Investigation on the Key Technologies of Micro Machine Tool and Prototype Development

Jiashun Shi[1], Jintai Mi[1], Jinsheng Wang[1,2], Kui Chen[1], Wanshan Wang[1], and Guangqi Cai[1]

[1] Laboratory of Advanced Manufacturing and Automation, Northeastern University, Shenyang, China
[2] Laboratoire de Génie Industriel et de Production Mécanique, Université de Metz, Metz, France
jshshi@mail.neu.edu.cn, jswang@neu.com.cn

Abstract. In this work, the key technologies of Micro Machine Tool (MMT) are discussed in detail. A three-axis MMT prototype is developed. It is driven by ultra precision linear motors with high resolution linear encoders as feedback. It is equipped with a high speed electro-spindle and an CCD stereo microscope as a monitoring device. Meanwhile, the entire machine is controlled with an open numerical control system based on motion controller. The Human-Machine Interface (HMI) software is developed with G code compatibility. At last, the evaluation tests have been done on the MMT, and the results are very satisfactory and show its excellent performances.

Keywords: Machine tool design; Micro machine tool; Motion control system; Human-machine interface; Positioning accuracy; Micromilling.

1 Introduction

Nowadays, with the emergency requirements in many industry fields for micro parts, such as aerospace, biomedical, electro communication and so on [1,2], various related manufacturing techniques emerges one after another, such as etching, LIGA, laser and plastic micro-injection etc. [3]. Compared with other micromachining methods, micromilling is specialized in machining 3D micro parts in large range of workpiece materials from the metal alloy to other machinable nonmetallic materials such as polymer, plastic, ceramics etc. [4]. Meanwhile, it is cheaper and more flexible than other techniques and it can be monitored and controlled in process [5].

Due to the specialities of micro machining, the demands to the machine tool include the long stroke, micro feed, high positioning accuracy, excellent dynamic performances. Two types of machines are adopted to achieve the micromachining either in the industry or laboratory level. The first one is the traditional precision machine tool [6]. The second one is the micro machine tool (MMT). Compared with the traditional precision machine tool, the MMT is cost-effective due to the less materials requirement, and it is easy to achieve good thermal balance

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and environmental isolation. And due to its lower mass, its natural frequency is higher and the vibration amplitude is lower. Hence, Since the introduction of Japans Mechanical Engineering Lab microfactory concept is put forward in 1998 [7], more and more researchers resorted to develop several MMTs.

Subrahmanian and Ehmann [8] developed a three-axis meso-scale machine with $15 \times 15 \times 15mm^3$ workspace, $0.5\mu m$ encoder resolution, and $200,000RPM$ spindle. In University of Illinois at Urbana-Champaign (UIUC), after Vogler et al. [9] developed the first generation MMT, Honegger et al. [10] has beed developed the seconde prototype. Both of them are 3-axis and actuated by voice-coil motors. The second one is equipped with $160,000RPM$ air-turbine, $0.1mm$ encoder and reaches $25 \times 25 \times 25mm^3$ workspace. Ni and his group [11] has developed a 3-axis micro/meso machine tool, which is driven by a miniaturized piezoelectric linear stage with $13mm$ stroke and $0.25\mu m$ encoder resolution in each direction, as well as an air-turbine spindle with $120,000RPM$ maximal speed. Some other MMTs development includes the contribution from Bang et al [12], Ashida and Okazaki [13].

In this work, the key technologies of MMT are discussed in detail. A self-developedvthree-axis MMT prototype is introduced. At last, the evaluation tests have been done on the MMT, and the results are satisfactory and show its excellent performances.

2 Key Technologies of MMT

The entire MMT system is composed by some key components, and frequently they can be categorized as follows. How to develop these high quality components is critical to the MMT performance.

2.1 Feeding System

Because the feeding system of MMT must satisfy the demands of large feed, precision position, fast respond etc, the high quality feeding system is very important to the MMT performances. Some approaches which are primarily adopted to achieve the requirements will be discussed as follows.

