QDaedalus : Augmentation of Total Stations by CCD Sensor for Automated Contactless High-Precision Metrology

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Key words: digital total station; optical target recognition; automated measurements; microtriangulation; image processing, metrology of accelerators.

SUMMARY

QDaedalus is a measurement system developed at the Institute of Geodesy and Photogrammetry at ETH Zurich. It is composed of both, hardware and software developments. The basic idea is to replace the eye-piece of an existing total station by a CCD camera in a non-destructive way in order to measure fully automatically very accurate spatial directions to visible objects without using corner-cube targets as in standard Automatic Target Recognition (ATR). In addition to the CCD camera and the total station, the hardware is composed of a motorized focuser and a small electronic interface for hardware synchronization of several systems.

The dedicated software of QDaedalus is based on a user-friendly graphical interface and controls all sensors including the total station. Furthermore it allows calibrating the system properly before starting the measurement of the targets. These measurements are based on different optical target object recognition and extraction algorithms (OTR), i.e. template least-squares matching, center of mass operator, robust circle and ellipse matching. Thus a fully automatic acquisition of numerous kinds of objects can be carried out. The performance of the system QDaedalus in terms of capability, precision, and automation level will be outlined in a practical example of industrial metrology at the European Organization for Nuclear Research in Geneva (CERN). The experiment focuses on the determination of high-precision 3D-coordinates of accelerating components (1x4x1 meters) of a future linear particle collider. In this application, several QDaedalus systems were set up simultaneously for measuring fully automatically the spatial directions of small ceramic spheres in order to realize a micro-triangulation network.

The results obtained reveal a 3D-accuracy at a level better than 10 microns. Comparisons with a commercial laser tracker and a coordinate measurement machine (CMM) are presented in order to demonstrate the performance of the system.

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1. INTRODUCTION

The determination of high precision 3D coordinates of objects up to 1-2 meters is an important issue in industry and research. In addition, and it is an intersection point of different technologies which are for concurrence. Advances in this field imply not only improvements of profitability but usually a source of new applications and possibilities.

In general, a geometrical state of an object and its kinematic behavior is determined by successive/continuous measurements of a basic set of control points. If we are looking at the space-time discretization, different key aspects should be considered:

- the density of points
- the accuracy and reliability of points
- the physical materialization of points
- the sampling rate

From this point of view, different measurement systems have to be considered with respect to the different key aspects. Nevertheless, it is not sufficient to qualify or disqualify a technology for a defined task. In fact, other very important features have to be taken into account:

- automation degree
- palpate / touchless
- measurement range
- transportability
- easy handling
- price

A summary of different 3D measurement systems used in metrology can be found in Table 1.

In this paper, a fully automated Microtriangulation system based on Total Stations augmented by CCD sensor is presented. The performance and automation level was tested and validated in the context of the precise measurement of accelerator components at the European Organization for Nuclear Research (CERN) in Geneva. Comparisons with other technologies like Laser Tracker and Coordinates Measurement Machine (CMM) are exposed to quantify the measurement quality in the current state of development.

	Coordinates Measurement Machine	Measurement Arm	Laser Tracker	Photogrammetry close-range	Laser Scanner	Microtriangulation classic	Microtriangulation CCD based
Density of points	good	good	good	very high	very high	poor	good
Accuracy	< 1µm/m	10 µm/m	~4 µm/m	~1e-5 x object size	~<1 mm	~25 µm/m	~4 µm/m
Physical materialization	very good	very good	very good	good	poor	good	good
Sampling rate (all object)	Middle	poor	poor	good	very good	very poor	poor
Sampling rate (1 point)	very good	middle	excellent	good	very good	poor	excellent
Automation degree	Very good	poor	very good	good	poor	poor	very good
Palpate / touchless	palpate/touchless	palpate	palpate	touchless	touchless	touchless	touchless
Measurement range	<1-2 m	<5 m	~1-100 m	~1-50 m	~1-100 m	~1-100 m	~1-100 m
Transportability	very poor	good	good	very good	good	good	good
Easy handling	poor	very good	very good	very good	middle	good	good
Price	++++	+	++	+	+++	+	+

Table 1. Comparisons between different metrological systems

2. QDAEDALUS SYSTEM DESCRIPTION

2.1 Hardware

2.1.1 Optical Layout

The concept developed for QDaedalus is based on the replacement of the ocular by the CCD chip, without adding new optical components in between (Bürki 2010). The direct consequence is that the image is not formed in the plane of the reticulum anymore but in the plan of the CCD chip, approximately 5 millimeters further. The displacement of the image in the plan of CCD can be accomplished by the existent focus dispositive of the Total Station for objects up to 13 meters (see Fig. 1).

