Design of a 5-Axis Ultraprecision Micro Milling Machine – UltraMill: Part 1: Holistic Design Approach, Design Considerations, and Specifications

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Abstract: High accuracy three dimensional miniature components and microstructures are increasingly in demand in the sector of electro-optics, automotive, biotechnology, aerospace, and information technology industries. A rational approach to mechanical micro machining is to develop ultraprecision machines with small footprints. In part 1 of this two-series paper, the state of the art of ultraprecision machines with micro machining capability is critically reviewed. The design considerations and specifications of a 5-axis ultraprecision micro milling machine – UltraMill are discussed. Three prioritized design issues: motion accuracy, dynamic stiffness and thermal stability formulate the holistic design approach for UltraMill. This approach has been applied to the development of key machine components and their integration so as to achieve high accuracy and nanometer surface finish.

Keywords: Precision machines design; Micro milling; Miniature mechanical components; Five-axis machine tool; Bench-top micro machine tool

1. Introduction

High accuracy miniature components with dimensions ranging from a few hundred microns to a few millimetres or features ranging from a few to a few hundreds of microns are increasingly in demand for industries, such as electro-optics, automotive, biotechnology, aerospace, information technology, etc. [1]. It has long been recognized that traditional MEMS manufacturing techniques, such as chemical etching and LIGA, are not suitable for producing true 3D micro components [2, 3].

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On the other hand ultraprecision machine tools have the unique advantage of being able to manufacture geometrically complex miniature components to high accuracy, with fine surface finish in a wide range of engineering materials [4]. Fig.1 shows some examples of high accuracy micro components and microstructures manufactured by micro milling. These examples show that miniature components having complex three dimensional geometries need to be made from a variety of materials and not just silicon. The materials are application dependant, optical components being made from glass, polymer or aluminium, medical components from polymer or glass, mechanical components from ferrous or non-ferrous metals and dies/moulds from copper alloys, aluminium or high hardness steels. Some of the micro components and microstructures require submicron accuracy and nanometer surface finishes. Mechanical micro machining is an ideal method to produce high accuracy micro components. Amongst several mechanical machining processes, micro milling is the most flexible process and thus is able to generate a wider variety of complex micro components and microstructures.

In this paper the state of the art development of ultraprecision machine tools with micro milling capability including both industrial and research efforts is reviewed. Some advantages of compact or bench-top machine tool are highlighted. The focus will be the design considerations and determination of key machine components of a novel 5-axis bench-top micro milling machine – the UltraMill which is a part of the EU FP6 MASMICRO project [11] aiming at offering high accuracy micro manufacturing in a small footprint. Finally the specification of the UltraMill is discussed.

2. The State of the Art in Micro Milling Machines

The requirements of micro component manufacture over a range of applications are: high dimensional precision, typically better than 1 micron; accurate geometrical form, typically better than 50nm departure from flatness or roundness; and good surface finish, in the range of 10 – 50 nm. These in turn require machine tools to have high static stiffness, low thermal distortion, low motion errors and high damping or dynamic stiffness.

In addition to these requirements a critical and comprehensive review was carried out on ultraprecision machines with micro milling capability at the design stage of the UltraMill. There are a number of industrial ultraprecision turning and milling machines available for high precision components manufacture. However, most of them are generally aimed at the optical components market and are not well suited to the manufacture of precision micro components due to high investment costs and lack of flexibility. Fig. 2 shows some examples of industrial precision machines with micro milling capability. They fall into two categories. One is conventional ultraprecision machine tools which are designed as diamond turning machine tools with add-on Z-axis, rotary table and a second high speed milling or grinding spindle. Typical examples are Moore Nanotechnoloy Nanotech 350FG and Precitecch Freeform 700 ultra as shown in Fig. 1 (g) and (h). Both of them require 5-7 m^2 floor space. Their very high cost and low flexibility limit their application to micro components of simple geometries and high added value, such as optical components. Another type of industrial precision micro milling machine tool has emerged in the last decade. A typical example is the Kern micro machine (Fig.1 (a)) which meets many applications but still suffers from its machining accuracy for precision micro machining due to the positioning accuracy of the ball bearings based feed drive mechanism. Kugler MicroMaster (Fig.1(e)) offers higher accuracy and surface finishes, but the relative larger space requirements and the high cost limit its general applications as a micro machine tool.

Numerous research efforts to develop miniaturized machines or micro factories have been undertaken for the manufacture of precision micro components [12-14]. Fig. 3 shows some examples of miniature machine tool. However, most of them are still at the research stage, and only a few of them have so far found their way into industrial applications [15], but their application to high accuracy and fine surface quality are still constrained by low static/dynamic stiffness.

