An Integrated Framework for Developing Generic Modular Reconfigurable Platforms for Micro Manufacturing and its Implementation

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A thesis submitted in partial fulfilment of the
requirements of Brunel University
for the degree of Doctor of Philosophy

May 2009

Abstract

The continuing trends of miniaturisation, mass customisation, globalisation and wide use of the Internet have great impacts upon manufacturing in the 21st century. Micro manufacturing will play an increasingly important role in bridging the gap between the traditional precision manufacturing and the emerging technologies like MEMS/NEMS. The key requirements for micro manufacturing in this context are hybrid manufacturing capability, modularity, reconfigurability, adaptability and energy/resource efficiency. The existing design approaches tend to have narrow scope and are largely limited to individual manufacturing processes and applications. The above requirements demand a fundamentally new approach to the future applications of micro manufacturing so as to obtain producibility, predictability and productivity covering the full process chains and value chains.

A novel generic modular reconfigurable platform (GMRP) is proposed in such a context. The proposed GMRP is able to offer hybrid manufacturing capabilities, modularity, reconfigurablity and adaptivity as both an individual machine tool and a micro manufacturing system, and provides a cost effective solution to high value micro manufacturing in an agile, responsive and mass customisation manner.

An integrated framework has been developed to assist the design of GMRPs due to their complexity. The framework incorporates theoretical GMRP model, design support system and extension interfaces. The GMRP model covers various relevant micro manufacturing processes and machine tool elements. The design support system includes a user-friendly interface, a design engine for design process and design evaluation, together with scalable design knowledge base and database. The functionalities of the framework can also be extended through the design support system interface, the GMRP interface and the application interface, i.e. linking to external hardware and/or software modules.

The design support system provides a number of tools for the analysis and evaluation of the design solutions. The kinematic simulation of machine tools can be performed using the Virtual Reality toolbox in Matlab. A module has also been developed for the multiscale modelling, simulation and results analysis in Matlab. A number of different cutting parameters can be studied and the machining performance can be subsequently evaluated using this module. The mathematical models for a non-traditional micro manufacturing process, micro EDM, have been developed with the simulation performed using FEA.

Various design theories and methodologies have been studied, and the axiomatic design theory has been selected because of its great power and simplicity. It has been applied in the conceptual design of GMRP and its design support system. The implementation of the design support system is carried out using Matlab, Java and XML technologies. The proposed GMRP and framework have been evaluated through case studies and experimental results.

Acknowledgements

I would first like to sincerely thank my PhD supervisor, Professor Kai Cheng, for his invaluable support, guidance and encouragement throughout the course of this research, without which the completion of the PhD project would not have been possible.

I would like to express my gratitude to Brunel University for its financial support through the PhD scholarship which has made this research possible. Special thanks also go to my friends and colleagues, Dr. Qingping Yang, Dr. Dehong Huo, Mr. Paul Yates, Mr. Khalid Mohd Nor, Mr. Rasidi Ibrahim, Mr. Lei Zhou and other friends for their support and valuable discussions in this research.

I am deeply obliged to my parents, Zhuode Sun and Sulian Zhou, for their love, patience, understanding and support, and I am also very grateful to Lizhi and Yanxing for their assistance and encouragement.

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Abbreviations

AI	Artificial intelligence
CA	Consumer attributes
DMS	Dedicated manufacturing system
DOM	Document object model
DP	Design parameter
DSS	Design support system
DTD	Document type definition
EDM	Electrical discharge machining
FE	Finite element
FMS	Flexible manufacturing system
FR	Function requirement
GMRP	Generic modular reconfigurable platform
KDP	Potassium Titanyl Phosphate
MD	Molecular dynamics
MRR	Material removal rate
NIF	National Ignition Facility
PV	Process variable
QC	Quasicontinuum
QFD	Quality function deployment
RMS	Reconfigurable manufacturing system
RMT	Reconfigurable machine tool
SMEs	Small and medium enterprises
VRML	Virtual reality modelling language
WTEC	World Technology Evaluation Centre
XML	Extensible markup language

Nomenclature

A	deformation gradient
E_α	energy of each repatom (J)
E	applied voltage (V)
E_i	aeienergy contribution from site x_i (J)
E_p	electric field at micro-peak (V/m)
E_{tot}	total energy (J)
I	the current (A)
K_p	constant
N_e	the number of elements
N	number of molecules per unit volume
N_{rep}	the number of representative atoms involved
P	external pressure (N/m^2)
$P(nuc)$	bubble pressure (N/m^2)
$P_v(T)$	pressure in the bubble at temperature T (N/m^2)
P_w	energy partition to the workpiece (J)
$R(t)$	plasmas radius at time t (m)
S_α	finite element shape function
S	nucleation rate per unit volume ($1/m^3 s$)
T_i	initial temperature (K)
T_{nuc}	temperature at which nucleation occurs (K)
T_0	room temperature (K)
T_{sat}	saturation temperature (K)
U	discharge voltage (V)

b	interelectrode gap (m)
c	specific heat capacity (J/Kg)
h_c	heat transfer coefficient
h_{fg}	latent heat of vaporization (J/Kg)
i	Boltzmann constant (J/K)
j	current density (A/m^2)
k	thermal conductivity (W/mK)
m	mass of one molecule (Kg)
n	direction that is normal to the surface
n_α	suitably chosen weight
q	heat flux (W/m^2)
r_{active}	active radius of the nucleate bubble (m)
r_0	initial radius of the nucleated bubble (m)
r_t	radius of an asperity (m)
t_c	time at which bubble reaches an active growth criterion (s)
u_α	displacement of each repatom (m)
u_j	displacement of non-representative atoms (m)
v	velocity of electron drift (m/s)
x_j^0	initial position of atom j (m)
Ω_k	unit cell volume (m^3)
α	representative atoms
$\varepsilon(A)$	strain energy density (J/m^3)
λ	heat of vaporization per molecule (J/mol)
ρ	material density (Kg/m^3)
ρ_v	density in the bubble (Kg/m^3)
σ	surface tension (N/m)

τ_g	time of growth (s)
τ_{nuc}	nucleation time (s)
ϕ	work function of metal (eV)

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Chapter 1 Introduction

1.1 Background of the research

1.1.1 Overview of precision and ultraprecision machining

Manufacturing is essentially concerned with changing raw materials to produce parts using equipment, operator, information and knowledge. Manufacturing processes can be categorized into three types, i.e. putting materials together, moving materials from one region to another, or removing unnecessary materials (Shaw, 1984). Specially, machining is the process of removing unnecessary materials from the bulk to create the required part. Based on the material removal method, machining can be further classified as turning, milling, drilling, grinding, laser machining, etc. To perform different machining processes, different machine tools have to be usually used e.g. lathes, milling machine tooles, drilling machine tooles, etc. Precision and ultraprecision machining are concerned with the fabrication of products/components with high form and dimensional accuracy and surface quality, which will affect the products or components' specified functionality and performance (Luo, 2004).

The historical development of achievable machining accuracy is depicted in Fig. 1.1 (Byrne et al, 2003), which has clearly shown the continuous progress in the machining performance of normal machining, precision machining and ultraprecision machining over half a century from 1940 to present. It can be seen from the chart that the concepts of precision manufacturing and ultraprecision manufacturing are essentially relative and dynamic. For example, ultraprecision machining has progressed from a machining accuracy of 0.1 μm in 1950s to 1 nm now. Today, ultraprecision machining means the achievement of dimensional tolerances on the order of 0.01 μm and surface roughness of 0.001 μm. The driving forces behind these continuous progresses are generally due to the ever advancing technologies and knowledge.

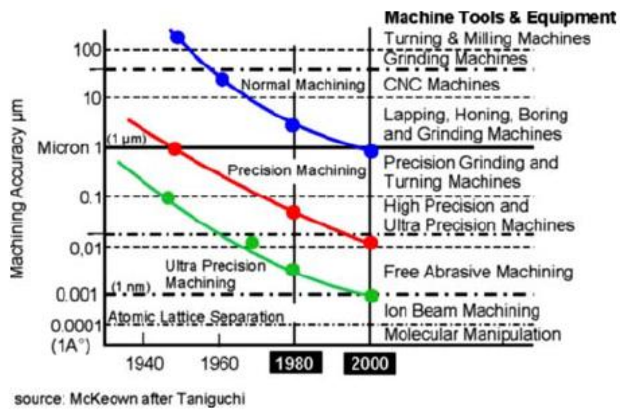


Fig. 1.1 The development of achievable machining accuracy

Fig. 1.1 also in fact shows a close relationship between high machining precision and miniaturisation. It is high precision machining that acts as an enabler for micro and miniaturised products in electronics, mechanical, electrical and optical applications. Likewise, the application of micro and miniature products further promotes the development of high precision machining. The development of ultraprecision machining may be further summarised in Table 1.1.

Table 1.1 The development of ultraprecision machining

	Key applications	**Processes/Machine tools**	**Companies**
1960s-1980s	Aerospace, Defence (optical surfaces), Electronics	Sing point diamond turning	Union Carbide, Philips, Lawrence Livermore Laboratories
1980s-1990s	Optics, Electronics, ICT hardwares, Mechanical devices	Sing point diamond turning, Diamond grinding, Large optics diamond turning machine	Moore Special Tool, Pneumo Precision, Toshiba, Hitachi
2000s-2010s	High value manufacturing represented by micro ultraprecision features: Consumer electronics, Automotive, Medical, MEMS, ...	Ultra precision 5-axis milling, Micro drilling, Micro grinding, Fly-cutting, Micro EDM, etc.	Kern, Precitech, Kugler, Sodick, Fanuc, ect.

The key applications, typical processes and machine tools, and representative companies since 1960 are given. Further trends can be identified from this table:

1) The applications started with defence and aerospace, have now entered many different sectors. A growing customer base has great implications to the future development requirements.
2) The technologies have also expanded significantly, covering a range of processes.
3) More and more industries are now involved and participate in this market.

