PACMAN STUDY OF FSI AND MICRO-TRIANGULATION FOR THE PRE-ALIGNMENT OF CLIC

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Abstract

The alignment precision of linear colliders is extremely demanding owing to the very narrow beam size at the interaction point. Unlike circular colliders, particles in linear colliders have only one chance to collide and are hence tightly focused to maximise the number of interactions per collision. The PACMAN* project is dedicated to study the integration of both fiducialization and alignment of the components on a common support. FSI (Frequency Scanning Interferometry) and Micro-triangulation will contribute to this goal. FSI realized by Etalon AG's Absolute Multiline system and Micro-triangulation implemented by QDaedalus system developed at ETH Zurich offer precision of 0.5 μm/m and 2.4 μm/m respectively. However, these systems need to be improved in order to provide the necessary geometric information via distance measurements (multilateration) and angle measurements (triangulation), respectively. The paper describes the current status and the future developments of Absolute Multiline and QDaedalus, which are the corresponding implementations of both methods.

INTRODUCTION

CLIC pre-alignment study overview

The Compact Linear Collider (CLIC) is a site independent feasibility study aiming at the development of a realistic technology at an affordable cost for an electron-positron Linear Collider. This multi-TeV (nominal 3 TeV) collider will expand the knowledge of particle physics in the post-LHC era [1].

CLIC will consist of two 20 km long linacs, which meet at the Interaction Point. It will have a total of 20,000 modules, each having a length of 2 m. The fact that it is an electron-positron collider, makes it particularly demanding in alignment precision. The final alignment of the components in the linacs will be performed by beam based alignment. This requires pre-alignment of the CLIC modules at the level of 10 μm over a 200 m sliding window [2].

The pre-alignment procedure can be divided into three steps [3].

First step: The magnetic axis of quadrupoles and the electrical axis of Beam Position Monitors (BPM) will be determined by means beyond the scope of this paper and will be realised by a stretched wire. The position of the wire will then be transferred to external alignment targets, also known as fiducials.

Second step: This step consists of the alignment of all the components on a common support (girder). The precision for this step can be expressed by a 5 μm radius cylinder, along a maximum 2 m length module [3].

Third step: During this last step, the modules will be positioned in the tunnel and will later be actively re-adjusted by actuators. According to the later studies, the re-adjustment will be based on sensors like optical and capacitor WPS (Wire Position Sensor), HLS (Hydrostatic Levelling System) and inclinometers [4].

In addition, research is currently being conducted at CERN SU section on the use of a laser beam as a straight line reference. This laser line could be used as an independent metrological approach, in order to validate the stretched wire method [5].

PACMAN study

PACMAN is a Marie Curie Initial Training Network, implemented as Innovative Doctoral Program, hosted by CERN. The project provides training to 10 Early Stage Researchers in a variety of disciplines like beam instrumentation, metrology, micrometric alignment, magnetic measurements, nano-positioning and high precision engineering [6]. This will be done in collaboration with 8 universities and 8 industrial partners which provide secondments and tailored training. The scientific objective of PACMAN is to propose and develop an alternative solution integrating the first two steps of the pre-alignment process, as described above. It also seeks to combine a large number of technologies at the same time and location, in order to gain the required precision and accuracy.

Due to the large number of modules that will need to be aligned, the solution proposed should be robust and applicable to an industrial setting. Towards the end of the program, a prototype alignment bench will be built in which the final demonstration of the PACMAN system (methods, alignment sequence and algorithms) will be implemented [7].

The project is divided into four Work Packages; WP1: Metrology and Alignment, WP2: Magnetic measurements, WP3: Precision mechanics and stabilization, WP4: Beam instrumentation.

The PACMAN Work Package 1 covers the research and development of:

- a non-contact high precision sensor for Leitz Infinity Coordinate Measuring Machine (CMM),
- an absolute Frequency Scanning Interferometry (FSI) multilateration network and

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- a stretched wire detection algorithm for use in Micro-triangulation.

The main purpose of this paper is to describe the current state and the future developments of both FSI and Micro-triangulation methods.

As part of this study, the FSI system will be improved to enable measurement of multilateration networks. On the other hand, the main goal of studying Micro-triangulation in this project is to detect the stretched wire and to determine its position in space. The successful development of the new features will give the two systems the capability of being used in the fiducialization and the alignment of the components on a girder inside a metrology laboratory. Furthermore the systems could be used in the future installation of the CLIC modules in the tunnel.