Linear Driving System. The prismatic DoF is frequently adopted in the machine tool configuration, and the linear driving system can be used without the transferring chain in order to achieve the direct driving (DD). With the rapid development of the linear driving system, it has been applied in the machine tool industry more and more widely. The voice-coil motor, linear motors, and some similar types are included in this category. These motors can supply outstanding dynamic response as much as 5G acceleration, fast-speed positioning, high stiffness and good control ability [9]. Hence they are widely used in the MMT equipment [14,15].

Rotatory Driving Unit + Ball Screw System. This combination is commonly used in the traditional machine tool system. The rotatory driving unit, primarily rotatory motor, outputs the moment. Through the coupling unit, the ball screw system leads the stage movement. Compared with the linear driving system, they are less-cost, but the main problems are backslash and creeping phenomena in the ball screw system. So the error compensation devices or algorithms must be developed in order to improve its performances.

Non-motor Driving System. The non-motor driving system includes the piezo-electric actuator (PA), shape memory alloy (SMA), etc. They are well-known for their nano positioning precision, and widely used in the fields as MEMS/NEMS, micro manipulation, sensors, actuators and others. Some researchers adopted them into the MMT systems. Rusnaldy [16] used the PA to drive a three-axis MMT. Malukhin and Ehmann [17] have developed a 2D micro stage by SMA for thin wall structure fabrication. But the stroke of PA and SMA is relative small, the normal value is less than $1mm$. And their dynamic response is lower, so the displacement amplifier should be adopted when the machining feed rate is higher.

Micro Parallel Stage. In recent years, the theory of parallel robot have been developed rapidly and realized in many fields. And some researchers have developed the micro parallel stage for micromaching. Their DoFs range from 2 to 6 with higher stiffness. Furutani et al. [18] adopted the stacked piezo-electric actuators to form a Stewart parallel platform, which is used for nanometer cutting research. However, the workspace of the parallel mechanism is smaller and it is expensive to setup a high precision parallel stage.

2.2 Spindle System

Due to the tool tip diameter of the micromill is always smaller than $1mm$, the cutting speed is much smaller than the common sense. In order to improve the cutting speed to prolong the tool life and enhance the surface quality, the high speed spindle ($\geqslant 10,000RPM$) must be integrated into the MMT system. It can be categorized as bellows [19].

Electro Spindle. Today, the electro spindles are the brushless DC motors. Their speed can achieve as high as $200,000RPM$, and it is easy to be controlled by the digital signal from inverter. However, they are larger dimensions, heaver mass and the additional cooling system is necessary to decrease the temperature due to the inner heat generation.

Air Turbine. The speed of air turbine ranges from $50,000RPM$ to $200,000RPM$. But the size of them are relative larger, about $45mm$ diameter. Due to the driving source is the air flow, they can be cooled by themselves.

2.3 Sensing System

Because the functions of MMT are in the microscale, the sensors in conventional range are not capable to detect the signals for MMT. Many special sensors have been developed to improve the MMT performances. The linear encoder system can reach nanometer resolution in long stroke. The precision dynamometer with $2mN$ resolution and $40KHz$ sampling frequency are already widely used in the laboratory level. Other novel type sensors, such as laser sensor, acoustic emission senor et al, are integrated in the advanced MMTs.

2.4 Control System

Nowadays about 90% MMTs utilize the hierarchical control system. The PC/IPC is in the top level, and the motion controller is in the middle level. The controller compiles and sends the commands to the motor drivers in the machine language format. The feeding system moves according to the command and the sensors feedback form a closed-loop control system. Most researchers work under the controller software environment. Some investigators resorted to develop the interface software between the motion controller and the operator to achieve the operation directly. In order to be compatible with the G-code programming, the numerical control (NC) systems for the micromachining are developed. Hence the MMT can fulfill complex surface fabrication.

