Calibration of industrial CT using two forest-balls

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Calibration of Industrial CT using two Forest-Balls

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ABSTRACT

A small forest-ball was manufactured and calibrated using CMM F25. An industrial CT called Metrotom1500 was calibrated by the small forest-ball and another big forest-ball produced by Carl Zeiss. These two forest-balls were separately measured at two different magnifications of the industrial CT, and the measurement results could meet the maximum permissible error of Metrotom1500.

Keywords: Industrial CT, Length measuring error, Forest-ball, sphere distance, Metrology.

1. INTRODUCTION

Similar to medical CT, industrial CT (ICT) is an abbreviation of industrial computed tomography. Differing from X-ray flaw detector which can only get two-dimensional overlapped information, industrial CT can give detailed three-dimensional geometry information of the workpiece by calculating and reconstructing a large number of projection data at different angles. In recent years, ICT has been applied from the traditional NDT field to dimensional measurement[1].

In the past, measurements of the internal structure of workpiece can only be achieved through the traditional instruments (such as CMMs), which have to disassemble workpiece or cut them into pieces. Therefore it is really time-consuming and laborious work, and what's worse is that the deformation of the workpiece will inevitably occur during this process, so it is hard to get the initial geometry information of the workpiece. When the ICT appears, it makes a revolution on this problem. The revolution benefits from its excellent capability making non-contact, non-destructive measurements of the internal and external structure of workpiece.

However, compared with traditional CMMs, the ICT system includes not only the basic motion mechanism, but also X-ray source, detector, image reconstruction algorithms and other complex parts, which makes the measurement traceability become extremely hard. Researchers all around the world have made a lot of valuable research on the calibration methods and reference standards of ICT[2,3,4,5]. But currently there isn't any general consent resolution for the calibration of ICT.

Referring to standards and calibration specifications of traditional CMMs, some national and international standards have been proposed or being drafted. Guided by these specifications, a series of calibration experiments have been conducted on Metrotom1500 at National Institute of Metrology (NIM), with forest-ball made by NIM and Zeiss respectively.

2. PRINCIPLE AND DEFINITIONS

2.1 Working principle of ICT

Figure1 shows the basic structure of a cone beam X-ray CT system. During the ICT measurement, X-ray with continuous energy is generated by the X-ray source, and penetrates the workpiece on the rotary table. Then the attenuated X-ray which carries the geometry information of workpiece is captured by the detector, and a projection is created in this position. Make the rotary table turn a slight angle and repeat this process, then another projection corresponding to this particular angle can be obtained. When enough projections (in one revolution of the rotary table) are acquired by this

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way, 3D model of the workpiece can be calculated according to some algorithms (e.g. Feldkamp reconstruction algorithm [6])

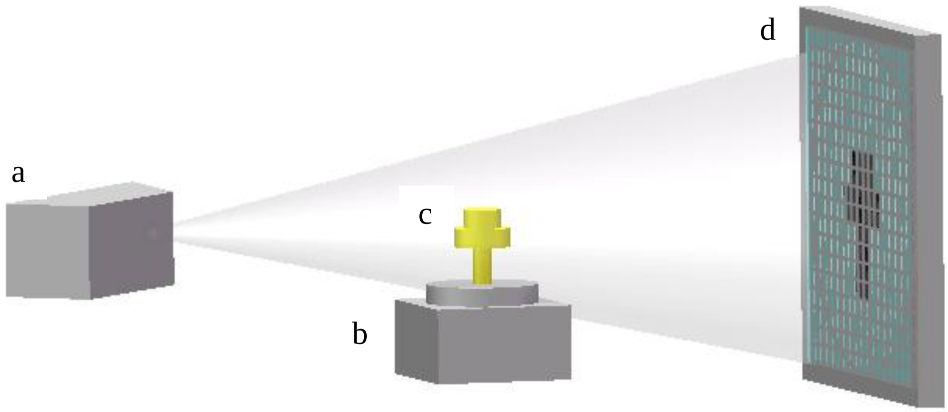


Figure 1 Construction of a typical cone beam X-ray CT system. a. X-ray source; b. rotary table; c. workpiece under scanning; d. detector

