

Computed tomography as a promising solution for industrial quality control and inspection of castings

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ABSTRACT

Recently X-ray Computed Tomography (CT) has successfully entered the field of industrial quality control, with interesting applications also for metal casting industry, including non-destructive testing and dimensional metrology. In particular, CT benefits of several advantages with respect to traditional dimensional measuring systems, as for example: simultaneous dimensional quality control and material quality control, non-destructive inspection of internal as well as external geometries, and reconstruction of complete and high-density point-clouds in relatively short time.

Due to these advantages, CT is increasingly recognised as a very promising non-contact measuring technique and, therefore, several manufacturers and research centres are now investing in the further development of metrological CT systems and in widening their application in industry.

This paper investigates accuracy and traceability of dimensional measurements carried out by state-of-the-art industrial CT systems, by examining selected results obtained from the “CT Audit” project, which is the first international interlaboratory comparison of CT systems for dimensional metrology. The project was organized by the Laboratory of Industrial and Geometrical Metrology, University of Padova, Italy, and was carried out in the period from September 2009 to June 2011, involving 15 CT systems, from research institutions and companies working actively on industrial CT metrology in Europe, America and Asia. The project was coordinated by Dr. Simone Carmignato.

KEYWORDS

Computed Tomography, Non-destructive testing, Dimensional Metrology, Quality control in metal casting, Accuracy, International intercomparison.

RIASSUNTO

I campi di applicazione delle tecniche di Tomografia Computerizzata a raggi X (*Computed Tomography, CT*) si sono estesi notevolmente negli anni recenti, grazie al miglioramento delle prestazioni e all'utilizzo industriale dei sistemi CT. Oggi i sistemi CT possono essere utilizzati con successo non solo per il controllo non distruttivo di difetti interni, ma anche per il controllo dimensionale e le misure 3D di oggetti di forma qualsiasi, inclusi prodotti metallici di fonderia. I vantaggi principali delle tecniche CT rispetto ad alle tecniche di misura 3D più tradizionali (come i sistemi ottici o a contatto) sono: (i) possibilità di effettuare simultaneamente verifiche dimensionali e controllo del materiale; (ii) controllo non distruttivo di geometrie interne ed esterne, incluse le superfici di pezzi assemblati e prodotti multi-materiale; (iii) ricostruzione di modelli virtuali 3D completi e dettagliati in un tempo relativamente ridotto.

Questo articolo pone l'attenzione sugli aspetti di accuratezza e riferibilità delle misure 3D ottenute da sistemi CT allo stato dell'arte. Nell'articolo in particolare sono esaminati alcuni dei risultati ottenuti del progetto “CT Audit”, ovvero il primo confronto internazionale di sistemi CT impiegati per il controllo dimensionale industriale. Il progetto ha coinvolto 15 partner di ricerca e industriali di diverse nazionalità, in Europa, America ed Asia, ed è stato coordinato dal dott. Simone Carmignato del Laboratorio di Metrologia Geometrica ed Industriale dell'Università di Padova.

INTRODUCTION

X-ray Computed Tomography (CT), developed in the late 1970's as a medical imaging technique, is used today also in several industrial applications, including quality control for the metal casting industry [1]. Figures 1 and 2 show applications of CT in dimensional metrology and non-destructive testing of parts produced by die-casting. In particular, Fig. 1 shows the results of dimensional measurements obtained from CT scanning of a casting and comparison with nominal CAD model, while Fig. 2 illustrates the application of CT scanning to porosity analysis in casting.

CT benefits of several advantages with respect to traditional dimensional measuring systems, as for example: simultaneous dimensional quality control and material quality control, non-destructive inspection of internal as well as external geometries, and reconstruction of complete and high-density point-clouds in relatively short time. Due to these advantages, CT is increasingly recognised as a very promising non-contact measuring technique and, therefore, several manufacturers and research centres are now investing in the further development

of metrological CT systems and in widening their application in industry [1-6]. For example, current development trends are in the direction of enhanced measurement resolution and reduced measuring time (including scanning, reconstruction and analysis time). These trends aim to obtain accurate and fast quality control by CT scanning.

A basic CT scanner consists of an x-ray emitting source, a moving system, a detector and electronic and computational devices for data acquisition and elaboration. The principle of tomography is straightforward: radiographic images of the part to be inspected are acquired from different angles; then, elaborating together all the acquired images, a virtual slice through the part is reconstructed [7]. When different consecutive slices are computed, a 3D visualization is obtained. In industrial CT systems, contrary to most medical systems, the part to be inspected is typically rotated on a rotary table, while x-ray source and detector remains stationary. Depending on whether a line or an area detector is used, CT systems are capable of measuring 2D or 3D geometry with one revolution of the part. The first case is referred as 2D CT systems (Fig. 3-a), while the second is called 3D CT systems (Fig. 3-b).