1.1.2 Nature of micro manufacturing

Micro manufacturing originally refers to the lithography based fabrication of semiconductor devices in integrated circuits, but the scope and techniques of micro manufacturing have been extended with the practical advances in MEMS (micro-electro-mechanical systems) and other micro/nano technologies. Although MEMS processes have been developed over a decade, they are fundamentally only suitable for 2-2.5 dimensional fabrications and very limited in the engineering materials employed, which means that they have no capability of manufacturing 3D features with a wide range of materials. Micro manufacturing has thus been extended to cover non-lithography based technologies, which are capable of high precision 3D manufacturing with a range of materials.

As defined by the WTEC panel, micro manufacturing is the creation of high-precision three-dimensional products using a variety of materials and possessing features with sizes ranging from tens of micrometers to a few millimetres (Ehmann et al, 2005). This is really the non-lithography based kinds of micro manufacturing. However, for simplicity the term of micro manufacturing in the following sections and chapters is also used according to this definition.

Micro manufacturing is precision manufacturing from the machining accuracy perspective, so traditional ultraprecision machining processes can be used to fabricate micro parts/components. Additionally, some innovative processes using various physical and chemical effects have been developed. Hence, there are two broad categories of processes in micro manufacturing, namely, a ‘top down’ approach where traditional ultraprecision technologies have been adapted and scaled down, and a 'bottom up' approach where fundamentally new technologies have been used.

Fig. 1.2 gives the relationship of micro manufacturing with existing technologies, i.e. ultraprecision manufacturing, MEMS and NEMS. Micro manufacturing can be seen as a bridging technology between MEMS/NEMS and ultraprecision manufacturing, with object size comparable to MEMS and relative accuracy similar to precision manufacturing.

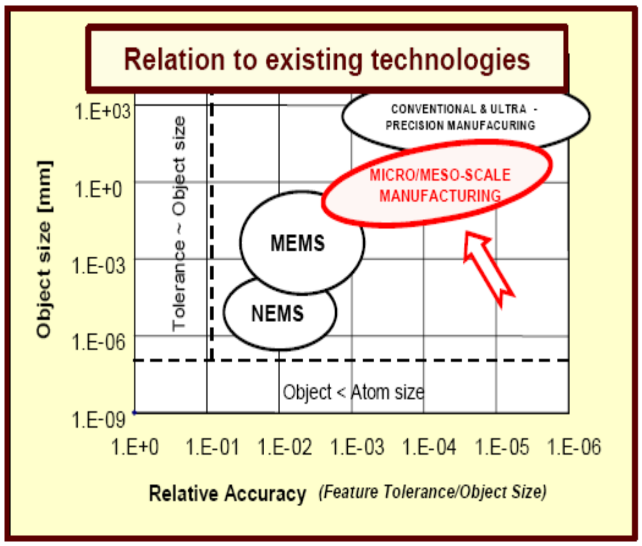


Fig. 1.2 Micro manufacturing size/precision domain

Micro manufacturing may be carried out on conventional ultraprecision machine tools (Fig. 1.3) or micro/meso machine tools (Fig. 1.4) (Venkatachalam, 2007). Although traditional mechanical ultraprecision machining has been used to fabricate miniature and micro components/products, there are still big issues in the predictability, producibility and productivity of the fabrication of micro products, especially for those miniature and micro components/products with complex surface forms/shapes. Moreover, small size, complex geometry and high quality of micro products also impose high demands on the machine performance. This will inevitably increase the investment and operation costs, making it difficult for manufacturers (SMEs, in particular) to access the technology and thus the high value-added manufacturing business.

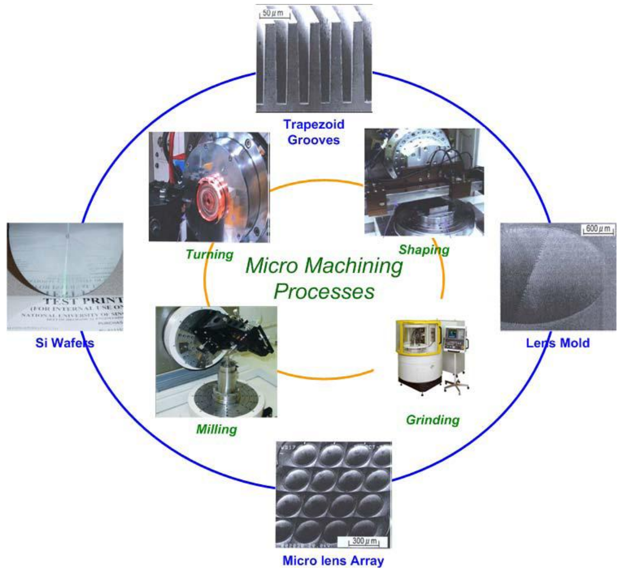


Fig. 1.3 Micro manufacturing with conventional ultraprecision machine tools

Micro/meso machine tools are more suitable for the fabrication of micro products in terms of cost, occupied space, energy consumption and mobility, etc. Although there are many distinguished advantages of micro machine tools, they are still at research and laboratory stage and have not been widely accepted in industry.

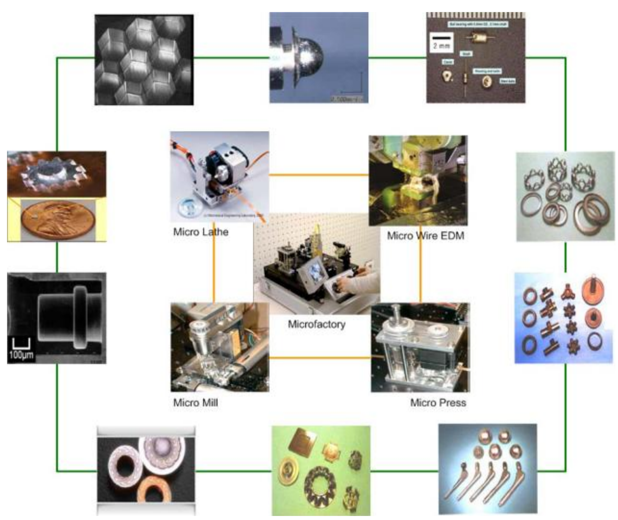


Fig. 1.4 Micro manufacturing with micro/meso machine tools

1.1.3 Micro manufacturing market

Miniature and micro products (typically with fabricated features in the range of a few to hundred microns) are increasingly needed in a variety of fields including optics, electronics, medicine, biotechnology, communications and defence, etc. Specific applications include medical implants, cameras, wireless devices, micro-scale fuels, fibre optic components, deep X-ray lithography masks and many more (Ehmann et al, 2005; Ehmann, 2007, Liu et al, 2004). All these products or components, often in a diverse range of engineering materials, need very fine surface finishes and high form accuracy. Many of these kinds of components and structures require submicron accuracy and nanometer surface finishes.

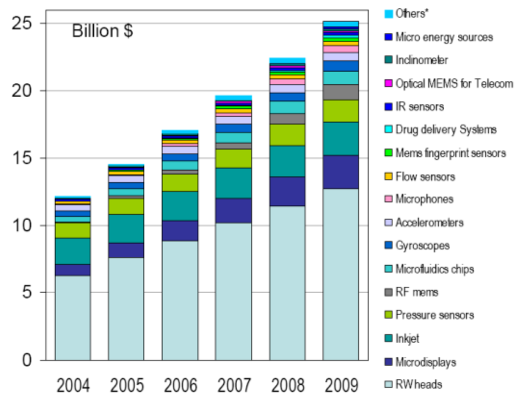


Fig. 1.5 MEMS and MST markets

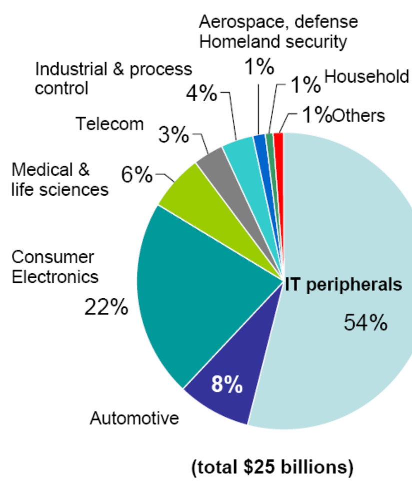


Fig. 1.6 MEMS/MST application fields in 2009

MEMS have been and will still be one of major driving forces for micro manufacturing. The forecasted MEMS/MST (micro system technology) market volume in 2009 is $24billion, as shown in Fig. 1.5. The completely new products such as micro fuel cells, MEMS memories, chip coolers, liquid lenses for cell phone zoom and autofocus will be included in this category. The size of each application area is given in Fig. 1.6, with IT peripherals, consumer electronics, automotive and medical applications representing about 90% of the market.

According to Bibber (2008), micro manufacturing is forecast to grow to a $68 billion (£34 billion) market in 2010, with applications in medical, electronics, industrial, military, aerospace, automotive, and microfluidics market sectors.

1.1.4 Trends and challenges of micro and ultraprecision manufacturing

Mass-customisation has become an established trend over the recent years, even more so because of the wide use of the Internet technologies and applications. In such a context consumers have generally high expectations with regard to product features, functionalities, quality and cost levels. This has created great pressure on manufactures to meet the ever changing needs of individual consumers with the development of novel technologies for high value manufacturing.

Furthermore, globalisation, consumer diversity and environment sustainability have been key drivers for the continual evolution of the manufacturing industry. The diverse consumer preferences and environmental considerations (e.g. energy and use of raw materials) have great impacts on manufacturing and business strategies. Future manufacturing technologies must address environmental concerns and responsibility for disposal and recycling. In the current open and competitive global markets, manufacturers must offer high quality products to meet the growing and changing demands of the end customers and the society, using environment-friendly technologies and/or processes.

