RECENT DEVELOPMENT OF MICRO-TRIANGULATION FOR MAGNET FIDUCIALISATION*

V. Vlachakis†, CERN, Geneva, Switzerland & ETHZ, Zurich, Switzerland
J.-F. Fuchs, H. Mainaud Durand, CERN, Geneva, Switzerland

Abstract

The micro-triangulation method is proposed as an alternative for magnet fiducialisation. The main objective is to measure horizontal and vertical angles to fiducial points and stretched wires, utilising theodolites equipped with cameras. This study aims to develop various methods, algorithms and software tools to enable the data acquisition and processing. In this paper, we present the first test measurement as an attempt to demonstrate the feasibility of the method and to evaluate the accuracy. The preliminary results are very promising, with accuracy always better than 20 µm for the wire position, and of about 40 µm/m for the wire orientation, compared with a coordinate measuring machine.

INTRODUCTION

High beam energy and high luminosity are key characteristics of particle accelerators and colliders. Collisions at high centre-of-mass energies increase the discovery potential for New Physics. At the same time, high luminosity provides increased event rates even for rare physics processes. High luminosity is ensured by preserving small beam size in the interaction point, and low emittance in the transfer lines. Misalignment of the accelerator components cause unintentional kicks to the beam, which results to the emittance growth. Tighter alignment tolerances aim to reduce the magnitude of the misalignment and therefore, to increase the luminosity of the future accelerators [1, 2].

The alignment process may involve various steps in order to locate an accelerator component in position and orientation. The main goal is to align the functional axis (e.g. Quadrupole magnetic axis) or functional centre (e.g. Beam Position Monitor R/F cavity centre) of a component with respect to another component or to a reference frame.

The first and most important step in the alignment process is the fiducialisation of a component. In most of the cases, the functional axis or centre of a component may become difficult or impossible to be materialised or inaccessible after the assembly. To anticipate this difficulty, the axis, the centre or any other geometrical feature is linked geometrically with the fiducials; accessible, visible targets on the external surface of the component.

The fiducialisation plays a major role in the alignment process. High uncertainty or potential error on the result of the fiducialisation will be propagated and affect the whole alignment process, no matter how precise the next alignment steps are. Moreover, an error in the later steps of the alignment can usually be corrected by the in-situ repetition of a few measurements while an error in fiducialisation might require to dismantle, transport and re-fiducialise the component in a special lab.

At CERN, the standard method for magnet fiducialisation involves two measuring systems: the Coordinate Measuring Machnine (CMM) and the Laser tracker. Recently, a novel method was proposed and evaluated [3, 4]. The new method involves three measuring systems: the CMM, the Wire Positioning Sensor (WPS) and the Laser tracker.

The use of different measuring systems, which means different type of observations, could be considered as a disadvantage of these methods. The stochastic model is difficult to be defined and the sequential transformations between different coordinate systems potentially increase the uncertainty. In addition, the fact that the measurements are not performed in the same time and in the same place can result to higher uncertainties due to environmental influence.

PACMAN – a study on Particle Accelerator Components' Metrology and Alignment to the Nanometre scale – aims to study innovative methods and technologies, and develop portable metrology solutions for the fiducialisation process [5, 6]. The project is divided into four Work Packages. The work package *Metrology and Alignment* covers the following three subjects:

- Prototyping of a non-contact high precision sensor for Leitz Infinity Coordinate Measuring Machine (CMM) [7],
- Validation of an absolute Frequency Scanning Interferometry (FSI) multilateration network [8], and
- Micro-triangulation for high-accuracy short-range measurements of fiducials and wires.

In this paper, we present the micro-triangulation method as an alternative approach for fiducialisation, the main features of the QDaedalus measuring system [10–12], and the developments of the system in the frame of the PACMAN project. Consequently, we describe the first validation test of micro-triangulation for magnet fiducialisation, and we discuss the preliminary results. For this test we used the Type 1 Main Beam Quadrupole [9] of the Compact Linear Collider [13, 14]. The magnetic axis of the quadrupole was determined by the vibrating wire technique [15]. Fiducials and a stretched wire were measured both by the QDaedalus measuring system and by the Leitz Infinity CMM, equipped with the PRECITEC LR Optical Sensor.