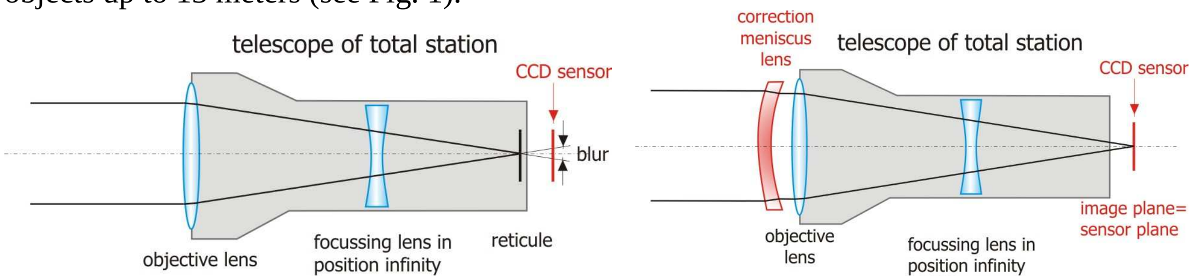

Figure 1. (Left) Removing the eyepiece and mounting a CCD sensor instead evokes optical blur at distances beyond 13 meters. (Right) Mounting a meniscus lens in front of the telescope objective moves the focal plane about 4 mm to the CCD sensor plane thus producing perfectly focused images

For longer distances, the image plane can be translated by adding an additional meniscus lens in front of the telescope. This front lens with a slight diverging effect (focal length = -4 meters) as shown in Fig. 1 moves the focal plane 4 mm towards the image sensor thus producing perfectly focused pictures at infinity.

2.1.2 Adaptation of the CCD Camera

After an extensive search of an appropriate CCD camera, the model Guppy F-080C, a monochrome camera from Allied Vision Technologies (AVT) was chosen. One essential feature for the choice of this camera was the possibility to trigger the shutter by means of external software driven pulses. In combination with a low cost GPS receiver this system enables to control the exposure start and exposure duration precisely. The CCD sensor is equipped with 1024 x 768 pixels with a size of 4.65 by 4.65 microns. The camera is capable to transfer up to 30 full frames per second using a firewire 1394a interface. The housing of the camera without objective lenses measures 48x30x30 mm (see Fig. 2).

As a constraint for the development of the QDaedalus system, no mechanical changes at the Total Station were allowed. Therefore the CCD camera had to be fixed at the telescope instead of the ordinary eyepiece by means of an identical mechanical interface.

Figure 2. (Left) Guppy CCD camera as available on the market. (Right) Transformed CCD camera. The left picture shows the CCD sensor and the mechanical interface for Leica instruments. The right picture shows the camera mounted at the telescope of a TCA 1800. This adapted flat layout allows to measure even in zenith direction

The optical system gives a resolution of approximately 4 arcseconds/pixel. Assuming that object extraction is as precise as 1/10 pixel or better, the angular accuracy measurements of the best Total Stations on the markets (0.5 arcsecond = 1.5 cc) can be completely exploited.

2.1.3 Focusing Layout

Optical target recognition requires sharp images which must be set for all targets situated at different ranges up to the hyperfocal distance of the optical system. Focusing needs to be controlled remotely in order to significantly increase the level of automation of OTR.
Besides the possibility to store the focus position of targets in order to measure automatically different objects, it is possible to start an auto-focus process at any time. This system was developed, in 2009, at the Technical University of Dresden (Knoblach 2009).
Similar to the camera, the focus layout can be mounted without modification of the Total Station. The principle of the motorization of the focus' ring is simple. A tooth belt is activated by an Escap P110 step motor associated with a conic gearwheel. All components are mounted on a base plate which can be easily screwed on the existing housing cover. The motor is

piloted by a Trinamic TMC-110-42-485 steering electronics and linked to the computer by an USB interface. The full range of the focus can be traveled in approximately 3 seconds.