Although no further details are given here, a parallel study is being conducted within PACMAN to develop a measurement head for the Leitz CMM currently used by the metrology lab at CERN to enable contactless measurements of the stretched wire. Leitz CMM has a very low measurement uncertainty of 0.3 μm + 1 ppm [8] but still lacks portability and has a major stroke axis of 1200 mm limiting its measurement volume. However, because of its accuracy, the CMM will be used to validate both FSI and Micro-triangulation implementations. If proved to have acceptable levels of accuracy, both methods will provide a portable means of coordinate determination.

DEVELOPMENT OF FSI NETWORK

Multilateration

Trilateration is a common technique of determining the 3D coordinates of a point by making only distance measurements to a target from three other points whose positions are known. This technique is employed in Global Navigation Satellite Systems (GNSS) to accurately determine the position of receivers on earth by making range measurements to satellites. When more than 3 distance measurements are made, the technique is referred to as multilateration. In this study, multilateration will be combined with FSI, a highly accurate absolute measurement technique to form an accurate, self-calibrating, six degrees of freedom coordinate measuring system.

Principle of FSI

FSI generally employs a tunable laser which is scanned through a known frequency while coupled to both a reference interferometer whose length, L_R is precisely known and a measurement interferometer whose length, L_M is unknown. The ratio of the phase change $\Delta\theta$ and $\Delta\varphi$ induced in both the measurement and the reference interferometers is proportional to their lengths. Therefore, the unknown length L_M can be determined using the relation below [9].

$$L_M = L_R\left(\frac{\Delta\theta}{\Delta\varphi}\right) \qquad (1)$$

The accuracy of traditional FSI is limited by both the stability of the reference interferometer and the accuracy to which its length is known. A brief explanation of how lengths are made relative to a stable reference to ensure metrological traceability will be given in the following section. The refractive index of the medium in which measurements are made also has an effect on the interferometric distances. However, relationship between the distance light travels and the refractive index of the medium in which it travels is well known and by measuring the factors on which refractive index of air depends i.e. temperature, pressure and humidity, corrections can be made to remove its effects.

Absolute Multiline FSI

Absolute Multiline is manufactured by Etalon AG, Germany and is the brand name of the FSI system that will be used for this research. Only a brief description concerning this system that was developed by University of Oxford FSI group is given here but a thorough explanation of the background, principles and methods is given in [9].

A tunable laser directs infrared light via optical fibres to a measurement head which terminates in a collimator. The fibre end which has been specially treated to give it beam splitter functionality is positioned at the focal length of the collimating lens. Some of the light at the fibre end is reflected back into the fibre thus forming the reference arm of the measurement interferometer. The rest of the light is transmitted to a retro-reflective target which reflects this light back to the collimating lens which in turn focuses it back to the fibre. On re-entering the fibre, the beam reflected from the retro-reflector combines with the beam reflected by the beam splitter to form an interference pattern which is detected by a photodiode and digitised by an Analog to Digital Converter (ADC). This system is designed to make measurements relative to a stable reference in the form of absorption peaks of an integrated gas cell ensuring traceability to the SI metre. It achieves this by simultaneously directing laser light to the measurement interferometer and a gas cell. As the variable laser light passes through an atomic transition of the gas in the cell, the intensity on the photo detector varies enabling the system to determine the exact time at which laser had the same frequency as the atomic transition frequencies [9]. A simplified schematic diagram showing the key components of the system (see Fig. 1). The system is capable of making multiple simultaneous measurements with an uncertainty of 0.5 μm per metre at a 95% confidence level [10].