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† vasileios.vlachakis@cern.ch

METHODOLOGY

The main objective of this study is to apply micro-triangulation in the fiducialisation process by measuring the fiducials and the stretched wire in a common coordinate system. The fiducial points are mounted on the surface of a magnet while a stretched wire represents the magnetic axis (Fig. 1).

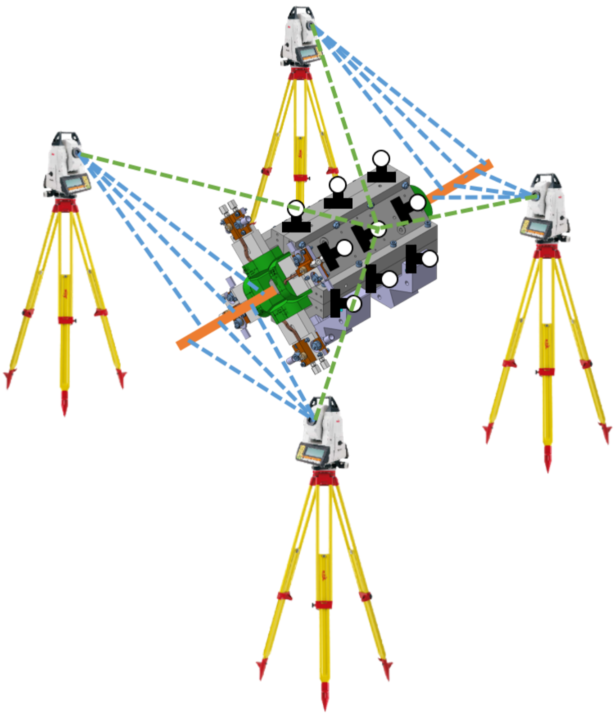

Figure 1: Concept of micro-triangulation for magnet fiducialisation. Four theodolites observe the fiducial points (white circles) and the stretched wire (orange line) constructing a geodetic network.

Although the measurement of the fiducials falls into the standard surveying technique, the measurement of the wire is the interesting and challenging part. The challenge arises due to the fact that the wire is uniform and it is impossible to distinct individual targets on it.

To face this challenge and resolve the problem we developed two algorithms: a wire detection and measurement algorithm, and an algorithm to solve a geodetic network consisting of the observations to the fiducials and the wire.

Micro-triangulation

Triangulation is a well-known method based on horizontal and vertical angle measurements between points (stations and targets). These measurements form a geodetic network with 5 degrees of freedom, i.e. three translations (X, Y, Z), horizontal orientation and scale. The 3D coordinates of the points are estimated by least-squares adjustment by adding the necessary information to constraint the degrees of freedom. The basic characteristic of the triangulation method is that the coordinate system of the network can always be linked to the earth gravity field (local plumb-line).

Micro-triangulation is a specific type of triangulation with two main features: it concerns short-range applications and it employs high accuracy industrial theodolites. These two features combined can lead to coordinates with precision in the level of a few micrometers.

The implementation of various modern technologies in the theodolites makes them very attractive for precise applications. These improvements help to perform fast, automated, high precision angle measurements without the need of an observer.

QDaedalus measuring system

In our study, the technique of automated micro-triangulation is applied by the QDaedalus measuring system [10]. The system is designed and developed primarily for astro-geodetic applications by the Geodesy and Geodynamics Lab, Institute of Geodesy and Photogrammetry, ETH Zurich.

Although the QDaedalus system was developed for astro-geodetic applications, tests have proven that it 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 [11].

