Development of high-precision micro CNC machine with three-dimensional measurement system and high-precision coplanar platform

Chih-Liang Chu*, Chin-Tu Lu, Tzu-Yao Tai, Yun-Hui Liu, Chen-Hsin Chuang, Hung-Chi Chen and Hong-Wei Liao

Abstract—This study aims to develop a machine center consisting of high-speed micro-milling machine, micro-EDM and coordinate measuring machine. A PC-based controller was used and its human-machine interface was written by Visual Basic 6.0 in this study. The machining and measurement performance of the proposed system was enhanced through the use of a rigid aluminum double-arch-bridge structure to support the Z-axis structure. For the working stage, a linear motor was used for long-stroke positioning and a piezoelectric actuator was then employed to fine-tune the positioning so as to achieve a requirement of high-precision. The platform has two characteristics: (i) the driving and measuring axes are designed along the same line so that Abbe error of the stage can be eliminated; (ii) the coplanar design makes the X and Y axes reach a goal of two-axis concurrent. The aforementioned two designs can reduce the error of the platform. Furthermore, a commercially available rapid adapter was installed in the Z-axis structure for the rapid assembly of C-axis rotation, high-speed micro-milling spindle and three-dimensional measuring probe. Besides, a fuel tank, a WEDG winding mechanism and a workpiece holder were fixed to the work platform. Therefore, the machine has the functions to quickly switch micro-EDM, high-speed micro-milling and three-dimensional measurement. The machine center has successfully produced micro probes with a front-end sphere diameter of less than 100 μm. Combining with a self-developed trigger circuit, it completed a three-dimensional touch trigger probe. The measurement software was self-developed by Borland C++ Builder. Integrating three dimensional touch trigger probe with three-axis linear scale, the three-dimensional coordinates of the measured values were calculated and processed. It has been successfully applied to the measurements of points, lines, circles and angles.

Keywords: micro EDM, high-speed milling, micro 3D CMM, WEDG, touch-trigger probe

I. INTRODUCTION

As technology advances and people seeks the use of objects toward light weight and convenience, the main development trend of products such as flat-panel displays, flexible electronics, biochips, micro-gear, micro-sensors, etc., is toward miniaturization. Currently the main micro-fabrication technology includes four processing methods: (1) lithography technique process, its light source can be an X-ray, electron beam, or UV light; (2) excimer laser processing; (3) micro-machining; (4) silicon micro-machining process. In the existing literature of EDM to create micro probes, the micro-EDM process not only needs no additional mold design, but has the advantages of finished products with anti-wear and high accuracy. In addition, micro-EDM can also be utilized to process ink jet printer heads [1], micro-nozzles of the atomizing film production [2], micro-vias [3], miniaturized biomedical products such as micro-delivery devices, micro-fluidic mixer [4], micro-biochip [5], micro-pump [6], and so on in the future. Therefore, in order to complete processing of micro-components, Chen [7] developed a multi-task small CNC machine. The machine has the functions of micro-milling, electrochemical discharge compound micro-processing, current fluid polishing and electrode inspection on the machine. It can be used for the fabrication of micro-mold, biochips, micro-channel with high aspect ratio structure. At present, most of foreign commercial micro-machines are single-function with high price. The machines with multi-functions will be more expensive and the relevant techniques are not mature. In Taiwan, it mainly relies on imported expensive machines, indicating that there are no equipment vendors to invest the multi-micro machines yet. Therefore, this study will develop a machine center consisting of high-speed micro-milling machine, micro-EDM and micro-coordinate measuring machine. Through its micro-EDM and high-speed micro-milling, various optical structure patterns will be produced on the roller surface to solve the discontinuous issue of roller mold. With three-dimensional measuring system for online real-time measurements, it can achieve effective mass production of optical-grade structure of roller type mold.
II. DESIGN PRINCIPLES

A. Double-arch-bridge structure

In commercial micro-CMMs, the measurement probe system is generally mounted on rectangular or arch-type bridge structures. By contrast, in the micro-CMM system developed in this study, the probe was mounted on a novel double-arch-bridge structure of the form as shown in Fig. 1. Utilizing finite element analysis (FEA) software ANSYS, a series of simulations were performed to compare the static rigidity of the three bridge structures. Table 1 lists the deformations of the three bridges in the Z-direction when subjected to a normally applied load of 30 N in their central position. Therefore, the results confirm that the double-arch-bridge structure yields a significant improvement in the structural rigidity of the probe support system and can be reasonably expected to enhance the measurement accuracy of the proposed micro-CMM.