The above trends of micro manufacturing, and the rapidly changing market of miniature and micro products with continuous emergence of new products and/or new materials, have imposed great challenges to micro manufacturing. Indeed, the current challenges for micro manufacturing include the hybrid manufacturing capability, modularity, reconfigurability, adaptability and energy/resource efficiency (Sun and Cheng, 2008).

The following R&D barriers have also been identified in the current development of micro manufacturing (Ehmann, 2005):

- System level tools, mathematical modelling and manufacturability data;
- Development of new processes, materials, energy;
- Lack of understanding the scaling effect;
- Lack of effective metrology methods/tools for measuring small parts and quality assurance;
- No integrated knowledge base.

For ultraprecision manufacturing, it should be competitive in terms of productivity and responsiveness which is essential as an advanced manufacturing technology. This means the ultraprecision machines would be ideally modular, reconfigurable and adaptive for supporting timely high precision productions such as high precision consumer goods, ICT hardware, medical devices, electronics, MEMS, etc. Further, for instance, the number of the needed KDP mirrors and switches (as shown in Fig. 1.7) in the USA NIF project is up to about 3750 (NIF, 2003); they indeed require an ultraprecision manufacturing system to fulfil the entire manufacturing work in a productive and producible manner.

And yet, the existing ultraprecision machine tools for micro manufacturing are generally only dedicated to specific micro manufacturing processes and individual applications, and tend to be very expensive. At the present time, however, it is becoming increasingly difficult for those machine tools to cope with fast dynamic requirements, such as those associated with mass-customisation, fast changing consumer goods, high quality, low cost and environmental sustainability, etc. It is therefore necessary to develop novel equipment and solutions for micro manufacturing.

(a)

(b)

Fig. 1.7 (a) A KDP crystal for NIF's optical system, and (b) a deformable mirror to eliminate wavefront aberrations in the laser beam (Walter, 2003)

1.2 Aims and objectives of the research

The key to creating products that can meet the demands of a diversified customer base is a short development cycle yielding low cost, high quality goods in sufficient quantity to meet demands. This makes flexibility an increasingly important attribute to manufacturing (Wiendahl et al, 2007).

The logical conclusion of such arguments will lead to a general solution, namely, a modular and reconfigurable machine tool. The modularity and reconfigurability (which are arguably the key features of such machine tools) will provide the flexibility, responsiveness and cost effectiveness required for the dynamically changing competitive global markets. They are particularly important in micro manufacturing because of its complexity and high value manufacturing in nature.

It is against such a background that this research has proposed a new micro manufacturing platform, i.e. a generic modular reconfigurable platform (GMRP), to provide effective means for fabrication of high value 3D micro products at low cost in a responsive manner. The GMRP has the potential to satisfy the fast changing demands and is also suitable for the applications of "point-of-use". The GMRP features hybrid micro manufacturing processes, modularity and reuse of key components, reduced material consumption, and reconfigurability of machine platforms and key components.

The proposed GMRPs should have ability to integrate (reconfigure for) several micro manufacturing processes. However, since the GMRP is very complicated with reconfigurable configurations, various manufacturing processes and a number of components, the complexity imposes great challenges to the design process. A general design support system or integrated framework is particularly required. Such an integrated framework has therefore been proposed in this research to facilitate the development of GMRP, which incorporates a number of software tools, modules and interfaces at system level. It has modules for the modelling/simulation of manufacturing process and machine tool, and also a knowledge base for design generation and design evaluation. The heart of the framework is the design support system (with a design engine), and the framework may indeed be viewed as a general design support system.

The overall aim of this research is to establish a framework for the development of GMRP for micro manufacturing.

The distinct objectives for this research include:

(1) To critically review the state of the art of micro manufacturing and design methodologies.
(2) To propose a sound framework for the GMRP development for micro manufacturing.
(3) To develop a conceptual design of the GMRP.
(4) To design and implement a design support system for GMRP.
(5) To develop modelling and simulation of nano cutting and micro EDM.
(6) To evaluate the proposed GMRP and framework with case studies.

1.3 Structure of the thesis

The thesis is divided into eight chapters as shown in Fig. 1.8.

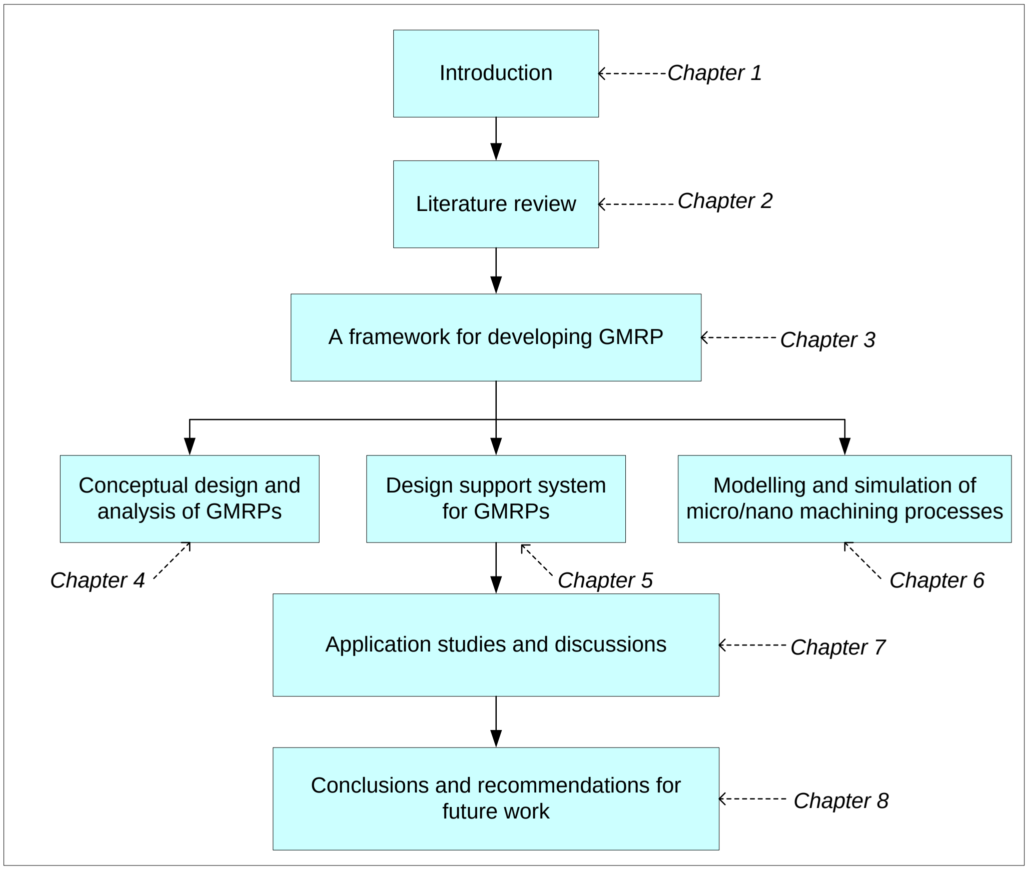


Fig. 1.8 Structure of the thesis

Chapter 1 introduces the background, problem and research aims/objectives.

Chapter 2 reviews the state of the art of micro manufacturing, the concept, characteristics and design methodologies of reconfigurable machine tools, followed by axiomatic design theory, design support system and other design methodologies. The XML technology is also briefly reviewed.

Chapter 3 proposes an integrated framework for the GMRP development, including the framework architecture, the theoretical model of GMRPs, design support system and extension interfaces, together with the applications of GMRP.

Chapter 4 discusses the conceptual design of GMRP using the axiomatic design theory, its error analysis and characteristics.

Chapter5 presents the development of the design support system for GMRP using axiomatic design theory. The chapter also details the implementation of the design support system using XML, Java, Matlab technologies.

Chapter 6 develops an environment for the multiscale model and simulation of nanometric cutting process. The comprehensive models of micro EDM are also presented, and they are further evaluated with experimental results and FEA.

Chapter 7 evaluates the proposed GMRP and framework with case studies.

Chapter 8 draws conclusions resulting from this investigation. Recommendations are also made for future work.

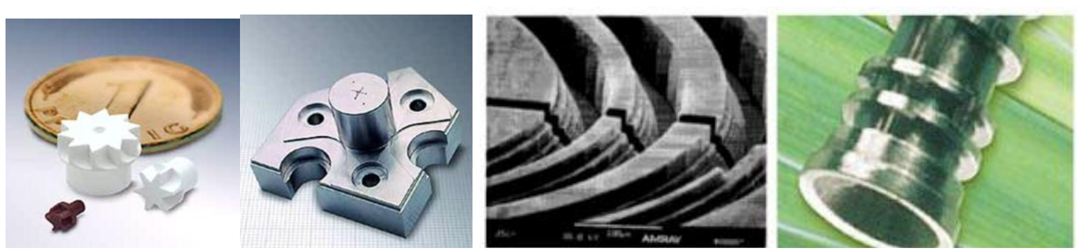
Chapter 2 Literature Review

2.1 Introduction

In this chapter, the state of the art of micro manufacturing is first reviewed. The concept, characteristics and design methodology of reconfigurable machine tools are then discussed. The axiomatic design theory is closely examined and compared with other relevant design methodologies, i.e. QFD and Taguchi design. This chapter also analysed the needs, approaches and trends of design support systems. The XML technology is briefly reviewed since it is related to the database and knowledge-base applications in the design support system.

2.2 State of the art of micro manufacturing

The explosion of micro-scale product development in fields such as optics, electronics, medicine, biotechnology, communication and avionics, etc. has the potential to bring about completely different ways people and machines interact with the physical world. The specific applications of micro scale products include, but are not limited to, medical implants, microfluidics, micro holes for fibre optics, micro nozzles and many more (Ehmann et al, 2005; Ehmann, 2007, Liuet al, 2004). Some of these micro parts are shown in Fig. 2.1. (Kern, n.d.; Liu et al, 2004).