QDaedalus consists of both software and hardware add-ons to a robotic total station. The fundamental idea is to replace the eye-piece with a CCD camera in a non-destructive way (Fig. 2). This enables automatic measurements of ac-

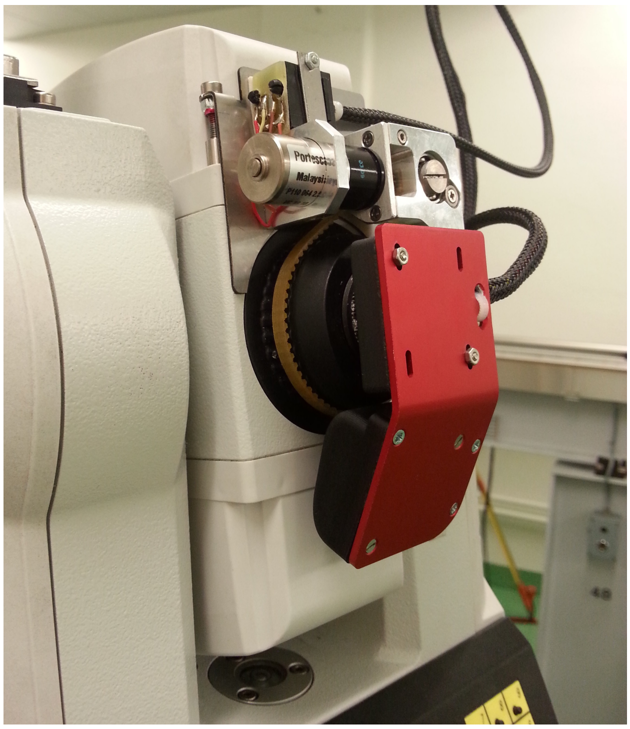

Figure 2: The QDaedalus measuring system on a Leica TDA5005. The CCD camera (in the red cage) reversibly replaces the eye-piece. The motor (above the camera cage) steers the focusing knob.

curate spatial directions to visible objects without using corner-cube targets [12].

The system provides detection algorithms for different type of targets. In our study, we use the *Template least-squares matching* algorithm, to calibrate the camera, and the *Circle matching* algorithm, to measure the spherical fiducial points.

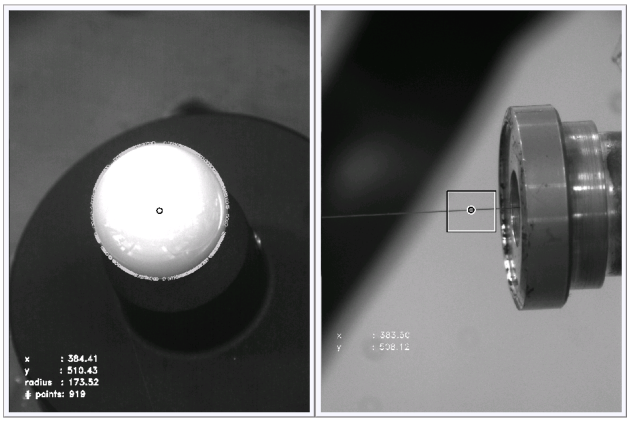

Figure 3: Left: *Circle matching* algorithm (provided with the QDaedalus software) used to measure the spherical fiducials. Right: *Line matching* algorithm (developed in PACMAN project) used to measure the stretched wire.

Developments in PACMAN project

As it is already mentioned, the aim is to measure the horizontal and vertical angles from the theodolites to the fiducials and the stretched wire. For the spherical fiducials we use the *Circle matching* algorithm (Fig. 3, left), provided with the QDaedalus software. For the stretched wire we developed a new algorithm based on computer vision techniques.

The wire detection and measurement algorithm was developed with the *Qt* platform, in *C++*, using image processing tools of the open-source library *openCV*. The algorithm is implemented in the QDaedalus software (Fig. 3, right). The implementation (called *Line matching*) enables us to perform automatic measurements at the same time with the measurements of the fiducials.

Standard commercial surveying/geodetic software can treat micro-triangulation networks of points but not when a different object, like a line, is observed. To tackle this problem, we developed in Matlab a software, based on least-squares analysis, that can solve such integrated networks. The stretched wire is modeled as a straight line. Neither the method nor the developed software restricts the number of lines in the network.

The software input data are designed to be:

- horizontal and vertical angles to the targets and wires (with the uncertainties),
- approximate coordinates of the network,
- the datum constraints, and
- user parameters.