2.2 Length measuring error of ICT

According to ISO 10360-1:2000[7], the CMMs are defined as "Measuring system with the means to move a probing system and capability to determine spatial coordinates on a workpiece surface". Referring to this definition, the ICT can be treated as a special CMM which is equipped with "CT sensors". Hence the calibration specification of traditional CMMs can be taken into account in the study of ICT's length measuring error[8]. The Germany national standard VDI/VDE 2630[9] "Computed tomography in dimensional measurement" and the ISO TC 213 working draft ISO 10360-CT both are following the calibration method of traditional CMMs.

The definition of length measuring error (E) in ISO 10360-2:2009[10] is described as follow: "Error of indication when measuring a calibrated test length using a CMM with a ram axis stylus tip offset of L, using a single probing point (or equipment) at each end of the calibrated test length." The length measuring error of ICT calibrated by material standards composed of spheres (e.g. forest-ball) can be named as E_{SD}, to distinguish with the E calibrated by gauge blocks.

The length measuring error describes the three dimensional error of the whole system, which is a combination of different independent error source, including the anisotropy of the probes, positioning error of the axis, and some other system or random errors, etc. The dimensional measurement ability of CMMs in the whole measurement space can be assessed comprehensively by this character.

Besides the length measuring error, there are also many other characters used to evaluate the measurement ability of ICT, such as probing form error *PF* and probing size error *PS*, which describe the three dimensional error behavior within a very small measurement volume of the entire system. These characters are not included in this paper.

3. CALIBRATION METHOD

3.1 Traceability chain

In this paper, the traceability chain of ICT is described in figure 2. Firstly, the primary standard of meter is reproduced by laser interferometer, and then delivered successively from a high precision CMM to the material standard (forest-ball). Finally the MPE *SD* of Metrotom1500 is proved by the forest-ball.

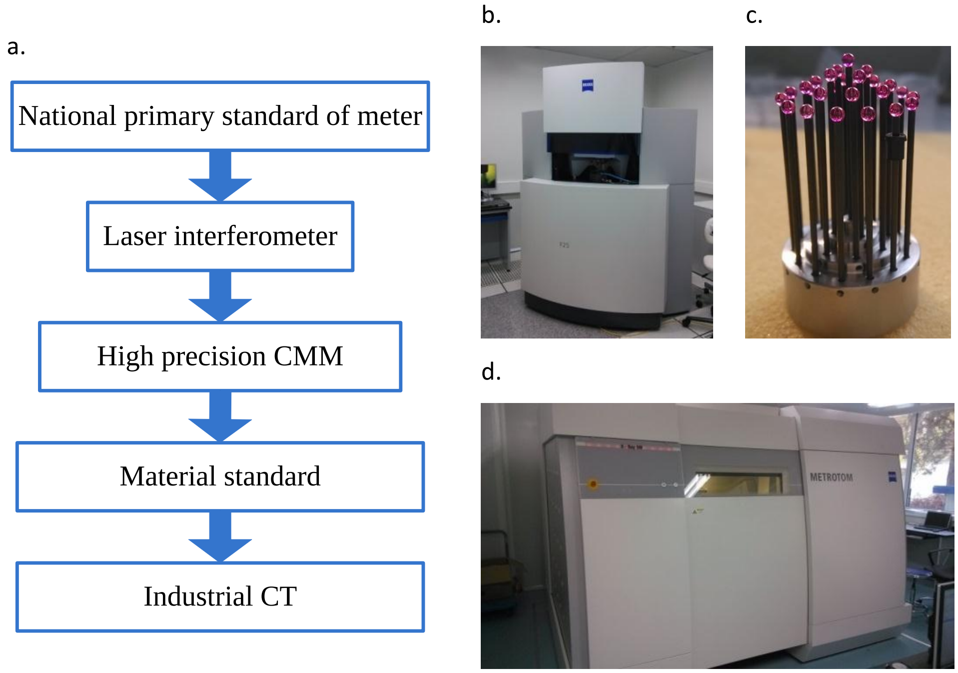
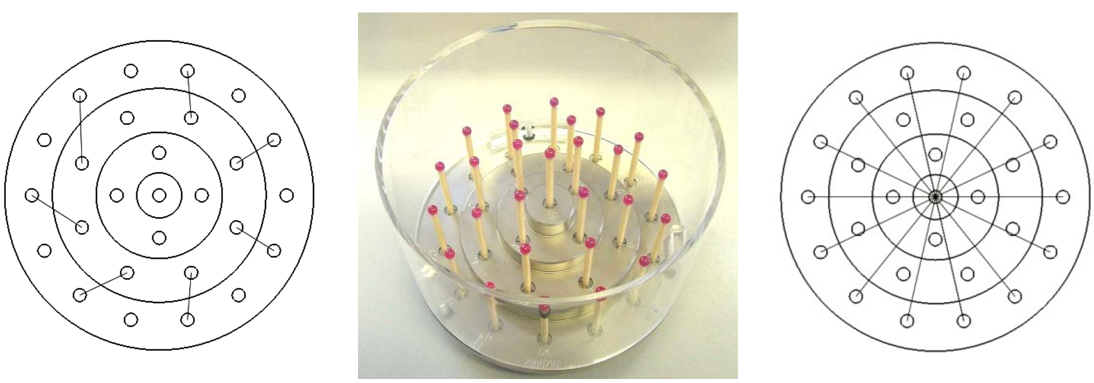


