euspen's 17th International Conference & Exhibition, Hannover, DE, May 2017
www.euspen.eu

Compact Linear Collider component fiducialisation using frequency scanning interferometry

Solomon William Kamugasa [1, 2], Jean-Christophe Gayde [1], Hélène Mainaud Durand [1]

[1]*CERN, Geneva, Switzerland*
[2]*ETHZ, Zurich, Switzerland*

solomon.william.kamugasa@cern.ch

Abstract
The Compact Linear Collider (CLIC) is a proposed next generation electron-positron collider under study at CERN. One of the main technological challenges of this project is the tight pre-alignment requirements of under 17 µm over a 200 m sliding window for its constituent components. Fiducialisation, the process of determining the position of external reference targets with respect to a component's functional axis, is one of the main contributors to this error budget. To this end, we have developed a solution for high accuracy fiducialisation of CLIC components using frequency scanning interferometry (FSI). Our developments include an innovative ceramic reference sphere for localizing the FSI optical fibre tip and a kinematic mount for repositioning the reference sphere with sub-micrometric repeatability. This design has enabled us to perform absolute distance measurements in different directions from the same point with micrometric precision. Using multilateration, we have realised a portable, self-calibrating coordinate measurement system that can handle larger measurement volumes than are possible with high accuracy coordinate measurement machines (CMMs). We have validated our solution using a Leitz Infinity CMM which has a Maximum Permissible Error of length measurement ($E_{L,MPE}$) of 0.3 µm + 1 ppm via a 3D Helmert transformation of target coordinates determined by both systems.

Compact Linear Collider (CLIC), fiducialisation, frequency scanning interferometry (FSI), multilateration

1. Introduction

The small beam sizes of approximately 1 nm x 40 nm at the interaction point of the Compact Linear Collider (CLIC) are unprecedented in the particle accelerator domain. As such, constituent components of this 40 km long electron-positron collider will be aligned using beam-based alignment. These components will need to be first pre-aligned to under 17 µm over a 200 m sliding window to allow a pilot beam to propagate through the collider. One of the main contributors to this error budget is fiducialisation; the determination of the position of external alignment targets with respect to a component's functional axis. The beam-focussing Main Beam Quadrupole (MBQ) magnet, for example, has a 10 µm fiducialisation error budget in the plane perpendicular to the beam [1].

The Leitz Infinity coordinate measurement machine (CMM) with a Maximum Permissible Error for length measurement of ($E_{L,MPE}$) of 0.3 µm + 1 ppm is considered at CERN to be the best fiducialisation solution due to its low measurement uncertainty. However, some components are larger than the measurement volume of this CMM. Additionally, the Leitz Infinity is not portable whereas some measurements are likely to be required outside the metrology laboratory.

We present a portable coordinate measurement solution based on multilateration that can cope with larger volumes. Our source of distance measurements is the Absolute Multiline frequency scanning interferometry (FSI) system which has a measurement uncertainty of 0.5 ppm [2]. This technology cannot perform distance measurements in different directions from the same point, whereas this is a requirement for multilateration. Consequently, we devised a solution where we inserted the FSI optical fibre tip into a high-precision, 38.1 mm diameter ceramic sphere supported by a kinematic mount [3] for micrometric repositioning. This way, it is possible to measure distances in different directions from the same reference, the centre of the sphere, and hence perform multilateration. However, there are two offsets of the fibre tip with respect to the centre of the sphere, one perpendicular to the beam which introduces a negligible cosine error and a constant along the beam. The constant can be calibrated by a number of techniques -- for this work, it is determined as part of the multilateration least squares adjustment routine. Next, we present our measurement strategy, fiducialisation test bench and results.

2. Methodology

Multilateration is a technique for coordinate determination which relies exclusively on distance measurements. The relationship between the 3D coordinates x_s, y_s, z_s and x_t, y_t, z_t of a measurement station and a target, and the distance D, between them is described by Equation 1. We have added a constant C, to represent the sum of the retroreflector offset and the offset along the beam of the FSI fibre tip with respect to the centre of the sphere. The residual of the distance measurement is represented by v.

$$D - C + v = ((x_s - x_t)^2 + (y_s - y_t)^2 + (z_s - z_t)^2)^{\frac{1}{2}} \quad (1)$$

Equation 1 represents one observation with one known parameter D, and seven unknowns $x_s, y_s, z_s, x_t, y_t, z_t$ and C. We created a network in which we made observations to several targets from any given station and from several stations to any given target. This way, we built a redundant network with more observations than unknowns and solved it by least squares using LGC++, CERN's survey adjustment software. The output of the analysis is the constant C, and the 3D coordinates of both stations and targets as well as their associated standard deviations. As such, we have a self-calibrating system that does not need prior knowledge of the exact station positions or the constant C.

2.1. Test Bench

Our test bench shown in Figure 1, consists of ten measurement stations each comprising a kinematic mount fixed on aluminium pillars of different heights. Both the 40 cm long CLIC MBQ, used as the measurement object and the measurement stations are mounted on the granite of a Leitz Infinity CMM. The MBQ is furnished with nine fiducial supports for 12.7 mm diameter spherically mounted corner cube retroreflectors.