The software output data are:

- for the stations: coordinates, orientations, and 3 systematic errors per instrument,
- for the targets: coordinates,
- for the wires: position and orientation, and
- the uncertainties of the estimated unknown parameters.

The software, which is still under development, can visualise the observations (Fig. 4) and apart from solving a measured network, it can also perform simulations.

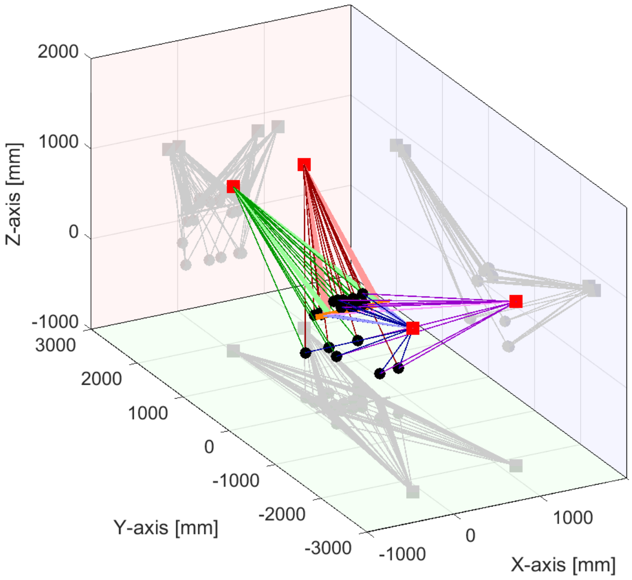

Figure 4: Visualisation of the network. The stations (red squares), the fiducials (black circles), the stretched wire (orange line), and the observations (different colour for each station) are illustrated.

PACMAN TEST BENCH

A test bench was assembled in the metrology lab at CERN in order to perform various first test measurements for the PACMAN project (Fig. 5, 6). Here, we describe only the part that concerns the micro-triangulation measurements.

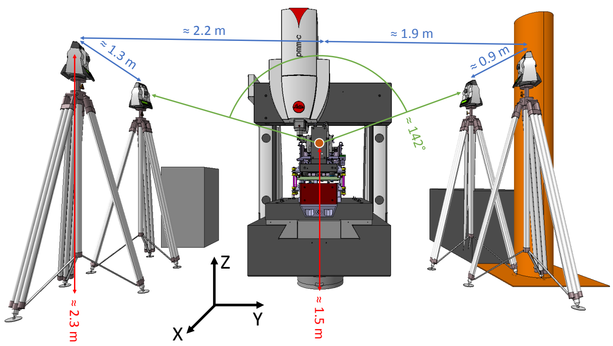

Figure 5: Measurement setup around the PACMAN test bench. The basic dimensions and the coordinate system are given for a better perception (credits: François Nicolas Morel, CERN).

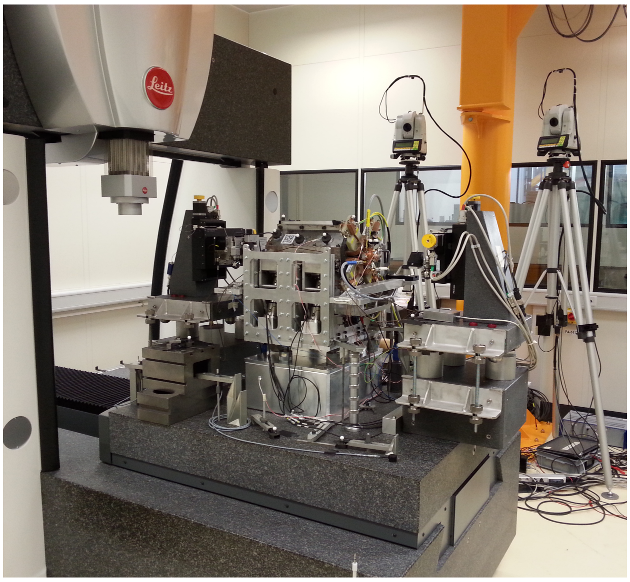

Figure 6: PACMAN test bench on Leitz Infinity CMM in the CERN metrology lab. In the background, two Leica TDA5005 equipped with QDaedalus measuring system.