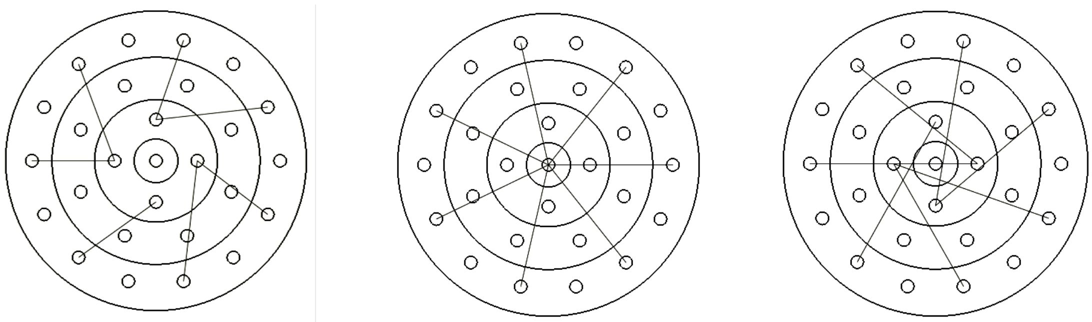
Figure 2 Traceability chain of ICT. a. traceability chain; b. high precision CMM (F25); c. material standard (forest-ball); d. ICT (Metrotom1500)

3.2 Forest-ball

Considering the measurement principle of ICT, some new material standards such as ball-bar, multi-sphere, ball-plate or hole-plate have been designed in recent years[1]. A commonly used multi-spheres standard is shown in figure 3, which is generally called forest-ball. 27 standard balls are distributed symmetrically in a cylinder space, and any two of these balls can be combined to a material standard of size. 35 sphere distances are selected in this way, as figure 4 displayed. The selected sphere distances can be classified as 5 groups, and the sphere distances distributed in 7 directions in each group are approximately the same size. Therefore the forest-ball can reach the requirement of material standard in ISO 10360-2: 2009: “Five different calibrated test lengths shall be placed in each of seven different positions (locations and orientations) in the measuring volume of the CMM.”