![Fig. 1 Proposed double arch-bridge structure](image)

Table 1 Static analysis of bridge structures under a load of 30 N

<table>
<thead>
<tr>
<th>Bridge structure</th>
<th>Z-axis deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular-bridge</td>
<td>3044.2 nm</td>
</tr>
<tr>
<td>Arch-bridge</td>
<td>213.4 nm</td>
</tr>
<tr>
<td>Double-arch-bridge</td>
<td>110.6 nm</td>
</tr>
</tbody>
</table>

B. The Z-axis structure design

The Z-axis was designed and constructed from a fixed frame with suitable size of arch stands. The arch stands of the double arch-bridge structure formed a frame based on a semi-circular arch. Thus, the addition of the Z-axis fixed frame should be cared about the four arch stands still remaining semi-circular in order to achieve the objective of increasing structural rigidity. The study used two linear guide ways for the Z-axis guiding. The linear guide ways were symmetrically attached to both sides of an octagonal fixed frame. Sliders on both sides were then connected by a bridge block. Due to the symmetrical geometry of the double-arch-bridge, two fixed pulleys were mounted in the centre of the bridge through a top arch. In order to reduce the load on the Z-axis linear motor, a coaxial counterweight was used to balance the driving force. The Fig.2 presents a photograph of the fully assembled Z-axis structure. Besides, a quick adapter was used for the rapid functional exchange between the micro-EDM, high-speed micro-milling, and three-dimensional measurement.

C. Coplanar platform

A coplanar platform was designed and driven by a linear motor for the long-stroke positioning in this study. Beneath the linear motor, a nano stage was designed to adjust the small displacement. An optical encoder was employed for a feedback control. Two bearings were placed in a groove for guiding the stage. On the right side of the bearing, a fine-tuning device was designed to ensure that the bearing was indeed in contact with the edge, as shown in Fig. 3. In the design of positioning fine-tuning, the nano stage was placed beneath the linear motor holder and promoted by a piezoelectric actuator. It brought the entire linear motor assembly forward in order to achieve the fine tuning function. The explored diagram of a single axis is shown in Fig. 4. In order to make the coplanar platform reduce the errors and improve the accuracy, the X and Y axes were designed and based on the concept of coaxial and concurrent. The coaxial is defined as the driving and measuring axes along the same line so that the Abbe error can be reduced. With a concurrent design, it further lowers the processing error of whole stage. An overall photograph of the coplanar platform is shown in Fig. 5. The platform has an overall size of 395×395×53 mm³ with the X and Y axis strokes up to 80 mm.

![Fig. 2 Photograph of the fully assembled Z-axis structure](image)

![Fig. 3 The fine-tuning device of side lever](image)

![Fig. 4 Explored diagram of a single axis](image)
In the design of the coplanar platform with fine-tuning, the fine-tuning was provided by the nano piezoelectric stage that was placed beneath the driving axis. Through analysis, it ensured that the displacement of the nano piezoelectric stage as expected. In the analysis, it assumed that the entire driving axis had a load of 30N and the piezoelectric actuator imposed a thrust of 173N to the stage. The X-direction displacement of the stage was 20μm as expected and shown in Fig. 6. Subjected to the weight of entire driving axis, the maximum Y-direction displacement was only 0.5μm as shown in Fig. 7.

In the coplanar platform, four air bearings were adopted and placed beneath the working stage to reduce the frictional force and to increase the loading capability of the stage. Finite element software was used to analyze the stage subjected to a loading situation and to understand the pros and cons of the different locations of the air bearings as shown in Fig. 8. In the analysis, a load of 50N was imposed to the stage. The result showed that the deformation was concentrated near the central position, but the maximum deformation was only 0.05μm as shown in Fig. 9. This proved that the location design of the air bearings was acceptable.