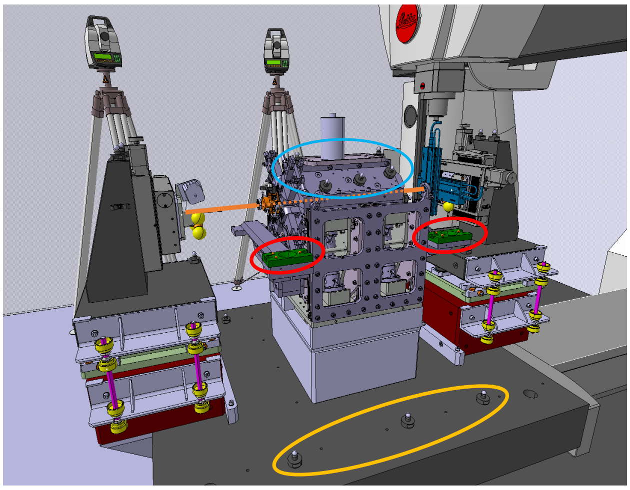

Figure 7: Design of the PACMAN test bench. 6 targets on the CMM table (3 on each side, yellow ellipse), 6 targets on the WPS supports (3 on each plate, red ellipses), 8 targets (fiducials) on the magnet (3 on each side and 2 on top, blue ellipse), and the stretched wire (orange line), (credits: François Nicolas Morel, CERN).

Metrology lab

The metrology lab at CERN is a measuring room classified as CLASS 1, according to VDE/VDI 2627 standard. It operates in a reference temperature of 20 °C and with temperature gradients of 0.2 K/h, 0.4 K/d and 0.1 K/m. The Leitz infinity CMM is installed on three vibration dumpers.

During the PACMAN measurement campaign, the CMM performed a measurement to be used as a reference for comparison with micro-triangulation. The CMM performed tactile measurements to the fiducial points[1] with various styli, depending on the accessibility of the targets, and contactless measurements to the wire with the PRECITEC LR Optical Sensor.

Two points were measured on the wire, one on each side of the magnet. The 3D coordinates of these two points result as a combination of the straight and the angular sensor, which measure the lateral and the vertical position of the wire, respectively.

Instruments

Four Leica TDA5005 were used in this measurement. According to the manufacturer specifications, the angular accuracy of these theodolites is 0.15 mgon ≈ 2.4 rad or 2.4 μm/m (1σ, ISO17123-3), and the reference to the vertical is $<$ 0.1 mgon.

The theodolites were positioned in the metrology lab around the PACMAN test bench (Fig. 5, 6). The Leica AT21 aluminium tripods were fully extended and the instruments had all the same height, about 2.3 m above the floor.

[1] For simplicity we call fiducial points or fiducials all the targets installed on the PACMAN test bench and not only those mounted on the magnet.

The monochrome CCD camera Guppy F-080C, with 1024 × 768 pixels and pixel size of 4.65 μm × 4.65 μm, was used as part of the QDaedalus system. The additional meniscus front lens and the synchronisation box, both provided together with the QDaedalus system, were not used in this test measurement.

Targets

Ceramic spheres were used as fiducial points. The spheres have 1 μm sphericity (Grade 40, ISO3290), and diameters of 12.7 mm (on the magnet and on the CMM granite table) and 8 mm (on the Wire Positioning Sensor support plates). The spheres were attached by magnetic force on aluminium supports which were mounted on the magnets and on the granite table with hot glue. 20 fiducials were measured in total: eight mounted on the magnet, six on the two Wire Positioning Sensor support plates, and six mounted on the CMM granite table (Fig. 7).

The magnetic axis was materialised by a Copper-Beryllium wire. The wire has 125 μm diameter and for this setup the length was about 861 mm. 80 points were measured on the wire (10 points × 4 theodolites × 2 sides of the magnet). The points were well distributed within a length of 100 mm on either side of the magnet (the wire is hidden by the magnet for about 500 mm).