Size 1 Forest-ball Size 5



Size 2 Size 3 Size 4

Figure 3 Sphere distance classification of forest-ball

A “tiny forest-ball” is produced in this research, see figure 2c and figure 4a. Ruby balls with diameter of 2mm and roundness error smaller than 0.2μm are chosen as standard balls, for its high hardness, low coefficient of thermal expansion, and moderate X-ray absorption coefficient. The supports of ruby balls are well manufactured carbon fiber rods, which are extremely stiff, lightweight and have a very low coefficient of expansion. Furthermore, benefit from the much lower X-ray absorption coefficient of carbon fiber rods compared with ruby balls, the spheres can be extracted easily in the data analysis process, as figure 4b shows.

a b

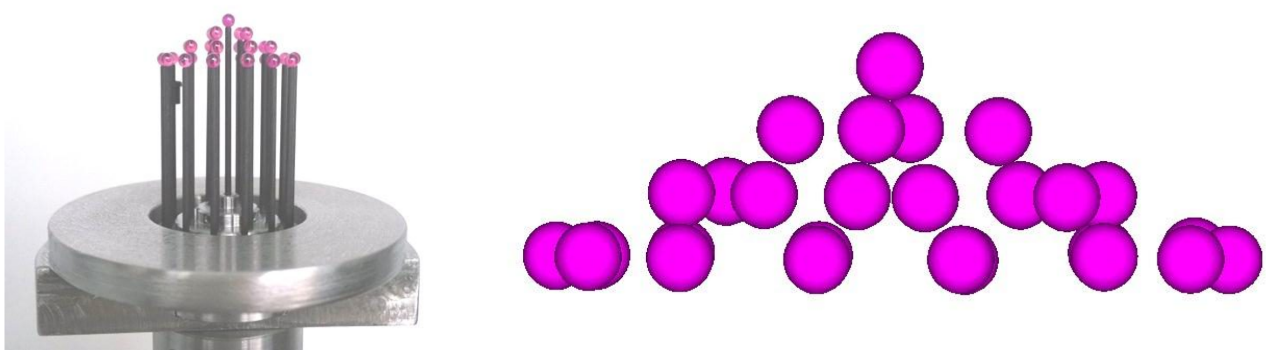


Figure 4 Tiny forest-ball. a. material object; b. CT reconstructed data (carbon fiber rods are filtered due to its low X-ray absorption coefficient)

3.3 Calibration of tiny forest-ball

The calibration of tiny forest-ball is carried out on F25 at National Institute of Metrology, China. The F25 is a high precision CMM produced by Carl Zeiss, with a measuring range of 130mm×130mm×100mm and maximum permissible error (MPE) of (0.25+L/666)μm. The F25 is well calibrated and traceable to meter.

