ORIGINAL ARTICLE

Development of High-precision Micro CNC Machine with Three-dimensional Measurement System

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Abstract: This study aims at developing a machine center consisting of high-speed micro-milling machine, micro-EDM and coordinate measuring machine. The machine center uses a commercially available PC-Based CNC controller and micro-EDM power supply. The structure design is based on an open L-shaped granite base, where a Z-axis platform is mounted on the top of an L-type base, while X and Y-axis platforms are assembled by stacking. Additionally, a fuel tank, WEDG winding mechanism and a work piece holder were fixed to the X-axis work platform. Three-axis positioning stages use servomotors to drive lead screws for motion control. Equipped with a commercially available PC-Based CNC controller, any processing path and precision motion control can be achieved. In addition, the Z-axis platform includes a commercially available rapid adapter for the rapid assembly of C-axis rotation, high-speed micro-milling spindle and three-dimensional measuring probe. This means that the machine can quickly switch between micro-EDM, high-speed micro-milling and three-dimensional measurement. The machine center successfully produced micro probes with a front-end sphere with a diameter of less than 100 μm. Combined with a self-developed trigger circuit, it also completed a three-dimensional touch trigger probe. The measurement software was developed with Borland C++ Builder. Integrating the three-dimensional touch trigger probe with the three-axis linear scale, the three-dimensional coordinates of the measured values were calculated and processed. It has been successfully applied to the measurement of point, line, circle and angle.

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

I. Introduction

As technology advances and people seek products offering lighter weight and convenience, the main development of products such as flat-panel displays, flexible electronics, biochips, micro-gear, and micro-sensors is trending toward miniaturization. Currently, the main micro-fabrication technology includes four processing methods: (1) lithography technique process, where the light source can be an X-ray, electron beam, or UV light; (2) excimer laser processing; (3) micro-machining; (4) silicon micro-machining process.

According to the existing literature on Electrical Discharge Machining (EDM), when creating micro probes, the micro-EDM process has many advantages. It not only doesn't need additional mold design, but also creates finished products with anti-wear and high accuracy. In addition, micro-EDM can be utilized to process a wide variety of products including ink jet printer heads [1], micro-nozzles for atomizing film production [2], micro-vias [3], miniaturized biomedical products such as micro-delivery devices and micro-fluidic mixers [4], micro-biochips [5], and micro-pumps [6]. Therefore, in order to complete the processing of micro-components, Chen [7] developed a multi-task small computer numerical control (CNC) machine. The machine has the

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functions of micro-milling, electrochemical discharge compound micro-processing, current fluid polishing and electrode inspection. It can be used for the fabrication of micro-molds, biochips, and micro-channels with high aspect ratio structure. At present, most foreign commercial micro-machines are single-function and expensive. The multi-function machines will be even more expensive and lacking in technical precision. Taiwan mainly relies on imported expensive machines, indicating that as yet there are no equipment vendors to invest in the multi-micro machines. 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 a roller surface to solve the discontinuous issue of the roller mold. With a three-dimensional measuring system for online real-time measurements, it can achieve effective mass production of optical-grade structure roller type molds.

II. Operational Principles

Machine structure design

The machine structure in this study is divided into four parts: the base, Z-axis cantilever, adapter and the fuel tank, as schematized in Figure 1. The overall size is 660 × 840 × 770 mm^3. The basic structure of the machine is composed of a base and a Z-axis inverted L-shaped cantilever. Both are made of granite. X- and Y-axis platforms are designed and assembled as a stacking platform. The adapter used is EROWA's manual quick adapter. The fuel tank is designed to be approximately 600 × 370 mm. In addition, the WEDG line rail supply mechanism is fixed to the X-axis work platform. The take-up system is hung on the left side of the fuel tank as shown in Figure 2. This design can save a lot of space and help reduce the volume of the machine.

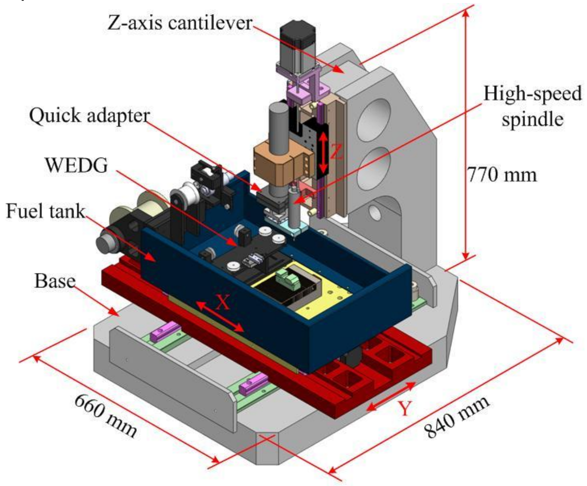


Figure 1. Schematic of the overall structure.