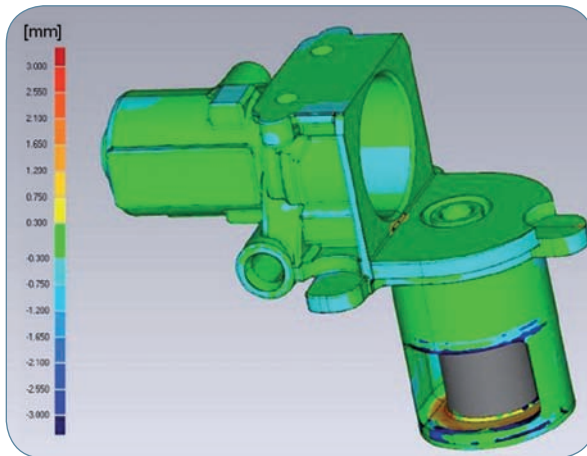


Fig. 1: CT measurement of a casting. The colour map represents the deviations of measured CT data from nominal CAD model, according to the colour scale on the right, in mm. Source: Twin Cities Die Casting and NSI Inc.

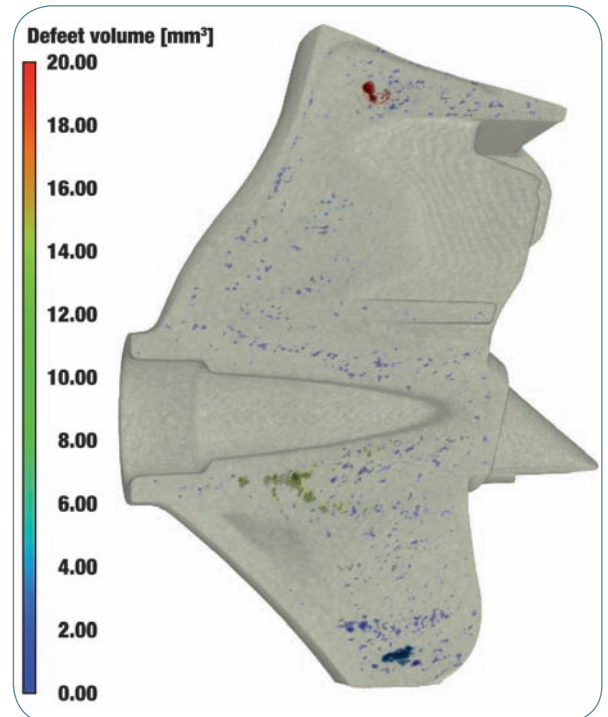


Fig. 2: Porosity analysis from CT data of a casting. Different volumes of voids are represented with different colours, according to the scale on the right, in mm³. Source: Jesse Garant & Associates.

Many different industrial CT systems are available on the market [8]: from huge scanners with linear accelerators that can penetrate hundreds of millimetres of steel and handling objects weighing several tons, to systems for inspection of small parts, with microfocus x-ray tubes that can yield spatial resolutions better than 1 μm (size of volumetric pixel, called voxel). Typical industrial applications are non-destructive analysis of faults (like cracks and flaws) and inspection of interior surfaces or parting surfaces of assembled parts. Since few years ago, the field of application of CT in industry is expanding into coordinate metrology [9]. For this application, CT data are processed to extract the coordinates of the points on the surface of the measured part. The measurement process chain includes the following fundamental steps:

1. The part to be inspected is scanned on the CT system;
2. Reconstructed CT images (grey value images) are converted by a threshold process into surface data (point cloud or triangulated surface data);
3. Optional reduction and filtering of surface data;
4. Analysis of surface data using metrological software for direct dimensional measurements on surface points or comparison to nominal CAD model (see example in Fig. 1).

As a result, CT scanners may be used as Coordinate Measuring Systems (CMS), performing dimensional and geometrical measurements. Recently, new CT systems have been developed specifically for metrological applications, to be used as independent measuring devices [5, 6], or integrated on multisensor Coordinate Measuring Machines (CMM) [7]. In any case, the advantage respect to traditional contact-probing or optical CMS is that CT systems can acquire geometrical data for both interior and exterior surfaces, without accessibility restrictions.