Therefore a rational approach to micro manufacturing is to develop compact or bench-top precision machines which offer a good trade-off between conventional ultraprecision machines and micro factory machines. The advantages over the conventional ultraprecision machines may include:

- Small footprint and energy-efficient;

- Ease of localized environmental control and thus low operational costs;
- Mobility.

Advantages over micro/meso machines commonly adopted in micro factories can be summarized as:

- A better machining envelope for covering a full spectrum of micro-machining applications;
- Higher static and dynamic stiffness, hence rendering better machining accuracy and surface quality;
- Key machine components with high performance and matured technologies available;
- Easy to integrate with other subsystems, including components/tools handling system, condition monitoring, micro tooling, and FTS, etc.

Therefore, a 5-axis ultraprecision micro milling machine with a small footprint is desirable to fill the gap for the demanding need of manufacturing 3D complex micro mechanical precision parts with nanometer surface finish.

3. General Design Considerations Applied to the UltraMill

In order to achieve mass production of three dimensional micro mechanical precision components with nanometer surface finish a design strategy has been proposed. This design strategy was applied to the design of an ultraprecision 5-axis micro milling machine – the UltraMill. At the design stage emphases were put on three major issues - motion accuracy, dynamic stiffness and thermal stability, which are directly related to machining accuracy and surface finishes. These three prioritized design issues together with other design considerations lead to the current development of the UltraMill. Some of general design considerations are discussed below.

The UltraMill is a general purpose ultraprecision machine, so 5-axis configuration with three linear axes and two rotary axes were pre-determined. The 5-axis configuration offers maximum flexibility in tool-workpiece orientation and minimum need for re-setup which is important to achieve high accuracy on micro parts.

Although it is specially designed for micro machining micro parts, a relative large machining envelope of 150 x 150 x 80 mm^3 was specified to enable it to machine large size components with micro features. The overall footprint is slightly greater than 1 m^2 including periphery which is only 10-20% percentage of the footprint required by conventional ultraprecision machines. The compact and energy efficient design also helps to keep the cost acceptable for mass production.

The machine kinematic configuration should provide sufficient flexibility in orientation and position of the tool and the part with highest possible speed and accuracy [28]. From the sequence of the motion axes point of view, there are hundreds of possible 5-axis machine configurations [29], however, most of the configurations have little industrial relevance. The configuration of two rotation axes and three linear axes has been chosen for the UltraMill, in which the two rotation axes are orthogonal to each other and one rotation axis is parallel to any of the three orthogonal linear axes. As for the spindle or workpiece holding axes, a hybrid type was adopted, i.e. one rotation is applied to the spindle and the other to the workpiece. This hybrid type is suitable for the production of smaller workpiece [30]. Besides the determination of machine kinematic configuration, part 2 of this two-series paper will discuss the analysis of the two typical configurations from the static and dynamic loop stiffness point of view.

One of the major features of the machine tool is that aerostatic bearings are employed in the machine tool throughout, which differs from most of the ultraprecision machine tools in the market. Three linear slides and rotary table are based on a novel new novel aerostatic bearing technology developed by UPM Ltd. The new aerostatic bearing design improves the stiffness and load capability by 50% which has been proved by theoretical study and validated by experimental testing. In addition to improvement of aerostatic bearing design, a patented technology to increase aerostatic bearing damping by using squeeze oil film damping is applied to all aerostatic bearings in the machine. Therefore, submicron machining accuracy under dynamic cutting force conditions is guaranteed by the above technologies. The extreme smooth and accurate motion provided by aerostatic bearings, along with diamond tooling, also make nanometer range surface finishes on micro components possible.

Thermal stability of a machine tool plays a critical role in determining its high machining accuracy and usually leads to unacceptable dimensional inaccuracy of the workpiece unless a proper cooling system and corresponding compensation measures are used. It is reported that the contribution of thermally-induced deformations of a machine tool may exceed 50% of the total machining error [31]. In ultraprecision machining, it is therefore imperative to minimize this effect by proper design and compensation. Analysis of heat sources contributing to the thermal deformation on the machine showed that bearing friction is negligible with the one exception of the high speed spindle running close to maximum speed. Apart from the micro machining process itself, motors become the major heat source, therefore, all the motors, the spindle, and rotary table in the developed machine tool are water cooled by a precise chiller with temperature control capability of ±0.2 ºC.