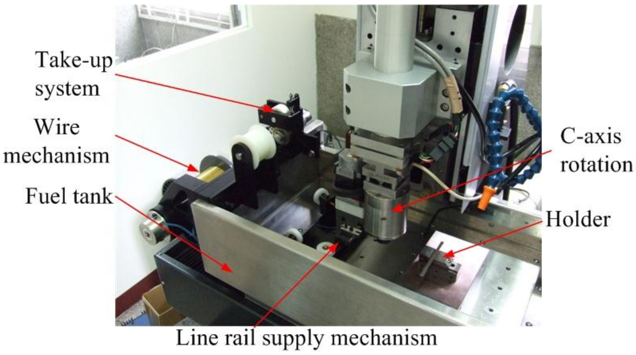


Figure 2. Photograph of WEDG line rail supply system

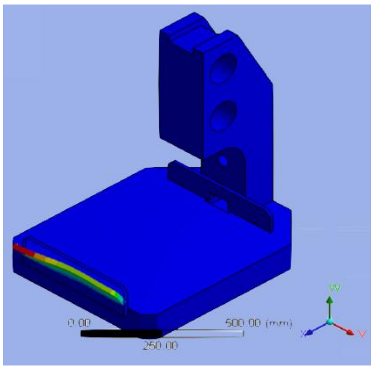


Figure 3. First mode.

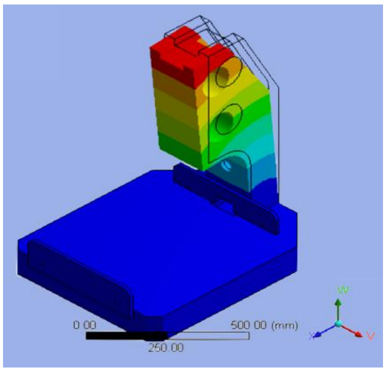


Figure 4. Eighth mode.

Table 1. Natural frequencies.

	Frequency
Mode 1	82.96 Hz
Mode 2	147.23 Hz
Mode 3	396.17 Hz
Mode 4	605.39 Hz
Mode 5	814.55 Hz
Mode 6	1060.5 Hz
Mode 7	1166.8 Hz
Mode 8	1383.1 Hz

ANSYS finite element software is used for analysis in this study. To reduce processing and measurement errors and structural damage due to vibration interference, it must be designed to avoid the occurrence of resonance as shown in Figures 3 and 4. In this study, the C-axis rotation of the electrical discharge machine was about 4000 rpm for processing, and the high-speed spindle reached a maximum speed up to 80,000 rpm. The corresponding frequencies were 66.67 Hz and 1333 Hz, respectively. Natural frequencies of the basic structure simulated by ANSYS modal analysis are listed in Table 1. According to the first eight frequencies, it will be able to select the working frequency range of a motor for the machine.

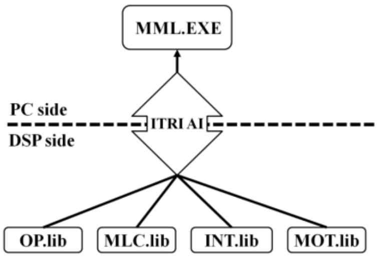


Figure 5. Schematic of PC-based CNC control system software.

