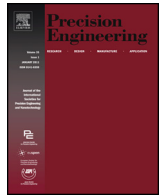




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Technical note

A precision CNC turn-mill machining center with gear hobbing capability

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ABSTRACT

With ever increasing demand for small parts with complex shapes and high dimensional accuracy, many traditional machine tools have become ineffective for machining these miniature components. Typical examples include dental implants, parts used in mechanical watch movements, and parts used in medical endoscopes. This paper introduces our PC-controlled CNC turn-mill machining center. It has 5 axes, an automatic bar feeder, an automatic part collection tray, and a tool changer. It features a special control algorithm for the synchronization of its axes that produces not only higher accuracy but also makes the machine easier to use. In addition, a volumetric error compensation algorithm is implemented to improve accuracy. Based on experiments, the machining error is $\pm 3 \mu\text{m}$ for turning, $\pm 7 \mu\text{m}$ for milling and the maximum profile error is less than $\pm 7.5 \mu\text{m}$ for gear hobbing.

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1. Introduction

Machining is one of the oldest and yet most commonly used manufacturing process. Machining has been studied in depth and the basic theory of machining is well understood, especially metal cutting principles [1], machine tool dynamics [2], tool path generation [3], high speed machining. However, machining precision miniature parts is still a challenge. Examples for such complex precision miniature parts are dental implants, gear racks used in camera focusing systems, as well as gears and pinions used in mechanical watch movements and only few machine tools are capable of making them.

Experts generally agree that smaller machine tools will be more effective for machining miniature parts. In recently years, the so-called “micro factory” has become a discussed research topic [4–6]. The idea of micro machine tools may be traced back to 1970s [7], but the first realization was not found until 1996 in Japan [8]. In 2000, Okazaki and Kitahara built a micro-lathe measuring only 32 mm in length [9]. Although it suffered from poor accuracy and limited

shape generation capability. Lu and Yoneyama [10] developed a micro-lathe measuring 200 mm in length and successfully turned a 300 μm brass wire down to 10 μm in diameter using diamond tools. But their lathe had no limited functionality, in particular, it did not offer CNC. Today, with the rapid advance of precision control technology, building a micro machine tool becomes much easier. Löffler [11] developed a micro lathe which is small enough to be used in the chamber of a Scanning Electron Microscope (SEM) and used it to investigate the micro cutting process under vacuum. Sun, Liang and Du [12] developed a high speed micro lathe with its own CNC software. It can cut 3D sculptures from a rod of 2 mm diameter. Vogler and et al. [13] developed a meso-scale machine tool. More recently, Davim and et al. developed a precision turning machine and used it to machine flexible polyamide composites [14]. Axinte and et al. built a 4-axes machine tool, which reached an accuracy of about 1 μm [15]. However, these machine tools are not meant for practical applications. They have limited functionality and can only make simple parts as tool changer, automatic loading and unloading of workpieces, as well as side or end milling capability are not included.

In practice, miniature parts from the industry are complex. Fig 1 shows a number of sample micro parts, including dental implants, a camera gear rack, and a parts used in mechanical watch movements. These parts are approximately 1–3 mm in diameter and the required tolerances are less than 10 μm . Multiple cutting steps and

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Fig. 1. Typical micro parts, their diameters are about 1–3 mm and required tolerance is 10 μm .

special functions such as gear hobbing are required to manufacture the parts. Because of their complex geometry, other processes, such as chemical milling and MEMS lithography, are imperative for today's manufacturing.

From the brief review above, it can be inferred that industrial micro machining is still in its infancy. This motivates us to design and build a low cost precision CNC turning milling machining center with gear hobbing capability which should be suitable for universal industrial use.

This paper will introduce the machine in Section 2. The control system is presented in Section 3. This is the key part of the research, as it dedicates the functionality and accuracy of the machine. An experimental study about the machine's synchronized axis is discussed in Section 4. Section 5 presents the results of machining experiments. Finally, Section 6 contains conclusions and an outlook on future research work.