However, CT is currently affected by a number of drawbacks that limits its applicability in industrial metrology. In particular, the measurements accuracy of CT is not well documented in literature [1]. Also, due to difficulties in evaluating measurement uncertainty and in determining metrological performances of CT systems, CT measurements are still lacking of traceability [8]. In fact, the uncertainty of CT dimensional measurements is

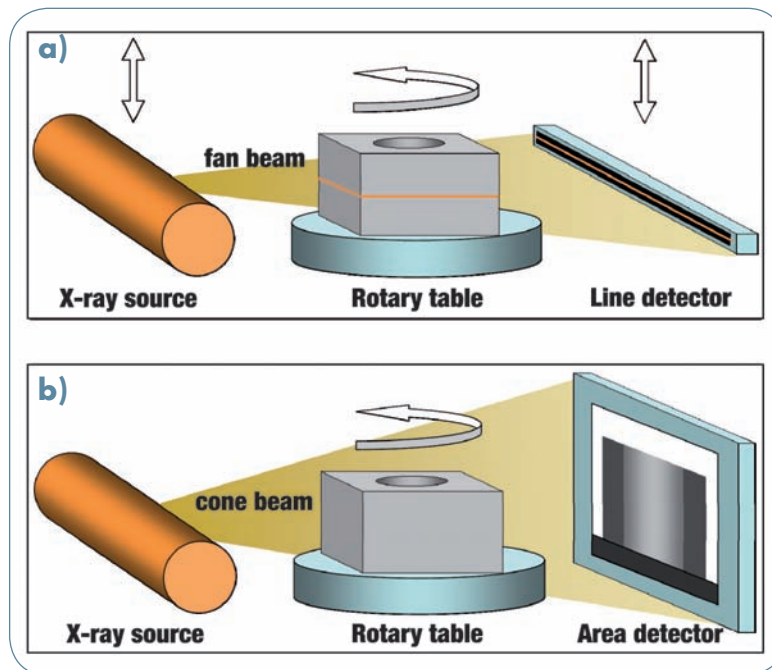


Fig. 3: Schematic representation of industrial CT systems: (a) 2D CT using line detector, and (b) 3D CT with flat panel detector.

influenced by many different and complex error sources so that some uncertainty components can hardly be thoroughly quantified. In addition to error sources that are relevant also with other dimensional measuring systems, such as temperature effects and geometrical deviations of mechanical axes, further errors take place in CT.

Important deviations result for example from the discrete sampling of CT projections, from the finite size of the x-ray tube spot, from the detector characteristics, from the relative distances of source, part and detector, from geometry, material and roughness of the part, from spectrum dependent x-ray absorption within the part (beam hardening), and from image processing of CT data. Moreover, internationally standardized procedures and guidelines dealing with metrological performance verification of CT systems and errors quantification are not available yet. Only draft international or national guidelines are available at present [1]. This lack of accepted procedures limits the comparability to other CT systems and coordinate measuring systems, and is one of the main reasons for scarce consideration of CT as a valid metrological technique in industry [10].

This paper reports the results of an extensive experimental investigation, examining the international state of the art in industrial CT metrology, with focus on accuracy and traceability issues. In particular, the paper examines selected results obtained from the "CT Audit" project, which is the first international interlaboratory comparison of CT systems for dimensional metrology.

“CT AUDIT” INTERNATIONAL COMPARISON

An interlaboratory comparison is a valid means to establish the effectiveness and comparability of measurement methods, and to validate uncertainty claims [11]. For this reason, the University of Padova organized the first international comparison of CT systems for dimensional metrology. This project, called “*CT Audit*”, involved important institutions and companies in Europe, America and Asia, including national metrology institutes, CT systems manufacturers, research institutes, and industrial users [12]. A total of 15 CT systems took part to the intercomparison. The project led to important and interesting results; some of them are going to be presented in this paper.

Motivations

The main objectives and benefits of the *CT Audit* project are to deepen the knowledge on CT dimensional metrology and to spread information on available reference geometrical standards and procedures for metrological verification of CT systems.

The Participants gain many benefits from the *CT Audit* Project. First of all they receive calibrated geometrical standards and procedures for testing their CT Systems. They have the possibility to evaluate their measurement’s results by comparing them to reference calibrated values and to results of other laboratories. Moreover they can validate their measurement and uncertainty evaluation methods. Finally, all Participants are now establishing an international network of laboratories using CT Systems for dimensional metrology; this network

can be the basis for promoting further international initiatives in the field of industrial CT.

Participants and Circulation

The international comparison involves 15 companies and laboratories from different Countries around the world, with a total of 15 CT systems. Names of participating organisations are listed in alphabetical order, for general information only, in Table 1. The confidentiality of results is ensured by associating an anonymous identification code to each Participant. Only the specific Participant and the Coordinator know the association with the identification code. Besides the Participants listed in Table 1, the following additional companies measured with their CT systems the calibrated samples during the circulation, but did not complete the entire reporting process and therefore their results are not included in this report:

- ▶ Varian Medical Systems Security & Inspection Products Div. (USA);
- ▶ Zebicon A/S (Denmark).