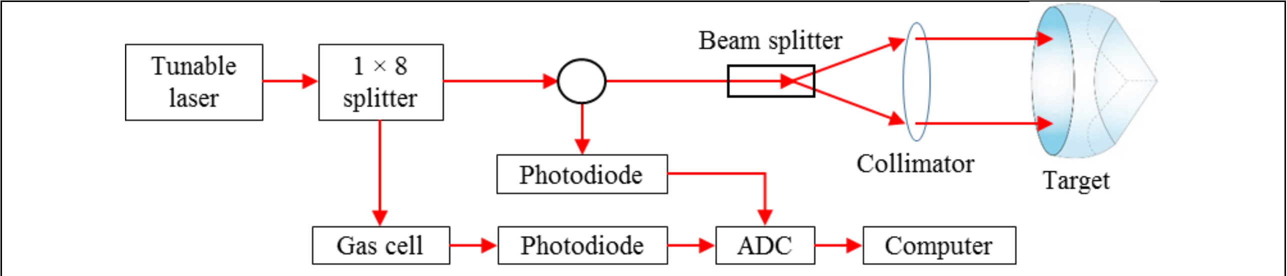

Figure 1: Simplified schematic diagram showing the key components of the Absolute Multiline.

Current system status

Hardware: The Absolute Multiline system at CERN has 8 measurement channels expandable to 100 and is capable of measuring distances of up to 20 m [10].The channels direct first a 640 nm red pilot laser beam used for initial coarse alignment to retro-reflectors and then a 1410-1510 nm infrared measurement beam. The measuring channels are 20 m long single mode optical fibres which terminate in a measurement head that contains a collimator. The measurement head is fixed to a mount which has adjustment knobs for aligning the beam to the retro-reflectors (see Fig 2). The system is connected via USB to an environmental sensor that provides information on temperature, pressure and humidity.

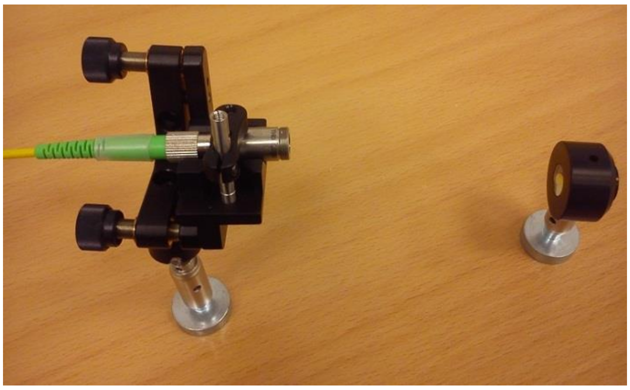

Figure 2: Absolute Multiline measurement head on adjustable mount and a retro-reflector target.

Software: The system comes with its custom Absolute Multiline software (developed in Matlab®) that is used to connect the lasers and environmental sensor. It aids alignment of the different measurement channels by showing the return intensity values of each line thus allowing fine adjustment of the different measurement heads with respect to the retro-reflective targets. While taking measurements, the software shows changes between individual distances and it has a facility for visualisation of 3 dimensional deformation. Measurement data is exported as a Microsoft Excel file with distances, temperature, pressure and humidity as well as time of individual measurements.

Developments under this study

The geometrical arrangement of FSI emitters relative to the retro-reflective targets has a bearing on the uncertainty of the coordinates determined using multilateration. A reflective target with a wide viewing angle would allow optimum arrangement of the transmitters relative to the target. One such target is a whole viewing angle glass sphere made of high index glass whose suitability as a retro reflective target albeit with low return intensity has been demonstrated [11]. It has also been shown that this target can be used for FSI [12], however, further tests will be conducted with FSI for various intensities as part of this study. Tests will also be conducted to assess its suitability as a Micro-triangulation target with the aim of making near simultaneous measurements using FSI and Micro-triangulation.

The current FSI measurement head is such that the 3 dimensional position of the beam splitter cannot be established from the exterior. A new measurement head will be developed with the aim of precisely establishing the geometrical relationship between the beam splitter and the exterior. This will allow the absolute distance between two given points to be accurately determined. Studies are underway to design this piece in such a way that it can be measured by Micro-triangulation and a CMM, hence allowing inter-comparisons of the networks created by these three systems to be made.

For the establishment of a network using multilateration, it is helpful to be able to make more than one distance measurement from any given measuring channel. One way of doing this would require a mechanism of moving the measurement head, but this would potentially become an additional source of error. An alternative that does not involve moving of the measurement head is to widen or split the beam from any given fibre end such that it can ‘see’ multiple reflectors. This would result in multiple interference patterns corresponding to the different optical path differences in any given interferometer. By taking the Fourier transform of the interferometer signal, the frequency corresponding to the different distances can be isolated. A prototype using a divergent beam has been produced at the National Physical Laboratory in the United Kingdom [10] but the measurement volume was limited to a 0.3 m diameter sphere due to the limited field of view of the FSI emitters and low intensity of the returned beam. It will be the object of this study to investigate the use of alternate optical devices that limit the loss of intensity of the beam, hence allowing longer ranges and a wider field of view of the FSI emitters in order to increase the measurement volume.