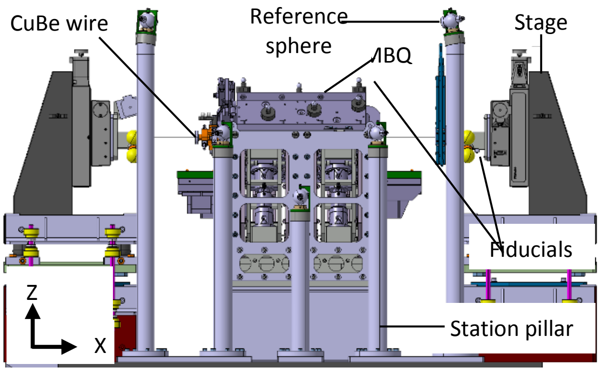

Figure 1. Side view of the FSI multilateration test bench for CLIC MBQ fiducialisation.

The magnetic axis, determined by magnetic measurements [4] is materialised by a 0.1 mm copper-beryllium (CuBe) wire and is supported at each end by two ceramic spheres. The position of the wire with respect to four, 38.1 mm diameter fiducials mounted on the wire support stages was determined indirectly thanks to the Zeiss O-Inspect optical CMM with a repeatability of 2 µm. Our goal is to determine the position of these fiducials with respect to those on the magnet. The temperature of the laboratory fluctuated by 0.3°C during the measurement and the temperature-induced uncertainty was in the region of 1 µm.

2.2. Observation Routine

We sequentially mounted one distance measurement channel, housed in a reference sphere on each of the stations. While at each station, we measured distances to all visible targets on the MBQ and on the wire supports. We also performed interstation observations using a corner cube target of the same diameter as the reference sphere. We used one 12.7 mm and one 38.1 mm diameter corner cube for the whole network. As such, each of these targets was moved from fiducial to fiducial in order to measure the whole network. In total we made 114 observations to solve for 64 unknowns.

3. Results

We performed a 3D Helmert transformation [5] between the coordinates determined by multilateration and those by the CMM using CERN's ChaBa coordinate transformation software. The differences DY and DZ between the coordinates determined by the two methods in the plane perpendicular to the wire axis are shown in Table 1. Fiducials T1 to T9 represent those on the magnet while the ones labelled W1 to W4 represent those on the wire support stages.

The coordinates of the magnet fiducials determined by multilateration and the CMM differed by less than 4 µm while those on the stages differed by less 9 µm. We suspect that the larger variation on the stages was due to their movement as the targets were moved from fiducial to fiducial. This is because of the strong magnetic force the fiducial socket has on the 38.1 mm targets requiring a strong pull which is likely to induce some movement. By performing the 3D transformation with only magnet fiducial coordinates, the difference between CMM and multilateration coordinates was less than 2.5 µm.

Table 1 Results of transformation between FSI multilateration and CMM coordinate measurements in the Y-Z plane perpendicular to the wire.

Fiducial label	DY [µm]	DZ [µm]
T1	-0.5	3.5
T2	0.5	-0.4
T3	-1.2	-1.7
T4	2.1	-2.4
T5	0.8	0.7
T6	-1.2	1.0
T7	-2.6	0.0
T8	-0.7	-1.6
T9	0.5	-1.0
W1	1.5	-4.8
W2	0.3	8.7
W3	0.0	2.6
W4	0.5	-4.6

4. Conclusion

We have developed a portable, self-calibrating solution for fiducialising CLIC components using FSI multilateration.

The results obtained agree closely with those of the Leitz Infinity CMM -- this proves the accuracy of our solution. We expect improved results when each fiducial on the stages is equipped with a separate corner cube retroreflector, removing the requirement to pull targets off the fiducial sockets. Even better results are envisaged with wide acceptance angle n=2 glass retroreflectors [6] that would not need to be moved at all.

We expect that this solution can be extrapolated to larger CLIC components that cannot be fiducialised by the Leitz Infinity.

5. Acknowledgement

This work has been conducted as part of the PACMAN project. Particle Accelerator Components' Metrology and Alignment to the Nanometre scale (PACMAN) research project is supported by a Marie Curie Early European Industrial Doctorates Fellowship of the European Community's Seventh Framework Programme under contract number (PITN-GA-2013-606839-PACMAN).

References

[1] Aicheler M, et al., 2012 A Multi-TeV Linear Collider Based on CLIC Technology *CLIC Conceptual Design Report*, CERN, Geneva
[2] Etalon AG 2016 Absolute Multiline Technology. http:/www.etalon-ag.com/en/products/absolute-multiline-technology/
[3] Kamugasa S W, Gayde J.-C and Mainaud-Durand H 2016 Frequency Scanning Interferometry for CLIC component fiducialisation. 14th International Workshop on Accelerator Alignment (IWAA 2016), European Synchrotron Radiation Facility, ESRF, Grenoble France
[4] Arpaia P et al., 2016 Sensors applications within the research framework of the PACMAN Project on metrology for particle accelerators at CERN. 2016 IEEE Sensors Applications Symposium (SAS). *Proceedings of the IEEE.* 1-6
[5] Ghilani C D and Wolf P R 2012 Elementary surveying: an introduction to geomatics. New Jersey (Prentice Hall) pp. 543
[6] Takatsuji T, Goto M, Osawa S, Yin R and Kurosawa T 1999 Whole-viewing-angle cat's-eye retroreflector as a target of laser trackers. *Measurement Science and Technology,* **10** N87-N90