Measurements

The aim of the measurements was the validation of the QDaedalus measuring system against the Leitz Infinity CMM. The measurements lasted for one day and took place on Friday, 29 July 2016 in the metrology lab at CERN. The measurement schedule consists of three parts:

Table 1: QDaedalus measurements precision, given as standard deviation of the coordinates (1σ).

	$X^{(1)}$ [µm]	$Y^{(1)}$ [µm]	$Z^{(1)}$ [µm]	$X^{(2)}$ [µm]	$Y^{(2)}$ [µm]	$Z^{(2)}$ [µm]
Points on the magnet						
M1	2	6	2	2	4	3
M2	1	5	3	3	3	3
M3	1	5	2	3	5	3
M4	–(*)	–(*)	–(*)	–(*)	–(*)	–(*)
M5	–(*)	–(*)	2	–(*)	–(*)	3
M6	1	6	2	2	7	2
M7	1	5	2	2	9	2
M8	1	5	3	2	6	2
Points on the WPS support plates						
P1	3	6	2	5	9	2
P2	4	6	2	6	9	2
P3	3	5	2	5	7	2
P4	2	6	2	4	9	2
P5	2	4	1	5	5	1
P6	2	2	2	5	5	3
Points on the CMM granite table						
T1	3	7	3	10	8	3
T2	5	5	3	12	6	3
T3	6	6	3	9	9	4
T4	4	4	2	9	5	5
T5	4	5	2	6	3	6
T6	5	6	3	9	8	5
Point on the wire						
WP	–(*)	3	2	–(*)	3	1
	[µm/m]	**[µm/m]**	**[µm/m]**	**[µm/m]**	**[µm/m]**	**[µm/m]**
Direction vector of the wire						
WV	–(*)	12	2	–(*)	27	1

* Constraint.

1 Standard deviation of 10 QDaedalus measurements, 1^{st} period: 5:30-7:20.

2 Standard deviation of 7 QDaedalus measurements, 2^{nd} period: 14:50-16:30.

- 1^{st} period: Ten series of micro-triangulation measurements by the QDaedalus system.
- Leitz Infinity tactile measurements to the fiducials and contactless measurements to the stretched wire.
- 2^{nd} period: Seven series of micro-triangulation measurements by the QDaedalus system.

In each of the 17 series, the 20 fiducials and the stretched wire were measured in two circles (left circle - right circle) by the four theodolites (Fig. 4). Each series was completed in about 11 min and each period lasted for about 2 h. The CMM measurement was completed in about 6.5 h.

RESULTS

The preliminary results presented in this paper, attempt to evaluate the wire detection and measurement algorithm as well as to test the novel geodetic network solution which combines points and lines and it is based on least-squares analysis. Both algorithms were developed in the PACMAN project.

Evaluation of precision

The comparison concerns the position of the fiducials, and the position and orientation of the wire in space. The precision of the micro-triangulation is defined as the repeatability of the coordinates of the network points and is expressed as standard deviation (1σ).

Each series of measurements was considered as a different network and it was solved with the least-squares software which is developed in the frame of the PACMAN project. The datum was fixed with 5 coordinates (X, Y, Z of the point M4 and X, Y of the point M5), which equals to the *default of the datum* (minimum constraints). For the preliminary results we did not use any outlier detection algorithm.

For the targets, the vast majority of the standard deviations of the coordinates (90%) was below 8 µm, while 67% was below 5 µm for both periods. The detailed results are shown in Table 1 (left and right for 1^{st} and 2^{nd} period, respectively).

For the wire, the precision of the position (WP) was approximately 3 µm for both periods, while the repeatability of the orientation (WV) showed remarkable differences in the lateral direction (Y axis) between the results of the two periods. As can be seen in Fig. 5, the higher uncertainty in the Y axis results from the obtuse angle (142°) between the stations and the bench.

Table 2: QDaedalus measurements accuracy, given as differences of the coordinates with respect to the CMM results.