Special attention was paid to flexibility, precision, computation efficiency and cost when addressing the control system design. After reviewing existing commercial control systems a PC-based open architecture control system was chosen to meet the requirements. This PC-based controller, together with other hardware including digital PWM amplifiers, high precision optical encoders, etc. and software construct a high performance and cost effective control system for the 5-axis micro milling machine. Some details will be discussed in section 4 of this paper.

The UltraMill is an industrial prototype machine tool, and some auxiliary functions were also developed. These include a robot based system for micro tools and components handling and inspection, and a stand alone condition monitoring system for on-line high speed spindle and workpiece monitoring.

4. Development of the Key Machine Components and the Machine Integration

4.1 Miniature Ultra High Speed Spindle

A flexible 5 axis micro milling machine may be expected to perform a wide variety of machining operations on a range of materials requiring tools from 2 or 3 mm in diameter to as small as 50 um diameter. The latter require extremely high rotational speeds to achieve even modest machining rates whereas the former require a high stiffness spindle to maintain high accuracy in the presence of large cutting forces. High machining accuracy also requires low spindle running temperatures to minimise thermal distortion whilst a fine surface finishing capability can only be achieved with a spindle having low motion errors. Thus the requirement is for an accurate running, wide speed range spindle.

A spindle operating speed range of 20 000 to 200 000 rpm was envisaged for the machining conditions expected to be performed. This necessitates a motorised drive as opposed to an air turbine for which reasonable efficiency is achieved only over a narrow speed range. DC brushless motors offer constant torque over a wide range of speeds and compared to other motor types produce low heat generation. The motor selected is capable of generating 440 Watts of power at 250 000 rpm. Such high speeds preclude the use of Hall sensors for motor commutation so a sensorless motor and drive combination were used.

The fine surface finishing requirement dictates the use of a spindle with air bearings. Diamond tipped tools widely used to machine optical surfaces are sensitive to spindle motion errors typically encountered with ball bearings and apart from the fact that the asynchronous vibration from ball bearings is a source of surface roughness during machining, diamond tool life is also compromised. Hydrostatic and hydrodynamic bearings were also considered but rejected on the grounds of excessive power consumption at the high rotational speeds required.

Perhaps the greatest challenge in designing a high speed air spindle is to overcome the phenomenon of ‘half speed whirl’. In practice aerostatic spindles are limited in speed to about twice that of the first shaft-bearing resonant frequency. Half speed whirl is commonly encountered in hydrodynamic bearings where the lubricant film collapses should the shaft orbit the journal in a forward direction at half rotational speed. The mechanism of instability is similar for ultra high speed aerostatic spindles because at such high speeds aerodynamic forces in the bearings completely overwhelm aerostatic forces. Half speed whirl is mitigated by optimising shaft and bearing design, tuning resonances to as high a frequency as possible. As part of this optimisation a non standard air bearing design was developed having high rigidity and reasonable damping capacity.

Optimization on bearing stiffness and heat generation has been conducted, together with dedicated spindle shaft balancing, leading to the ultrahigh speed spindle as shown in Fig.4. The spindle developed is 63 mm in diameter and 115 mm in length and weighs 2.5 kg. It has a maximum speed in excess of 200 000 rpm and a radial stiffness of 3 N/um measured at the collet end. Bearing friction losses are less than 50 Watts at maximum speed but even so, water cooling is used to minimise thermal distortion.

4.2 Feed Drive and Guidance System

A high speed and accurate motions and positioning system are essential for ultraprecision micro machines. The direct feed drive system, using linear motors for linear slideways in particular, is becoming increasing popular in fulfilling such applications. The main advantages over the indirect feed drives can be summarized as follows [18, 32-33]:

- no backlash, no lead screw error, no belt stretch, and less friction, resulting high accuracy;
- no mechanical limitations on acceleration and velocity, the velocity is only limited by the encoder bandwidth or by the power of the electronics;
- high jerks and high K_v factor which characterises the ability of high precision at high speed;
- mechanical simplicity, resulting in ease of maintenance and installation, higher reliability and enabling higher frame stiffness to be achieved;

With respect to the guidance mechanism, several types of bearings have been frequently applied in ultraprecision machine tools for slides and rotary tables, including precision roller bearings, aerostatic bearings, hydrodynamic bearings and hydrostatic bearings, etc. Aerostatic bearings provide extremely smooth and accurate motion and positioning and are normally better than other bearings. Aerostatic bearings can provide sufficient static stiffness and load capability for micro machining due to the very light cutting loads, while other bearings such as hydrostatic bearings provide much higher stiffness and load capability but this offers only a small advantage under light cutting conditions.