2.2 Software

The software associed with the system QDaedalus is developed in c++ on the open source development platform Qt[1]. The management of the data is based on the database engine SQLite[2] which permits high flexibility in the storage with advanced functionalities for statements. The image processing algorithms are based on the open-source library, OpenCV[3], which gives an easy access to powerful computer vision standard processes. The hardware components are managed in parallel using multithreading functionalities of Qt. Basically, the measurement of targets can be are carried out by the following steps:

1. Create or open a Project (database file)
2. Connect the Total Station, the CCD Camera and the Focuser Motor.
3. Calibrate the CCD Camera by choosing a fixed target
4. Define a New Station
5. Define New Targets (by Learning or Automatic Mode). Every parameter can be defined for each target individually.
6. Carry out the series of New Observations. The number of repetitions, the telescope's face and the ordering of the targets which have to be carried out can be defined.
7. Control the measurement process using real-time statistical values and the actual view augmented by graphical indicators incoming from the matching algorithms.
8. Export the Raw Data or Reduced Observations (robust mean) in text file format adapted to adjustment softwares (Trinet+[4], LGC[5])

2.3 Optical Target Recognition Algorithms

Form the huge spectrum of existing image processing algorithms, four different algorithms of optical target recognition and measurement are yet implemented in QDaedalus:

1. Center of mass.
2. Template least-squares matching.
3. Circle matching.
4. Ellipse matching

In a general way, computer vision processing execute following basics operations:

1. Image acquisition.
2. Pre-processing (resampling, denoising,…).
3. Feature extraction (lines, circles, regions,…).
4. Segmentation.

[1] Qt is an open source development platform for c++. http://qt.nokia.com/products/
[2] SQLite is an open source database engine based on SQL. http://www.sqlite.org/
[3] OpenCV is an open source library for computer vision. http://sourceforge.net/projects/opencvlibrary/
[4] Trinet+ is a 3D network adjustment software developed at the HEIG-VD in Yverdon-les Bains, Switzerland.
[5] LGC is a 3D network adjustment software developed at CERN in Geneva, Switzerland.

5. High-level processing (compute center, size,...).

In this paper, only the steps 3 to 5 are presented.

2.3.1 Center of Mass

The center of mass algorithm (see Fig. 3) consists of extracting regions in the image and determines their position by using a center of mass operator. The algorithm implemented in QDaedalus can be resumed as follows:

- Extraction of pixels belonging to objects by simple thresholding. The threshold can be fixed in two ways:
  - manually.
  - as the mean of all pixels + 3x standard deviation.
- Determination of regions by OpenCV Flood Fill neighborhood operator.
- Computation of the center of mass of all regions with an area > 4 pixels.
- The center of mass of the most centered region with respect to the principal point is returned.

This algorithm gives very accurate and robust results for active objects like diodes, lamps or over exposed retro-reflective targets. Due to its simplicity, it is also appropriate for real-time tracking applications.
The disadvantage is that it can be scarcely used for passive objects.

2.3.2 Template Least-Squares Matching

Template Least-Squares Matching (see Fig. 3) is one of the most accurate sub-pixel template matching technique. It is largely used in photogrammetry and remote sensing where predefined templates are known. The idea is to match the gray value of a given template on an image as good as possible, in sense of least-squares, authorizing some radiometric and geometric transformation of the template (Grün 1996). The algorithm implemented in QDaedalus can be resumed as follows:

- OpenCV normalized square difference cross-correlation template matching for the estimation of approximate coordinates of the center of the template.
- Least-squares template matching:
  - 1 radiometric offset.
  - 2 translations (x,y).
  - Bilinear resampling.
- The result of least-squares matching is accepted if the empirical standard deviation of the unknown translations are < 0.5 pixels.

For our application, the principal advantage of this algorithm is the high accuracy and repeatability matching of any predefined templates. The templates can be defined manually on the field for any objects. This method is used for the measurements during the calibration of the CCD camera.

The principal disadvantage occurs for absolute determinations of object positions. In fact, if the template is not perfectly centered, all upcoming measurements will be affected by an undetectable systematic error. Moreover, in this configuration, the algorithm does not work for predefined templates observed from different points of view.

2.3.3 Circle Matching

This algorithm was developed in order to measure precisely the center of spheres from different point of view, mainly for micro-triangulation applications (see Fig. 4). As usual, the computer vision literature propose different algorithm to perform this non-trivial task. Algorithms are based on the circular Hough transformation or on contour points detection based on radial profiles.

In our application, the estimation of the center of the circles with sub-pixel accuracy is mandatory; moreover the algorithm must operate even in the case where the sphere is partially occluded and randomly textured. In QDaedalus, the algorithm combines the extraction of contour and robust circle fitting:

- Extraction of edges by the OpenCV Canny edge extraction operator.
- Formation of contours from the edges detected by Canny with neighborhood properties.
- Extraction of line segments with OpenCV Hough lines transformation operator.
- For each contour: delete pixels belonging to a segment extracted by the Hough operator.
- For each contour: compute a robust circle fit according to (Pratt 1987).
- a circle is accepted if :
  - # points > pre-defined min # points.
  - pre-def. min radius < radius < pre-def. max radius.
  - # points used > 50 % # points of current contour.
- The center of the most centered circle which is not rejected is returned.

