Calibration of Length Measurement Error and Uncertainty Analysis of X-ray 3D Dimensional Measuring Machine

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Abstract. Propose a length measurement error calibration method for X-ray 3D dimension measuring machine based on forest sphere. Based on the length measurement error calibration method of the X-ray 3D dimension measuring machine based on forest balls, establish an evaluation model for measurement uncertainty and analyze the sources of various uncertainties. Based on measurement examples, this paper elaborates on the process of evaluating the measurement uncertainty of the length measurement error of the X-ray 3D dimension measuring machine based on forest balls, calculates its extended uncertainty, and provides reference for the evaluation of the measurement uncertainty of the length measurement error of the X-ray 3D dimension measuring machine.

Keywords: Metrology, X-ray 3D Dimensional Measuring Machine, length Measurement Error, uncertainty in measurement.

1. Introduction

The X-ray 3D dimension measuring machine is a 3D dimension measuring instrument that utilizes X-ray computed tomography technology [1]. Compared to traditional coordinate measuring machines, X-ray 3D dimension measuring machines can perform tomographic scanning and reconstruct 3D images of the measured object without disassembly, damage, or contact, in order to obtain internal and external geometric features, dimensions, and other information of the measured object. The X-ray 3D dimension measuring machine has a wide range of applications in non-destructive testing, reverse engineering, tomography measurement, and other fields [2]. Due to the complex structure of X-ray 3D dimension measuring machines, in addition to mechanical motion mechanisms, there are also complex error sources such as X-ray sources, detectors, and image reconstruction algorithms, making it difficult to trace the measurement values of X-ray 3D dimension measuring machines [3]. Therefore, many scholars at home and abroad have conducted relevant research [2-9] and achieved many valuable results. The national standard GB/T 34874.3-2017 Part 3[10] provides relevant technical basis for the acceptance and retesting of X-ray three-dimensional dimension measuring machines. On the basis of the above research, this article conducts a study on the calibration of length measurement errors and evaluation of measurement uncertainty for X-ray 3D dimension measuring machines based on forest spheres.

2. Calibration Method

The main steps in the calibration process of length measurement error for X-ray 3D dimension measuring machine are: obtaining the projection data of the forest sphere standard; Reconstruct the projection data to obtain a 3D voxel model of the forest sphere; Extract the edges of the 3D voxel model of the forest sphere; Finally, the geometric features of the forest ball are measured for size, and the difference between the measured center distance and the standard value is the calibration result.

Before calibration, the following preparations should be made according to the manufacturer's operating instructions: power on the X-ray 3D dimension measuring machine and preheat it; Configure the X-ray 3D dimension measuring machine as required, and perform system debugging if necessary; Ensure that the installed forest ball standard is stable enough and does not deform as much as possible; Adjust the measurement parameters of the X-ray 3D dimension measuring machine as required. At the same time, manufacturers should provide necessary information, such as limit values for parameter settings. During the calibration process, the specified environment and operating conditions should always be maintained. The various parameter settings involved in the calibration process, such as X-ray tube voltage value, film type, projection quantity, exposure time, measurement point density, etc., should be kept as consistent as possible with daily work. When detecting detection errors and length measurement errors, it should be ensured that the parameter settings are consistent. During calibration, the laboratory temperature should be within the range of (20±2)℃, and the calibrated instrument and calibration standard should be continuously equilibrated indoors for at least 12 hours. The length error calibration process of the X-ray 3D dimension measuring machine based on forest balls is shown in Figure 1.

