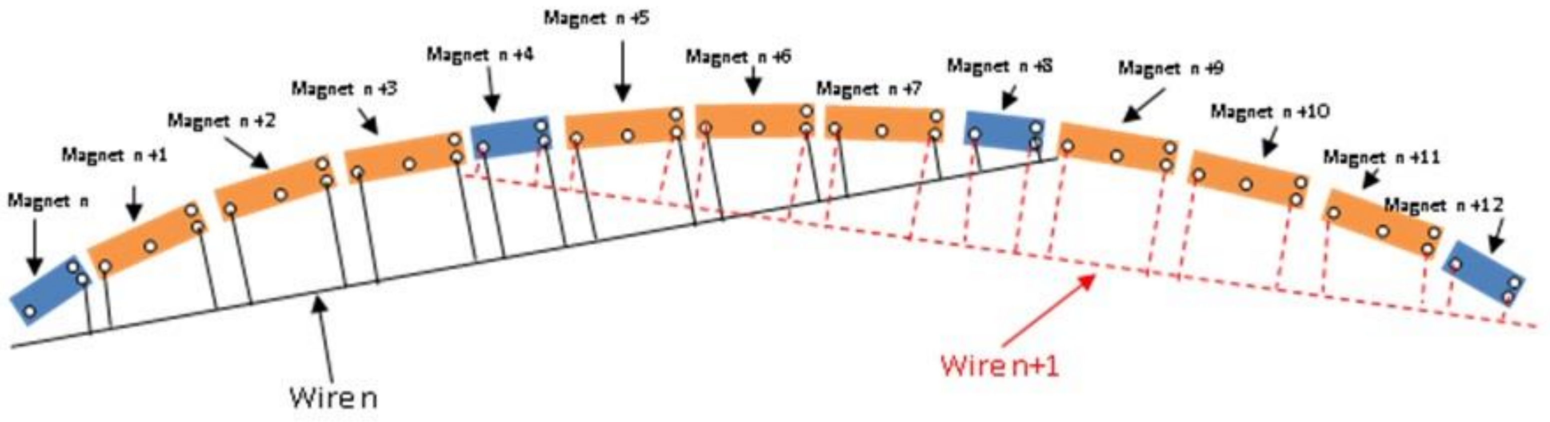
- **Geometrical calculation for each offset with LGC**

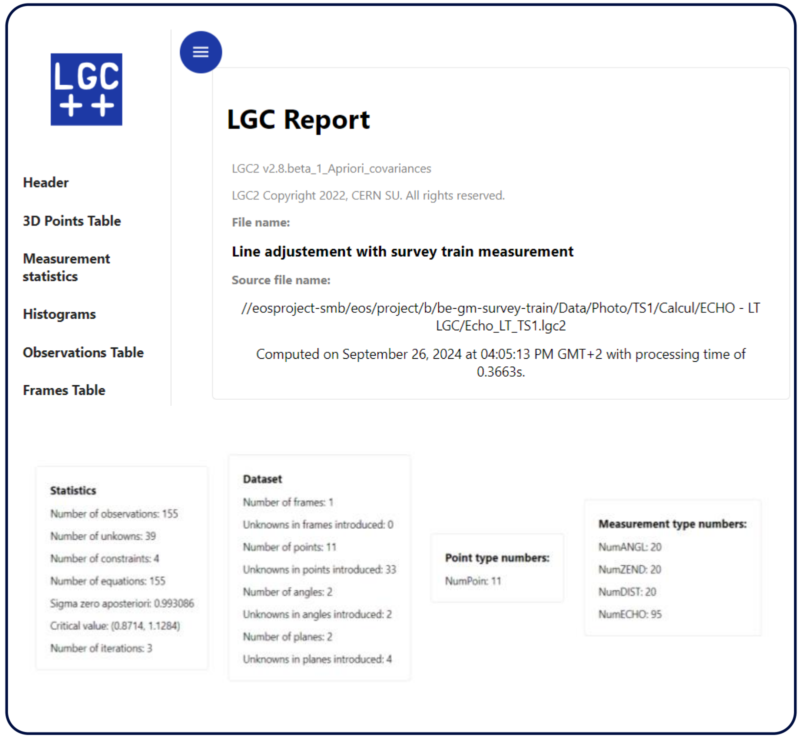
- **Relative precision between wire and target can be extracted**



Train camera calibration | Inclinometers calibration | Data acquisition | 2D Target and Wire measurement | 3D offset calculation | **Offset adjustment**

- **Extraction of individuals offsets and associated precision**
- **Completion of the LGC file for line calculation**
- **Least squared adjustment**




LGC ++

Header
3D Points Table
Measurement statistics
Histograms
Observations Table
Frames Table

LGC Report

LGC2 v2.8.beta_1_Apriori_covariances

LGC2 Copyright 2022, CERN SU. All rights reserved.