Fig. 4 shows the distribution of Participants on the world map. Besides the Participants and the other companies that measured the calibrated samples during the circulation, also the three Organizations that provided the calibrated samples are indicated:

- ▶ University of Padova – Lab. of Industrial and Geometrical Metrology (Italy), Items 1 and 2;
- ▶ PTB, Physikalisch-Technische Bundesanstalt, Braunschweig (Germany), Item 3;
- ▶ University of Erlangen-Nürnberg – QFM (Germany), Item 4.

All organizations listed above, and others, are now establishing an international network in dimensional CT.

Table 1. Participants of the CT Audit project, in alphabetical order.

Participant	Country
AIST – Human Technology Research Institute	Japan
AIST – NMIJ, National Metrology Institute of Japan	Japan
BAM, Federal Institute for Materials Research and Testing	Germany
Elettra Sinc. S.C.p.A., Trieste	Italy
Industrial Technology Center of Tochigi Prefecture	Japan
Katholieke Universiteit Leuven	Belgium
Nikon Metrology, X-Tek Systems Ltd	UK
Novo Nordisk A/S, Device R&D	Denmark
Novo Nordisk A/S, DMS Metrology & Calibration	Denmark
Pratt & Whitney, Austin	USA
RayScan Technologies GmbH	Germany
RWTH Aachen University – WZL	Germany
Universidad de Zaragoza	Spain
University of Erlangen-Nürnberg – QFM	Germany
Werth Messtechnik GmbH	Germany

A website was built for distributing information and measurement procedures (www.gest.unipd.it/ct-audit) [13]. The circulation phase lasted one year, from March 2010 to March 2011. A final Workshop

took place in Padova (Italy) in October 2011, where all Participants met and discussed the results of the intercomparison.

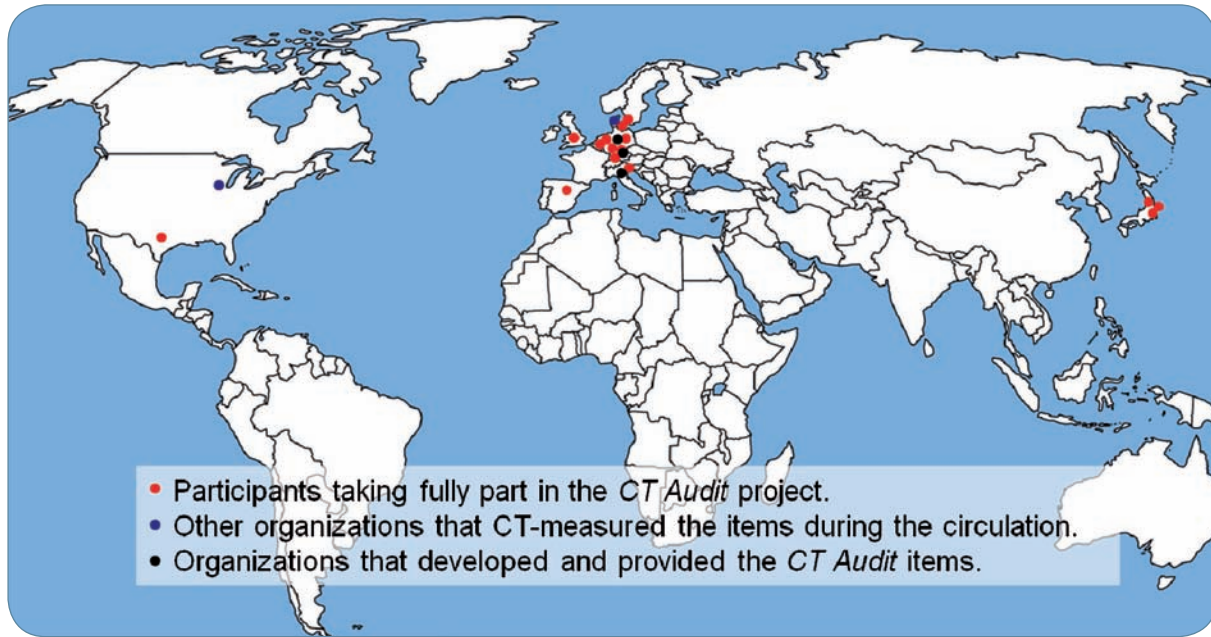


Fig. 4: Distribution of Participants on the world map.