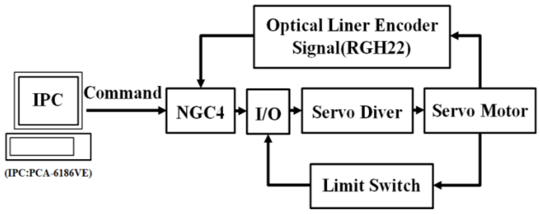
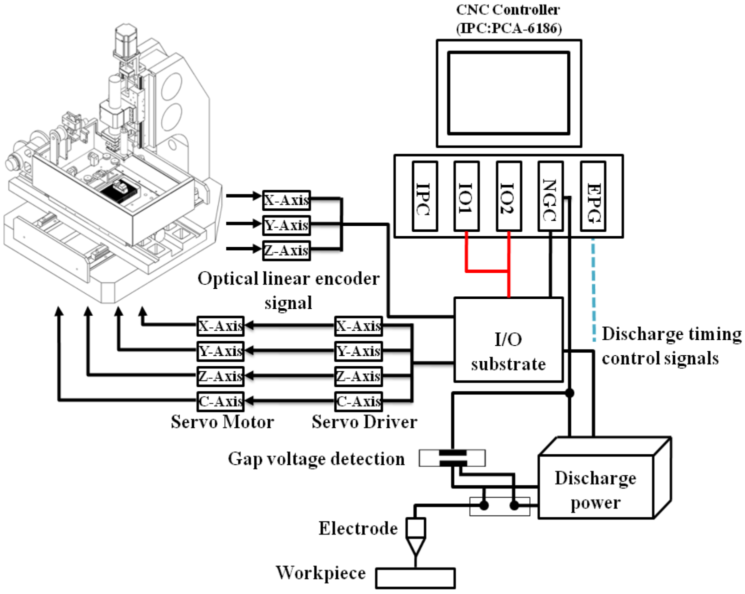


Figure 6. Schematic of single-axis control.

Three-axis positioning platform with CNC controller

This study adopts a PC-Based CNC Controller, developed by the Industrial Technology Research Institute. The DSP side of the controller consists of four modules, including the operation module, mechanical logic control module, interpreting module and movement module. The functions of the four modules are integrated into a running program. Through the user interface module of the PC side, PC-based CNC control system software will be integrated, as shown in Figure 5. Figure 6 shows a schematic of single-axis control. Industrial PCs set the given displacement command through the NGC-axis card to drive the servo motor driver and then platform displacement. Optical linear scale for position measurement and feedback is installed on the other side of the platform. Through the NGC-axis card, the AB-Phase signal generated by the linear scale is used for error calculation, and ultimately for the closed-loop control to achieve accurate positioning. Regarding the hardware used, the CNC control box is from Lien Sheng Mechanical & Electrical Co., Ltd. It contains the power supply of a micro-electrical discharge machine and PC-Based CNC Controller. Figure 7(a) is the schematic diagram for the EDM control system, and Figure 7(b) shows the PC-Based CNC control box.



(a)

(b)

Figure 7. (a) Schematic of EDM control system; (b) Photograph of PC-Based CNC control box.

Micro EDM Equipment

The EDM power supply in this study is accompanied by a WEDG mechanism. As shown in Figure 8, 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, which is singled out in Figure 9. The rotation accuracy and positioning accuracy of the C-axis rotation is 1 μm, driven by a servomotor. The motor can rotate 360° for positioning and angle split. In processing, the probe is clamped onto the C-axis for rotation, while the line guide mechanism transfers a wire electrode for electrical discharge machining. The U-shaped slot has fixed wire electrodes to minimize vibrations and to facilitate the improvement of processing accuracy. Figure 10 shows the schematic for the EDM. In our study, a micro-probe with a front-end ball having a diameter less than 100 μm was successfully produced, as shown in Figure 11. The roundness is up to 3 μm.

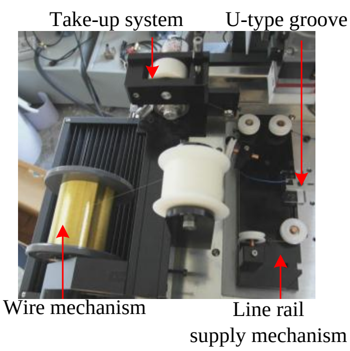


Figure 8. Photograph of WEDG mechanism.

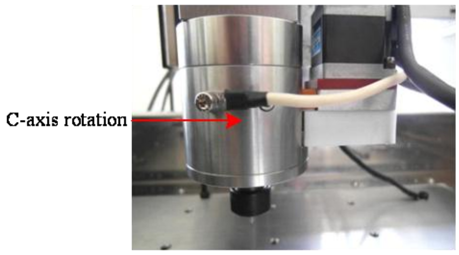


Figure 9. Photograph of C-axis rotation.

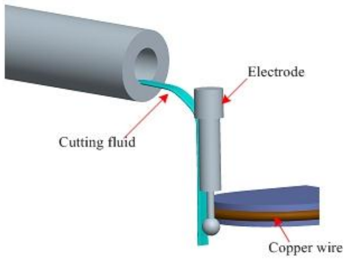


Figure 10. Schematic of wire electrical discharge grinding (WEDG).