2. Precision CNC turn-mill machining center

The CAD model of our CNC turn-mill machining center is shown in Fig. 2, a photo is shown in Fig. 3. It has three spindles (W1, W2, W3) and five axes (Z1, X2, Y2, X3, Z3), as well as an auxiliary axis θ . The overall dimension of the machine is 480 $\times$ 580 $\times$ 1500 ($L \times W \times H$) mm and the work volume is 100 $\times$ 100 $\times$ 100 ($L \times W \times H$) mm. The main spindle (W1) is equipped with a guide bush and can automatically feed the workpiece. The angular encoders deliver 10,000 counts per revolution and the resulting angular position accuracy is 0.036 degrees for the main spindle (W1) and the 2nd spindle (W2), and 0.03 degrees for the 3rd spindle (W3). The position resolution of the linear guides is 1 μm . The linear guides are mounted on a marble base to reduce the effect of thermal expansion.

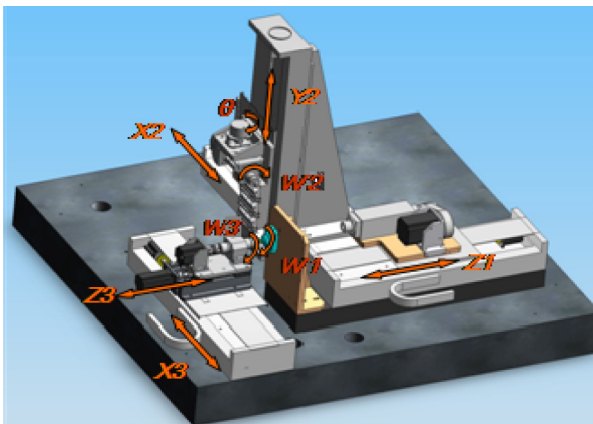


Fig. 2. The CAD model of our CNC turn-mill machining center.

To illustrate the functions of the machine, it is useful to consider two modes of operation: turning and gear hobbing as shown in Fig. 4(a), and milling and grinding as shown in Fig. 4(b).

The turning operation is shown in Fig. 5(a). The turning tool rack can accommodate up to five turning tools and the tool change is done by aligning the 2nd table using axis X2 and Y2, and the workpiece table, Z1. The gap between the tools is 12 mm and the tool changer can accommodate 8 mm or 10 mm tool holders. In particular, we use 710 and 740 series of Applitec turning tools [16].

Invented some 100 years ago, gear hobbing is a very efficient process for gear production [17]. Its principle is as follows: as the hob (or gear cutter) rotates, the so-called basic rack is generated in the workpiece. When a synchronized motion of the workpiece is added, the desired gear profile is cut into the workpiece. Thus, from a geometric point of view, it is the relative motion between the gear hob and the workpiece that generates the gear profile as the image of the gear hob. Note that at any time, more than one tooth of the hob are engaged in the cut making the operation very efficient.

In our machine, gear hobbing is done using the 2nd spindle, as shown in Fig. 5(b). In addition to the synchronized motion of hob and workpiece, a key parameter of the hobbing process is the helix pitch for helical gears. The pitch is achieved by changing the angle between the hob's axis and workpiece's axis. Gear hobs (gear cutters) can be purchased from a number of companies, such as Daimetal.

The milling and grinding function is done by the 3rd spindle, as shown in Fig. 5(c). In order to achieve higher accuracy, the motions of the 3rd table and the 1st table can be synchronized with linear and circular interpolation.

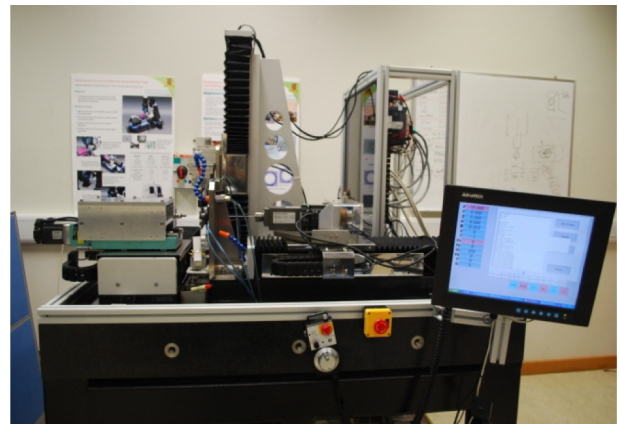


Fig. 3. The photo of our CNC turn-mill machining center.

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