Calibrated Items

Four calibrated samples were chosen in order to represent a variety of dimensions, geometries and materials; they were designed and manufactured suitably for testing several measurement characteristics on different CT systems. The four items were sent within a dedicated suitcase from one Participant to the next one in a sequential participation scheme [11]. Each Participant received from the project coordinator detailed measurement procedures, reporting sheets and Items' CAD models with nominal values.

Items were protected in thin plastic sealed boxes for reducing the risk of damages, limiting contamination and avoiding measurements with other sensors. The sealed cylindrical boxes are made of polyethylene, with wall thickness of 0.8 mm circa. Participants were asked to measure the items without opening the sealed boxes. The four Items are shown in Fig. 5.

Item 1, which is called "*CT Tetrahedron*", consists of four calibrated ruby spheres on a carbon fiber frame. Item 2 is called "*Pan Flute Gauge*"; it is composed of five calibrated glass tubes of different lengths [14].

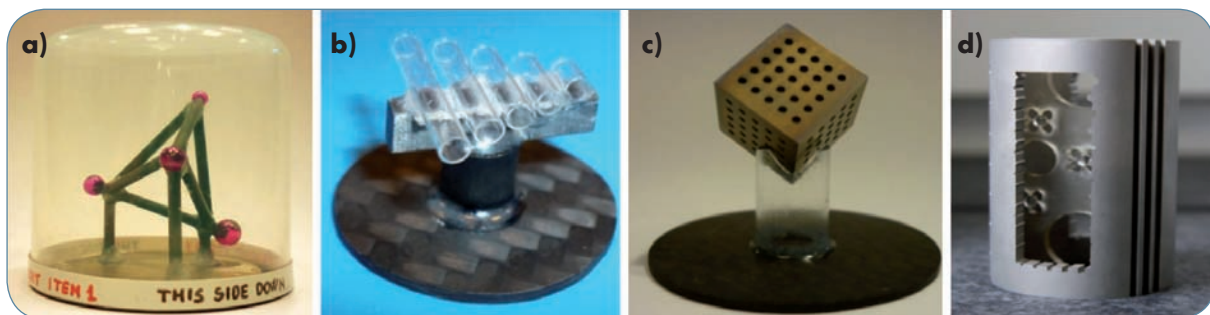


Fig. 5: The four CT Audit items: (a) *CT Tetrahedron*, (b) *Pan Flute Gauge*, (c) *PTB Calotte Cube*, (d) *QFM Cylinder*.

Both items 1 and 2 were developed by University of Padova, Italy. Item 3 is the “Calotte Cube”, which consists of 75 spherical calottes on three sides of a titanium hollow cube.

This item is provided by Physikalisch-Technische Bundesanstalt, Germany. Finally, item 4 is the “QFM Cylinder”, consisting of a titanium cylinder and a ball plate with five sapphire balls. This item is provided by QFM – University Erlangen-Nuremberg, Germany.

The four Items have been calibrated using tactile CMMs. They were calibrated before and after the circulation period, in order to verify and document their stability.

form errors of the four spheres, and the distances between the spheres. As an example, the results of diameters measurements are summarized in Figure 6. The results show that the values obtained by the Participants for measurements of diameters and distances between spheres are closer to the actual calibrated values than those of form errors (taking into account the stated uncertainties). In particular, the comparison of diameters measurements with form error measurements is summarized in Figure 7 in terms of the “ E_n value”, which describes the difference between the calibration results and the measured ones compared to the stated uncertainties [11]. It is defined as:

$$E_n = \frac{\text{Value (participant)} - \text{Value (calibration)}}{\sqrt{U(\text{participant})^2 + U(\text{calibration})^2}}$$

2. SELECTED RESULTS

Item 1

15 CT Systems measured the “CT Tetrahedron”. The Participants were asked to measure diameters and

If $|E_n| < 1$ there is good agreement between calibration and measured data [11].