2.5 Monitor System

Due to the tiny tool size, the tool wear and breakage issues are really important to the micromilling operation [20]. Meanwhile, according to some tool catalogs, the tool life of micromill is only a few hours. Therefore, monitoring the machining process online is very useful to check the tool condition. In microscale machining process, the CCD stereo microscope is capable to supply large field-of-view and accepted depth-of-view. And the cutting force and acoustic emission sensors are also available.

3 Prototype Development

In this paper, the three-axis micromilling machine prototype is composed by a electro high speed spindle, three ultra precision linear motor, three linear encoders, open numerical control system, 3-component precision cutting force dynamometer, CCD stereo microscope with $40\times \sim 240\times$ magnification, HMI with G-code programming function, vibration-isolation system and spindle-cooling system. The entire prototype is shown in Fig.1. The dimension of the prototype is $400 \times 320 \times 100mm^3$ with $50 \times 50 \times 50mm^3$ workspace.

3.1 Feeding System

In order to realize the requirements of the machine motion, three micro feeding units are adopted. Each unit is composed by a Parker permanent magnet servo linear motor with $4G$ acceleration and $50mm$ stroke and a Reinshaw linear encoder with $10nm$ resolution. This configuration forms a closed-loop control system to improve the performance of the micromilling process.

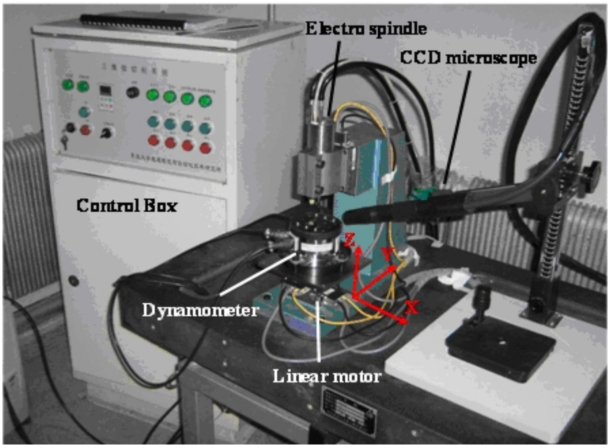


Fig. 1. Three-axis MMT system

3.2 Spindle System

A high speed electro spindle is integrated into the MMT system and moving in Z direction. The maximal rotating speed is $60,000RPM$. The run-out in radial and axial directions are $3\mu m$, which is satisfactory with the requirements of micromilling operation.

3.3 Control System

This control system structure is PC + 6K multi-axis motion controller + VIX linear motion driver, shown in Fig.2. The PC communicates with the 6K motion controller either by ethernet or serial port. The controller drives three linear motor drivers in each direction. With the feedback of linear encoders, the PID control is used to improve the motion performance and the motor conditions are monitored in real-time.

3.4 Human Machine Interface (HMI)

Because 6K motion controller couldn't provide the interface for numerical control of the micromilling process with G-code compatibility, a specialized HMI software is developed. It includes 4 function module, communication setting, parameters setting, manual manipulation and auto manipulation. The software can replace the programming environment of the 6K controller, and the G-code is interpreted into the corresponding commands to the motion controller. Fig.3 is the interface that the auto manipulation module is working with G-code.

3.5 Other Components

A CCD stereo microscope with $40\times \sim 240\times$ magnification is used to monitor the micromilling process and to do the online measurement. A three component