In order to handle data relating to several distances being made from a single measurement channel, upgrades of the current Absolute Multiline software will be necessary. Furthermore, the current output file is not useful for network analysis and therefore, it will need to be improved to include approximate coordinates of points, include key words and relate distances to the concerned points.

Once the system software and hardware have been fully upgraded as described above, various configurations of the FSI network will be studied via simulations performed using CERN's least squares compensation program LGC++ with the aim of choosing the best one for the measurement sequence. The FSI solution will then be extrapolated for use in an industrial setting to facilitate mass alignment of the components of 20,000 CLIC modules.

MICRO-TRIANGULATION

Method

Triangulation is a well-known method used to measure 3D geodetic networks and to estimate planar coordinates and height differences between points. Micro-triangulation is a kind of triangulation with two main features, i.e. it applies to short range measurements which can give precision of a few micrometres and it employs high accuracy industrial theodolites. According to the manufacturer's specifications of the modern theodolites, the angular accuracy can reach the level of 0.15 mgon ≈ 2.4 µrad [13], i.e. ≈ 2.4 µm/m.

Micro-triangulation is based on horizontal and vertical angle measurements, which are calculated as differences of orientations. These measurements form a geodetic network with 5 degrees of freedom i.e. translations (X, Y, Z), horizontal orientation and scale. The coordinates are estimated by least-squares adjustment, adding the needed external information to constrain the degrees of freedom.

The main feature of the method is the link of the network to the local plumb-line (earth's gravity field) with accuracy of 0.1 mgon [13]. This aspect makes triangulation useful in large scale geodetic metrology applications such as the alignment of particle colliders.

Despite the fact that the origins of triangulation are lost in the mists of time, the integration of various modern technologies in theodolites still makes it attractive. The most important improvements are:

- servo or piezo motors for the rotation of the instrument,
- automatic biaxial liquid compensators for the vertical circle compensation,
- encoders for fast and precise angle measurements,
- digital camera for automatic target recognition,
- auto-focus mechanism.

These improvements help to produce fast, high precision, reliable measurements independent of an observer. In addition, Micro-triangulation can be used in environments that are harmful to humans such as those with extreme temperatures or high levels ionizing radiation.

QDaedalus system

The technique of automated Micro-triangulation is applied with the QDaedalus system which is designed and developed primarily for astro-geodetic applications by the Geodesy and Geodynamics Lab., Institute of Geodesy and Photogrammetry, ETH Zurich.

QDaedalus consists of both hardware add-ons to a robotic total station and software (see Fig. 3). The fundamental idea is to replace the eye-piece with a CCD camera in a non-destructive way. This enables automatic measurements of accurate spatial directions to visible objects without using corner-cube targets [14].

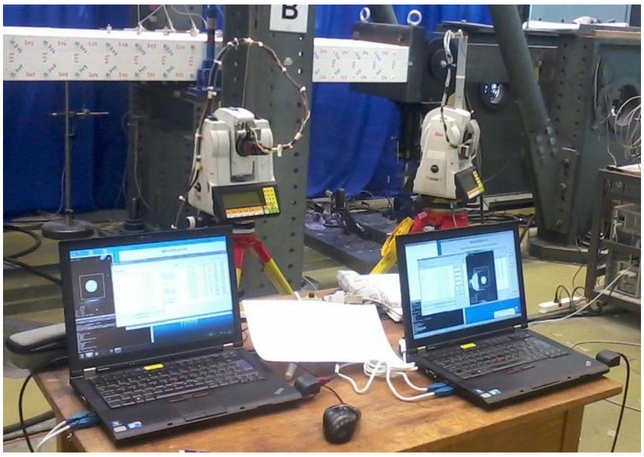

Figure 3: Two QDaedalus systems on robotic total stations Leica TDA5005.

Although QDaedalus system was developed for astro-geodetic applications, tests have proven that it is a versatile system that can successfully be used in various geodetic metrology applications and reach precision levels of 10 µm in 3D coordinates, when compared with Laser Tracker and CMM [14-16].