The principal application of this algorithm is certainly for measuring sphere in very precise industrial metrology networks as used at CERN. In fact, high precise spheres which represent very good mechanical benchmarks for discretizing objects can be easily measured from any points of view. Moreover, the algorithm is able to measure spheres partially occluded.

2.3.4 Ellipse Matching

The ellipse matching algorithm is very useful for measuring circular or elliptical features (in object space) which are transformed in ellipses after their projection in the image plane (see Fig. 4). The processing can be resumed as following:

- Extraction of pixels belonging to objects by simple thresholding. The threshold can be fixed in two ways:
  - manually.
  - as the mean of all pixels + 3x standard deviation.
- Determination of regions by OpenCV Flood Fill neighborhood operator.

- Extraction of edges by the OpenCV Canny edge extraction operator of the most centered region.
- Formation of contours from the edges detected by Canny with neighbourhood properties.
- For each contour: compute a robust ellipse fit according to (Fitzgibbon 1995).
- The ellipse is accepted if :
  - # points > pre-defined min # points.
  - pre-def. min radius < radius < pre-def. max radius.
  - # points used > 50 % # points of current contour.

This algorithm can be very useful for the precise determination of circular photogrammetric targets or for the measurements of holes machined directly on the objet. A further possibility is the direct measurement of the tilt of the target given by the direction of the principal axis of the ellipse. Finally, like the circle matching, the algorithm is able to measure ellipses which are partially occluded.

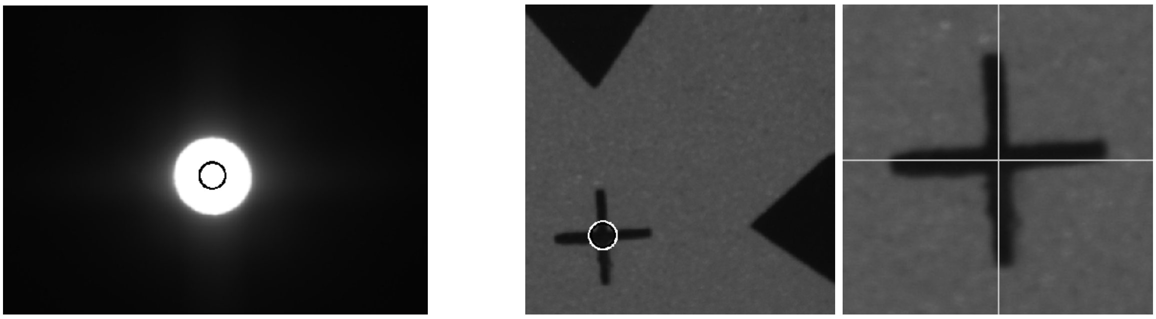

Figure 3. (Left) Example of a lamp measured by QDaedalus with center of mass. (Right) Example of a point measured by QDaedalus with template least square matching algorithm.