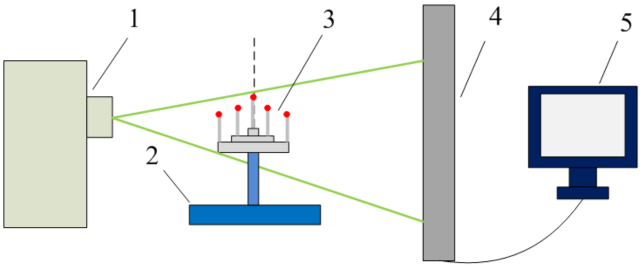

Figure 1. Schematic diagram of length error calibration for X-ray 3D dimension measuring machine based on forest sphere

1- X-ray source. 2- Rotating table. 3- Forest ball. 4- Detector. 5- Caomputer

According to the above calibration method, it can be concluded that the measurement model for the length measurement error of the X-ray 3D dimension measuring machine is

$$\Delta L = L_i - L \tag{1}$$

where, ΔL is the length measurement indication error, L_i is the measured value of ball center distance, L is standard value of ball center distance.

3. Evaluation of Measurement Uncertainty

3.1. Measurement Result

Under laboratory environmental conditions, calibrate the length measurement error of the X-ray 3D dimension measuring machine using a forest ball according to the above calibration method. Before calibration, the relative positions of the radiation source, rotating table, and detector are first subjected to geometric error self calibration and rotation axis error self calibration. Error correction is performed based on the calibration parameters, and calibration is carried out only after the error correction meets the requirements. The geometric magnification during calibration is 2.85 and the voxel size is 75 µm. The 3D reconstruction model of the forest ball obtained from the measurement is shown in Figure 2. The measurement results are shown in Table 1.

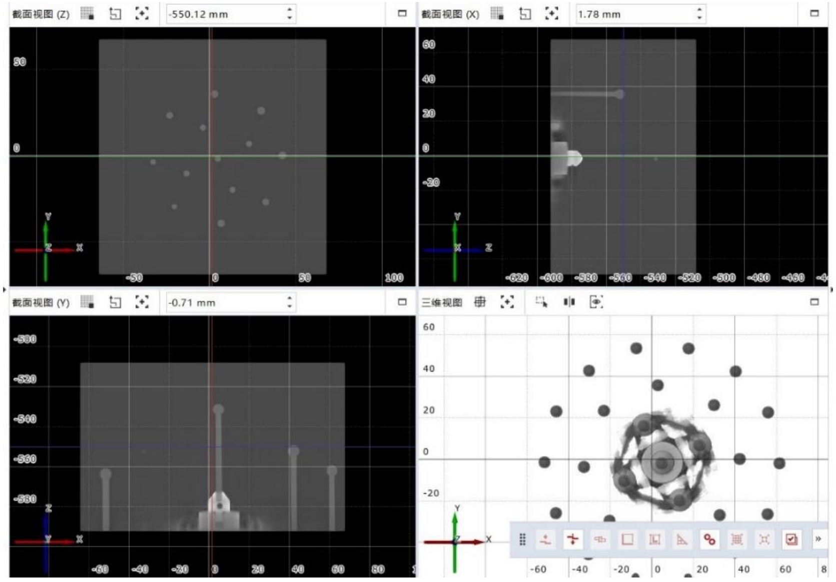

Figure 2. Schematic diagram of Forest ball scanning and reconstruction of 3D model

Table 1. Measurement results of length measurement error of X-ray 3D dimension measuring machine

No.	Standard value of ball center distance / mm	Indication value / mm	Indication error / μm
1	25.1336	25.1332	-0.4
2	49.0647	49.0644	-0.3
3	70.4767	70.4771	0.4
4	88.3418	88.3423	0.5
5	110.1420	110.1426	0.6

3.2. Measurement Uncertainty Model

The measurement model for length measurement error of X-ray 3D dimension measuring machine is shown in equation (1). According to the measurement model, the input variables Li and L are independent and unrelated to each other, so the calculation formula for the composite standard uncertainty is

$$u_c^2(\Delta L) = c_1^2 u^2(L_i) + c_2^2 u^2(L) \tag{2}$$

Where, $c_1 = \frac{\partial(\Delta L_i)}{\partial L_i} = 1; c_2 = \frac{\partial(\Delta L_i)}{\partial L} = -1$.