D. Micro EDM Equipment

This study has designed a discharge circuit by means of a transistor to control the capacitors. The control loop circuit was used to detect the capacitor’s voltage and spacing, and then to decide whether to activate the transistor and the discharge process. Figures 10 show the discharge circuit and the control circuit.

This study designed a WEDG mechanism. As shown in Fig. 11, it is mainly divided into a line supply mechanism, a line guide mechanism, a pulling motor mechanism, a line closing mechanism, and a C-axis rotation. The C-axis rotation was driven by a servo motor which could rotate 360° for positioning and angle split. The rotation accuracy and positioning accuracy of the C-axis rotation is 1μm. In processing, the probe was clamped in the C-axis for rotation, while the line guide mechanism transferred wire electrode for electrical discharge machining. The U-shaped slot fixed wire electrode to minimize vibrations and to facilitate the improvement of processing accuracy. Figure 12 is schematic for the EDM. This study has successfully produced a micro-probe with front-end ball diameter less than 100 μm and roundness up to 3 μm as shown in Fig. 13.
E. High-speed micro-milling equipment

The high-speed spindle adopted in this study is pneumatic and has a maximum speed of 80,000 rpm. It could be used for EDM with WEDG mechanism and for high speed drilling. A quick adapter was used for the rapid functional exchange between the C-axis rotation and three-dimensional measurement probe. The photograph of high-speed spindle is shown in Fig. 14.

F. Development of a scanning touch probe

The probe incorporated in the micro-CMM developed in this study consisted of two optical sensors and a structure of only three degrees of freedom [8]. The structure can be divided into a Z-axis structure and an XY-axis structure. Displacement of Z-axis of the pivot spring influences the Z-axis structure and causes error. In order to prevent such error, a live center was mounted to the center of the structure to inhibit the displacement of Z-axis so that the structure had only angle variation in X- and Y-axis, which accounted for the characteristic of two degrees of freedom. Figure 15 presents a schematic illustration of the Z-axis structure and the XY-axis structure. Referring to Fig. 15, the XY-axis structure suppresses translational motions along the X-axis and Y-axis (i.e., δAx and δAy), respectively, and prevents a rotational motion around the Z-axis (θz). As a result, the suspension structure has only three degrees of freedom. In the CMM developed in this study, the translational (δAz) and angular displacements (θx and θy) of the scanning touch probe were measured using a one-dimensional displacement sensor and a two-dimensional angle sensor, both based on a commercial Position Sensor Detector (PSD). In the design of optical path, the light beam emitted from a laser diode was used as the light source. Figure 16 presents a schematic illustration of the orientation of the two optical sensors relative to the Z-axis structure and XY-axis structure, while Fig. 17 presents a photograph of the fully-assembled scanning touch probe.

G. Set-up and measurement results

The design of the machine center in this study adopted a PC-based approach. The machine center integrated four-axis motion systems with the measurement system through a four-axis control card and a data acquisition card as shown in
In Fig. 19, the scanning touch probe holder was mounted on the Z-axis structure, and then was integrated with the double-arch-bridge structure and the coplanar platform to carry out measurement tests. In order to satisfy the Abbe principle, the three-axis positioning platforms and an optical encoder were constructed in such a way that three axes intersect at a point (see Fig. 19). In this way, when the working area moved along one axial direction, the movements in the other axial directions were suppressed and hence the Abbe principle was satisfied. The total working volume of the CMM could be $80 \times 80 \times 40 \text{ mm}^3$. Accordingly, the three positioning platforms in the proposed CMM were independently driven by linear motors with an accuracy of $\pm 0.1 \mu\text{m}$. Figure 20 presents a photograph of the fully-assembled micro-CMM with its all various components. The whole system was controlled by an industrial computer using a software system self-developed in the Visual Basic 6.0 environment as shown in Fig. 21.