Figure 11. Photograph of a microprobe with ball diameter less than 100 μm.

In addition, we successfully designed a discharge circuit using a transistor to control the capacitors. The control loop circuit is used to detect the capacitor's voltage and spacing, and then decides whether to activate the transistor and the discharge process. Figures 12 and 13 show the discharge circuit and the control circuit.

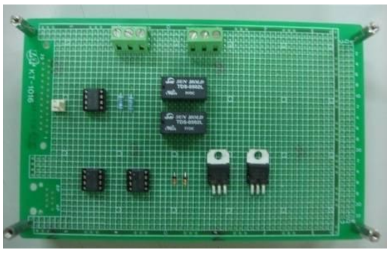


Figure 12. Photograph of discharge circuit.

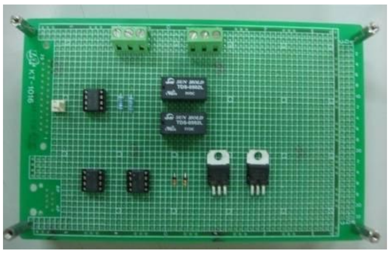


Figure 13. Photograph of control circuit.

High-speed micro-milling equipment

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

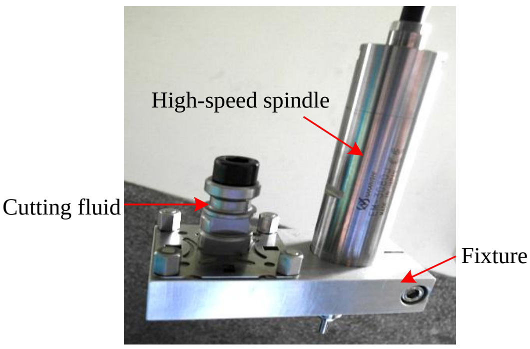


Figure 14. Photograph of high-speed spindle.

Three-dimensional measurement system

This system also contains a probe trigger circuit to trigger the measurement. The design takes advantage of low energy (low voltage, low current) and conductive characteristics of metals. Essentially, the circuit removes the capacitor in the discharge circuit, while keeping the transistors always on. When the probe contacts the work piece, the resistor in a parallel circuit is conducted and the resistor's voltage is detected as a trigger basis. Figure 15 shows the circuit diagram and the change of the trigger signal.

The micro probe, with a front sphere of diameter less than 100 µm, was produced by micro-EDM. The probe is clamped in a small three-jaw chuck as shown in Figure 16.

Measurement software used was developed by Borland C++ Builder. Integrated with three-dimensional touch trigger probe and three-axis linear scales, the trigger probe measures and calculates the values of the three-dimensional coordinates. Three-dimensional measurement software was applied to take the measurements of point, line, circle, and angle as shown in Figure 17.

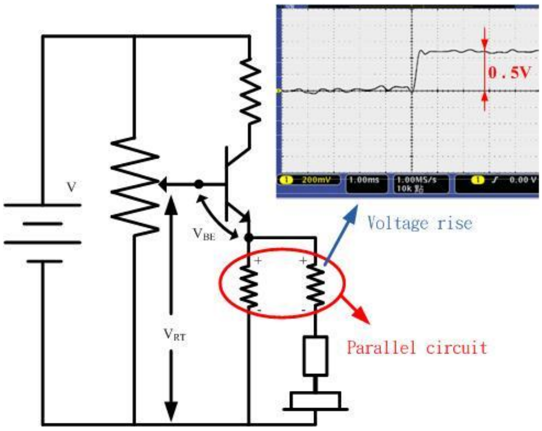


Figure 15. Circuit is on when the voltage changes.

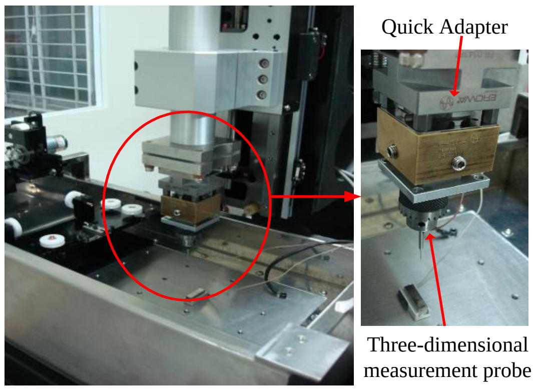


Figure 16. Photograph of three-dimensional measurement probe.

