Development of a Pantograph Based Micro-Machining Machine

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This paper proposed a pantograph based micro-machining machine to satisfy the need of achieving high accuracy and process efficiency as manufacturing the gradually miniaturized industrial products. The novel machine system is driven by two pantograph mechanisms and a traditional X-Y-Z platform with common precision to form a machine with 50 nm precision. The theoretical and simulating results showed that the proposed method is feasible to develop micro-machining machine which can achieve the nano-level precision. And the test results showed that the micro-machining machine can position the target platform with 50nm resolution.

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NOMENCLATURE

ρ = the theoretical positioning resolution
p = the pitch of the ball screw
α = the step resolution of the stepping motor
β = the zoom-out ratio of the pantograph

1. Introduction

According to the miniaturization of industrial products, the component size of these products must be more miniaturized and precision then the products. And the material may not be silicon based and the shape may be a complex three dimensional form, so the technology of MEMS is not still suitable, thus the micro/nano-scale manufacturing technology by non-MEMs methods will be the key to form such a product. The demand for miniaturized devices with high aspect ratios and superior surfaces has been rapidly increasing in aerospace, automotive, biomedical, optical, military and micro-electronics packaging industries[1]. Therefore, to develop a micro-even a nano-level machine to satisfy the need for fast, direct, and mass manufacturing of miniaturised functional products from metals, polymers, composites, or ceramics will be more important. Fig.1, from Taniguchi as modified in [2], shows micromachining capability in terms of Taniguchi's unit removal, the amount of workpiece removed during one cycle of process- one engagement of the tool, for example. CIRP has had a long history of contributing to the research and development of micromachining technology. For the high-precision machine tools, the mechanical and electrical integration, miniaturization and high performance is more important on the design considerations [3], high-precision machining making the product quality and reliability have improved dramatically, allowing for the miniaturization of size and weight are reduced, making the product more competitive, so that the industry increased demand for micro-components [4]. For the micro-machine tools, the micro-machine tools design needs to consider the accuracy requirements are higher [5-8].

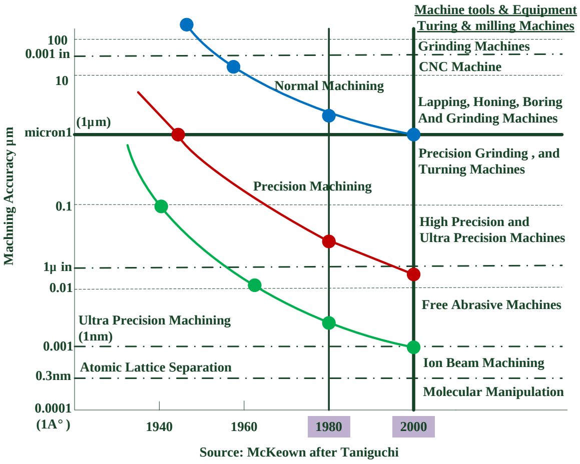


Fig.1 Micromachining capability over time[1].

However, the above research of literatures indicated the price of micro-components are very expensive. Thus, Wang [9] proposed a low-cost micro-machine tool development, using the toggle to design institutions to screw control mechanism to reduce the displacement, achieve the status of high precision, while use of the screw control, so that need many compensation method to achieve the desired positioning [10].Therefore, we proposed a pantograph based micro machine to manufacture the 3-D micro-miniature products in this paper. In addition, the control and driving systems are well development in the traditional numerical control machining machines, we considered to drive the micro-platform by a traditional X-Y-Z table and transfer the motion by two pantograph mechanism.The benefits are that the X-Y-Z table does not need high-precision, through the mechanism design the target platform can be achieved micro- or nano-scale precision and we can use the traditional motion controllers and compensators to control the micro-machining machine. From the theoretical and simulating results showed that the proposed method in this paper is feasible to develop micro-machining machine which can achieve the nano-level precision. And a micro-machining machine with the target X-Y and Z axes are 50nm are built up to test and verify the proposed mechanism.

2. Design of the Pantograph based micro-platform

We tried to use the pantograph mechanisms to enhance the accuracy of a 3-DOF xyz platform with micrometer precision to be a nano-level precision in the target platform for milling machine tools. The novel 3-DOF positioning system is shown in Fig. 1.A traditional three-axis xyz platform driven by stepping motors with encoder is the actuator. Two well designed pantograph mechanisms are the connecting structures. One is to link the processing spindle at the target platform with the z-axis of the driving xyz platform. The other is to link the workpiece platform with the xy-axes of the driving xyz platform. By the pantograph, it is used to enlarge or reduce movement. Thus, we can use it to zoom out the original micro scale displacement to a nano scale displacement into the moving target in order to achieve the purpose of high positioning precision.