Aerostatic bearings are applied to all the three linear slideways and the rotary table in the machine tool developed. Ironless brushless linear motors are used to drive the slideways. A disadvantage of aerostatic bearings is known as their low damping capacity or dynamic stiffness, which directly limits the surface finishes and accuracies that can be achieved by the machine tool. In order to improve dynamic stiffness of the aerostatic bearing, a novel squeezed oil film damper is fitted to all slides and the rotary table in the machine tool developed. It uses magnetic oil to contain leakage and when connected in parallel with the aerostatic bearings provides additional damping forces for any vibrational motion normal to the bearing surfaces. The use of an oil based damper on aerostatic slides and rotary tables increase viscous friction in the direction of motion but because of relatively lower operating speeds on these types of aerostatic bearing it is not a significant disadvantage. In fact on slides and tables fitted with direct drive motors, viscous drag in the direction of motion has been found to increase damping of motor vibration, leading to smoother motion and to aid tuning of the control system. Fig. 5 shows the photograph of an aerostatic bearing slide fitted with squeezed oil film damper.

4.3 Machine Base

The material selection for a machine tool base is one of the critical factors in determining final machine performance, with many criteria being considered, such as temporal stability, specific stiffness, homogeneity, easiness of manufacturing and cost, etc [34].

Although there are a number of structural materials available, up to now only a few materials have been chosen for building precision machine tool structures. Cast iron has been widely used on general industrial machine tools for many years due to low cost and reasonable damping characteristics, but there are not many cast iron applications in precision machine tools. Polymer concrete is becoming a popular machine base material due to its light weight and good damping compared to cast iron, however the low stiffness and strength of polymer concrete limits its application in high accuracy machine tools. Invar, zerodur and alumina ceramics are very expensive materials, and although they have the best thermal stability their use has been limited to research machine tools [35].

Granite provides better rigidity, damping capacity and thermal stability to minimize the influence of dynamics loads and transients. By taking these capability and reasonable cost into account, granite has been chosen as the machine base material for the UltraMill.

4.4 Control System

Computer numerical control (CNC) was introduced into the machine tools industry in early 1970's and since then many companies started to develop their own control systems for machine tools. The control system normally includes motors, amplifiers, switches and the controlled sequence and time. High speed multi-axis CNC controllers are essential for efficient control of, not only servo drives in high precision position loop synchronism for contouring, but also thermal and geometrical error compensation, optimized tool setting and direct entry of the equation of shapes [36].

From the dynamics viewpoint, stiffness in control system indicates the capability to hold a position when dynamic forces try to move it. Therefore, a proper design of control system and its algorithms can lead to a high servo-stiffness and hence guarantee machining accuracy through the machine tools.

A Delta Tau UMAC controller was chosen to implement numerical control system of the UltraMill. The modular UMAC controller is based on open architecture and provides more flexibility and higher performance than conventional CNC system to meet the highest requirements of 5-axis micro milling. Three dimensional complex micro parts with contoured surfaces and small features require small and precise moves and hence a high servo loop update rate. The servo frequency of the controller has been optimized to achieve higher servo stiffness, which makes it possible to design the system performance at the design stage. The UMAC controller also provide interfaces to high resolution encoders and many non-standard functions required in the micro milling machining, such as a robot-based tool/workpiece handling subsystem, a condition monitoring subsystem and other miscellaneous functions. In addition, the cost effective feature of control system is suitable for mass production. Fig. 6 shows the schematic of the PC-based control system architecture for the UltraMill.

A human-machine interface has been developed by customizing in a standard CNC software environment. The interface provides all the important information before, during and after machining. The human machine interface not only outputs or displays information but also enables the operator to input information for machining purposes. The interface would integrate the CAD/CAM software and machine control unit software. Fig. 7 shows an example of the HMI development.

4.5 Machine Integration

The development of key machine components or sub-systems discussed above was emphasised on the three prioritized design issues, i.e. motion accuracy, dynamic stiffness and thermal stability. The successful development of these sub-systems is important to meet design requirements. Optimization at the system level, i.e. the integrated machine system, is also imperative to achieve required machine performances. The effects of machine and its integration on a machining system performance are illustrated in Fig. 8.

From a machining viewpoint, the main function of a machine tool is to accurately and repeatedly control the point of contact between the cutting tool and the uncut material - the ‘machining interface’. This interface is normally better defined as tool-workpiece loops (Fig. 8). The position loop - the relative position between the workpiece and the cutting tools which directly contributes to the precision of a machine tool and directly lead to the machining errors. Deformations introduced by stiffness/compliance and thermal loop are two important aspects in tool-workpiece loops. Besides improving the performance of individual sub-systems, efforts also should be put into optimizing machine integration performance in terms of static loop stiffness, dynamic loop stiffness, etc. Therefore, it is necessary to develop an integrated design approach in which the machine tool is treated as a complete mechatronic system to enable evaluation of the whole machine’s performance at an early design stage. Part 2 of this two-series paper will discuss an integrated design and modelling approach applied to the machine developed.