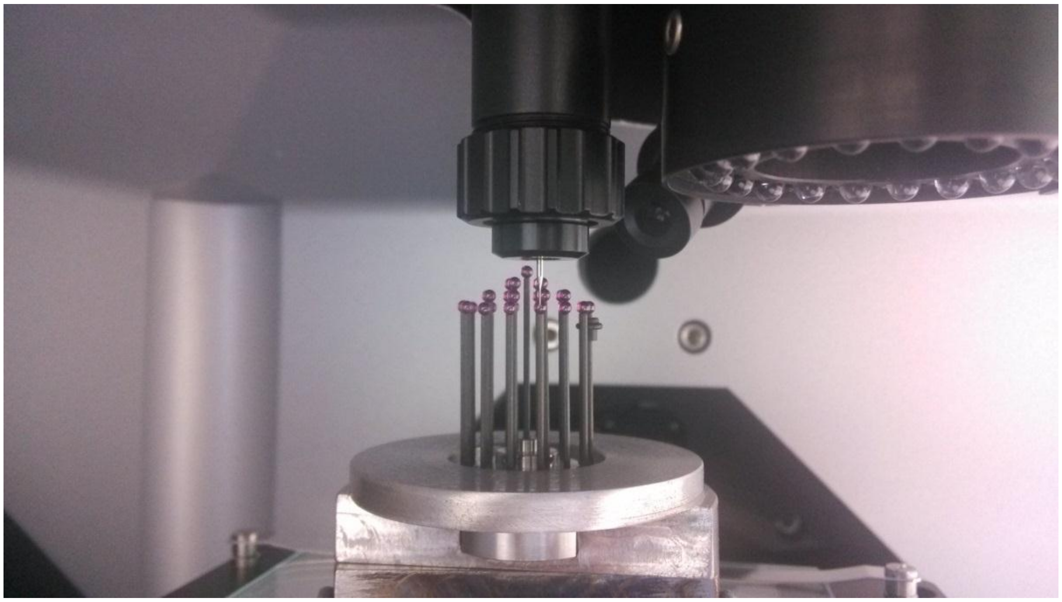


Figure 5 Calibration of tiny forest-ball by F25. (Room temperature (20±0.5) ℃, relative humidity (50±2)%RH)

During the calibration of tiny forest-ball, a typical sphere probing strategy has been used: 4 probing points distributed uniformly on the equator and 1 probing point on the top pole. The calibration result of tiny forest-ball is shown in table 1.

Table 1 Calibration result of tiny forest-ball. Coordinates of each sphere are calibrated, from which 35 sphere distances were calculated.

Distance number	**Sphere distance** /mm	**Distance number**	**Sphere distance** /mm	**Distance number**	**Sphere distance** /mm	**Distance number**	**Sphere distance** /mm
SD 1-15	5.5808	SD 5-17	4.3605	SD 9-19	4.0093	SD 13-21	4.3297
SD 1-23	9.1729	SD 5-24	8.4625	SD 9-25	8.2634	SD 13-26	7.8257
SD 1-27	11.2196	SD 5-27	11.3445	SD 9-27	11.3621	SD 13-27	11.2139
SD 1-25	12.3474	SD 5-26	12.9382	SD 9-23	13.3599	SD 13-24	13.4155
SD 1-8	19.6452	SD 5-12	19.7661	SD 9-2	19.7122	SD 13-6	19.6273
SD 3-16	4.9846	SD 7-18	4.3535	SD 11-20	3.8802		
SD 3-23	7.6620	SD 7-25	10.5957	SD 11-26	9.6434		
SD 3-27	11.3608	SD 7-27	11.4878	SD 11-27	11.2128		
SD 3-25	13.4255	SD 7-23	11.6216	SD 11-24	12.0142		
SD 3-10	19.6060	SD 7-14	19.8174	SD 11-4	19.4965		

4. EXPERIMENTS

The cone beam CT's measuring range changes with the magnification, which is determined by the position of the rotary table. Therefore different reference standards with difference sizes should be used to make the assessment result more credible. The largest sphere distance of tiny forest-ball is 19.8174mm, so it is only suitable for the calibration task close to the X-ray source (large magnification). As a supplement, another big forest-ball produced by Zeiss is also used in this calibration experiment. The big forest-ball has been calibrated by DKD with uncertainty of 0.001mm, and the largest calibrated length is 113.0490mm, therefore it can be measured relatively far away from the X-ray source (small magnification).