(a) (b) (c) (d)

Fig. 2.1 (a) turbine wheels for micro fluid pumps, (b) a jointing element for optical fibre connections, (c) trenches with stepped walls, and (d) neurovascular device component

Fabrication of micro/miniature products with micro level features in a broad range of materials is becoming one of key requirements for modern manufacturing industry, because of the increasing strong demand from the global market for ever-smaller parts and systems at reasonable cost and superior performance (Ehmann et al, 2005).

Micro manufacturing is an important new technology (Ehmann et al, 2005). It bridges the gap between the nano and macro worlds, and will completely change our thinking as to when and where products will be manufactured. Micro manufacturing is also a strategic technology that will enhance the competitive advantage including reduced capital investment, reduced space and energy costs, increased portability, and increased productivity.

It is increasingly evident that the era of mass production is being replaced by the era of market niches (Wiendahl et al, 2007), and there is also an increased need for mass customisation and personalization of micro/miniature products. Moreover, designers constantly add new features into existing micro/miniature products to meet increasing customer needs. Micro/miniature products with new features and materials are appearing in the market, forming an uncertain and dynamic micro products market. To survive in this competitive global market, it is essential for manufacturers to be able to respond quickly and effectively by obtaining high throughput, low cost and industrial scale micro manufacturing.

While micro scale technologies related to semiconductor and microelectronics fields are highly developed, the same can not be said for manufacturing products involving complex 3D geometry and high accuracies in non-silicon materials. Currently, researches in micro manufacturing can be identified in two main categories, i.e. manufacturing processes and precision machine tools, as given in Fig. 2.2. However, due to the wide spectrum of micro manufacturing processes, the review of this chapter is largely based upon the research work in mechanical micro manufacturing.

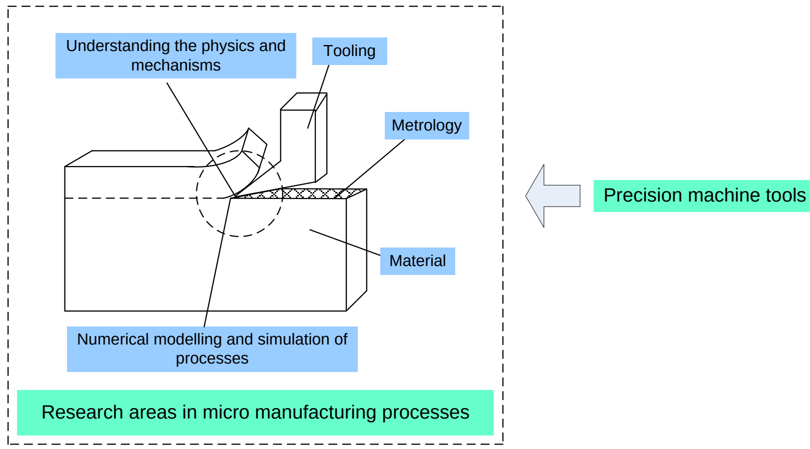


Fig. 2.2 Researches in micro manufacturing technology

2.2.1 Current research areas in the micro manufacturing process

Current researches in micro manufacturing processes mainly involve the understanding of physics and process mechanisms, micro tools, metrology of micro parts, workpiece materials and the numerical modelling and simulation of micro manufacturing processes.

2.2.1.1 Understanding of physics and process mechanisms

Whilst the mechanisms of conventional cutting are well established, micro/nano cutting mechanics and the associated intricate issues are less well understood. The depths of cut involved are several orders of magnitude smaller than those of conventional cutting, so that it is necessary to closely examine the micro/nano cutting processes. Unlike conventional machining, where shear and friction dominate, micro/nano cutting may involve significant sliding along the flank face of the tool due to the elastic recovery of the workpiece material. The effects of ploughing may also become important due to the large effective negative rake angle resulting from the tool edge radius. In addition, the sub-surface plastic deformation and the partition of thermal energies may also be quite different from those of traditional cutting (Lucca et al, 1991). This section discusses the fundamentals of the micro/nano cutting process.

Specific energy and cutting force

Specific energy and cutting force are important physical parameters for understanding cutting phenomena, as they clearly reflect the chip removal process. As shown in Fig. 2.3

(Lucca and Seo, 1993), the specific energy generally increases with the decreasing of the depth of cut within the range of from 10nm to 20 μm. This is because the effective rake angle will increase as the depth of cut decreases and the larger the rake angle the greater the specific energy. This phenomenon is often called the size effect.

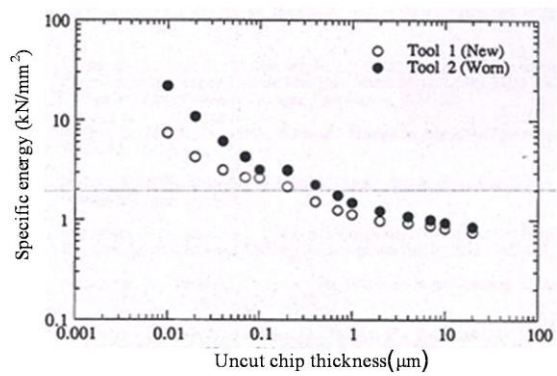


Fig. 2.3 Specific energy vs uncut chip thickness for new and worn diamond tools

Micro/nano cutting is also characterised by the high ratio of the normal to the tangential components of the cutting force, as shown in Fig. 2.4 (Lucca and Seo, 1993), that is, the resultant cutting force becomes closer to the thrust direction when the depth of cut becomes smaller. Since the depth of cut is very small in micro/nano cutting, the workpiece is mainly processed by the cutting edge and the compression will thus become dominant in the deformation of the workpiece material, which will result in larger friction force at the tool - chip interface and consequently in a greater cutting ratio. This indicates a transition from a shearing-dominated process in conventional cutting to a ploughing-dominated process in micro/nano cutting.

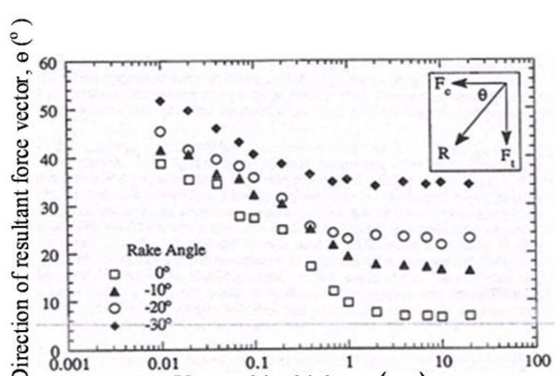


Fig. 2.4 Resultant force vector vs uncut chip thickness at various rake angles

Minimum chip thickness and chip formation

The definition of minimum chip thickness is the minimum undeformed chip thickness below which no chip can be formed stably.

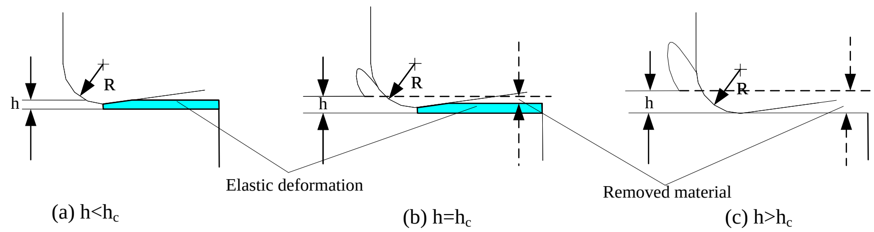


Fig. 2.5 Schematic diagram of the effect of the minimum chip thickness

Fig. 2.5 shows the chip formation with respect to chip thickness (Chae et al, 2006). In Fig. 2.5 (a), where the uncut chip thickness, h, is smaller than the minimum chip thickness, h_c, only elastic deformation results and no workpiece material will be removed by the cutter. When the uncut chip thickness approaches the minimum chip thickness, as shown in Fig. 2.5 (b), chips will be formed due to the shearing of the workpiece. However, since elastic deformation still exists, the removed depth is generally smaller than the desired depth. If the uncut chip thickness is larger than the minimum chip thickness, as shown in Fig. 2.5 (c), elastic deformation is significantly reduced and results in the removal of the entire depth of cut as a chip.

Due to this minimum chip thickness effect, the micro/nano cutting process is affected by two mechanisms: chip removal ($h>h_c$) and ploughing/rubbing ($h<h_c$). From a practical point of view, the minimum chip thickness is a measure of the extreme machining accuracy attainable because the generated surface roughness is mainly attributed to the ploughing/rubbing process when the uncut chip thickness is less than the minimum chip thickness. The extent of ploughing/rubbing and the nature of the micro-deformation during ploughing/rubbing contribute significantly to the increased cutting forces, burr formation, and the increased surface roughness. Therefore, knowledge of the minimum chip thickness is essential in the selection of appropriate machining conditions (Liu et al, 2006). Ikawa et al (1992) obtained an undeformed thickness on the order of a nanometre, as shown in Fig. 2.6, by a well-defined diamond tool with an edge radius of around 10 nm.

