Comparison of Three Compensation Methods for the Touch-trigger Probe Pretravel Errors

Simi Li¹, Long Zeng²*, Pingfa Feng¹,² and Dingwen Yu¹

¹Department of Mechanical Engineering, Tsinghua University, 100084 Beijing, P.R.China
²International Graduate School at Shenzhen, Tsinghua University, 518055 Shenzhen, P.R.China

*Corresponding author’s E-mail address: zenglong@sz.tsinghua.edu.cn

Abstract. On-machine inspection (OMI) system has been used extensively for automatic setting of the workpiece and determination of kinematic error in machine tool. There is a necessity not only for knowledge of touch-trigger probing error characteristic, but also for the compensation method of probe error because probing error is an important component of system errors. The comparison of compensation accuracy of three compensation methods is presented. To compensate the touch trigger probe pre-travel errors the calibration experiments with a reference sphere are conducted. Subsequently, the calibration data are used in three compensation methods that the bilinear interpolation method, the bicubic Coons pitch interpolation method and the neural network method. Finally, the validate experiments are conducted on the OMI system, and the compensation results show that the bicubic Coons pitch interpolation method is the most accuracy compensation method.

1. Introduction
On-machine inspection (OMI) system mounts a touch-trigger probe on a CNC machine’s spindle. It can inspect part quality during or after manufacturing processes without moving it, avoiding the second-clamping error [1]. It is widely applied in automatic workpiece set-up and determination of machine tool’s kinematic errors. The error of touch-trigger probe usually exceeds 10 μm, larger than machine tool’s geometric error. Its accuracy is usually compensated by a calibration process.

Current probing error compensation methods mainly based on two models: theoretical probe-model and data-driven based model. The formers usually develop a mechanical model of the used probe, considering various factors of calibration process, such as the measurement direction, the measurement velocity, the stylus length, gravity and so on. One classical theoretical model analyzed a touch-trigger probe’s mechanical structure. It considered the elastic bending of the stylus w.r.t. triggering directions. This error is called probe pre-travel variation. This theoretical model is generalized in ref.[2], by considering the influence of friction and gravity. The Hertz deflections of the probe and the workpiece surface were considered in ref. [3]. However, Using the Lavenberg-Marquardt method[4] to identify the undetermined parameters of the mechanical model of the probe is complex. The data-driven based compensation models directly build an error map and it mainly contains two parts. The first part is the discrete error map of all pre-travel errors in calibrated directions, while the second part is a computational method (e.g., interpolation) to estimate the error of un-calibrated directions. The most widely used computational method is interpolation. Others are...
neural network[5], fuzzy logic[6] and Monte Carlo simulation[7]. During the inspection process, the compensation error for an arbitrary measurement directions can be easily obtained by query the error map. The interpolation method for probe error map includes two categories: the global interpolation method and the local interpolation method. The global interpolation method fits calibrated directions’ pre-travels as a 3D surface that the pre-travels are increasing with polar angle decreasing and pre-travels in one latitude form a triangle as mentioned in ref.[8]. The local interpolation method, local points are selected to construct pitches, and a large number of pitches are combined to form a whole surface. For example Ref. [9] applied the bilinear interpolation method to build the probe error map. The piecewise surface from bilinear interpolation method is not accurate enough. First, the patch boundary is sharp. Second, the errors of the un-calibrated directions are lost since they are a bi-linear interpolation of known calibrated-direction errors.

In this paper, the comparison of three compensation method for touch trigger probe pre-travel errors is proposed. First, the calibration method of the reference sphere by the OMI system is presented. Second, three compensation method that include the bilinear interpolation method, the bicubic Coons pitch (BCP) interpolation method and the neural network method are applied to compensate the pre-travel errors. To compare the accuracy of three compensation method, verification experiments are conducted in the measurement direction different from the calibration process, and the experiment results show that the BCP method is the most accuracy method.

2. Calibration of pre-travel errors

2.1. Definition of pre-travel error

The pre-travel error is the distance between and , which represents the probe characteristic (as shown in figure 1). Pre-travel error is affected by many factors, including the probe structure, the measurement direction, the measurement speed, the triggering force, length and stiffness of the probe system, time delay between probe signal and machine position sensor reading, etc. However, without changing the measuring environment, the repeatability of the probe is typically within 1.0 μm at the stylus tip. Therefore, the repeatability of compensation probe error with 3D error map is typically within 1.0 μm. Establishing 3D error map generally includes two steps: 1) calculating probe error of calibrated point (or direction), 2) calculating probe error of uncalibrated point (or direction) by the interpolation method.