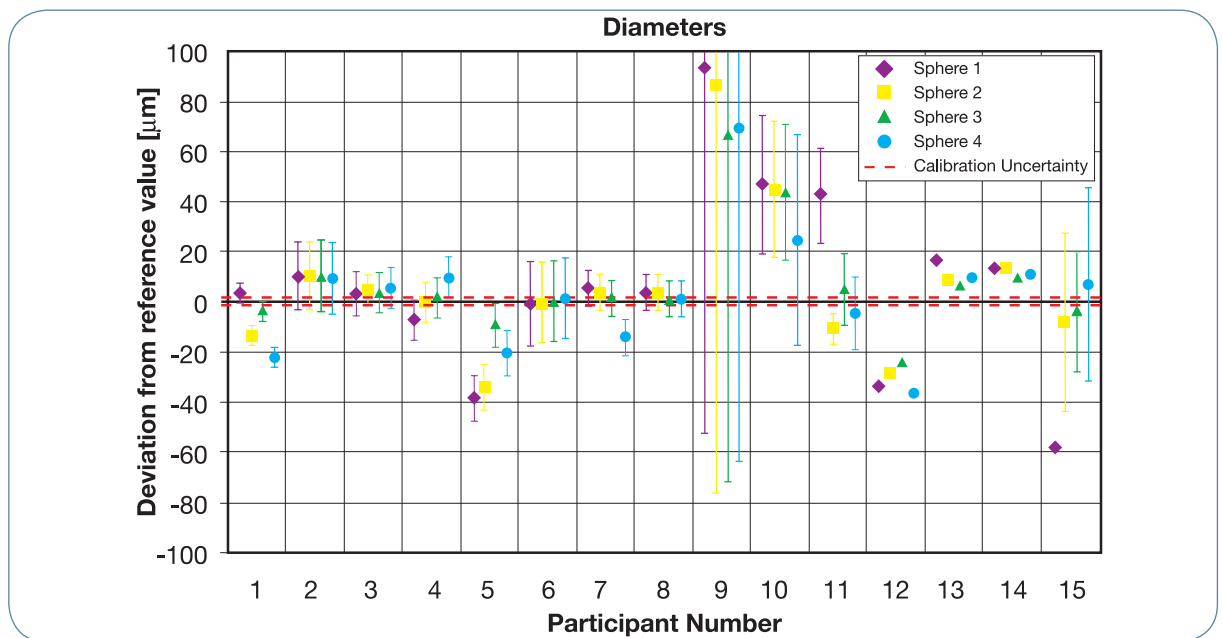


Fig. 6: Summary of results obtained by the CT Audit Participants: Item 1, Diameters measurements. Vertical error bars represent expanded uncertainties specified by the Participants.

Item 2

15 CT Systems measured the “Pan Flute Gauge”. The Participants were asked to measure Inner and Outer Tubes’ Diameters and Tubes’ lengths. The majority of the Participants measured with E_n value smaller than 1. Moreover, a very interesting result

trend has been observed: the deviations of inner and outer diameters from the calibrated values have a systematic “mirror distribution”. The causes of this systematic trend are related to the geometry of the item and the measurement position; further investigations are on-going to better understand these causes.

In order to correct the lengths' measurements results of Item 2, the calibration values of the tubes diameters were distributed to all Participants at the end of the *CT Audit* round robin in March 2011.

The values were obtained from CMM calibration. In particular, the Participants could use the calibrated internal and external diameters values to correct their systematic errors, including errors due to threshold determination and scaling factor. Each Participant was free to decide which correction procedure to apply and was asked to send the new lengths' results to the project coordinator. This second part was facultative, and only 6 Participants corrected their values; most of them obtained significant improvement from this correction of systematic errors. Results of Participant Nr. 10 has been reported as an example in Figure 8.

Item 3

12 CT Systems measured "Calotte Cube". The Participants were asked to measure x, y and z coordinates of calottes centres respect to given reference coordinate system, diameters and form errors of the calottes, and also some selected distances between calottes.

E_n values are better ($|E_n| < 1$) for distances measurements than for diameters evaluations,

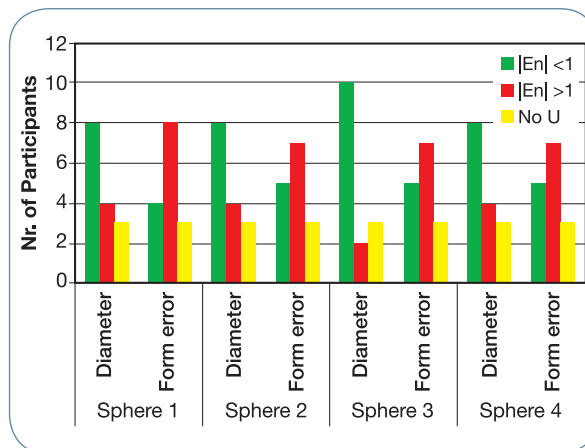


Fig. 7: Item 1, E_n -values for Diameters and Form errors measurements obtained by the Participants.

and E_n of diameters are better than those of form errors. Distances between calottes, in fact, are less subject to the influence of specific errors, due to their bidirectionality.

Form errors measurements, instead, are affected by the influence of scatter and noise of data. Indeed, measurement results show that there is an overestimation of the form error value by all Participants.