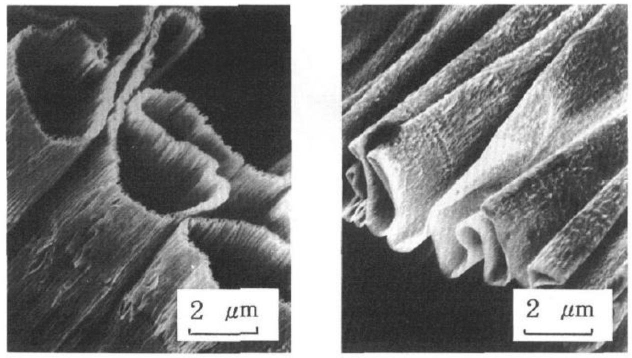


Fig. 2.6 SEM micrographs of chips generated from nanometric cutting: (a) Thickness of chip 1 nm, and (b) Thickness of chip 30 nm

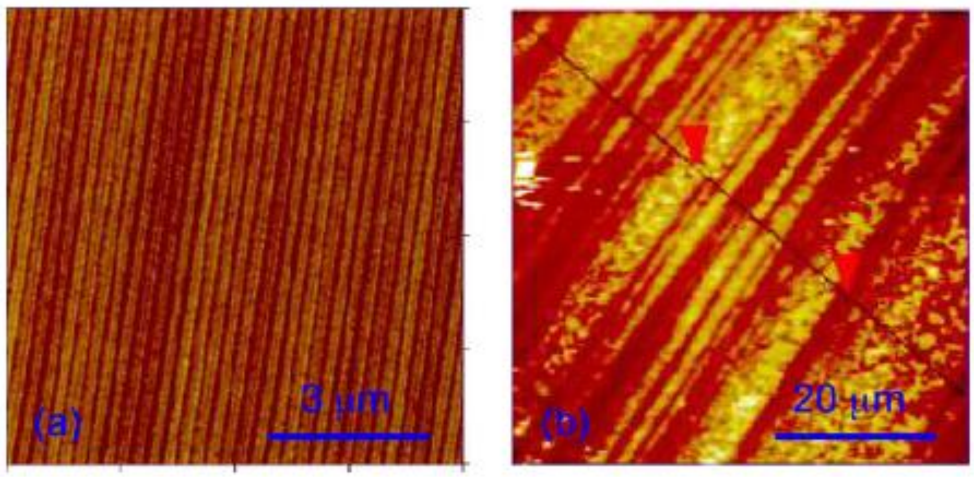
The minimum chip thickness depends upon the cutting edge radius, workpiece material and the cutting process. For example, Volger et al (2004) conducted finite element simulation of the micro cutting of steel, finding that the minimum chip thickness is 20% and 30% of the cutting edge radius for the pearlite and ferrite, respectively. However, Shimada et al (1993) observed that the minimum chip thickness can be around 5% of the cutting edge radius for the cutting of copper and aluminium, through molecular dynamics simulation.

Ductile mode cutting

Machining brittle materials such as germanium, silicon and optical glasses at a large depth of cut in conventional cutting has a tendency to generate a rough surface and sub-surface cracking. As a result, the machining of brittle materials is normally achieved using conventional processing techniques such as polishing. However, intricate features, the surface finish quality of the workpiece produced and a greater material removal rate of processing demand an effective means for the fabrication of brittle materials.

There is a transition in the material removal mechanism of brittle materials, from brittle to ductile, when the depth of cut decreases (Shimada et al, 1995). Based upon this feature, cutting in a ductile mode below the critical depth of cut has been attempted with the aim of obtaining a good surface finish and an uncracked surface. Since the chip thickness in micro cutting can be of the order of the critical depth of cut, micro cutting can serve as a novel means of fabricating unique features with brittle materials that are not achievable by polishing or other techniques (Dornfeld et al, 2006).

Many researches indicate that the tool geometry and the cutting conditions are two major factors affecting the value of the critical depth of cut. It was found that the critical depth of cut increases with the cutting velocity and negative rake angle (Li et al, 1999; Ichida, 1999). However, it is difficult to achieve ductile mode cutting with a greater feed rate, as shown in Fig. 2.7 (Fang et al, 2007).



(a) (b)

Fig. 2.7 Silicon surfaces machined at a cutting speed of 90 m/min and a depth of cut of 1 μm: (a) feed rate of 0.4 mm/min (ductile mode cutting), and (b) feed rate of 1 mm/min (brittle mode cutting).

2.2.1.2 Numerical modelling and simulation of processes

Although involving many assumptions as the analytical model does, the numerical modelling and simulation of nanometric cutting provides a powerful tool for assisting scientific understanding of the cutting physics, chip formation mechanisms, size-effects, and the machined surface integrity. Using the numerical model and simulation, the effect of various cutting conditions can be emulated and manipulated easily and effectively while it also leads to reduction of costly physical cutting trials and the process optimisation. Finite element (FE) modelling and molecular dynamics (MD) modelling are two popular numerical modelling and simulation techniques for the investigation of machining processes although each technique has its own strengths and limitations.

FE method is based on the principle of continuum mechanics, in which the materials are defined as continuous structure and effects of micro-constituents such as crystal structure, grain size and inter-atomic distances are ignored. Application of FE simulation to the cutting process provides an effective means to understand the mechanics and characteristics of the cutting process. It has been used successfully for the prediction of cutting forces, temperature distribution and stress distribution, etc. (Yan and Strenkowski, 2006; Mamalis et al, 2001; Simeoneau et al, 2006; Shi et al, 2002). However, FE method can not be used for the simulation of nanometric cutting because the constitutive equations have vital errors when the mesh size approaches to the atomic scale. At nanoscale, the expression for the elastic energy does not represent localized bonds, and the standard distributed mass expression for the kinetic energy does not account for the fact that essentially all of the mass is localized in the atomic nuclei, i.e. at least four orders of magnitude smaller than the interatomic spacing (Shiari et al, 2007). FE method is therefore not suitable for the simulation of nanometric cutting due to the inappropriate physics of governing equations.

Molecular dynamics (MD) simulation is a well established methodology for detailed microscopic modelling at a molecular scale. It is based upon the molecules model of the matter or system concerned according to their atomic structures. Potential functions are used to describe the molecular interactions, and the interatomic forces can be derived from the differentiation of the potential function. In this case, MD simulation is suitable for nanometric cutting. It can be specially performed to study the tool-workpiece interaction (Cheng et al, 2003) and the effect of crystallographic orientation and direction on cutting, which is very difficult to obtain in FE simulation (Komanduri et al, 2000; Komanduri et al, 1999). On the other hand, MD simulation has limitations in examining large structures and computational speed and time, the number of atoms considered in the workpiece material is thus rather small in most published MD cutting simulation. Such limitations may cause some unwanted computational artificial results from small model boundaries. To bring the MD simulation closer to realistic nanometric cutting conditions, the size of the simulation must be increased dramatically beyond that which has been presently reported (Shiari et al, 2007).

In order to reduce the computational cost and enlarge the simulation scale, efficiency and effectiveness while maintaining the simulation resolution, multiscale modelling and simulation of processes are emerging. The multiscale modelling will likely play an important role in the characterization of the machining process at reduced size scales, particularly in explaining phenomenological effects across the nano-micro-meso continuum (Liu et al, 2004). To date, few multiscale simulation has been applied to the machining process (Shiari et al, 2007), although it shows considerable promise for dealing with the multiplicity of issues that arise over multiple scales in the machining process.

2.2.1.3 Metrology methods

In macro manufacturing, proper process control is a key to the successful manufacture of micro products. Sensor based monitoring yields valuable information about the micromachining that can serve the dual purpose of process control and quality monitoring, and will ultimately be the part of any fully automated manufacturing environment (Alting et al, 2003; Dornfeld et al, 2006). A variety of sensors are used to capture necessary information about the manufacturing process (Dornfeld et al, 2006).

While the metrology and standards infrastructure exist in traditional manufacturing industries, development of traceable metrology of micro products is at the early stage (Yacoot et al, 2009; Leach et al, 2009; Leach et al, 2006) and standardisation in the field of micro technology is required if some sort of unified language has to be developed. The ability to calibrate and determine the capability of microscale metrology system is limited (Ehmann et al, 2005). Moreover, it is very difficult to measure micro features such as pockets, holes, and channels. Masuzawa et al (1993) developed a vibroscanning method to measure the inside dimensions of micro-holes.

2.2.1.4 Materials

Materials used in micro manufacturing are the same as those used in macro manufacturing, encompassing the full range of metals, polymers and ceramics/glasses (Alting et al, 2003).

However, one material-related issue that has to be considered in micro manufacturing is material microstructure effects which play a significant role in material removal processes.

In micro cutting, the crystalline grain size of most materials is of the same order as the depth of cut, so that chip formation normally takes place by breaking up the individual grains of a polycrystalline material. Most polycrystalline materials are thus treated as a collection of grains with random orientation and anisotropic properties (Dornfeld et al, 2006). The crystalline graphic orientation affects the chip formation, the surface generation and the variation of the cutting forces (Liu, 2004). There is a distinct difference between micro cutting and conventional cutting where the material can be treated as isotropic and homogeneous. To et al (1997) obtained the effects of the crystallographic orientation and the depth of cut on the surface roughness by conducting the diamond turning of single crystal aluminium rods.

Geiger et al (1997) demonstrated that, in forming process, the flow stress of copper alloys is reduced by decreasing specimen dimensions. Size effect depends upon the microstructure of the material: for fixed ratios of the specimen geometry, the difference in the flow stress decreases with grain size. The size effect on the flow stress is attributed to the increasing portion of grains lying on the free surface of the specimen when the specimen dimensions are reduced (Dornfeld et al, 2006; Geiger et al, 1997).

2.2.1.5 Micro tooling

Micro tooling is the essential enabler for micro/nano cutting processes. It also determines the feature sizes and surface quality of miniatures and micro components machined. Smaller tools have decreased thermal expansion relative to their size, increased static stiffness from their compact structure, increased dynamic stability from their higher natural frequency, and the potential for decreased cost due to smaller quantities of material utilised (Chae et al, 2006).

Single crystal diamond is the preferred tool material for micro/nano cutting due to its outstanding hardness, high thermal conductivity, and elastic and shear moduli. The crystalline structure of the diamond makes it easy to generate a very sharp cutting edge e.g. a cutting edge in tens of nanometres can be achieved. More recently, CVD (Chemical Vapor Deposition) diamond cutting tools have become available, as shown in Fig. 2.8. They are extremely hard and can be used to cut tungsten carbide with a cobalt percentage of 6% or more.