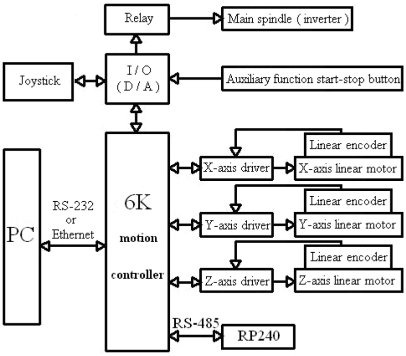


Fig. 2. MMT control system

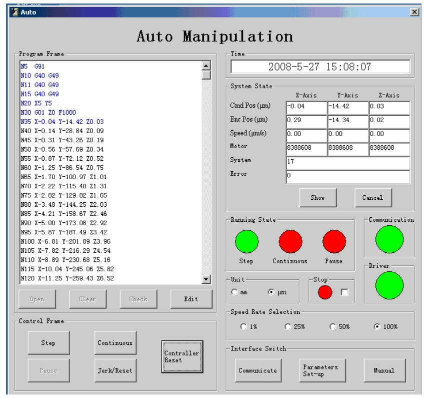


Fig. 3. HMI of MMT prototype

precision dynamometer SDC-CJ3SAS is assembled on the X-Y stage, with $10mN$ threshold and $250N$ maximum. The marble platform is used for the machine tool base in order to isolate the environmental vibration. The cooling system is used for decreasing the spindle temperature.

4 MMT Prototype Test

In order to evaluate the MMT prototype performances, the positional accuracy test and the machining test have been conducted on it.

4.1 Positional Accuracy Test

The evaluation criteria of the machine tool positional accuracy includes bi-directional positional accuracy, bi-directional repeatability and reversal value. According to the ISO-230-2:1997 standard, the positional accuracy tests of the motion platform used bidirectional evaluation method and linear circulation measurement. The target location points number $n = 10$, sequential numbered by $j = 1, 2, ..., n$, and the target measurement interval $t = L/n = 5mm$, with the cycle number $m = 5$.

The motion stage in each direction stopped steadily after it arrived the target point, the actual position from the linear encoder was fed back to the PC and displayed in the HMI. The Z axis test data were shown in Fig.4. And the X and Y directions were tested in the same way.

In Fig.4, $\uparrow$ and $\downarrow$ represented the test data were obtained from the positive and negative directions respectively, for example $X_{ij} \uparrow$ and $X_{ij} \downarrow$. Based on the evaluation data, the positional accuracy of the MMT was listed in Table.1. The test results showed the bi-directional positional accuracy and the bi-directional repeatability of the prototype is in sub-micron level, which is satisfactory to the requirements of micromilling operation.

Point j	1		2		3		4		5	
P_j (mm)	0		5.510		10.025		14.953		20.042	
Direction	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓
Position Error X_{ij} (um) i	-0.38	-0.36	-0.46	-0.48	-0.38	-0.54	-0.55	-0.55	-0.33	-0.32
	-0.54	-0.44	-0.44	-0.41	-0.36	-0.40	-0.35	-0.32	-0.42	-0.43
	-0.44	-0.36	-0.38	-0.36	-0.38	-0.36	-0.37	-0.40	-0.50	-0.42
	-0.38	-0.46	-0.52	-0.42	-0.36	-0.56	-0.38	-0.36	-0.38	-0.39
	-0.54	-0.52	-0.42	-0.51	-0.48	-0.36	-0.57	-0.57	-0.37	-0.38

Point j	6		7		8		9		10	
P_j (mm)	25.051		30.066		34.879		40.027		45.048	
Direction	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓
Position Error X_{ij} (um) i	-0.53	-0.54	-0.43	-0.36	-0.51	-0.52	-0.49	-0.49	-0.44	-0.42
	-0.37	-0.38	-0.42	-0.43	-0.37	-0.38	-0.41	-0.42	-0.52	-0.51
	-0.43	-0.39	-0.33	-0.37	-0.43	-0.43	-0.38	-0.46	-0.39	-0.38
	-0.53	-0.42	-0.45	-0.45	-0.42	-0.43	-0.36	-0.36	-0.41	-0.41
	-0.42	-0.46	-0.46	-0.45	-0.43	-0.42	-0.41	-0.42	-0.44	-0.42