5. Specifications of the UltraMill

The UltraMill, Fig.9, has been built based on the design considerations discussed in this paper. It offers the capability of manufacture of 3D miniature mechanical components and micro-featured surfaces in a wide range of engineering materials in a small footprint. The main specifications of the UltraMill are summarized in Table 1.

6. Concluding Remarks

The demand for micro manufacturing technology for miniature and micro products fabrication has a high potential for growth, and is driving the development of high performance ultraprecision machine tools. Bench-top ultraprecision machines will be one of the future development trends since they enable ultraprecision machining of high-accuracy miniature and micro products economically, and enable the technology affordable for a wide audience of manufacturing SMEs to engage high value micro and nano manufacturing in an efficient and effective manner. In this paper a 5-axis ultraprecision micro milling machine – UltraMill was developed to provide a compact and energy efficient solution to manufacture 3D complex micro components at submicron accuracy and nanometer surface finishes. The state of the art micro milling machines was critically reviewed and the advantages of bench-top micro milling machines were highlighted. Design considerations and challenges of the UltraMill were discussed with emphasis on three major issues - motion accuracy, dynamic stiffness and thermal stability.

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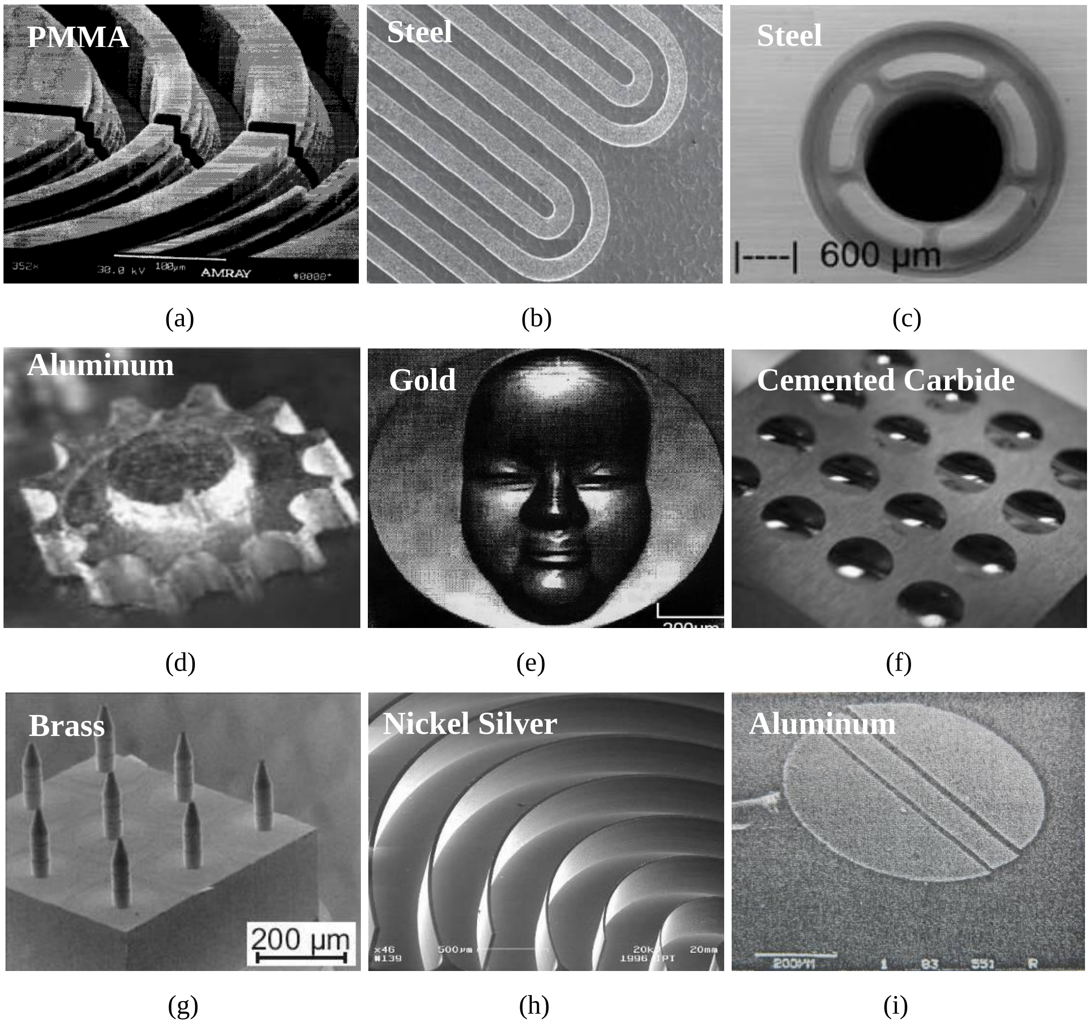
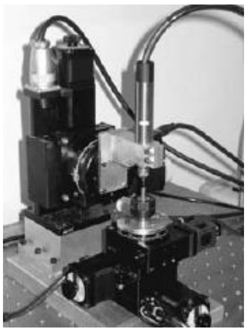