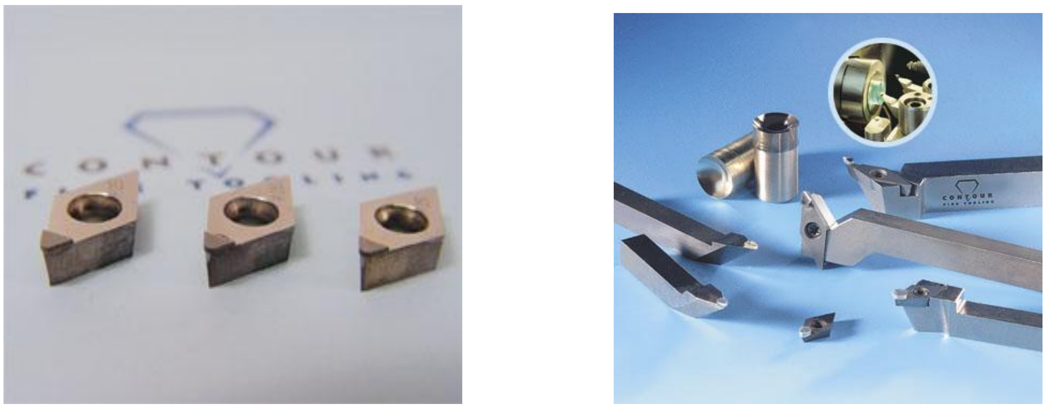


Fig. 2.8 Cutting tools: (a) CVD diamond cutting tools, and (b) Diamond cutting tools (Contour Fine Tooling Ltd, n.d.)

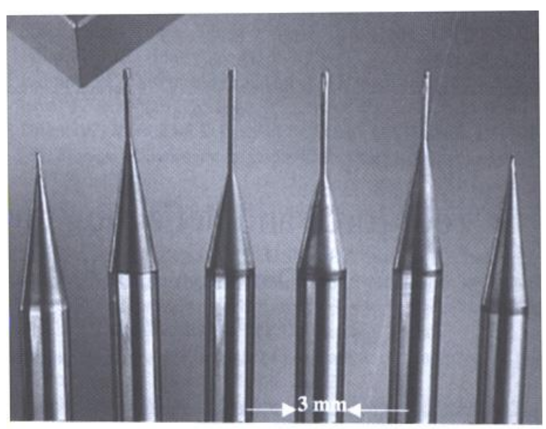


Fig. 2.9 Micro-milling tools (Jabro Tools Ltd, n.d.)

However, diamond is limited to the cutting of non-ferrous materials because of the high chemical affinity between diamond and iron. Micro tools which are used to machine ferrous materials are normally made from tungsten carbide. As shown in Fig. 2.9 (Dow et al, 2004), these micro-milling tools are made from tungsten carbide with a diameter of from ϕ0.2 mm to ϕ1.5 mm.

Commercially available micro-drills are typically on the order of 50 µm in diameter (Dornfeld, 2006). However, methods for minimizing micro tools continue to be developed such as focused ion beam, EDM, WEDG and grinding, etc. Fig. 2.10 (Adams et al, 2001) shows micro end-mills, developed by the focused ion beam process, their diameter being less than ϕ25 µm.

Other trends in the development of micro tools include the optimization of the geometric and coating properties of micro tools for longer tool life, accuracy enhancement, and characterization and condition monitoring of micro tools.

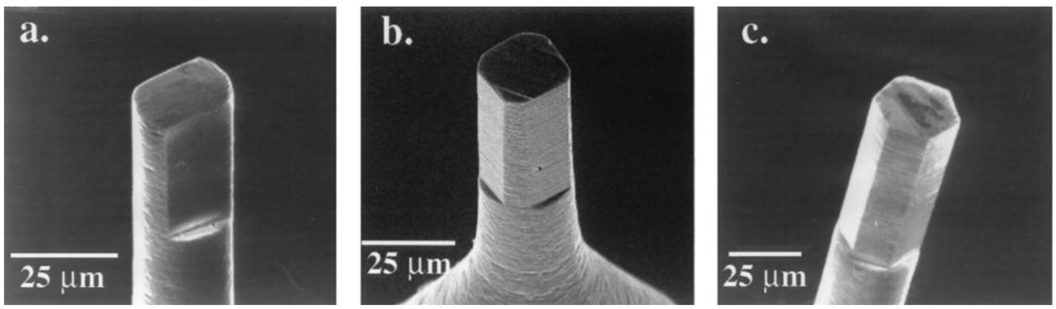
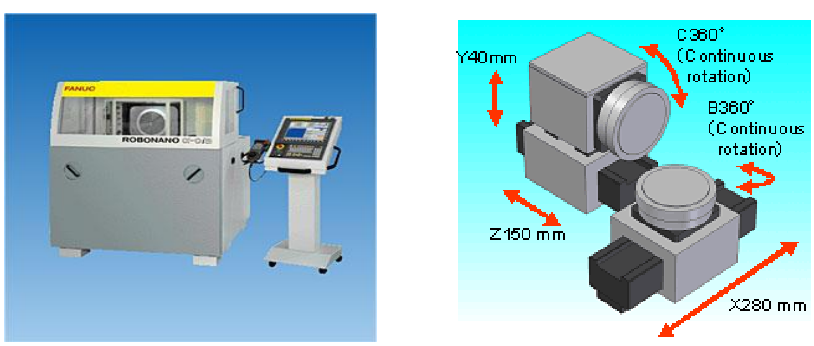


Fig. 2.10 Micro-end mills made by focused ion beam sputtering having: (a) two cutting edges, (b) four cutting edges, and (c) five cutting edges (scanning electron micrographs)

2.2.2 Precision machine tool for micro manufacturing

2.2.2.1 <u>Standard size machine tools</u>

Machine tools play a very import role in micro manufacturing. Traditional standard size precision machine tools are currently the major forces for undertaking micro/nano cutting because of their feasible performance and availability.



(a) ROBONANO α-0*i*B

(b) Nanotech 250UPL (c) Microgantry nano3/5X (d) Nanoform 250ultra

Fig. 2.11 Standard size precision machine tools

Fanuc ROBONANO α-0***i***B is a well known 5-axis ultraprecision machine tool. Its configuration is shown in Fig. 2.11 (a). Rotary table B is installed on X slideway which has a stroke of 280 mm and C is installed on Y slideway with a stroke of 40 mm. Z slideway has a stroke of 150mm. The ultraprecision 5-axis machine adopts a platform machine structure on which spindles, tools and workpieces can be mounted according to the purpose. It can function as a 5-axis milling machine tool, a turning machine tool, a 5-axis grinding machine tool or 5-axis scribing machine tool by choosing needed spindle and tools. It features all static air bearings, linear motion units and rotary units driven by linear motors and built-in servo motors, which makes the resolution of 1 nm on linear axes possible (Fanuc Ltd, n.d.). It has wide applications in areas ranging from optical, electronics, semiconductor to medical and biotechnology fields.

The Nanotech 220UPL (shown in Fig. 2.11 (b)), developed by Moore Nanotechnology System, LLC in USA, is a 2-axis (X, Z with 200 mm travel) ultraprecision diamond turning lathe with T configuration, and it is expandable to 3 or 4 axis by adding optional rotary axis B & C or vertical axis Y. Its groove-compensated air bearing work spindle provides motion accuracies of less than 50 nm throughout the 10,000 rpm speed range. It can be used for diamond turning of small spherical and aspheric surfaces in a wide range of materials. Moore Nanotechnology System, LLC also provides other ultraprecision machine tools including Nanotech 220 UPL, Nanotech 350 FG and Nanotech 450 UPL, etc.

The Microgantry® nano3/5X made by Kugler, as illustrated in Fig. 2.11 (c), is a high precision 3 to 5-axis machining centre, which can be used specially for the micromachining of a variety of materials with high precision. It is capable of fabricating 3D freeform surfaces by combining three linear axes (X, Y, Z) with the optional rotary and swivelling unit (C and A axes). The base of the unit is made of solid, fine-grained granite, which guarantees the highest long term thermal and mechanical stability (Kugler, n.d.).

Nanoform 250ultra manufactured by Precitech, an ultraprecision diamond turning lathe, is shown in Fig. 2.11 (d). With two basic linear axes X, Z and two optional rotary axes (B, C), it can be configured from 2 to 4 axes to produce aspheric and freeform surfaces. It features hydrostatic oil bearing slideway with optimized stiffness and damping characteristics, sealed natural granite base providing exceptional long term machine tool stability, liquid cooled slideways for thermal stability, etc. (Precitech, n.d.)

The main specification of the above typical standard size machine tools are summarized in Table 2.1.

Table 2.1 Main specification of the typical standard size machine tools

	ROBONANO -0iB	**Nanotech 250UPL**	**Microgantry nano3/5X**	**Nanoform 250**
Configuration	5-axis: X, Y, Z, B, C	2-axis: X, Z, T configuration Optional axis (Y, B, C)	3-5 axis: X,Y,Z (A,C)	2-4 axis: X,Z, (B,C)
Base structure	Cast iron base with concrete	Natural black granite	Granite base	Sealed natural granite base
Control system	Fanuc	Delta Tau	CNC contouring control system	UPX control system
Spindle	Air turbine, static air bearing Milling: 50,000rpm (max) Turning: 7000rpm (max)	Frameless brushless DC motor, air bearing 50-10,000rpm	Aerostatic bearing 20,000rpm (max)	Integrated brushless motor, air bearing Motion accuracy: $\leq 20nm$ 18,000rpm (max)
Motion axes	X,Y,Z: Linear motor, resolution 1nm B, C: resolution 0.0001^{o} Static air bearing	X, Z: Brushless DC linear motor, resolution 1nm B, C: Brushless DC motor, motion accuracy $\leq 50nm$ Oil hydrostatic bearing	X,Y,Z: Resolution$\leq 0.5um$ C: Motion accuracy: $\leq 0.15um$ Air bearing	X,Z: AC linear motor, B,C: DC brushless direct drive motor Oil hydrostatic bearing

2.2.2.2 Micro/meso machine tools

Standard size precision machine tools have good machine characteristics, but small size, complex geometry and high quality of micro products impose high demands on the machine performance. This will of course increase the investment and operation costs and make the manufacturing SMEs difficult to access the technology and thus the high value-added manufacturing business (Luo et al, 2005). Furthermore, these machines are generally very expensive, working in a tight temperature controlled environment, and they are energy and resources inefficient. To match the micro manufacturing of miniature and micro components, the concept of micro and meso machine tools has been proposed by some researchers.