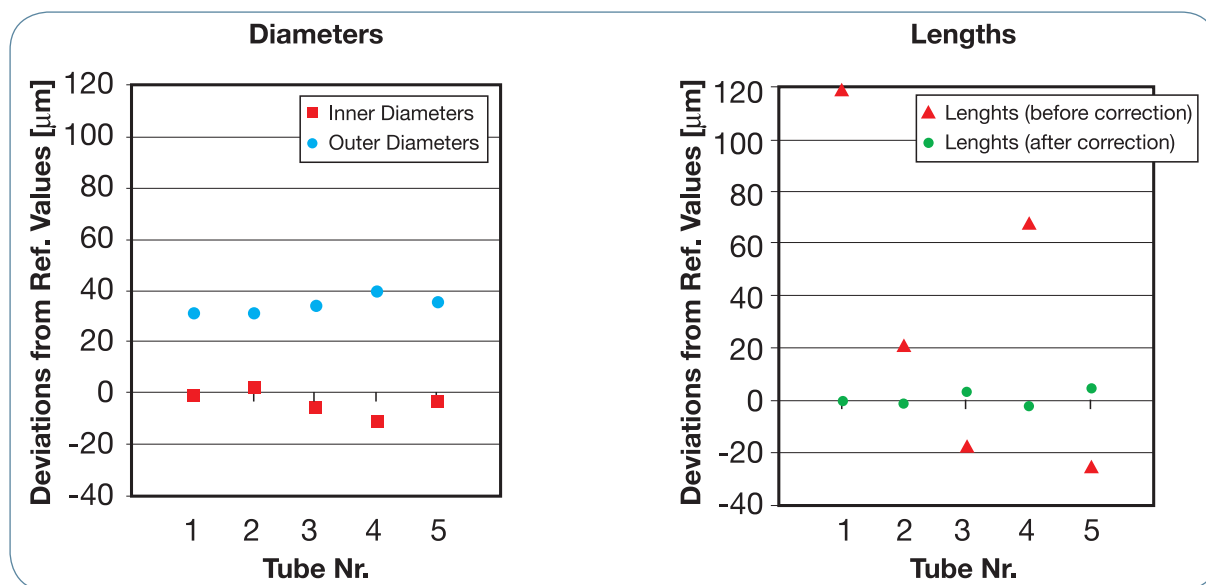


Fig. 8: Item 2, results of Participant Nr. 10.

Item 4

8 CT Systems measured "QFM Cylinder". The Participants were asked to measure Inner and Outer Cylinder diameters, Calottes diameters, Spheres distances of the ball plate, Diameter of the smallest

cylindrical structure and the distance of the micro cylinder axis from the bottom face of titanium cylinder.

"QFM Cylinder" revealed to be the most challenging item to measure, indeed only 8 Participants