The standard uncertainty model for the synthesis of length measurement errors in X-ray 3D dimension measuring machines is [11]

$$u_c(\Delta L) = \sqrt{u^2(L_i) + u^2(L)} \tag{3}$$

3.3. Sources of Standard Uncertainty

According to Appendix C of GB/T 34874.3-2017 [10], the main sources of measurement uncertainty for length measurement errors in X-ray 3D dimension measuring machines are, (A) uncertainty introduced by standards. (B) Uncertainty introduced by the measurement environment. (C) uncertainty introduced by measuring equipment. (D) uncertainty introduced by software and computation. (E) the uncertainty introduced by the measurement program. For (A), its main influencing variable is the measurement uncertainty of the center distance calibration of the forest ball. For (B), due to the sufficient isothermal treatment between the ball plate (forest ball) and the environment where the industrial CT measuring machine is located. Meanwhile, due to the consistent orientation of each club on the ball board (all facing the Z-axis), the difference in club length is small, and the impact of club expansion caused by temperature deviation on the ball center distance is minimal. Therefore, the uncertainty introduced by the measurement environment is ignored. For (C), it mainly comes from the measurement uncertainty introduced by measurement repeatability. For the uncertainty components of (D) and €, they both belong to the standard uncertainty. Considering that the measurement mode and various measurement parameter settings have been determined before the measurement, these two components are not considered in this evaluation example. The sources of standard uncertainty components for measurement results are shown in Table 2.

Table 2. Source and explanation for standard uncertainty of measurement results

$u_i(x)$	Source of standard uncertainty	method
u_{Li}	Measurement repeatability introduces standard uncertainty components	A-class evaluation method
u_L	The standard uncertainty component introduced by the calibration value of the distance between the center of the ball and the ball	B-class evaluation method

3.4. Calculation of Standard Uncertainty

3.4.1. Calculation of u_{Li}

Due to the long calibration time using forest balls, the range method is used for experiments when calculating the uncertainty introduced by measurement repeatability. Under repetitive conditions, using 5 different lengths of forest balls for 3 repeated measurements, the range coefficient *C*=1.69. Calculate the standard deviation s of 5 sets of data separately, and use the maximum standard deviation as the estimated value of the uncertainty component introduced by measurement repeatability. The uncertainty component u_{Li} introduced by measurement repeatability is

$$u_{Li} = 0.47\mu\text{m} \tag{4}$$

3.4.2. Calculation of u_L

According to the traceability certificate for the calibration of the center to center distance of the ball, the expanded uncertainty of the center to center coordinates of the ball is U=2.0 μm (k=2). Since the center to center distance is calculated using the coordinates of two ball centers (X, Y, Z directions), the uncertainty component u_L introduced by the calibration value of the center to center distance of the ball is

$$u_L = \frac{\sqrt{6}U}{k} = \frac{\sqrt{6} \times 2.0\mu\text{m}}{2} \approx 2.45\mu\text{m} \tag{5}$$

3.5. Combined Standard Uncertainty

According to the formula for calculating the composite standard uncertainty, the composite standard uncertainty $u_c(\Delta L)$ of the length measurement error of the X-ray 3D dimension measuring machine is

$$u_c(\Delta L) = \sqrt{2.45^2 + 0.47^2}\mu\text{m} \approx 2.5\mu\text{m} \tag{6}$$

3.6. Expanded Uncertainty

If the inclusion factor k=2 is taken, the extended uncertainty of the length measurement error calibration of the X-ray 3D dimension measuring machine is

$$U = ku_c(\Delta L) = 5.0\mu\text{m} \tag{7}$$

4. Conclusion

Based on the length measurement error calibration method of the X-ray 3D dimension measuring machine based on forest balls, establish an evaluation model for measurement uncertainty and analyze the sources of various uncertainties. Based on measurement examples, this paper elaborates on the process of evaluating the measurement uncertainty of the length measurement error of the X-ray 3D dimension measuring machine based on forest balls, calculates its extended uncertainty, and provides reference for the evaluation of the measurement uncertainty of the length measurement error of the X-ray 3D dimension measuring machine.

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