Micro and meso machines and their integration for the micro manufacturing system/micro factory are suitable for the fabrication of micro products at low cost with greater mobility. Compared to a standard size machine, a micro or meso machine has the essential characteristics of decreased heat deformation, less material consumption, smaller vibration amplitudes, smaller footprint and thus smaller space occupation, and less energy consumption (Alting et al, 2003). Other advantageous features are the increase of machinery accuracy due to the short force/energy loop and control loops, and lower vibration amplitudes than those of large machine tools (Qin, 2006; Kussul et al, 2002)

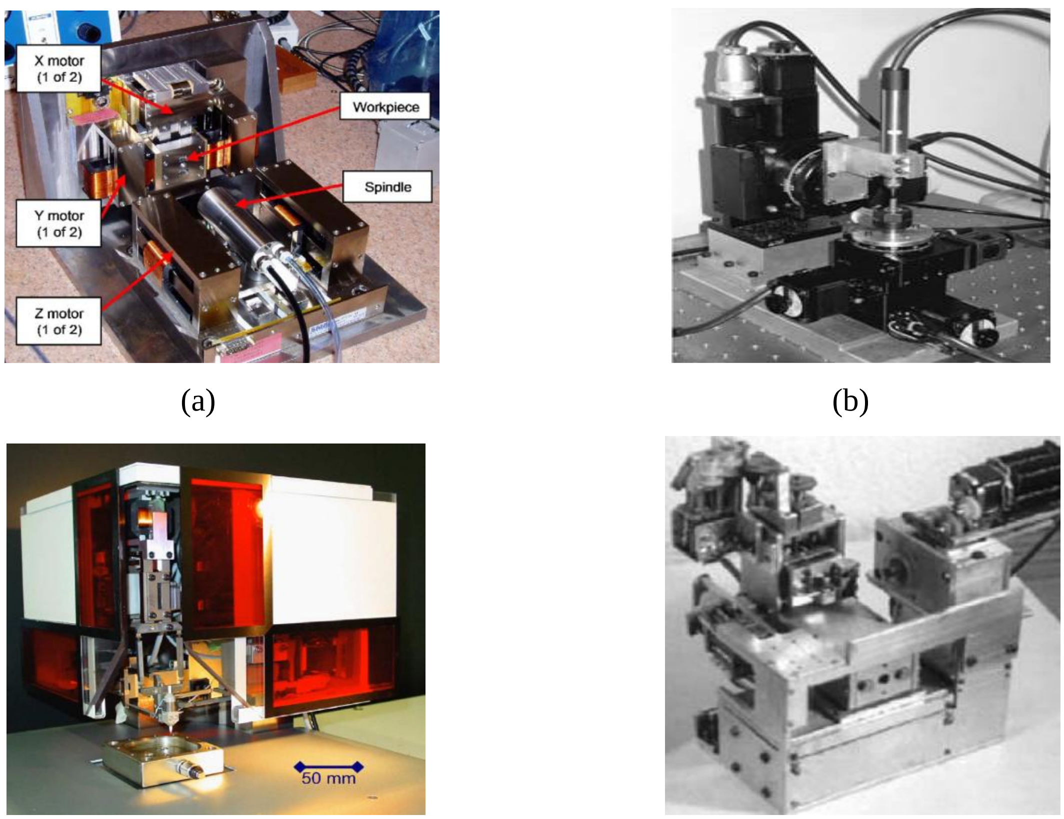
(a)

(b)

Fig. 2.12 (a) microlathe and (b) microparts machined by the microlathe

In 1996, the AIST in Japan developed the first micro/meso machine tool, microlathe, in size of 32.0×25.0×30.5 mm^3 and weighs only 100 grams, as shown in Fig. 2.12. The linear stages in X and Y directions are driven by piezoelectric actuators with positioning resolution of 25 nm. The power consumption of the spindle motor is 1.5 W with rotational speed up to 10,000 rpm (Tanaka, 2001). The microlathe can cut brass with a 1.5 μm roughness in the feed direction. Fig. 2.12 (b) shows the microparts machined by the microlathe.

The success of the microlathe has spurred widespread interests to further develop and exploit the advantages of micro/meso machine tools, and more micro/meso machine tools have been developed (Ehmann et al, 2008), and some of them are presented in Fig. 2.13.



(a) (b)

(c) (d)

Fig. 2.13 Typical micro and meso machines: (a) 3-axis milling machine (Phillip et al, 2006), (b) 5-axis milling machine (Bang et al, 2005), (c) a small precise EDM machine (Beltrami et al, 2004), and (d) micro machine tool (Kussul et al, 2002)

The micro/meso machine tool developed at University of Illinois at Urbana-Champaign (UIUC) is a 3-axis horizontal milling machine with size of 180×180×300 mm^3, as given in Fig. 2.13 (a). It has voice coil motors and a 160,000 rpm air-turbine, air bearing spindle. Optical linear encoders with 100 nm resolution are used for the 3-axis milling machine. Linear ball-bearing slideways are used for the linear motion of each axis.

Fig. 2.13 (b) shows a 5-axis micro milling machine developed by Bang et al (2005). This precision machine is constructed for micro 3D parts machining. The oversize of machine is 294 mm×220 mm×328 mm. It has three precision linear stages (X, Y and Z-axis) and two rotary stages (A, C) which are driven by corresponding motors. With a TurboPMAC2 controller, it can fabricate micro products such as micro walls, micro cylinder, micro blades, etc.

A small, very precise EDM machine called Delta^3 was developed at EPFL, as illustrated in Fig. 2.13 (c). It can be connected to a new generation EDM-generator from AGIE. Three linear electromagnetic motors are used to drive three linear slideways. It has a working volume of 8 mm×8 mm×8 mm, a high resolution of 5 nm and a high bandwidth dynamic of 600 Hz (Beltrami et al, 2004).

As given in Fig. 2.13 (d), Kussul developed a 3-axis micromachine tool which has the size 130 mm×160 mm×85 mm. For X axis and Z axis, each of them has a travel range of 20 mm. The Y-axis has 35 mm of travel range. The theoretical resolution is 1.87 μm per motor step. Machined workpieces on this machine tool have dimensions from 50 μm to 5mm with a tolerance range of 20 μm.

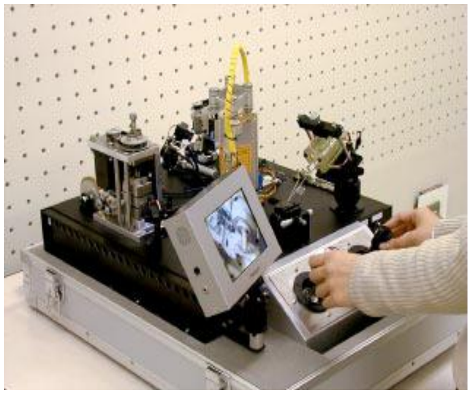
The main specifications of the typical micro machine tools are shown in Table 2.2. Developments are not only limited to micro/meso machine tools for machining operations, but encompass an array of processing as well as assembly and metrology systems (Ehmann et al, 2008).

Table 2.2 Main specifications of the typical micro machine tools

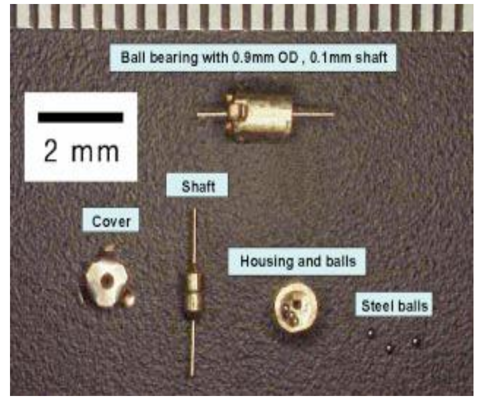
	Fig. 2.4 (a): UIUC 3-axis micro machine tool	Fig. 2.4 (b): 5-axis milling machine tool	Fig. 2.4 (c): Delta3	Fig. 2.4 (d): 3-axis micromachine tool
Overall Size	180×180×300 mm^3	294×220×328 mm^3	N/A	130×160×85 mm^3
Controller	Delta Tau Turbo PMAC2	N/A	N/A	Delta Tau Turbo PMAC2
Spindle	Air turbine, air bearing 160,000rpm	Air spindle, 20,000~30,000rpm Runout: 2μm	N/A	Aerostatic bearing 20,000rpm (max)
Motion axes	X,Y,Z, travel range: 25mm; DC voice-coil linear motor, resolution: 100nm, rolling element bearing	X, Y, travel range: 20mm, resolution: 50nm; Z travel range: 30mm, resolution: 50nm; A, travel range: 360^0,resolution: 0.002^0; C, travel range: 360^0,resolution:0.0012^0 X,Y,Z,A,C: stepping motor	X,Y,Z, three linear electromagnetic motor, resolution: 5nm Each axis has travel range of 8mm	X,Y,Z, travel range: 20mm, 35mm, 35mm; resolution: 1.87μm

2.2.2.3 Micro manufacturing systems and micro-factories

The advance of micro/meso machines has led to the development of micro factories. The first micro factory, as shown in Fig. 2.14 (a), was prototyped in Japan in 1990s (Okazaki et al, 2004). This portable micro-factory has external dimensions 625 mm long, 490 mm wide and 380 mm high and weighs approximately 34 kg. It functions entirely stand-alone, requiring a single 100V AC power source. The micro factory has components including a microlathe, a two-fingered microhand, a micro press, a micro milling machine and a micro robot. It uses three miniature CCD cameras mounted on each machine tool, displaying the image of a machined section on a 5.8-inch LCD monitor. The machines are controlled manually using two multi-DOF joysticks and visual aid for the operator. With this equipment, different samples of micro parts are produced, as presented in Fig. 2.14 (b).