File name:

Line adjustement with survey train measurement

Source file name:

//eosproject-smb/eos/project/b/be-gm-survey-train/Data/Photo/TS1/Calcul/ECHO - LT LGC/Echo_LT_TS1.lgc2

Computed on September 26, 2024 at 04:05:13 PM GMT+2 with processing time of 0.3663s.

Statistics
Number of observations: 155
Number of unkowns: 39
Number of constraints: 4
Number of equations: 155
Sigma zero aposteriori: 0.993086
Critical value: (0.8714, 1.1284)
Number of iterations: 3

Dataset
Number of frames: 1
Unknowns in frames introduced: 0
Number of points: 11
Unknowns in points introduced: 33
Number of angles: 2
Unknowns in angles introduced: 2
Number of planes: 2
Unknowns in planes introduced: 4

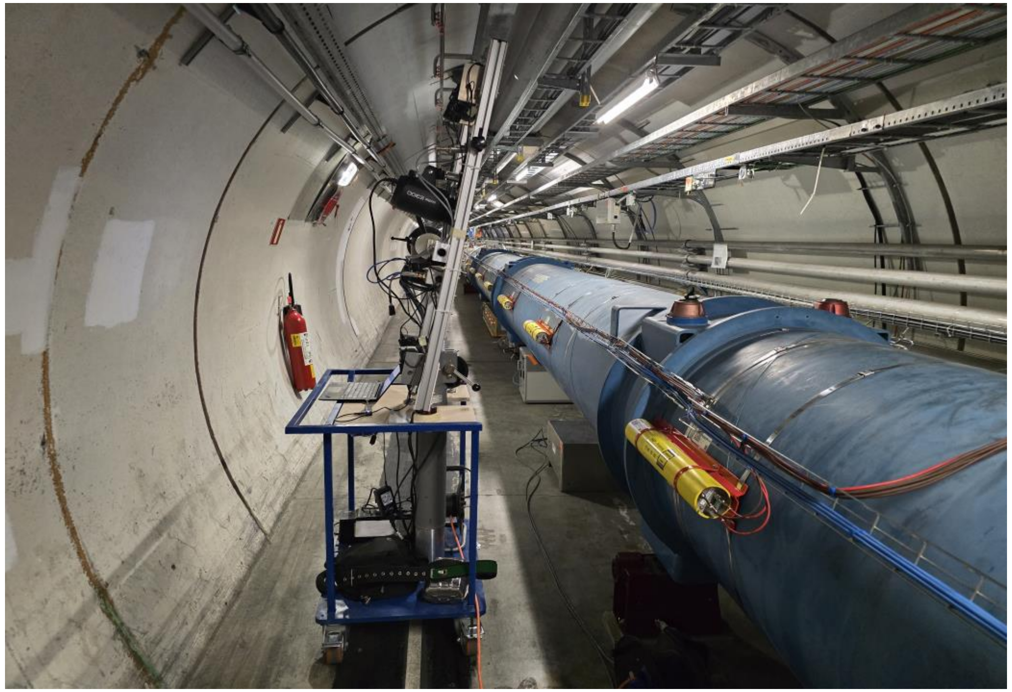
Point type numbers:
NumPoin: 11

Measurement type numbers:
NumANGL: 20
NumZEND: 20
NumDIST: 20
NumECHO: 95

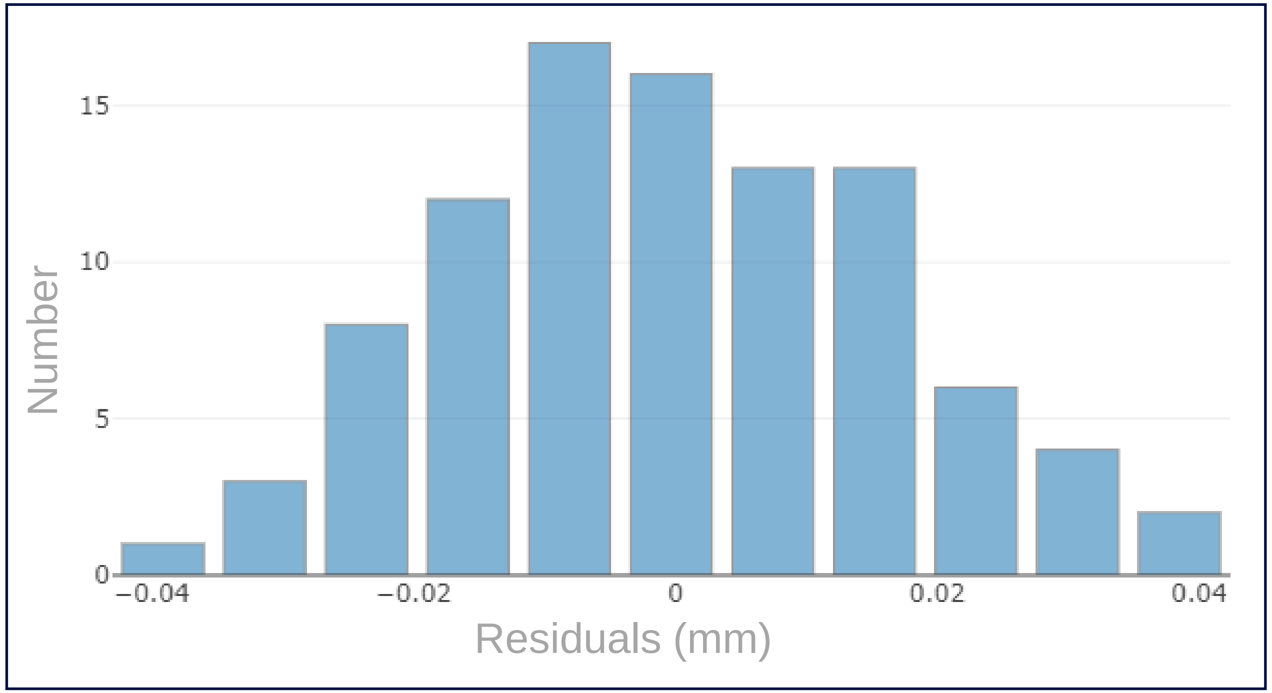
Early Repeatability Results

Tests were conducted in the LHC and SPS environments, with promising results.

The initial tests have shown excellent repeatability, with a precision of 50 µm or better.