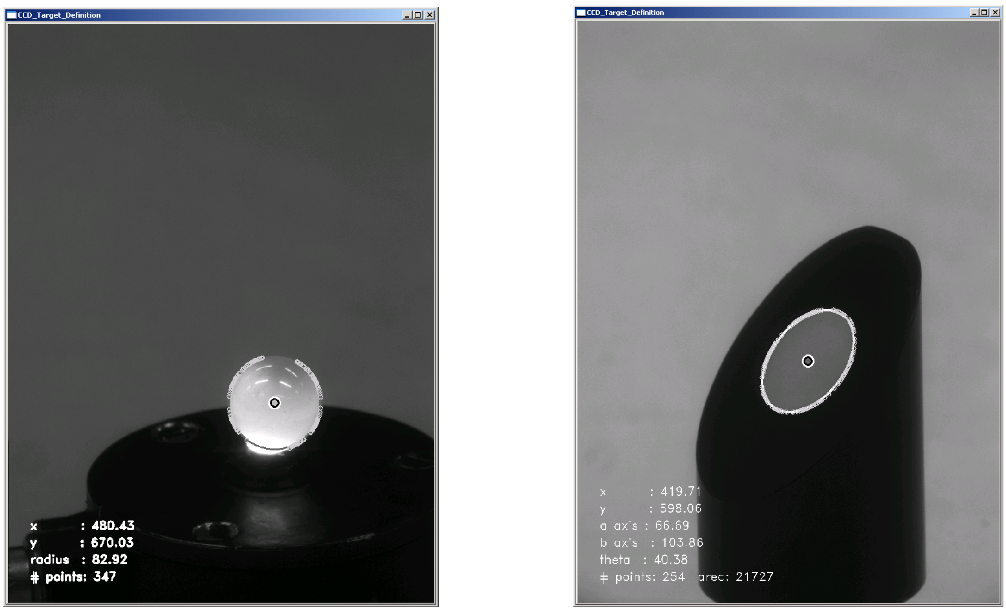

Figure 4. (Left) Example of an illuminated ceramic sphere measured with the circle matching algorithm. (Right) Example of a

photogrammetric circular target measured from the side with the ellipse matching algorithm.

3. PRACTICAL EXPERIMENT WITH QDaedalus

3.1 Introduction

High precision metrology is a very important and decisive task for the alignment of particle accelerators. In fact, reference axes of every accelerator component have to be aligned, with respect to theoretical axes with extremely high precision. This is crucial for maximizing the luminosity capability (ability to produce a lot of collisions) of the accelerator. Usually the alignment is realized in several steps using different measurement techniques and different reference systems. One step is named fiducialisation. It consists of determining the positions of accessible benchmarks with respect to the reference axes. This is an essential step because the references axes are no longer accessible during the assembly of the final alignment of the accelerator.

In this paper, we are investigating the fiducialisation of components of the Compact Linear Collider (CLIC). This is a project under studies at CERN which is a 3 TeV (tera electron volts) electron-positron linear accelerator of ~50 km in length composed of ~20’000 elements of 2 meters which have to be aligned with respect to a straight line with a precision of 10 microns over 200 meters sliding window (Schulte 2009). Currently, at CERN, several techniques are under studies and tested for this purpose:

- Laser Tracker (Leica AT401)
- Coordinate Measurement Machines (Olivetti)
- Short Measurement Arm (Romer)
- Automatic Microtriangulation with QDaedalus

Two CLIC test girders of 2 meters, half of a module, are equipped with 2 types of benchmarks (see Fig. 5):

1. 9 support for 1.5’’ corner cube reflectors CCR for the Leica AT401 and short measurement arm
2. 9 fixed and illuminated spheres[6] of 8 mm diameter for the Microtriangulation with QDaedalus and short measurement arm

Both types of fiducials are measured (separately for both girders) with the CMM and the Measurement Arm with a precision of 6 microns MPE[7] and respectively 10 microns. In this paper, only the results with respect to the CMM are discussed. In contrary the fiducials of both girders, determined by the AT401 and QDaedalus, are carried out in a single reference system (1 per technique). The reference axes of the modules are represented by 2 points (per girder) and are only measured with the CMM, see Fig. 6.
From this point of view, we are able to make 2 types of comparisons. Firstly, it is possible to compare, separately for each girder, the positions of the benchmarks measured with

[6] The ceramic spheres illuminated with power diodes were developed at CERN in the section survey.
[7] Maximum Permissible Error, ISO 10360-2

QDaedalus and the CMM, and the positions of the benchmarks measured with the AT401 and the CMM. This was done by analyzing the residuals of 3D Helmert transformations between the set of coordinates (Griffet 2012).
Secondly, we are also able to control the alignment of the mechanical axes with both systems independently. This can be done if we determine indirectly (with 3D Helmert transformations of the CMM measurements in the other systems) the coordinates of the axes points in the coordinate systems of the AT401 and QDaedalus respectively (Griffet 2012).