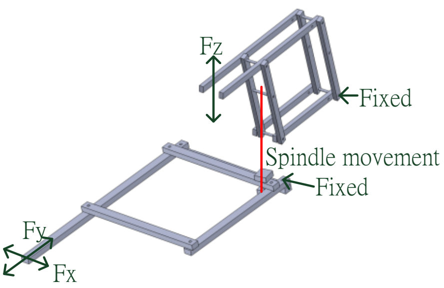


Fig.2 Pantograph based micro-platform

The pantograph mechanism shown in Fig.3 uses four links to form a parallelogram. The position relationship of points A and H can be expressed as:

$$\frac{\overline{AH}}{\overline{HD}} = \frac{\overline{AB}}{\overline{BC}} = constant \quad (1)$$

That is, as the point A moving, there will be the similar but reducing moving trajectory at the point H. Unfortunately, the phenomenon is only satisfied at the point H, the other points in the neighborhood of H will move and rotate as H is driven by A. Therefore, we need to design a rotation joint in the target platform to make it moves following the point H but not to rotate. Furthermore, consider the different load capacities and motion demands, both structures of the pantograph designed as shown in Fig.4 (a) and (b). In the z-axis, it needs to support the weight of the spindle, so we design the pantograph to clip the motion table mounted on the linear guide from both sides. In the xy-axes, the target platform is supported by a small two dimensional platform, the pantograph is just to drive it moves without rotating, so the design point is to make the rotation joint running smoothly.

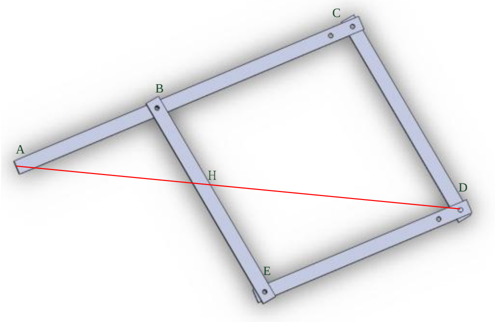
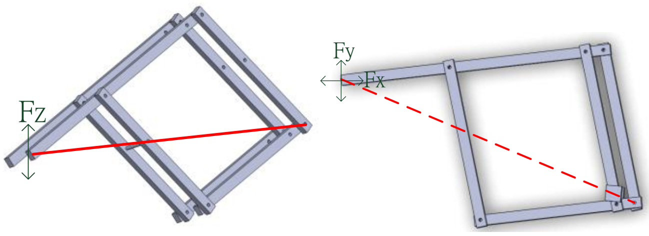


Fig.3 Pantograph mechanism



(a) z-axis (b) xy-axes

Fig.4 Detail Structure of the proposed pantograph mechanisms

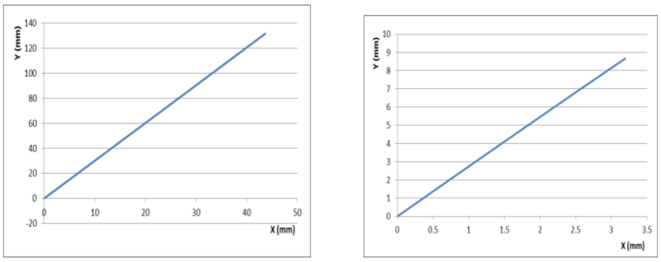
Neglecting the assembly errors and components tolerances, the theoretical positioning resolution ρ of the proposed machine can be calculated by the step resolution α of the stepping motor, the pitch *p* of the ball screw and the zoom-out ratio β of the pantograph, expressed as:

$$\rho = \frac{p}{\alpha\beta} \quad (2)$$

That is, if we wish to develop a micro-machining machine with the positioning precision is 50nm by the proposed method, we need to check the three parameters of α, β and *p*. For example, if the original processing ball screw pitch is 4mm and the step resolution α=5000. That is the traditional three-axis platformaccuracyis20μm.In order to achieve the precision of proposed 50nm, we need to design a pantograph mechanism with zoom-out ratio *p*=16, then the system should fill the bill.

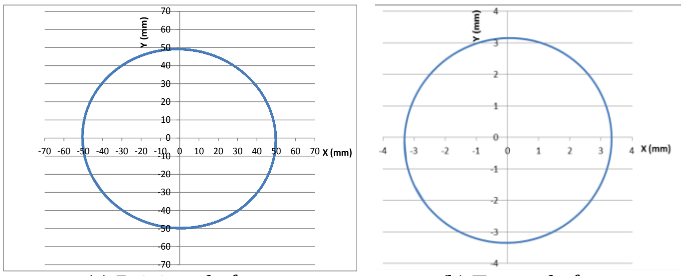
3. Simulation and Experimental result

To verify the effectiveness and feasibility of the design pantograph mechanism, we simulated the pantograph mechanism motion through the Solidworks software. Fig. 5~7 shows the linear motion, circular motion and elliptical motion of the driven platform and the target platform. The results show that the displacement of micro-processing point accuracy match our design, the system can make the motion in the target platform to be zoom-out as one divide sixteen in the driving platform.