Fig. 4. Positional accuracy test data for Z axis

Table 1. The positional accuracy of the MMT prototype

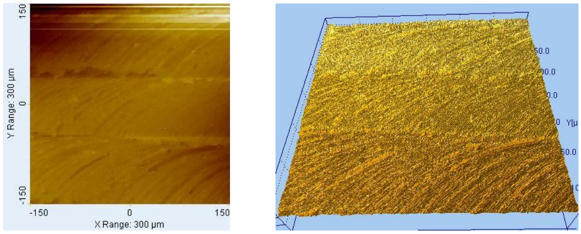
Dir.	Bi-dir. positional accuracy	Bi-dir. repeatability	Reversal value
X	$0.2734\mu m$	$0.2682\mu m$	$0.04627\mu m$
Y	$0.2800\mu m$	$0.2618\mu m$	$0.0347\mu m$
Z	$0.4534\mu m$	$0.4510\mu m$	$0.0520\mu m$

4.2 Micromilling Experimental Test

Some micromilling tests were done by the prototype. One 4-flute carbide micromill with $0.4mm$ diameter was chosen for the test. The workpiece was a specialized Mg-Zn-Y alloy for biomedical application [21]. Here, the slab and thin wall micromilling tests are given.

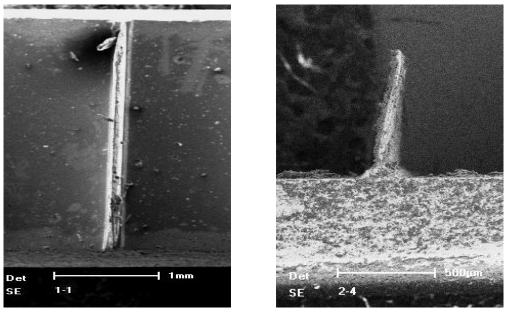
Slab Micromilling Experiment. In this test, the spindle speed was $30,000RPM$, the feed rate per tooth $3\mu m$, and the axial depth was $15\mu m$. Three slabs with $3 \times 2mm^2$ dimension were fabricated. The surface quality was measured by optical profiler and the average roughness value was $S_a = 0.123 \pm 0.0181\mu m$. The 2D and 3D surface figures from the profiler of one sample are shown in Fig.5. Obviously, the MMT prototype is able to produce the surface with high quality.

Thin Wall Milling Experiment. The parameters setting was $30,000RPM$ spindle speed, $1.5\mu m$ feed rate per tooth and $20\mu m$ axial depth in each step.



(a) 2D view (b) 3D view

Fig. 5. The micro slab surface figures



(a) Top view (b) Front view

Fig. 6. The thin wall structure

The desired section dimensions of the thin wall were $70\mu m$ in thickness and $780\mu m$ in height. The actual dimensions of it were about $65.5\mu m$ in average width, $778.7\mu m$ in height and $3.43mm$ in length, with high aspect ratio near 12 as shown in Fig.6. In this test, the axial machining error was acceptable. But from the front view, the wall bottom thickness was greater than the one in the wall top, because the tool vibration and deflection influences as discussed by Gong et al. [22].

5 Conclusions

In this work, the critical technologies of MMT are discussed in detail. A 3-axis MMT prototype is developed with large workspace and precision resolution. Through the positional accuracy test of the motion stage, the prototype expressed the excellent performances. In the machining test, the MMT prototype is able to produce high quality surface with suitable machining parameters setting. Meanwhile, it is capable to create high aspect ratio as thin wall structure.