H. Positioning Accuracy Tests

The optical encoders in the CMM system were to measure the displacements of the micro-positioning platforms during the CMM measurement procedure. To confirm the precision of the optical encoders, a series of positioning tests were performed in which the displacement measurements obtained from the optical encoders were compared with those obtained using a Doppler laser interferometer. Since the three positioning platforms were all driven by identical linear motor drivers, the positioning accuracy tests were carried out in a single axial direction only. In the experiments, the positioning platform was driven through a total distance of 10 mm in incremental steps of 1 mm and was then returned to its starting point again in the same incremental steps. The experiment was repeated nine times for each stationary position of the platform. Figure 22 plots the differences between the nine times positioning precision measurements and the corresponding Doppler measurement at each stationary position. From inspection, it was determined that the displacement measurements of the encoder deviated from those of the laser interferometer by no more than $\pm 0.1 \mu\text{m}$. If the influence of the environment was isolated, the positioning precision of the platform could be further improved.
Fig. 22 Measurement errors of optical encoder relative to displacement values determined using Doppler laser interferometer

I. Scanning Touch Probe Tests

The data detected through this experiment was uncertainty; the lower value indicated the higher accuracy of the measurement. The experimental configuration is shown in Figs. 23. The linear motor serving as driving shaft drove the ball at the end of stylus horizontally and its displacement was measured by a Doppler laser interferometer (Model MCV-500). The interferometer, with a device to compensate pressure and temperature, had a resolution up to 0.1μm. Through interferometer measurement, the positioning could be performed accurately in order to reduce the error during measuring. In Fig. 23, the voltage signal was processed by an amplifier and a signal processing circuit, then A/D signal transfer was accomplished with the data acquisition card PCI-6013, manufactured by National Instruments Company, and finally the data were read and recorded by an industrial computer which played a core role in the overall measurement. The platform of the linear motor was moved to a proper location, and then moved 5μm forwards to allow simultaneous observation on the output signal of X-, Y-, and Z-axis of the probe. When the platform reached the designated location, it triggered A/D and repeated this measuring process. The displacements triggered by this process were recorded as listed in Table 2. It is clear that this scanning probe had measuring unidirectional repeatability 0.6 μm within the range of 5μm.

![Experimental setup for evaluating the measurement capabilities of a scanning touch probe](image)

**Table 2 Unidirectional repeatability**

<table>
<thead>
<tr>
<th>Number</th>
<th>Pre-travel (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.4</td>
</tr>
<tr>
<td>2</td>
<td>5.2</td>
</tr>
<tr>
<td>3</td>
<td>4.8</td>
</tr>
<tr>
<td>4</td>
<td>4.7</td>
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<td>5</td>
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<td>7</td>
<td>5.3</td>
</tr>
<tr>
<td>8</td>
<td>4.6</td>
</tr>
<tr>
<td>9</td>
<td>5.3</td>
</tr>
<tr>
<td>Average</td>
<td>5.1</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Standard deviation (σ)</th>
<th>Unidirectional repeatability (2σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>0.6</td>
</tr>
</tbody>
</table>

III. CONCLUSION

This study has developed a high-precision micro CNC machine with three-dimensional measurement system and high-precision coplanar platform. In such a way, the Abbe error is effectively suppressed. The working stage was driven by a linear motor for the long-stroke positioning, while a nano piezoelectric stage was employed to achieve the precise positioning for the short stroke. By using air bearings between the working stage and back plate, the working stage could withstand a larger loading, minimize the friction, and effectively improve the overall positioning precision of the coplanar platform. In this study, a symmetrically dual arch fixed bridge structure was used for the frame of the developed machine. In contrast to the traditional rectangular fixed bridge structure, this structure could further reduce the machine structure error. The micro CNC machine integrated four-axis motion systems with the measurement system through a four-axis control card and a data acquisition card. Commercially available adapter was used to online quickly switch the functions of micro-EDM, high-speed micro-milling, and three-dimensional measurements. This machine has been successfully processed micro-probes with a sphere diameter less than 100 μm. With the self-developed trigger circuit, a three-dimensional measurement system was constructed. This study has demonstrated how to combine the traditional and non-traditional machining with micro measurements on a single machine which can complete a variety of processing with high accuracy.

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