Fig. 1. Examples of high accuracy micro-milled components and microstructures: (a)Micro trenches [5]; (b)Micro reactor [6]; (c)Micro mould [7]; (d)Micro-gear [2]; (e)3D micromachined part – Noh-mark (source: Fanuc); (f)Micro projection array (source: Fanuc); (g)Micro needles array [8]; (h)Micro wall [9]; (i)Target foil for nuclear fusion [10]

Fig. 2. Industrial precision machine tools with micro milling capability: (a)Kern micro [16]; (b)Sodick AZ150 [17]; (c)Fraunhofer IPT Minimill [18]; (d)Makino Hyper2J [19]; (e)Kuglar MicroMaster MM2 [20]; (f)Fanuc ROBOnano [21]; (g)Precitech freeform 700 Ultra [22]; (h)Moore Nanotech 350FG [23]

(a) [24]



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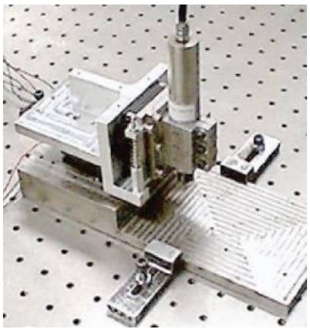

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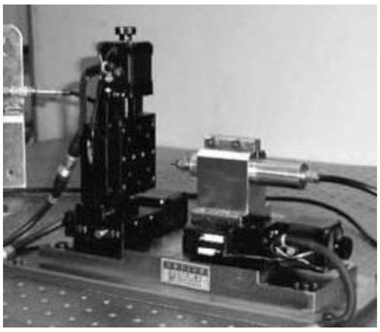

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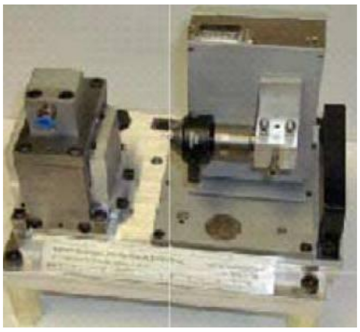

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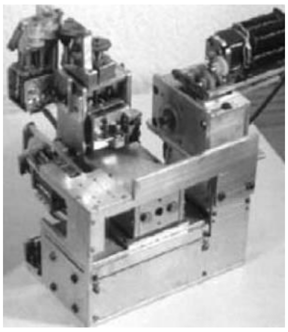
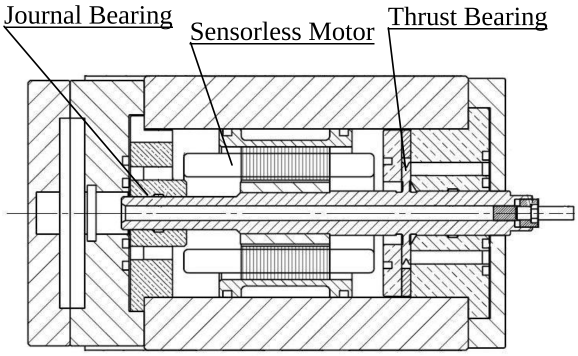


(f) [13]

Fig. 3. Examples of miniature machine tools and micro factories



(a) (b)

Fig. 4. The ultrahigh speed aerostatic bearing spindle driven by a sensorless DC motor (UPM Ltd.) (a) Photograph of the developed miniature spindle; (b) A schematic of the spindle

