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Uncertainty estimation for the coordinate measuring machine calibration by using one LaserTRACER

Po Hsu[1], Huay Liou[2], Kam Lui[3]

Email: [1]samhsu@itri.org.tw, [2]pascal_LIOU@itri.org.tw, [3]Paul.Lui@itri.org.tw

Abstract

The coordinate measuring machine (CMM) is widely used in the industry and research. Demonstrating traceability to national standards and estimating the accuracy of measurements made with CMM is of importance for maintaining confidence and reliability of measurements. LaserTRACER is designed to measure and compensate the geometric error of CMMs or machine tools, which the calculation algorithm is implemented with multilateration. Many research used four LaserTRACERs to demonstrate its capability and applications. However, few studies describe using one LaserTRACER to calibrate the CMM.

This paper aims to estimate the uncertainty of the CMM calibration system by using one LacserTRACER. The estimation process is divided into three steps, which are software verification, length measurement uncertainty of LaserTRACER and expanded uncertainty for the CMM calibration system. In the software verification, the simulation data which is no geometric error was utilized to input into the software and to verify the result. Then, according to the ISO/IEC Guide 98-3:2008, the evaluation result of length measurement for LaserTRACER is 0.2 µm + 6.0 $\times 10^{-7} \times L$ (L in m), which is considering the interferometer, form error of the retro-reflector and length reference sphere, etc. For the expanded uncertainty, the Monte Carlo method was applied to estimate the influence from the positing accuracy of the tested machine and the length measurement uncertainty of LaserTRACER.

Keywords: Uncertainty evaluation, Coordinate measuring machine calibration, LaserTRACER

1. Introduction

LaserTRACER developed by PTB (Physikalisch-Technische Bundesanstalt) and NPL (National Physical Laboratory) is composed of a laser interferometer, reference sphere and two-axis rotation stages [1]. It can automatically track a moving retro-reflector mounted on the machine, such as coordinate measuring machines (CMMs), machine tools and robots, to assess its geometric errors.

The multilateration is applied to LaserTRACER to determine the unknown coordinates which are the positions of LaserTRACERs and moving retro-reflector [2, 3]. Therefore, the geometric errors of the machine can be only calculated by the precision length measurement of LaserTRACER. For the multilateration, at least four LaserTRACERs which are setup in non-coplanar condition are required. In addition to using four or more LaserTRACER to assess the geometric errors of the machine, some research presented the sequential multilateration method to reduce the number of LaserTRACERs into one [4, 5]. Comparing these two methods, the measuring process of the sequential multilateration needs to be divided into three or more measurement rounds to finish the whole process. And the moving path of the tested machine has to be defined in each round first, which is used to replace the unknown retro-reflector coordinates. Thus, the positing accuracy of that tested machine is included, and have an influence on the measurement uncertainty.

This paper aims to estimate the uncertainty of the CMM calibration system by using one LacserTRACER, which the sequential multilateration is applied to geometric errors calculation. The Monte Carlo method will be employed to simulate the influence from the positing accuracy of the tested machine. Moreover, the length measurement uncertainty of LaserTRACER will be also considered in evaluating the measurement uncertainty of the CMM calibration system.

2. Measurement uncertainty estimation procedure

The measurement uncertainty of the CMM calibration system estimation process in this research is divided into three steps, which are software verification, length measurement uncertainty of LaserTRACER and expanded uncertainty evaluation.

Figure 1 shows the actual measurement setup, and the user interface for planning the CMM moving path. One of the setups is used to verify the homemade software and to simulate the position determination error of LaserTRACER, which the positing accuracy of the tested machine is introduced.

Leitz PMM-C Ultra, Sizes in x, y, z-axis: (1200, 1000, 700) mm

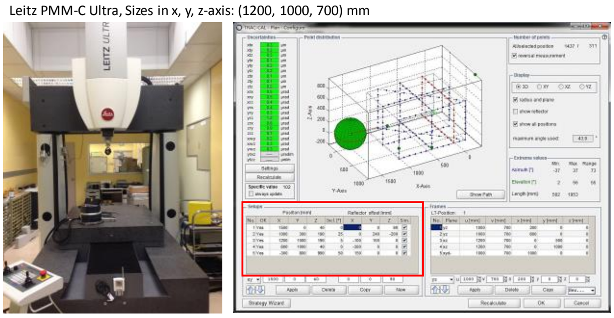

Figure 1. Measurement setup and the user interface of LaserTRACER.

In the software verification, the simulation data which is no geometric error was utilized to verify the results of the homemade coordinate determination algorithm. And the calculation result is matched with the test data.

Then, the length measurement uncertainty of the LaserTRACER is analyzed and calculated based on the ISO/IEC

Guide 98-3:2008 and Dr. Kniel's research [6]. Table 1 shows the uncertainty budget of LaserTRACER. The deviation of the interferometer, wavelength and refractive index are calibrated by the NMI in Taiwan. The form error of the retro-reflector and reference sphere, thermal expansion, etc. are disclosed by Etalon, the manufacturer of laserTRACER. The combined standard uncertainty (k = 1) is 0.2 µm + 6.0 ×10^{-7} × L (L in m).