Brief overview of QDaedalus system

As described earlier, the key feature of QDaedalus is the replacement of the eye-piece with a CCD camera in an easy, rapid and non-destructive way. The details and specifications of the current system can be divided into three categories; hardware, software and algorithms [17].

Hardware: It consists of the following parts (see Fig. 4):

- Leica TDA5005 robotic total station with angular accuracy of 0.15 mgon and compensator accuracy of 0.1 mgon [13].
- AVT Guppy F-080B CCD camera, which is monochrome (peak at 500 nm), externally triggered, has 1024 × 786 pixels, 4.65 µm × 4.65 pixel size and up to 30 frames/sec [18].
- Remote controlled focusing mechanism using stepper motor, conic gearwheel and tooth belt passing around the focusing ring [19].

- A meniscus diverging front lens with -4 m focal length to displace the focal plane 4 mm towards the image plane. This lens should be used when distance to the target exceeds 13 m.
- Frequency generator for the synchronization of multiple QDaedalus systems or GPS receiver, which enables the absolute time tagging of the observations.

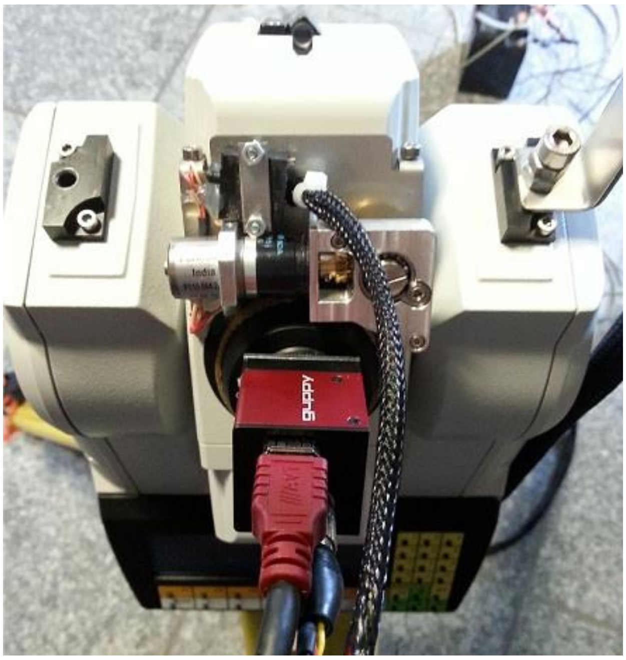

Figure 4: Leica TDA5005, AVT Guppy F-080B and focusing mechanism.

Software: It has the ability to control the surveying instrument and the focusing mechanism, to receive and process images of the CCD camera and to extract angle measurements. The QDaedalus software is developed in Qt, an open source cross-platform application framework, using C++. It integrates SQLite, an open source library to create and manage SQL databases, and the open source library OpenCV used for image processing.

Target detection algorithms: These are developed and implemented for the detection of different kind of targets. Each algorithms has specific advantages and disadvantages depending on the characteristics of the targets (see Fig. 5) [14].

Centre of mass operator is a simple and fast algorithm suitable for real-time applications. It is precise for active targets, like LED or retro-reflective, however it is inadequate for passive targets. For network measurements it should be used with targets that keep the same shape independently of the angle of view. The precision of the algorithm cannot be estimated and this can be considered as a drawback.

Template least-squares matching algorithm is based on the template that should be determined manually. The matching is very precise, however, the targets should look identical with the template. The deficiency of the algorithm is the fact that the precision of the measurement relies on the eccentricity of the template.

Circle matching algorithm is used to measure networks whose targets are spheres, which are always projected on the image plane as circles. The algorithm fits a circle on the edge of the target using least-squares which means that parts of the target can be covered. The spheres can be surveying targets or any other spherical element permanently mounted on the measured object.

Ellipse matching algorithm has similarities with the circle matching algorithm. It can detect ellipses projected on the image plane coming from circular targets. It does not need the whole edge of the ellipse as it uses a least-squares fitting. It is applicable in retro-reflective, photogrammetric targets or any precisely machined hole on the surface of the measured object.