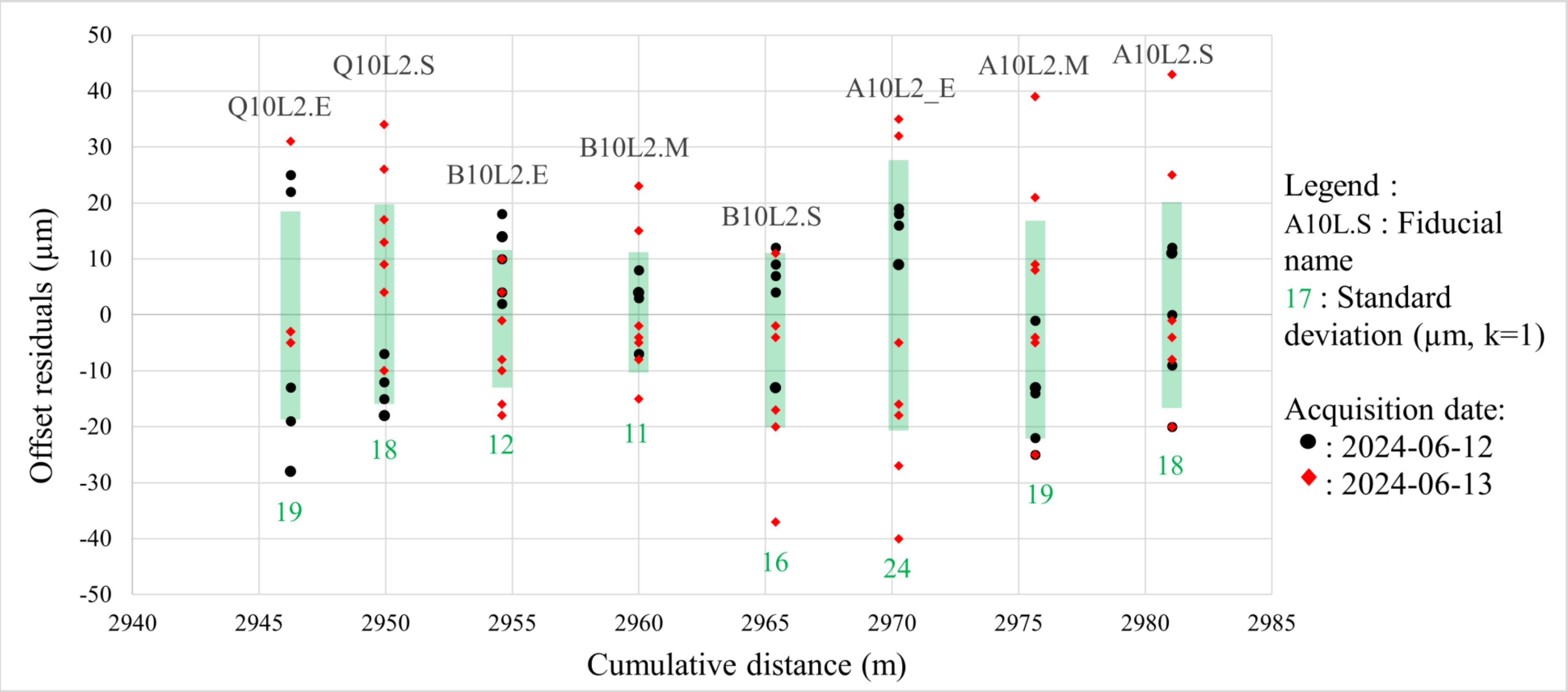
LHC measurement with the survey train prototype



Histogram of residuals for 95 offsets observation with survey train

Calculation with Laser tracker and Train measurement

The standard deviation for 95 observation is ~ 20 µm. The specification of an automated system < 50 µm for horizontal offset measurement seems reachable.



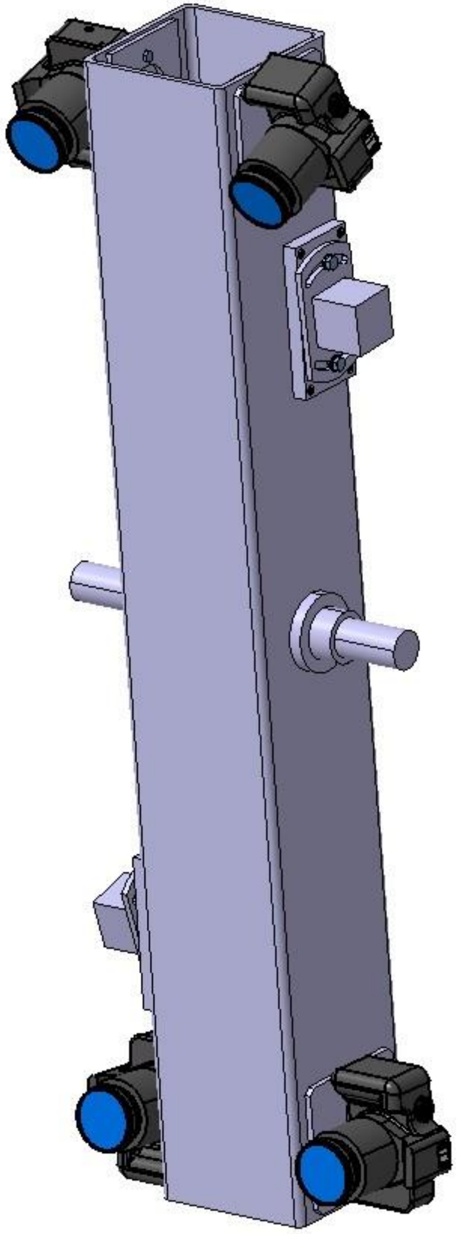
Development Timeline and Key Milestones

- **New carbon frame with girder shape has been ordered to increase the rigidity of the system**