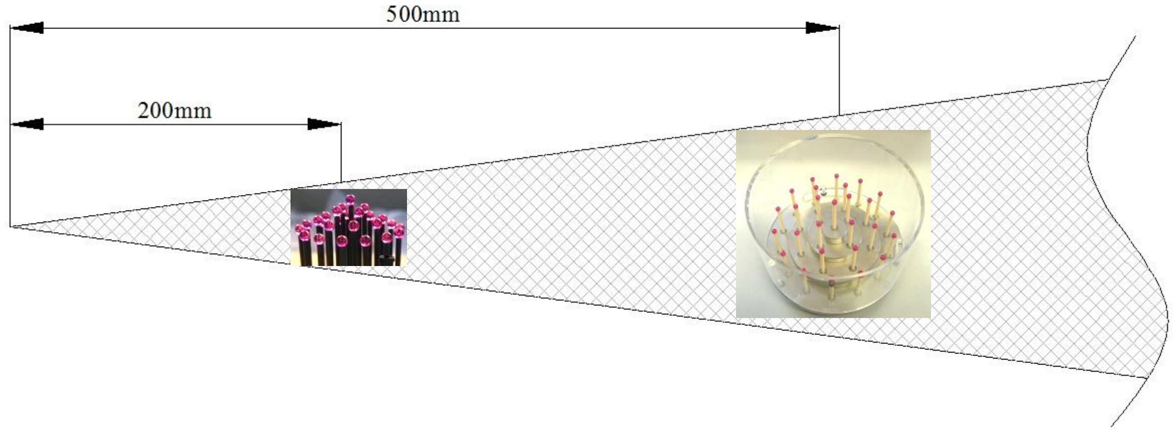


Figure 6 Two different positions or magnifications used during the calibration experiment. In the position X=200mm, tiny forest-ball is used, and the big forest-ball is applied in the position X=500mm.

The calibration experiments were carried out on Metrotom1500 with the Measurement software Calypso. The technical data of Metrotom1500 and its parameter settings during the experiment are shown in table 2 and table 3 separately.

Table 2 Technical data of Metrtom1500 (summarized from the specification document of Metrotom1500)

Characteristic		**Data**	**Unit**
Measuring range	Max. image diameter	300	mm
	Max. image height	350	mm
MPE E_{SD}		4.5+L/100	μm
Maximum workpiece weight		10	kg
X-ray source	Max. tube voltage	225	kV
	Max. tube current	1000	μA
	Max. power	225	W
	Min. focal spot size	7	μm
Detector	Number of pixels	2048*2048	——
	Pixel size	200	μm
Travel path of the mechanical system	X axis	1250	mm
	Y axis	580	mm
	Z axis	150	mm

Table 3.Parameter settings of Metrotom1500 during the calibration

Standards	**Filter Cu**/mm	**U**/kV	**I**/μA	**T**/ms	**Gain**	**binning**	**x**/mm	**y**/mm	**Pro.**
Big FB	0	180	280	400	16x	2*2	500	40	1000
Tiny FB	0	180	280	400	16x	2*2	200	60	1000

5. RESULTS

The calibration results are shown in figure 7 and figure 8. The deviation corresponds to each sphere distance is the difference between calibrated value and measured value by Metrotom1500.

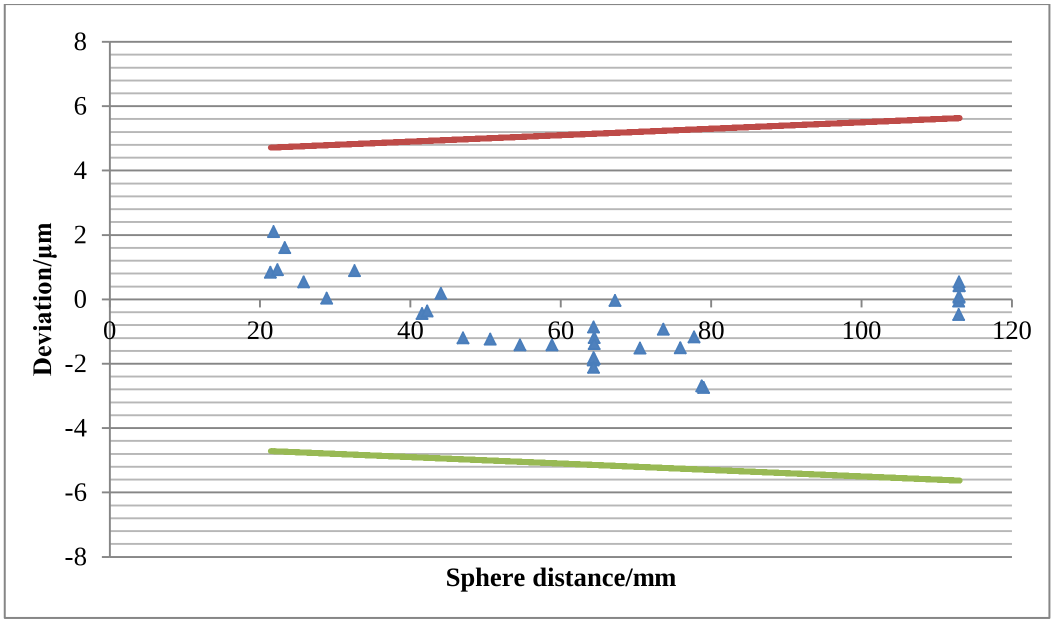


Figure 7: Measuring result of big forest-ball at the position X=500mm. The measuring deviation of big forest-ball distributes symmetrically around the zero line, and far away from the MPE SD.