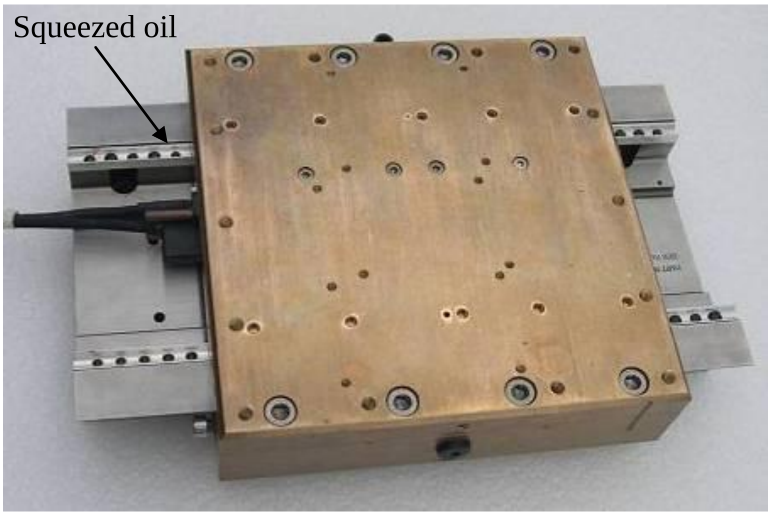


Fig. 5. The aerostatic bearing slide fitted with squeezed oil film damper

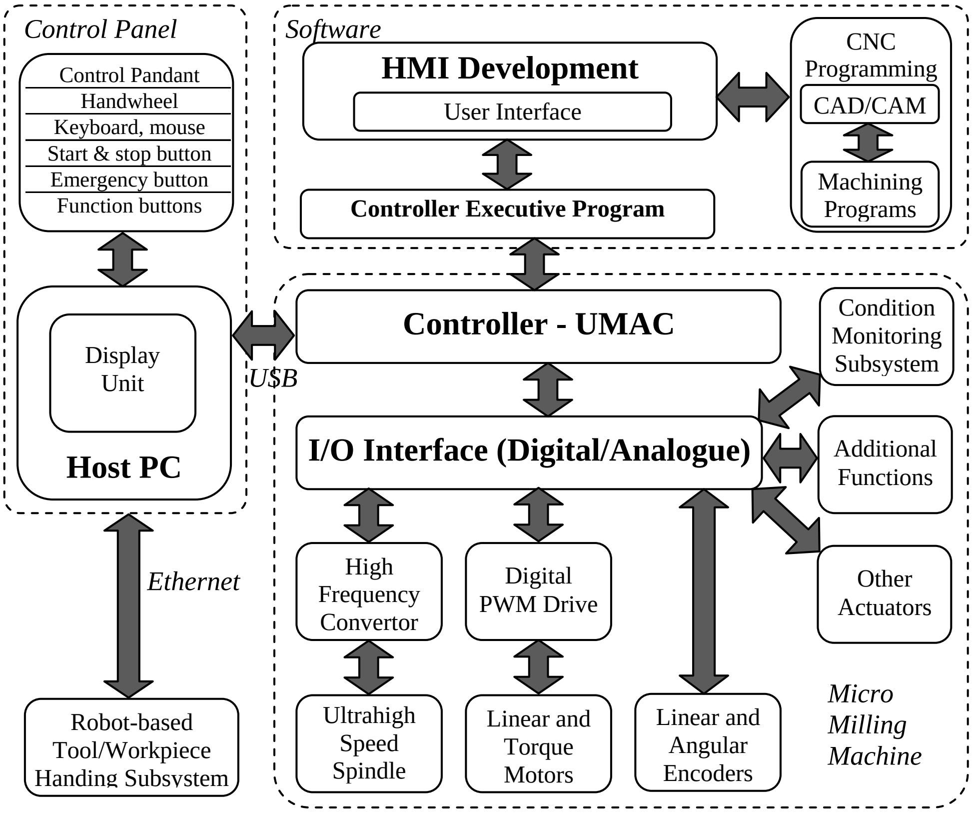


Fig. 6. PC-based control system architecture for the UltraMill

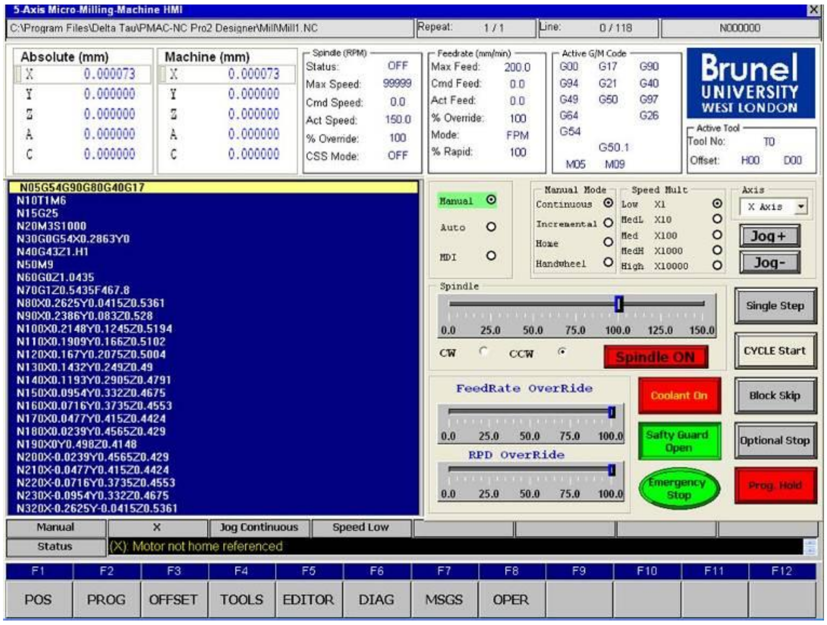


Fig. 7. An example of customized HMI

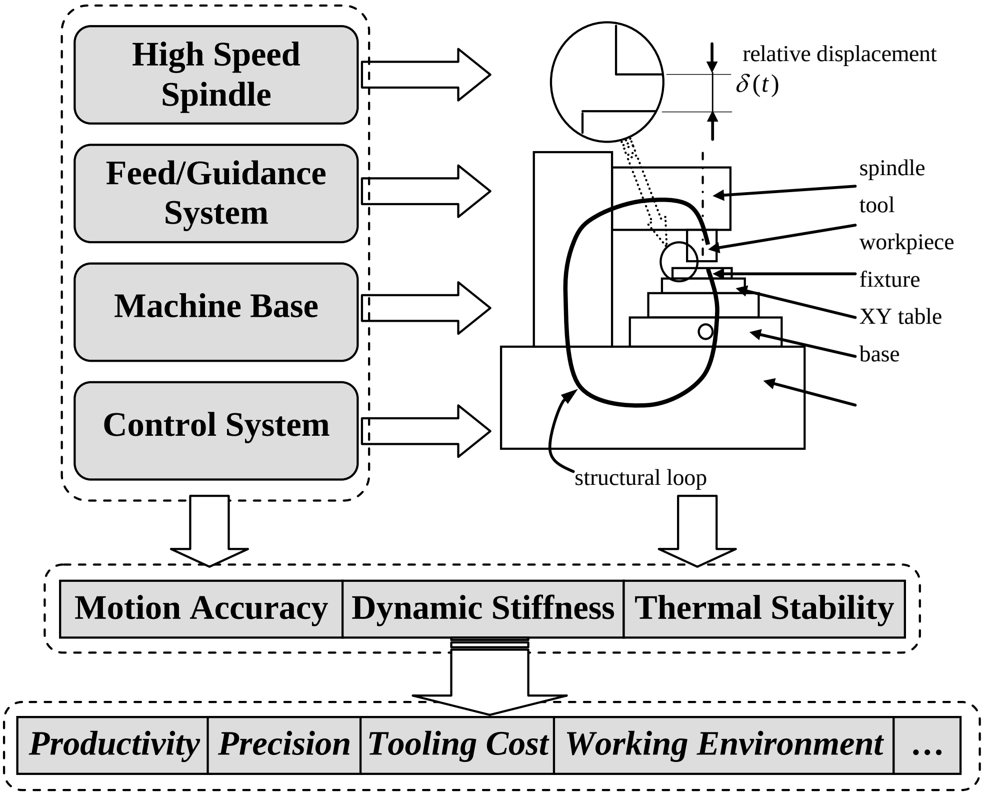


Fig. 8. The effects of machine and its integration on a machining system

Fig. 9. The ultraprecision micro milling machine - UltraMill

Table 1. Specifications of the micro milling machine - UltraMill

Axes	X, Y and Z axis	B axis (rotary table)	C axis	Spindle
Type	Air bearing slides fitted with squeeze film dampers		Precision ball bearing	Air bearing
Stroke	X:230mm Y:225mm Z:160mm	360°	± 90°	N/A
Motion accuracy	<1.0 μm over total travel	<1 arcsec	<10 arcsec	<1.0 μm axial TIR and <2.0 μm radial TIR
Resolution	5 nm	0.02 arcsec	0.02 arcsec	N/A
Drive system	brushless Linear motor	DC brushless torque motor	DC brushless torque motor	DC brushless motor
Maximum speed	3000 mm/min	100 rpm	30 rpm	200,000 rpm