Table 1. The uncertainty budget of LaserTRACER.

Error source	Deviation	Sensitivity coefficient	Uncertainty
Fringe number of the interferometer (N)	0.577	0.315 µm	0.181 µm
Wavelength (λ_0)	5.50 × 10^{-9} µm	1.58 L µm^{-1}	9.48 × 10^{-9} L
Refractive index (n_{tpf})	6.31 × 10^{-7}	0.9997 L	6.31 × 10^{-7} L
Form error of the reference sphere (S_{form})	14.4 × 10^{-3} µm	1	14.4 × 10^{-3} µm
Thermal expansion ($S_{thermal}$)	-	1	96.8 × 10^{-3} µm
thermal expansion of the reference sphere	84.3 × 10^{-3} µm	1	84.3 × 10^{-3} µm
thermal expansion of the reference sphere base	47.6 × 10^{-3} µm	1	47.6 × 10^{-3} µm
Lateral offset(S_{offset})	2.3 × 10^{-3} µm	1	2.3 × 10^{-3} µm
Form error of the retro-reflector ($S_{reflector\_form}$)	49.1 × 10^{-3} µm	1	49.1 × 10^{-3} µm
The combined standard uncertainty (u_c): 0.2 µm + 6.3 ×10^{-7} × L (L in m)			

3. Expanded uncertainty of the CMM calibration system

LaserTRACER is the standard for the CMM calibration system, and the sequential multilateration is applied to determine the positions of LaserTRACER to assess the geometric errors of the CMM. In this research, the variation of the LaserTRACER's positions determination, which is affected by the positing accuracy of the test machine is used to evaluate the expanded uncertainty of the CMM calibration system.

One of the CMM actual measurement setup and result, which is described in Figure 1 is to be the reference data to calculate the LaserTRACER's position determination error. There are two steps for the expanded uncertainty evaluation of the CMM calibration system. The positing accuracy of the CMM is the only factor considered in the first step, and then the length measurement uncertainty of the LaserTRACER is combined with the positing accuracy to analyse the expanded uncertainty of the CMM calibration system.

In the first step, the positing accuracy of the CMM is given to ± 5 µm, which is assigned in x-, y- and z-axis randomly in the actual measurement setup. The Monte Carlo method is applied to simulate 2000 measurement rounds to analyse the variation of position determination errors. In the simulation result, the error is ± 0.16 µm while positing accuracy of the CMM is ± 5 µm.

In order to analyse the relationship between the measuring length and the position determination error, the measurement setup is divided into 4 groups which are 0 mm ~ 500 mm, 500 mm ~ 1000 mm, 1000 mm ~ 1500 mm and 1500 mm ~ 2000 mm to introduce the measurement uncertainty of the LaserTRACER. Moreover, the probability distribution of the LaserTRACER's measurement uncertainty are assumed to the normal distribution in the simulation process.

Figure 2 illustrates the simulation result for the expanded uncertainty in 1500 mm to 2000 mm measuring length. Based on the simulation result, the CMM calibration capabilities in different measuring range are as follows.

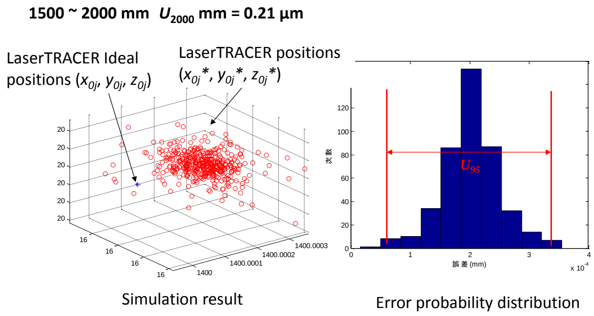

Figure 2. Expanded uncertainty (in 1500 mm to 2000 mm).

- 0 mm ~ 500 mm, $U_{500\ mm}$ = 0.34 µm
- 500 mm ~ 1000 mm, $U_{1000\ mm}$ = 0.34 µm
- 1000 mm ~ 1500 mm, $U_{1500\ mm}$ = 0.25 µm
- 1500 mm ~ 2000 mm, $U_{2000\ mm}$ = 0.21 µm

4. Conclusion

This paper aims to estimate the uncertainty of the CMM calibration system by using one LacserTRACER, which is based on the sequential multilateration. The Monte Carlo method is implemented in the simulation of the positing accuracy of the tested machine and the measurement uncertainty of LaserTRACER.

From the simulation result, the expanded uncertainty of CMM calibration system is getting smaller when the measuring length is increased. The reason is that the number of the length measurement positions of the planned CMM moving path in different measuring length. For instants, there are only 8 positions of the planned CMM moving path in the 0 mm ~ 500 mm measuring length. However, there are 165 positions in the 1000 mm ~ 1500 mm measuring length. The simulation result is reflected that LaserTRACER which is used to be the standard for the CMM calibration system is suitable for long measuring length. Especially, the sequential multilateration is employed to determine the LaserTRACER's position.

In the future, a test will be conducted to obtain the actual data to verify the simulation result. And a long gauge block will be also used to calibrate the CMM, and to compare the compensation result of the CMM.

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