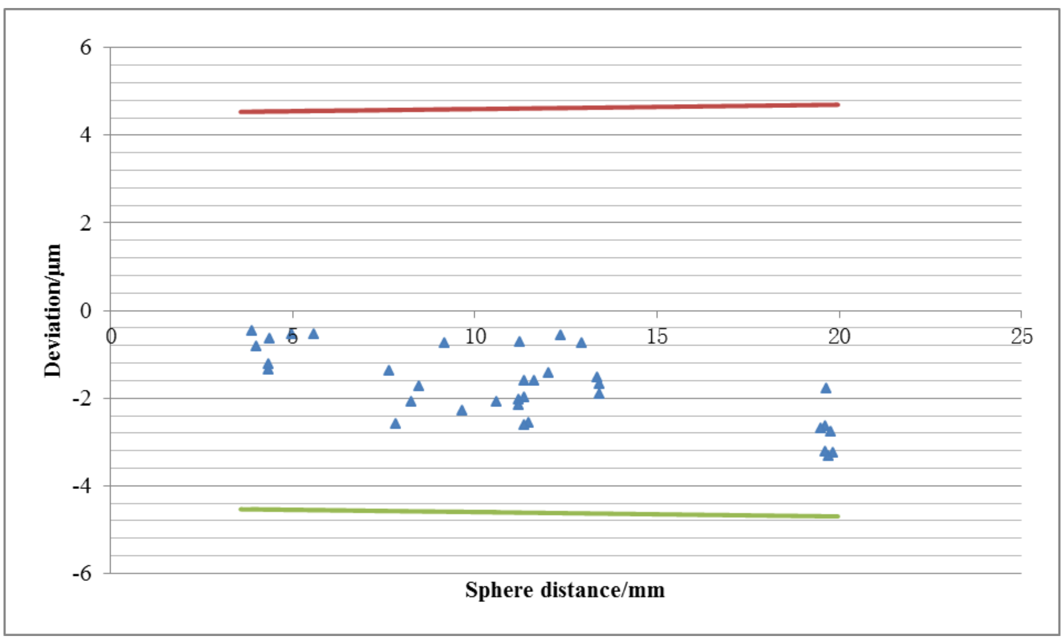


Figure 8: Measuring result of tiny forest ball. In the position X=200mm, the measuring deviation of tiny forest ball all stay below the zero line.

Explanation and analysis of the calibration results:

a. The length measuring error E_{SD} various with different magnification

b. As to Metrotom1500, the E_{SD} is much larger at the position X=200mm than X=500mm

c. For the position X>500mm, the current forest-ball are not big enough to qualify the specific calibration task, so some larger forest-balls need to be designed in the following research.

6. CONCLUSIONS

Treating the ICT as a kind of special CMM, and referring to the calibration specification of traditional CMMs, some calibration methods of ICT's length measuring error have been proposed. As a typical reference standard, forest-ball can meet the requirements of ISO 10360-2:2009. Though the forest-ball performs well in the assessment of ICT's length measuring error, it is still not a perfect standard, for instance, the absence of vertical size. There are still many improvements could be done in the following research.

Attention is drawn to the fact that the length measurement error assessed by the forest-ball is different from the bidirectional measurement of gauge block. When calculating the sphere distance error, the probing error isn't taken fully into account when calculating the fitted sphere due to averaging effects arising from the large number of permissible probing points in the characteristic. Therefore, the probing error should be considered and added separately to E_{SD} to reach comparability with the bidirectional measurement of gauge blocks.

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