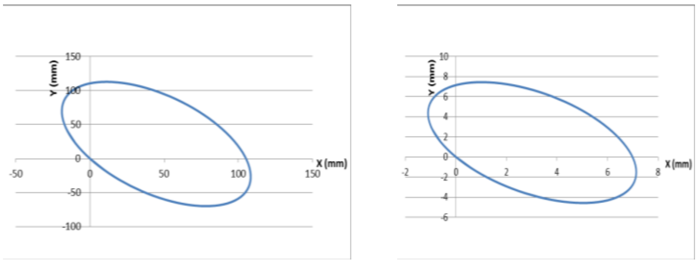
(a) Driving platform (b) Target platform

Fig.5 x-y platform with 100mm linear motion



(a) Driving platform (b) Target platform

Fig.6 x-y platform with circular motion



(a) Driving platform (b) Target platform

Fig.7 x-y platform with ellipse trajectory motion

Fig. 8 is the photograph of the prototype. The micro-machining machine with the target X-Y axes are 50nm. It was built up to test and verify the proposed mechanism. The control flow chart of an open-loop control test for the prototype is shown in Fig. 9. The cutting tool and workpiece path command is send to the traditional three-axis xyz platform to drive the target platform, and the encoder signal of the stepping motor is measured to modify the motion of traditional xyz platform..

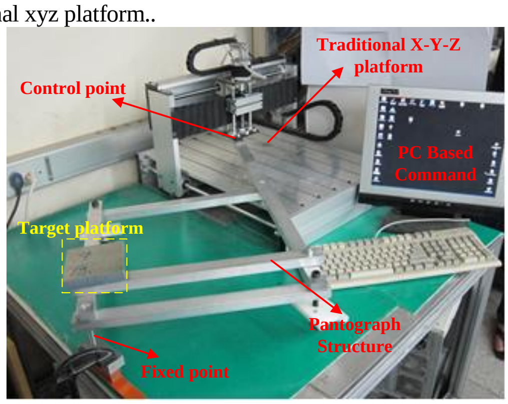


Fig.8 Prototype of Micro-Machining Machine

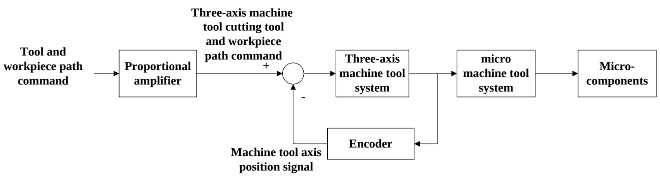


Fig.9 Schematic diagram of open-loop control system

The experimental results of linear motion test was shown in Fig. 10. The test data showed that the proposed machine can positioning the target platform with a 2 μm precision in linear motion by the open-loop control system as the driving platform precision is 20μm. There is some gap comparing with the initial design. It maybe causes by the assembly errors and components tolerances and the measurement errors. If we wish to compensate these errors, a closed-loop control system shown in Fig.11 is a suitable solution

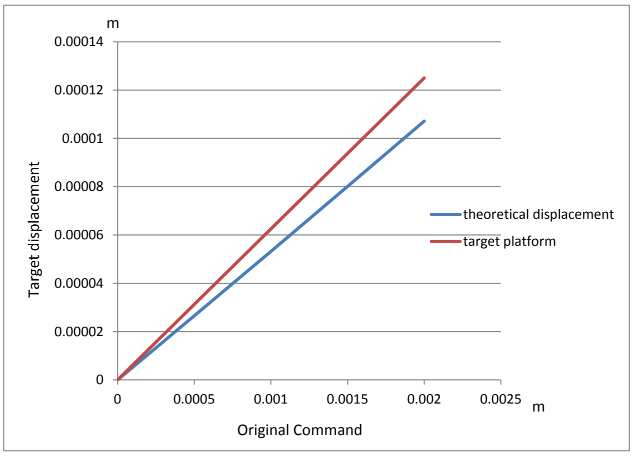


Fig.10 Experimental results of linear motion

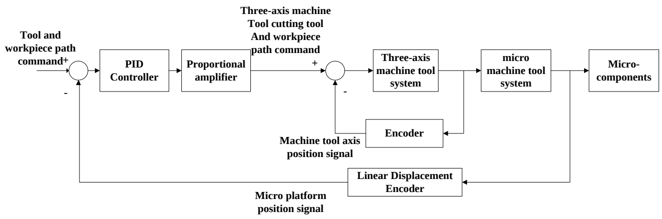


Fig.11 Schematic diagram of closed-loop control system

4. Conclusions

Simulation and experimental results verify that using the proposed mechanisms of pantograph can successfully increase the precision of the 3-DOF positioning machine. The data also demonstrate the feasibility of the mechanism design. The prototype with the 16 zoom-out ratio is built up and it successes to upgrade the precision from the original 20μm to 2μm level. Through this mechanism design we can make a highly accuracy machining machine do not require complex control methods. And the preliminary test results showed that the micro-machining machine can position the target X-Y and Z platform at 50nm in each axis.

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