- **The development is planned in stages, with final qualification tests scheduled for 2025 with the IT String test.**

- **The system must be ready in time for the different tasks during the Shutdown periods (LS3).**

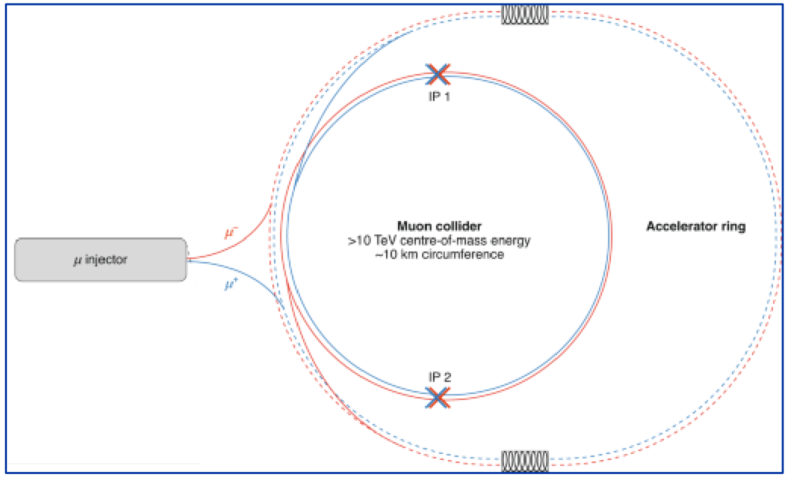
- **Integration into TIM and full automation are the next major milestones.**

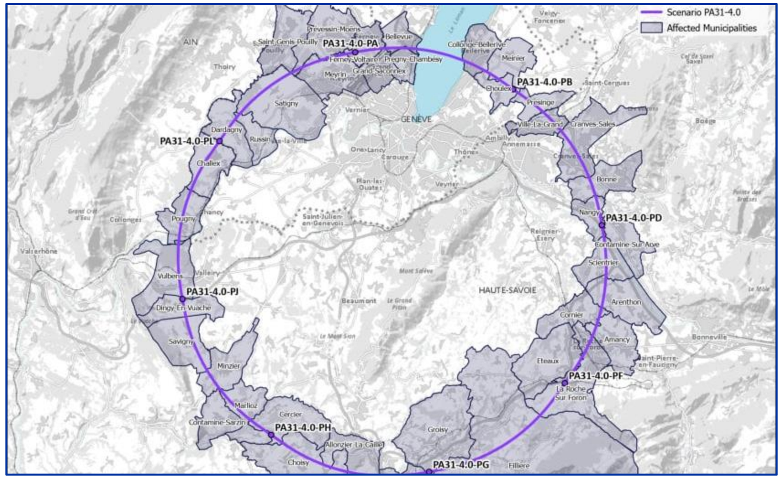


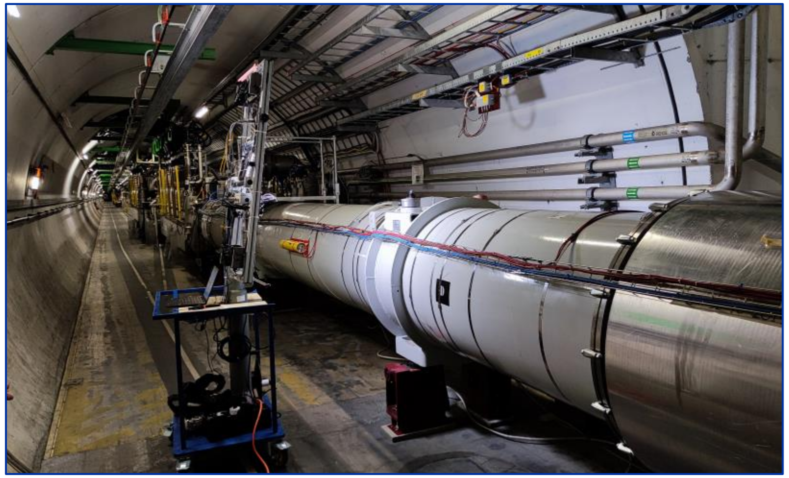
Extending the System to Future Accelerators

- **The principles developed for HL-LHC alignment are applicable to other accelerators, such as the SPS, the arc of the LHC, Muon Collider or the Future Circular Collider (FCC), etc…**