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References

1. Dornfeld, D., Min, S., Takeuchi, Y.: Recent advances in mechanical micromachining. Annals of CIRP 55(2), 745–768 (2006)
2. Filiz, S., Xie, L., Weiss, L., Ozdoganlar, O.: Micromilling of microbarbs for medical implants. International Journal of Machine Tools & Manufacture 48, 459–472 (2008)
3. Alting, L., Kimura, F., Hansen, H., Bissacco, G.: Micro engineering. Annals of CIRP 52(2) (2003); STC–O
4. Wang, J., Gong, Y., Abba, G., Chen, K., Shi, J., Cai, G.: Surface generation analysis in micro end-milling considering the influences of grain. Microsystem Technologies 14(7), 937–942 (2008)
5. Wang, J., Gong, Y., Abba, G., Cao, J., Shi, J., Cai, G.: Micro milling technologies for mems. In: Proceeding of 3rd MEMSTECH, Lviv-Polyana, Ukraine, May 2007, pp. 86–95 (2007)
6. Luo, X., Cheng, K., Webb, D., Wardle, F.: Design of ultraprecision machine tools with applications to manufacture of miniature and micro components. Journal of Materials Processing Technology 167, 515–528 (2005)
7. Furuta, K., Ishikawa, Y., Mikuriya, Y., Takahashi, Y.: The microfactory system in national r&d project of miti. In: Proceedings of the International Workshop on Microfactories, Tsukuba, Japan, December 1998, pp. 193–196 (1998)
8. Subrahmanian, R., Ehmann, K.F.: Development of a meso-scale machine tool (mmt) for micro-machining. In: Proceeding of Japan-USA Symposium on Flexible Automation, Hiroshima, Japan, July 2002, vol. 1, pp. 163–169 (2002)
9. Vogler, M., Liu, X., Kapoor, S., DeVor, R., Ehmann, K.: Development of meso-scale machine tool (mmt) systems. Transactions of North American Manufacturing Research Institution 30, 1–9 (2002)
10. Honegger, A., Kapoor, S., DeVor, R.: A hybrid methodology for kinematic calibration of micro/meso-scale machine tools (mts). ASME Journal of Manufacturing Science and Engineering 128, 513–522 (2006)
11. Lee, S.W., Mayor, R., Ni, J.: Dynamic analysis of a mesoscale machine tool. ASME Journal of Manufacturing Science and Engineering 128, 194–203 (2006)
12. Bang, Y., Lee, K., Oh, S.: 5-axis micro milling machine for machining micro parts. International Journal of Advanced Manufacturing Technology 25, 888–894 (2005)
13. Okazaki, Y., Mishima, N., Ashida, K.: Microfactory-concept, history, and developments. ASME Journal of Manufacturing Science and Engineering 126, 837–844 (2004)
14. Wang, J., Shi, J., Gong, Y., Abba, G., Cai, G.: A micro milling model considering metal phases and minimum chip thickness. Key Engineering Materials 375-376, 505–509 (2008)
15. Zhang, L., Zhao, D., Zhang, J., Sun, X., Pang, C.: Development of miniaturized numerical control milling machine tool used in micro cutting. Journal of Southeast University (Natural Science Edition) 137(1), 26–29 (2007)

16. Rusnaldy, T.J.K., Kim, H.S.: An experimental study on microcutting of silicon using a micromilling machine. International Journal of Advanced Manufacturing Technology (2008), doi:10.1007/s00170–007–1211–9
17. Malukhin, K., Ehmann, K.: Identification of direct metal deposition (dmd) process parameters for manufacturing thin wall structures from shape memory alloy (niti) powder. Transactions of the North American Manufacturing Research Institution of SME 35, 481–488 (2007)
18. Furutani, K., Suzuki, M., Kudoh, R.: Nanometer-cutting machine using stewart-platform parallel mechanism. Measurement Science and Technology 15(2), 467–474 (2004)
19. Kapoor, S.: Current state of micro-scale machine tool systems and machining research. In: Workshop on micromanufacturing, natural science foundation, University of Illinois at Urbana-Champaign (2004)
20. Tansel, I., Arkan, T., Bao, W., Mahendrakar, N., Shisler, B., Smith, D., McCool, M.: Tool wear estimation in micro-machining. part 1: tool usage ccutting force relationship. International Journal of Machine Tools & Manufacture 40, 599–608 (2000)
21. Zhang, E.L., He, W.W., Du, H., Yang, K.: Microstructure, mechanical properties and corrosion properties of mg-zn-y alloys with low zn content. Materials Science and Engineering: A 488(1-2), 102–111 (2008)
22. Gong, Y., Wang, J., Abba, G., Antoine, J., Shi, J.: Tool tip trajectories investigation and its influences in micromilling operation. IEEE Review on Advances in Micro, Nano and molecular Systems (in press)