Development of high precision Coordinate Measuring Machine (CMM)  
(1st report, Evaluation method of XY stage)
Department of Precision Engineering, The University of Tokyo
Ping Yang, Shusaku Shibata, Satoru Takahashi, Kiyoshi Takamasu
Advanced Industrial Science and Technology
Osamu Sato, Sonko Osawa, Toshiyuki Takatsuji

Abstract: To develop a high precision Coordinate Measuring Machine (CMM), it is important to evaluate the XY stage on the CMM. In this paper, multi-laser interferometers are mounted in a stationary sensor stage, and a standard bar mirror is fixed on the moving table. A multi-probe measurement method is developed to analyze the motion error of horizontal straightness and the yaw error simultaneously.

Keywords: Coordinate measuring machine, XY stage, multi-probe measurement, straightness

1. Introduction
As micro-systems have been developed continuously, the demands for higher measurement accuracy have increased in the field of dimensional metrology. Conventional measuring methods restrict the possibilities for three-dimensional measurements on micrometer products. Conventional coordinate measuring machines (CMMs) lack the required level of uncertainty and do not comply with the proper probing systems in many applications.[1] The micro-CMMs are currently developed with special micro-probes. The micro-CMMs are discussed in the following projects.

Isara is commercial small CMM which is now available from IBS Precision Engineering. Its design is a metrology frame with thermal shielding on which three laser sources are mounted and a moving product table.[2]

F25 micro-CMM is another commercial product available from Carl Zeiss.[3] The National Physical Laboratory (NPL) is currently carrying out research into reducing the size of the probing sphere to allow measurement of even smaller structures. VSL is studying the traceability of the F25. The Physikalisch-Technische Bundesanstalt (PTB) works together with Carl Zeiss that are researching on the field of 3D micrometrology.

M-NanoCoord designed by Mitutoyo is a flexible 3D vision measuring machine using the UMAP switching probe system.[4]

The specifications of these products are shown in Table.1.

<table>
<thead>
<tr>
<th>Micro-CMMs</th>
<th>Range-XYZ(mm)</th>
<th>Uncertainty(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isara</td>
<td>100x100x40</td>
<td>30</td>
</tr>
<tr>
<td>F25</td>
<td>100x100x100</td>
<td>Less than 100</td>
</tr>
<tr>
<td>M-NanoCoord</td>
<td>200x200x100</td>
<td>200</td>
</tr>
<tr>
<td>M-CMM</td>
<td>160x160x100</td>
<td>Aim for 50</td>
</tr>
</tbody>
</table>

2. System configuration of the micro CMM structure
A novel high precision CMM called M-CMM has been developed, and a prototype has been settled up at the Advanced Industrial Science and Technology (AIST). The structure of the M-CMM includes three main components: Z-axis, probe unit, and XY-axis.

2.1 Z-axis
The Z-axis structure is embedded in the center of the frame which is built on the base plate, as show in Fig.1. Z-axis motion system is composed of a counterbalancing weight, air bearing sliders, an AC servomotor, etc. The Z-axis moves separately so that the Z-axis performs better static stiffness. The structure is mainly made of alumina ceramic (CTE=7ppm).

![Fig.1 Main Structure of M-CMM](image)

2.2 Probe unit
The probe unit that has a changeable connector is mounted on the Z-axis, as shown in Fig.2. The M-CMM will measure with the different probing systems that contain Renishaw TP200 and Mitutoyo UMAP103 to indentify the 3D uncertainty.

2.3 XY-axis
The XY-axis is a stacking-type mechanism made by two linear stages that composed of air bearing sliders, Lorentz actuators, linear scales, moving tables, etc., as shown in Fig.2. Each axis motion is actuated by a Lorentz actuator and its motion is detected by a linear scale mounted on the moving table. The whole stage is made of alumina ceramic of 7ppm CTE, and the base plate is made of granite of 5ppm CTE. Therefore, the thermal deformation dues to...
the driving heat and temperature changes can be significantly reduced.

![Fig.2 Structure of XY stage and probe unit](image)

3. Calibration of M-CMM
The Abbé error of the XY stage is high and the accuracies of components are made in the range of micrometer. More considerations should be taken into account when the XY stage is required for high motion accuracy. To improve Abbé error in vertical direction of the motion accuracy, it is important to measure the straightness profiles and the yaw error of each moving table on the M-CMM. The multi-probe method has been proposed for this purpose.

3.1 Multi-probe method of XY stage
The multi-probe method detects the XY stage movements and the profile of the mirror separately. The multi-probe method utilizes the sequential two point method which measures by two position sensors, and one autocollimator that measures the yaw error. \(^{[5]}\)

Unlike fixing sensors on the moving scanner, the two position sensors are mounted on a stationary sensor stage to probe the profile of the standard bar mirror which is fixed on the moving table, and one autocollimator is used to measure the yaw error simultaneously, as shown in Fig. 3. Let the corresponding probe outputs be 

\[
\begin{align*}
m_1(x_n) &= f(x_n) + e_x(x_n) + 0 \cdot e_y(x_n) + u_1 + b_1, \\
m_2(x_n) &= f(x_n + D) + e_x(x_n) + D \cdot e_y(x_n) + u_2 + b_1, \\
m_3(x_n) &= e_y(x_n) + u_3,
\end{align*}
\]

where \(D\) is an interval of the position sensors, \(N\) is the data number over the entire scanning length, \(e_x(x_n)\) and \(e_y(x_n)\) are the motion error and the yaw error of the moving table, \(u_1\), \(u_2\) and \(u_3\) are the offset of each probes, and \(b_1\) is an unknown fixed number. The algorithms of straightness profile were analyzed numerically using the simultaneous equation method and least square techniques. The \(e_x(x_n)\) calculated by the equations (1) and \(e_y(x_n)\) measured by autocollimator are compensated into the motion control system to yield moderately accurate motion results.

4. Simulation
The experiments were evaluated theoretically by computer simulation where the simulated sensor outputs are derived from the predefined straightness profile of bar mirror \(f(x)\), and motion error \(e_x(x_n)\) and yaw error \(e_y(x_n)\) is the random number from the simulation. The real profile of \(f(x)\) is picked up by the predefined function. The reconstructed profile of \(f(x)\) is fitted by the sampling points by using the least square algorithms. When \(D = s = 5\) mm and the measuring step distance is the same as the distance of the probes, the standard deviation of each sensor is considered as \(\sigma_{m1} = 1\) nm, \(\sigma_{m2} = 1\) nm, \(\sigma_{m3} = 1\) μrad, the equations from (1) can be simplified. The sampling length equals 100 mm. The result value of the standard deviation \(\sigma\) is 7.6 nm. When \(D = s = 10\) mm, the standard deviation \(\sigma\) reaches to 9.2 nm.

5. Conclusions
The multi-probe measurement method is found to have a good performance in measuring the straightness profile and the yaw error with low standard deviation. The theoretical analysis reported in this simulation study encouraging the author to perform an experiment study in the near future.

6. Acknowledgements
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7. References