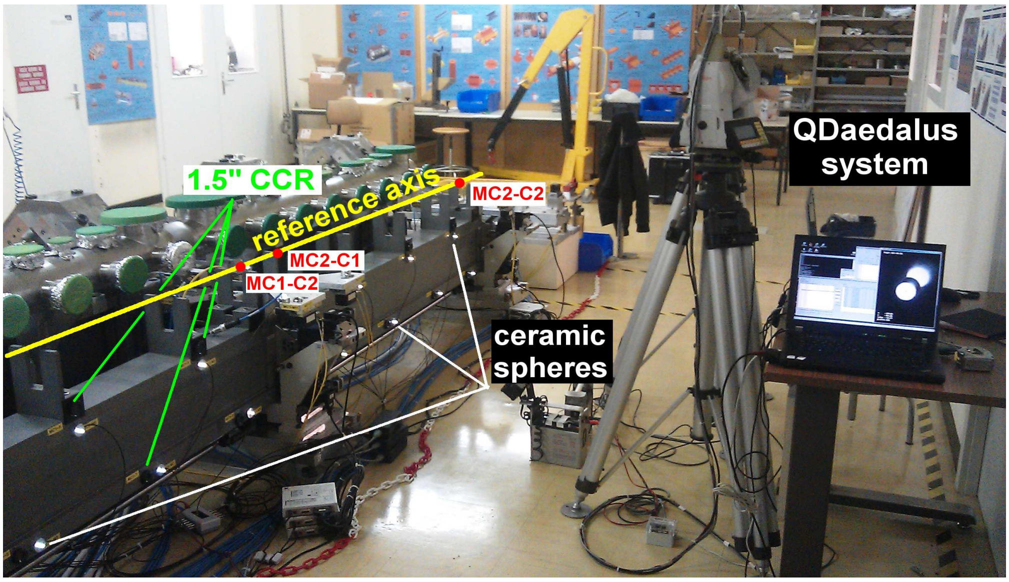

Figure 5. Photography of a part of the modules and the fiducials and one QDaedalus system installed at CERN in Geneva.

3.2 Measurements

3.2.1 Laser Tracker Leica AT401

The measurements were carried out at three different stations. Traditional series in both positions of the telescope were introduced in the 3D adjustment software LGC (internal development at CERN). After adjustment, the empirical standard deviations of the observations are:

- 0.9 cc, horizontal direction
- 1.2 cc, zenithal angles
- 2.5 microns, 3D distances

In Table 2 we can find the empirical standard deviation of the adjusted coordinates (sX, sY, sZ) and the residuals of a 3D Helmert transformation with the coordinates measured with the CMM (dX, dY, dZ, d3D) (Griffet 2012).

	sX [microns]	sY [microns]	sZ [microns]	dX [microns]	dY [microns]	dZ [microns]	d3D [microns]
MC1-3	0	0	0	-1	-2	2	3
MC1-4	4	4	3	-3	-2	2	4

MC1-5	3	3	3	5	3	1	6
MC1-6	3	3	3	3	0	-4	5
MC1-7	3	3	3	-5	1	-7	9
MC1-9	0	4	4	0	-1	6	6
MC2-3	5	4	3	3	9	-5	10
MC2-4	6	3	3	-1	7	8	10
MC2-5	6	3	4	-4	1	-3	5
MC2-6	7	4	3	2	-4	1	5
MC2-7	8	4	3	1	-6	-4	7
MC2-9	9	5	4	0	-6	2	7

Table 2. Empirical standard deviation and differences with respect to the CMM of the points measured with the AT401.

We can see that the performances of the AT401 are very good. The empirical standard deviation of the adjusted coordinates as well the differences with respect to the CMM are mostly below 10 microns.

3.2.2 Microtriangulation QDaedalus

The systems were mounted on two Leica TDA 5005. The measurements were carried fully automatically with the target definition process based on the approximate coordinates of the illuminated high precise ceramic spheres. The algorithm of circle matching was used in order to determine the center of the spheres. The observations were carried out from three different stations, see Fig 6. Traditional series in both positions of the telescope were introduced in the 3D adjustment software Trinet+ (Guillaume 2008). The scale of the network is fixed by introducing a distance measured with the CMM. After adjustment, the empirical standard deviations of the observations are:

- 1.5 cc, horizontal direction
- 1.5 cc, zenithal angles

In Table 3 we can find the empirical standard deviation of the adjusted coordinates (sX, sY, sZ) and the residuals of a 3D Helmert transformation with the coordinates measured with the CMM (dX, dY, dZ, d3D) (Griffet 2012).

	sX [microns]	**sY** [microns]	**sZ** [microns]	**dX** [microns]	**dY** [microns]	**dZ** [microns]	**d3D** [microns]
MC1-M3	5	6	9	-3	-2	1	4
MC1-M4	5	4	7	8	-6	7	12
MC1-M5	4	3	6	1	-5	-10	11
MC1-M6	4	4	5	-11	9	-5	15
MC1-M7	4	5	4	2	7	4	8
MC1-M8	4	6	3	3	-3	3	5
MC2-M3	3	5	4	1	8	2	9
MC2-M4	3	4	4	5	16	0	17
MC2-M5	4	3	6	0	8	-7	11
MC2-M6	4	3	5	-5	-2	4	7
MC2-M7	5	5	8	-8	-8	-4	12
MC2-M9	6	11	10	7	-23	6	24

Table 3. Empirical standard deviation and differences with respect to the CMM of the points measured with the system QDaedalus.