	$X^{(0)}$-$X^{(1)}$ [µm]	$Y^{(0)}$-$Y^{(1)}$ [µm]	$Z^{(0)}$-$Z^{(1)}$ [µm]	$X^{(0)}$-$X^{(2)}$ [µm]	$Y^{(0)}$-$Y^{(2)}$ [µm]	$Z^{(0)}$-$Z^{(2)}$ [µm]
Points on the magnet						
M1	7	-20	-9	7	-13	-7
M2	5	-16	-11	4	-15	-9
M3	3	-9	-10	0	-5	-7
M4	2	-6	-19	4	-4	-16
M5	-4	10	-19	-4	4	-17
M6	1	3	-11	3	-2	-14
M7	0	27	-2	0	25	0
M8	0	10	-6	1	11	-7
Points on the WPS support plates						
P1	1	6	8	2	6	7
P2	5	-5	-1	5	-6	-1
P3	1	8	-2	2	7	-3
P4	2	0	5	2	-1	7
P5	1	15	9	2	15	11
P6	0	7	15	1	9	18
Points on the CMM granite table						
T1	-3	-26	16	-8	-17	11
T2	-10	-2	1	-10	2	-4
T3	-7	-17	11	-4	-20	12
T4	2	9	15	1	7	11
T5	0	10	12	-4	7	11
T6	-5	-5	-3	-5	-10	-3
Point on the wire						
WP	–(*)	-17	-15	–(*)	-17	-14
	[µm/m]	**[µm/m]**	**[µm/m]**	**[µm/m]**	**[µm/m]**	**[µm/m]**
Direction vector of the wire						
WV	–(*)	-54	-44	–(*)	-30	-46

* Constraint.

0 CMM measurement: 7:30-14:00.

1 Standard deviation of 10 QDaedalus measurements, 1^{st} period: 5:30-7:20.

2 Standard deviation of 7 QDaedalus measurements, 2^{nd} period: 14:50-16:30.

Evaluation of accuracy

Due to the fact that the two coordinate systems (of the micro-triangulation and of the CMM) are not parallel, we applied a 3D Helmert transformation in order to compare the coordinates.

The average coordinates of ten networks of the 1^{st} period were transformed to the CMM coordinate system. The differences are presented in Table 2 (left side). The same approach was followed for the average coordinates of the seven networks of the 2^{nd} period (Table 2, right side).

For the targets, 88% of the absolute differences of the coordinates was smaller than 15 µm, 72% was less than 10 µm and about 43% was found to have absolute differences less than 5 µm. Higher values appear in the Y axis due to the poor geometry of the network (Fig. 5).

For the wire position (WP), we observe an agreement between the results of the two periods. However, the differences between the micro-triangulation and the CMM measurement is 17 µm in the Y axis (lateral to the wire) and about 15 µm in the Z axis.

For the wire orientation (WV), the two periods are consistent in the vertical component of the vector (within a few µm/m), while a disagreement of about 25 µm/m is observed for the lateral component. The calculated values for both periods indicate a difference of about 40 µm/m compared to the vector measured by the CMM.

CONCLUSION

The standard and the lately proposed methods at CERN for fiducialisation are based on multiple measuring systems which increase the complexity and potentially the uncertainty of the result.

In the frame of the PACMAN project, the micro-triangulation method is adapted to be used for magnet fiducialisation. Only one measuring system is used, consisting of several theodolites, equipped with cameras. The system can perform contactless measurements to the fiducial points and the stretched wire in a common coordinate system.

The advantages of the micro-triangulation method are: the portability, the automation and the efficiency in terms of time and space. The lack of scale, which is necessary to be provided by other means (e.g. laser interferometer), should be considered as a disadvantage of the method.

To adapt the micro-triangulation for magnet fiducialisation, we developed a wire detection and measurement algorithm, and an algorithm to solve a geodetic network consisting of the observations to the fiducials and the wire.

The first test measurement, which took place at CERN, helped to evaluate the feasibility of both the method and the measuring system. Moreover, the preliminary numerical results are quite satisfactory, showing repeatability in the level of 10 µm and accuracy of approximately 20 µm, when compared with a coordinate measuring machine.

New measurements are planned for the near future, specially focusing on better light conditions in the measuring room, and optimal geometry for the geodetic network, in order to fully exploit accuracy of the measuring system.

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