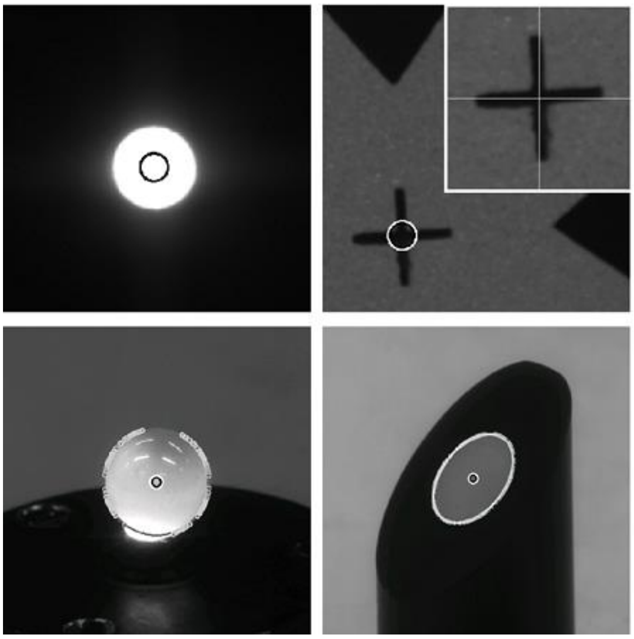

Figure 5: Example of the four target detection algorithms applied on various targets.

ATR versus OTR

The ATR (Automatic Target Recognition) is applied on the robotic total stations to allow automated measurements without manual aiming. The technique relies on the laser beam that is emitted from the total station and is reflected back by a corner-cube prism. Therefore, the precise measurement of a surveying network in short time is difficult. This is because a corner-cube prism should be used for every point and the prisms should be turned manually towards the instruments.

On the contrary, QDaedalus relies on the OTR (Optical Target Recognition), which uses the previously described target detection algorithms. The main advantages of the OTR method are the following:

- There is no need to touch the targets during measurement, which is very important at the micrometre level precision.
- It can work with distant, fragile, hot or cold targets.
- It can be used in hazardous environments such as very hot, very cold or in high ionized radiation, which

makes the system advantageous in research institutes and laboratories of high energy physics.

- It uses relatively economic targets that can be active, passive or retro-reflective photogrammetric targets.
- It can be used with precisely machined holes or spheres that may exist permanently on the object.

Future developments

In the frame of the current study, various enhancements and improvements will be integrated on the QDaedalus system.

The optical system of the LeicaTDA5005 combined with the Guppy camera provides resolution of 4 arcsec/pixel. Given that the target extraction is better than one tenth of a pixel, it can be easily proven that the system fully exploits the 0.5 arcsec angular precision of the total station.

Although the existing hardware is adequate to support the foreseen research, improvements in the components' size and wireless connectivity, would be very helpful.

An important improvement would be the ability to connect, control and measure using multiple total stations simultaneously. This will further automatize and speed up the measurement of a surveying network. Moreover, this will give QDaedalus the ability to monitor dynamic objects in real-time.

The user-friendly software is currently fully functional. Foreseen enhancements of the existing functionality and further development would improve the ease and speed of the measurement procedure.

The greatest challenge of this study is the development of an algorithm to detect a stretched wire and provide contactless angle measurements. Particularly important would be the simultaneous measurement of the specific stretched wire that will be used to determine the electro-magnetic centres of CLIC components as well as the fiducials.

Similar but extremely optimized techniques have been developed by the collaboration between OSI (Open Source Instruments) [20] and CERN. The instrument, called optical WPS (Wire Positioning Sensor) gives results at the level of 10 μm [21].

Another study at CERN, on the detection and measurement of different kinds of stretched wires using photogrammetric method, shows equally encouraging results in the order of 30 μm [22].

CONCLUSION

The successful integration of both fiducialization and alignment of the components on a common support, will lead to a lower cost, time efficient and more precise pre-alignment. Absolute Multiline and QDaedalus systems have the potential to help realise this objective. However, there are a number of challenges such as the development of an algorithm to detect a stretched wire and the ability to measure several distances from one FSI emitter over a larger measurement volume. In addition, the two systems will become reliable portable solutions without the current measurement volume restrictions of CMM. Furthermore, they can then be valuable not only in the CLIC pre-alignment measurements and installation but also in other geodetic metrology application at CERN and especially in hazardous environments, where automation is needed.

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