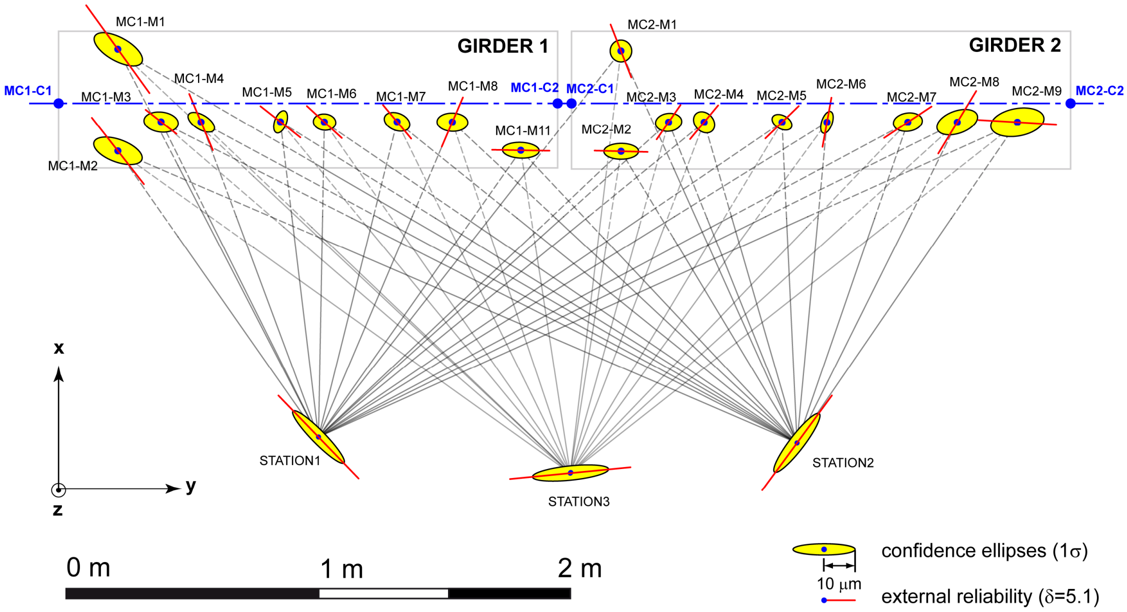

Figure 6. Microtriangulation Network measured with QDaedalus with the confidence ellipses and the vector of external reliability. The datum was fixed by minimizing the trace of the coordinates of all points on the modules.

The empirical standard deviations of the observations are consistent with the nominal values of the constructor which is very encouraging. This shows that the materialization as well as the image processing does not degrade the nominal precision of the Total Station given by the constructor. The empirical standard deviations of the coordinates are mostly under 10 microns. Of course, a better geometry of the network and additional stations will directly improve the precision without increasing the acquisition time (only if additional systems are installed). Concerning the comparisons with the CMM, the residuals on the coordinates are mostly below under 10 microns but larger than what we can find with the AT401. This can be partly explained by the fact that very accurate distances are measured with the AT401 and only horizontal directions and zenith angles are measured with QDaedalus.

3.2.3 Control of the Alignment of the Mechanical Axes

The control of the aligment is an indirect comparison of the AT401 and QDaedalus. The misalignement is simply computed by analysing the residuals of a the least-squares best fit line (3D) passing through the axes points MC1-C1, MC1-C2, MC2-C1, MC2-C2. Theoretically, the misalignement determined with both systems should be the same. In Fig.8, we can see that the differences are under 10 microns in both X and Z components expected for the Z component of MC2-C1 where the difference is 20 microns.