![Figure 1. Probe error and pre-travel formation process](image)

2.2. Calibration of pre-travel errors

According to the limited direction of the calibration ball, the error map can be established by modeling or numerical analysis. It is calibrated but generally distributed uniformly in the upper hemisphere of the calibration ball, as shown in figure 2.
It is very important to accurately fit the centre of the sphere for calculating the pre-travel in different directions. The calibration data contain anisotropic pre-travel errors, therefore a calibration data processing strategy is purposed to calculate the accurate centre of the sphere. The pre-travel errors with different azimuth angles present triangular trend, while the pre-travel errors increase with the polar angle increase. The contact force acts on the supporting structure of the measuring rod. When the moment generated exceeds the moment generated by the spring force, the supporting structure of the measuring rod will deflect. Trigger signal is generated when the deflect angle reaches the threshold value. Therefore, the pre-travel error value is positive proportion to the arm of trigger force, and it is negative proportion to the trigger force.

As shown in figure 3, a reference sphere is mounted on the force sensor, the probe measure the reference sphere from 33 directions, the measurement points uniform distribution in the upper half of the reference sphere. The measuring points are distributed in three latitudes 30 degrees apart and the polar, while 8 points in each latitudes. The measurement results show that the deviation of points in the same latitude is much less than that of between different latitudes. And the trigger force at the polar is ten times of it at the equator. Therefore, all the calibration points except the poles are symmetrical in the XY plane. The reference sphere centre in the XY plane could be calculated by the lease square method. The location on Z axis could be calculated by assume the pre-travel at this point is zero.

3. Compensation of pre-travel errors
The preset travel error is a vector that changes with the direction of measurement. The direction of the vector is the direction of measurement and the modulus of the vector is the pre-travel error value. All calibration data contains a distributed error map. Three compensation method are used to the same calibration data to build the continuous 3D error map. Subsequently, the residuals of error
compensation of validate experiments that measuring the reference sphere from directions different from the calibration data.

First compensation method is bilinear interpolation method. As shown in figure 4, the error vector of each direction can be expressed as \( Q(\theta,\phi_i) \), where i and j are the indexes of the polar angle \( \theta \) and azimuth angle \( \phi \) of the probe, respectively. When the measuring point \( Q(\theta,\phi) \) is on a surface consisting of four points \( Q(\theta,\phi_j), Q(\theta,\phi_j+1), Q(\theta+1,\phi_j), Q(\theta+1,\phi_j+1) \). The probe pre-travel error of the point \( Q(\theta,\phi) \) could be calculated by four corner points, the equation is

\[
Q(\theta,\phi) = (Q(\theta_i+1,\phi_j) - Q(\theta_i,\phi_j))\theta + (Q(\theta_i,\phi_j+1) - Q(\theta_i,\phi_j))\phi
\]

\[
+ Q(\theta_i+1,\phi_{j+1}) + Q(\theta_i,\phi_j) - Q(\theta_i+1,\phi_{j+1}) - Q(\theta_i,\phi_j)\phi + Q(\theta_i,\phi_j)
\]  

(1)

Bilinear interpolation method is \( C^0 \) continuously.

Second interpolation method is bicubic Coons pitch (BCP) interpolation method. As shown in figure 5, assuming that the error vector of the uncalibrated point is \( Q(\theta,\phi) \). It can be calculated as follows:

\[
Q(\theta,\phi) = \begin{bmatrix}
F_\theta(\theta) \\
G_\theta(\theta) \\
G_\phi(\theta) \\
F_\phi(\theta)
\end{bmatrix} \begin{bmatrix}
Q(\theta_i,\phi_j) \\
Q^\theta(\theta_i,\phi_j) \\
Q^\phi(\theta_i,\phi_j) \\
Q(\theta_i,\phi_j)
\end{bmatrix} = \begin{bmatrix}
F_\theta(\theta) \\
G_\theta(\theta) \\
G_\phi(\theta) \\
F_\phi(\theta)
\end{bmatrix}
\]

(2)

where the specific calculation method can be referred to our previous research[10].

**Figure 4.** Mesh generation of the bicubic interpolation method

**Figure 5.** Mesh generation of the bilinear interpolation method

Third, neural network method is used to calculate the pre-travel errors in un-calibrated directions. A two-layer feed-forward network with sigmoid hidden neurons and linear output neurons network is built. The neural network toolbox in Matlab is used. The structure of the neural network and the fitting performance of the neural network is shown in figure 6 and figure 7, respectively.
4. Experimental Verification and discussion

To validate the proposed method, three error maps is built to compare the accuracy of compensation. The experiments are conducted on 541 points of a reference sphere, 121 of them are used to build the error maps and the other data is used to validate the accuracy of compensation.