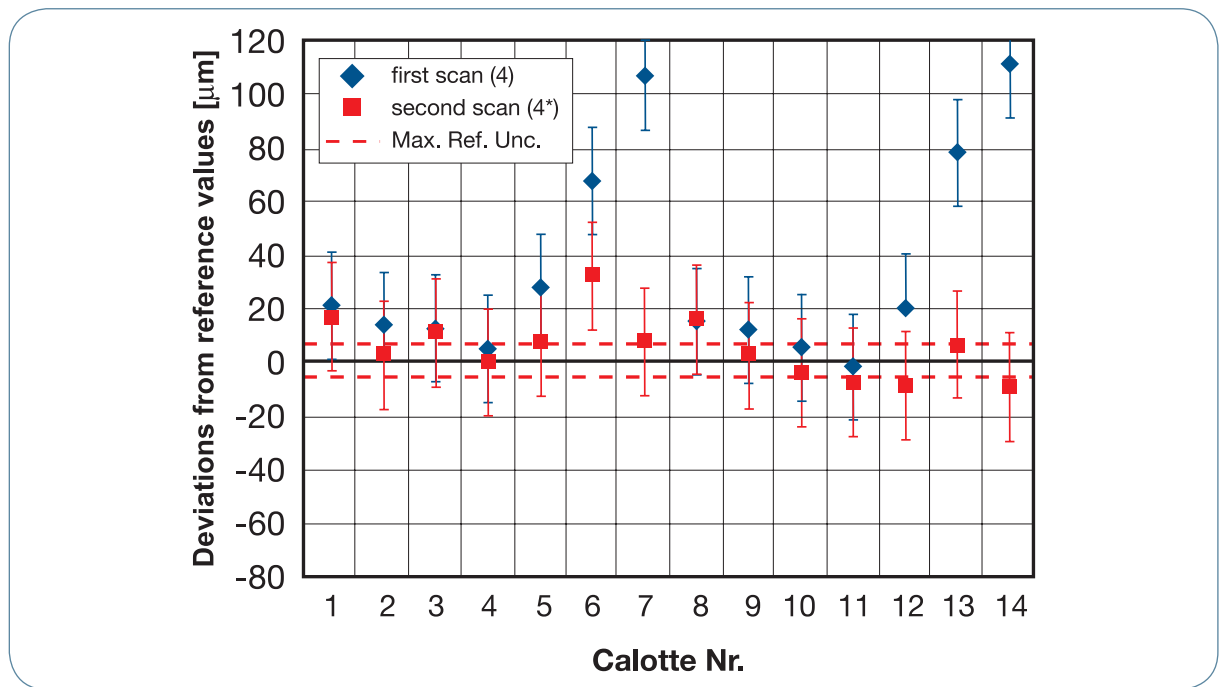


Fig. 9: Item 4 – Diameters of top calottes – comparison between two scans with different magnification, performed by Participant Nr. 4.

measured it and the deviations from the calibrated values were higher compared to the other items.

Since Item 4 is a relatively big item, some Participants decided to scan the object in three different ways, with their own magnifications and voxel sizes:

- ▶ The whole item,
- ▶ Only the top calottes,
- ▶ Only the bottom calottes.

In Figure 9, the results provided by Participant 4 are reported, in order to show the improvement obtained in terms of deviations concerning the Top Calottes Diameters. Top calottes have been measured twice, first scanning them with the whole sample and then with the top calottes in the centre plane of the image with a different magnification and voxel size. From Figure 9 it is possible to deduce that the second measurements are generally closer to the calibrated values.

DISCUSSION AND CONCLUSIONS

X-ray Computed Tomography is a very promising technique for industrial quality control, applicable to a large number of different sectors, including non-destructive inspection of casting.

CT scanning is capable of achieving 3D reconstructions that are characterized by important advantages, including: simultaneous dimensional quality control and material quality control,

nondestructive inspection of internal as well as external geometries, and reconstruction of complete and high-density point-clouds in relatively short time. However, industrial CT is still in its youth and suffers of limitations concerning accuracy and traceability of dimensional measurements from CT data.

This paper reported the results of an extensive experimental investigation, examining the international state of the art in industrial CT metrology, with focus on accuracy and traceability issues. In particular, the paper examined selected results obtained from the “CT Audit” project, which is the first international interlaboratory comparison of CT systems for dimensional metrology. The project was organized by the *Laboratory of Industrial and Geometrical Metrology*, University of Padova, Italy, and was carried out in the period from September 2009 to June 2011.

The interlaboratory comparison involved 15 CT systems, from research institutions and companies working actively on industrial CT metrology in Europe, America and Asia. The interlaboratory comparison produced a number of important results, including:

- ▶ Quantification of specific errors occurring in CT scanning;
- ▶ Evaluation of uncertainty calculation methods;
- ▶ Contribution to standardization of testing procedures;
- ▶ Establishment of an international network of laboratories using CT systems for industrial quality control.

A general comment on the overall results from all CT systems is that form measurements are more problematic than measurements of sizes, such as diameter and distance measurements. This is visible when comparing the distribution of E_n numbers for form measurements to that for size measurements, independently on the measured sample.

Results from Item 1 and Item 3 show also that diameter measurements give larger E_n numbers than spheres' distances measurements. This can be explained by the fact that spheres' distances are unidirectional length measurements, while diameters are not unidirectional and therefore are subject to additional uncertainty components – such as threshold determination errors – that are not properly taken into account by users.

Furthermore, the correction of measurement results for Item 2, based on distribution of calibrated diameter values after the conclusion of the circulation, revealed that for some *CT Audit* participants the influence of basic systematic errors connected to scale factors and threshold determination is strongly affecting their measurement results. For these participants, identification and correction of such systematic errors within the *CT Audit* project produced remarkable improvement of measurement accuracy.

From the participants' measurement results, Item 4 was found to be the most challenging sample to measure, due to its multi material configuration and its larger size.

A final general inference from the analysis of the CT Audit results is that typically the users have difficulties in evaluating the measurement uncertainty appropriately. This confirms that traceability of dimensional measurements is still a major challenge in CT scanning, even for experienced users.

An important outcome of the CT Audit project is the establishment of an international network in dimensional computed tomography. The network includes more than 20 organizations worldwide, working actively in the field of computed tomography for dimensional metrology. The aims of this network are to deepen the knowledge on CT dimensional metrology and promoting further international initiatives in the field of industrial CT, including international research projects. The first meeting of the international network took place in Padova, Italy, on October 26th, 2011, in the occasion of the final CT Audit Workshop.

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