Figure 17. Interface of multi-axis measurement system software.

III. System Integration and Measurement Results

Width measurement for gauge block

The integration of hardware was installed in the CNC machine center (as shown in Figure 18) for the actual measurement. Gauge blocks of 9 mm in width were used for measurement. The measurement method is shown in Figure 19, and the measurement results are listed in Table 2. The measurements have a maximum value of about 9.0117 mm, and a minimum value of about 9.0099 mm, with a standard deviation of 0.56 μm.

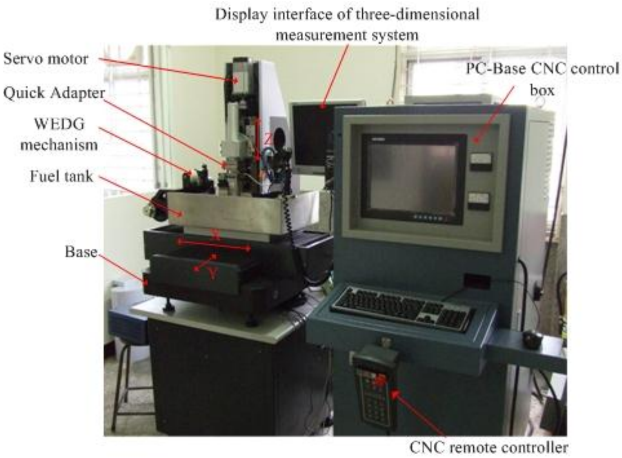


Figure 18. Photograph of the high-precision CNC machine.

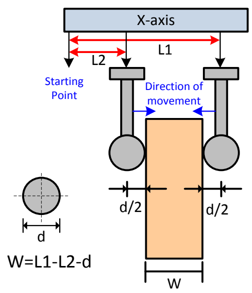


Figure 19. Schematic of the width measurement.

Table 2. Results of width measurement.

Meas. No.	L1(mm)	L2(mm)	D(mm)	w(mm)
1.	74.0461	64.9362	0.1	9.0099
2	74.0485	64.9377	0.1	9.0108
3	74.0564	64.9448	0.1	9.0116
4	74.0516	64.9401	0.1	9.0115
5	74.0602	64.9485	0.1	9.0117
6	74.0232	64.9118	0.1	9.0114
7	74.0242	64.9133	0.1	9.0109
8	74.0186	64.9082	0.1	9.0104
9	74.0013	64.8905	0.1	9.0108
Average	74.0367	64.9257	0.1	9.0110

Height measurement for gauge block

A ladder-shaped geometry composed of gauge blocks with a height difference of 1 mm between each step was created. The measurement method is shown in Figure 20. For each step, nine measurements were taken, and the results are listed in Table 3. The standard deviation is about 2.5μm and the accuracy is about 0.6147 μm.

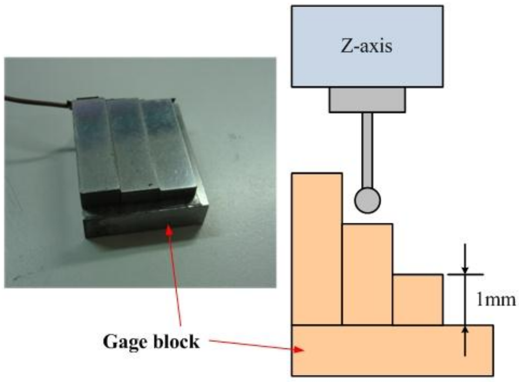


Figure 20. Schematic of height measurement for a ladder composed of gauge blocks.

Table 3. Results of height measurements.

Step	Average of nine measurements (mm)	Standard Deviation (μm)	Precision (μm)
0→1	1.0006	1.25	0.556
1→2	1.0006	3.36	0.588
2→3	1.0007	2.89	0.700
average	1.00063	2.50	0.6147

IV. Conclusion

This study has successfully developed a CNC machine center consisting of a high-speed micro-milling machine, a micro-EDM, and a micro-coordinate measuring machine. A commercially available adapter is used to quickly switch the functions of micro-EDM, high-speed micro-milling and three-dimensional measurements while online. This machine has successfully processed micro-probes with a sphere diameter less than 100 μm. With the self-developed trigger circuit, a three-dimensional measurement system was completed. This study has demonstrated how to combine traditional and non-traditional machining and micro-measurements in the same machine, which can complete a variety of processing with high accuracy.

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