4.1. OMI experiment setup

A Renishaw strain gauge probe is mounted on the machine tool’s spindle to calibrate a reference sphere in 541 different directions (as shown in Figure 3). 121 of 541 points are selected to build the compensation model in three different methods. Subsequently, the other calibration data are used to validate the accuracy of models.

4.2. Experimental Verification and discussion

To compare the accuracy of three compensation methods, 121 calibration data are used to build the error map for the probe pre-travel errors. The trend of the average residual of the three compensation methods varying with the polar angle is shown in figure 3. The average residual after compensation by BCP and neural network method is increasing with polar angle increasing and that of bilinear method is fluctuating with polar angle increasing. As shown in Table 1, the overall average absolute residual of BCP method is smallest. As shown in figure 8, the deviation of residual after all three compensation method are increasing with the polar angle increasing, which is because the uncertainty of measurement results for large polar angle points are increasing. Compare three method (as shown in figure 9), the deviation of residuals compensation after BCP method is slightly smaller than neural network method. Therefore, the accuracy of BCP method is better than other two methods.

5. Conclusions

This paper compares three error compensation method based on the 3D error map for an OMI system mounted with a strain gauge probe. First, the calibration experiments was conducted by measuring a reference sphere in 121 different directions. Second, three different compensation methods were applied to the same calibration data. Final, the validate experiments were conducted by measuring the same reference sphere in 541 different directions. Comparing with the experiment data the model
compensation residuals are computed. No matter comparing the average absolute residual or the average residual deviation BCP method is better than another two. The reason why the uncertainty of the probe is large when the polar angle of measurement direction is large needs further study.

Acknowledgments
This paper is supported by the National Natural Science Foundation of China (Grant No. 51705281, Grant No. 61972220), Beijing Science and Technology Program (Grant No. D131100002713003), and National Defence Basic Scientific Research Program JCKY2018208B014.

References
[1] Guiassa R., Mayer J.R.R., St-Jacques P., and Engin S., Calibration of the cutting process and compensation of the compliance error by using on-machine probing. The International Journal of Advanced Manufacturing Technology, 2014. 78(5-8): p. 1043-1051.
[2] Estler W.T., Phillips S.D., Borchart B., Hopp T., Witzgall C., Levenson M., Eberhardt K., Mcclain M., Shen Y., and Zhang X., Error compensation for CMM touch trigger probes. Precision Engineering-Journal of the American Society for Precision Engineering, 1996. 19(2-3): p. 85-97.
[3] Woźniak A. and Dobosz M., Metrological feasibilities of CMM touch trigger probes. Part I: 3D theoretical model of probe pretravel. Measurement, 2003. 34(4): p. 273-286.
[4] Woźniak A., Simple method of 3d error compensation of triggering probes on coordinate measuring machine. Metrology and measurement systems, 2006. 13: p. 289-299.
[5] Achiche S. and Wozniak A., Three-dimensional modeling of coordinate measuring machines probing accuracy and settings using fuzzy knowledge bases: Application to TP6 and TP200 triggering probes. Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 2011. 26(04): p. 425-441.
[6] Achiche S., Wozniak A., and Fan Z., 3D CMM Strain-Gauge Triggering Probe Error Characteristics Modeling Using Fuzzy Logic. Annual Meeting of the North American Fuzzy Information Processing Society, 2008: p. 194-197.
[7] Sładek J. and Gaśka A., Evaluation of coordinate measurement uncertainty with use of virtual machine model based on Monte Carlo method. Measurement, 2012. 45(6): p. 1564-1575.
[8] Mayer J.R.R., Ghazzar A., and Rossy O., 3D characterisation, modelling and compensation of the pre-travel of a kinematic touch trigger probe. Measurement, 1996. 19: p. 83-94.
[9] Jankowski M., Woźniak A., and Byszewski M., Machine tool probes testing using a moving inner hemispherical master artefact. Precision Engineering, 2014. 38(2): p. 421-427.
[10] Li S., Zeng L., Feng P., Li Y., Xu C., and Ma Y., Accurate compensation method for probe pre-travel errors in on-machine inspections. The International Journal of Advanced Manufacturing Technology, 2019.