- **The system needs to stay modular and universal, even if specific tasks are targeted.**





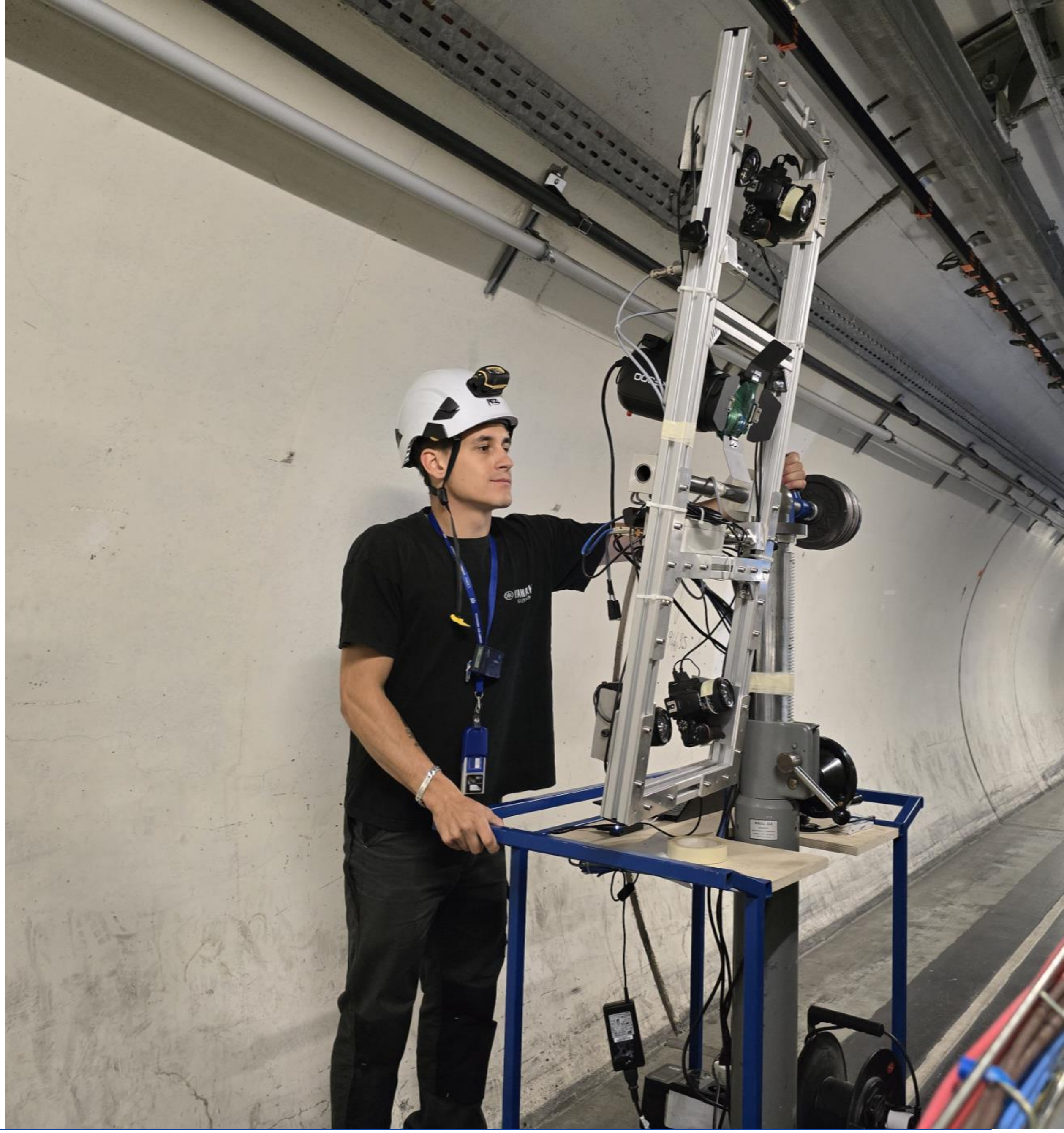


Conclusion

- Direct photogrammetry paves the way for fully automated measurement in high-radiation environments.

- The survey train and photogrammetry-based measurement system have proven effective in achieving the required precision

- The project is well on track, with promising future developments.



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