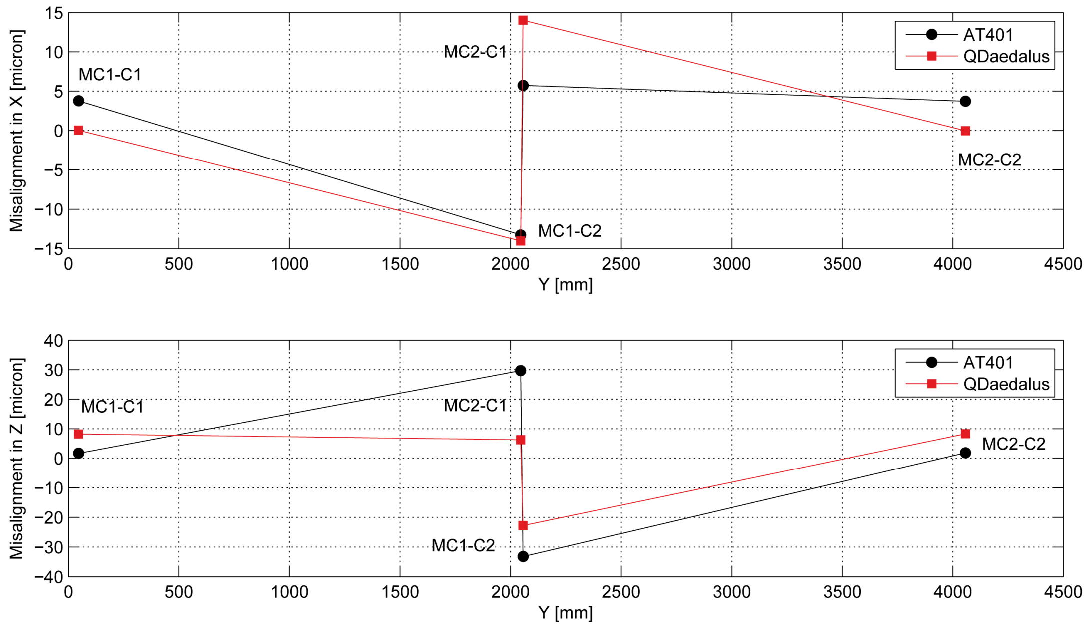

Figure 7. Misalignments in X and Z measured with the AT401 and QDaedalus .

4. CONCLUSION

We are investigating the automated micrometric determination of 3D coordinates by Microtriangulation for industrial metrology applications. In the first part, the system QDaedalus is presented. The specific hardware developments as exposed show that a non-destructive update of common Total Stations can be realized. Then, the software components as well as the different Optical Target Recognition (OTR) algorithms are outlined. Finally, a practical example in the field of accelerator alignment demonstrates the high precision and the high automation performances of the system QDaedalus.

Comparisons with a Coordinate Measurement Machine (CMM) and a Leica AT401 laser tracker show that the nominal accuracy of the angles measured with the Total Station given by the constructor can be fully exploited at very short distances (1-4 meters). The precision of benchmarks measured with QDaedalus can be well predicted and are completely depending on the configuration of the Microtriangulation network. In our example, we obtain precision better than 10 microns for an object of 1x4x1 meters even in suboptimal network geometry, room temperature stability and disturbing human activities in the surrounding.

This demonstrates that it is possible to envisage the installation of several QDaedalus systems in a temperature stabilized metrology room for remote touchless measurements of objects with high precision.

In the future, the synchronization of the image acquisition of multiple QDaedalus systems observing an object will be investigated in order to make possible real-time high precise touchless dynamic measurements in 3D with a high acquisition rate (30 Hz or more).

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BIOGRAPHICAL NOTES

Sébastien Guillaume is currently PhD student in the Institute for Geodesy and Photogrammetry, ETH Zurich, and at CERN in Geneva. His current thesis is focused on feasibility studies in the determination of highly precise underground equipotential profiles of the gravity field for the alignment of the future linear accelerator CLIC (Compact Linear Collider). His diploma thesis was concerning the development of a GNSS signal processing algorithm which is able to detect rapid and small movement with a single L1 GNSS receiver. In parallel, he is active in the development of astrogeodetic and video-based Total Station instrumentations and software. He is also the main developer of the 3D network adjustment software Trinet+.

Dr. Beat Bürki is senior scientist at the Institute of Geodesy and Photogrammetry at ETH Zurich. His researches are focused on the development of astrogeodetic instruments and geodetic systems for the determination of water vapor in the atmosphere (radiometer and solar spectrometer). Since 30 years, he is also a permanent lecturer at ETH Zürich for various courses in Geodesy. He is member of the Swiss Geodetic Commission (SGC) and expert in the Swiss Federal Commission for Geometers.

Sylvain Griffet is a fellow at CERN, Switzerland. He holds a diploma in surveying engineering from the ESGT of Le Mans (France). He is a specialist of monitoring of large structures. His research expertise covers fiducialisation, metrology and micrometric alignment of accelerators.

Dr. Hélène Mainaud Durand is responsible for the Micrometric Technology and Instrumentation unit in the Large Scale Metrology section at CERN, in Switzerland. She holds a diploma in surveying engineering from the INSA Strasbourg and a PhD in metrology from the Université Louis Pasteur (ULP) in Strasbourg (France). Her research expertise covers accelerator alignment, micrometric instrumentation calibration, Hydrostatic Leveling Systems (HLS) and Wire Positioning Systems (WPS).

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