(a)



(b)

Fig. 2.14 Micro factory and machined samples (Okazaki et al, 2004)

Except for the development of the first micro factory, there are also other research efforts carried out on micro factories in Japan including the Micro-Workshop and the desktop flexible manufacturing system (Qin, 2006; Asami, 2003; Aoyama, 1995). In addition, a micro factory based upon electrochemical machining was developed (Suda, 2000). The recent development is the Danish Micro-Factory which intends to manufacture products with characteristic scales of from millimetres to nanometres (Qin, 2006).

The development of micro/meso machine tools and micro factories has demonstrated the potential to create small-scale manufacturing systems for fabrication of micro/miniature products, enabling the optimisation of the use of the energy and resources for micro manufacturing, as well as the optimisation of the production organisation in these industries (Qin, 2006).

2.3 <u>Reconfigurable machine tools</u>

2.3.1 Reconfigurable manufacturing systems

Currently, as shown in Fig. 2.15, manufacturing systems can be conceptually classified into three types, i.e. dedicated manufacturing system (DMS), flexible manufacturing system (FMS) and reconfigurable manufacturing system (RMS), although a fully RMS does not yet exist today (Wiendahl et al, 2007).

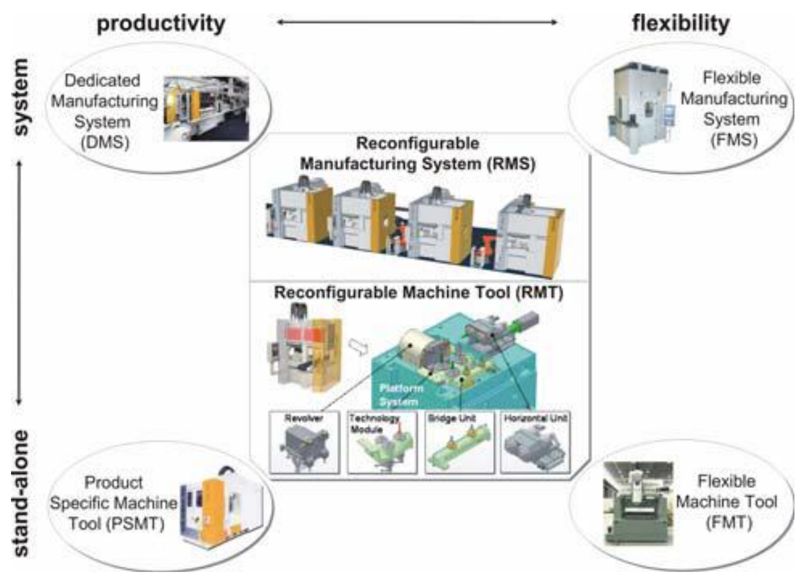


Fig. 2.15 Classification of manufacturing systems (Abele, 2006)

DMS is typically designed for the production of a specific part, and it can produce one specific part type cost-effectively at high production rate. The RMS emerged few years ago in an attempt to achieve changeable functionality and scalable capacity. Compared to FMS which offers general flexibility to increase the variety of parts produced, RMS provides customized flexibility to produce a part family (Hu et al, 2006). RMS is designed to cope with situations where both productivity and the ability to react to changes are of vital importance, so an ideal RMS comprehends the advances of DMS and FMS (Wiendahl et al, 2007).

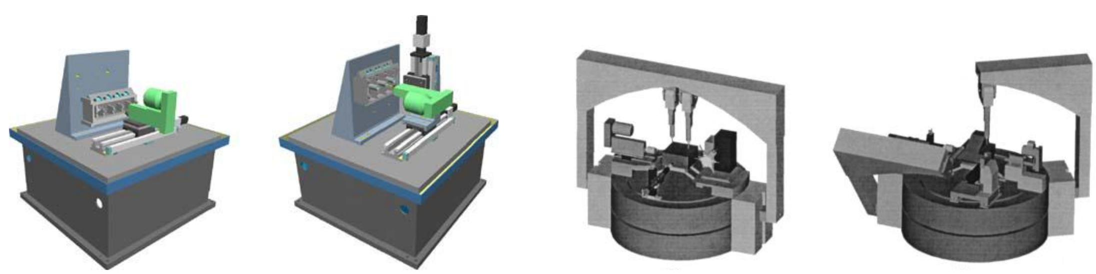
2.3.2 Characteristics of reconfigurable machine tools

As production requirements for an RMS change, so will the operation requirements (i.e. features to be machined and cycle times) for an individual machine tool. Dedicated machine tools used in the DMS are designed for specific operation requirements, having no ability to be converted to meet new operation requirements, while flexible machine tools used in the FMS are designed with general flexibility, resulting in high cost. Reconfigurable machine tool (RMT), therefore, has been proposed to enable the RMS (Landers et al, 2001; Tilbury and Kota, 1999).

RMT is designed with customized flexibility for specific sets of features, providing a cost effective solution to mass customisation and high-speed capability. RMTs are tailored to the initial operation requirements and, when operation requirements change, RMT may be economically converted to meet new requirements (Landers et al, 2001). The limited, customized flexibility allows reduction of investment costs on one hand and fast response when a product changes on the other, both representing economical benefits (Katz, 2007).

The conceptual RMT proposed by Landers is given in Fig. 2.16 (a). As the features needed to be fabricated change, the two-axis configuration can be converted to three-axis configuration by adding a vertical translational motion.

Fig. 2.16 (b) shows the illustration of another RMT in two different configurations. The size, type and number of modules and their interconnections of the RMT can be changed to quickly satisfy new changes in the product design. In the process of reconfiguration, new modules replace some old modules and the degrees of freedom of the machine tool are also changed. The three degrees of freedom of parallel manipulators facilitate the reconfiguration (Moon and Kota, 2002a).



(a) (b)

Fig. 2.16 Two conceptual RMTs

Although RMTs seen as an essential enabler of RMS are not yet broadly used in manufacturing systems due to the higher initial costs and the developing technologies, several prototype RMTs have been built to demonstrate the concept of RMT. Fig. 2.17 is an arch-type RMT built around a part family of products with inclined surfaces (Dhupia et al, 2007). It is designed aiming at a mass production line for both milling and drilling on inclined surfaces. Except for the three controlled degrees of freedom along its column, along the spindle axis and along the table axis, the spindle of the machine tool has the angular reconfiguration motion, allowing reconfiguring the spindle's angular position into five pre-designed locations to perform machining on different inclined surfaces (Kota and Moon, 2000).

In addition, based upon the conceptual RMT shown in Fig. 2.16 (a), a prototype RMT has been developed by Yigit and Ulsoy (2001), as demonstrated in Fig. 2.18.

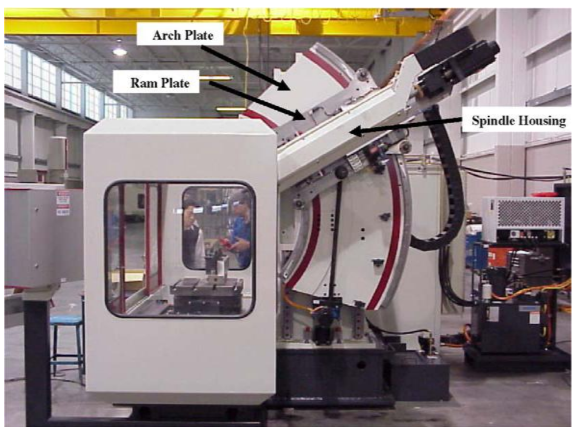


Fig. 2.17 The arch-type RMT

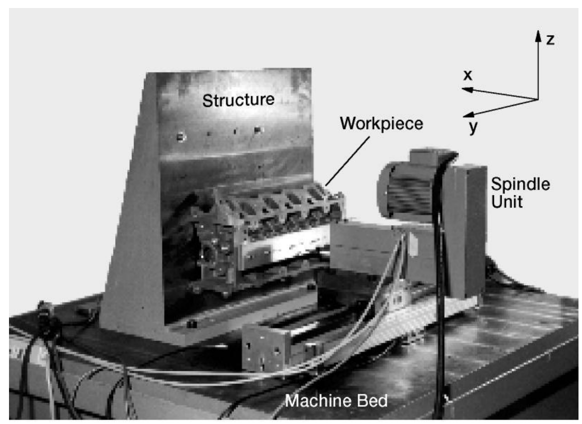


Fig. 2.18 The prototype RMT

2.3.3 Design methodologies of RMT

The initial work on the design methodology for a RMT is credited to Moon and Kota (Moon and Kota, 2002a, 2002b; Kota and Moon, 2000). In this methodology, the given description of machining tasks to be performed (processes planning data) is first transformed into a series of homogeneous transformation matrices representing desired motion using screw theory. Graph theory is then used to determine a set of feasible structural configurations of the machine. Next, the kinematic motion functions are mapped to individual entities in each structural configuration. Finally, using a precompiled parameterized library of commercially available machine modules, each function is mapped to a feasible set of modules, which provides a set of kinematically feasible machine tools offering desired motions. Fig. 2.19 gives the overview of the design methodology.

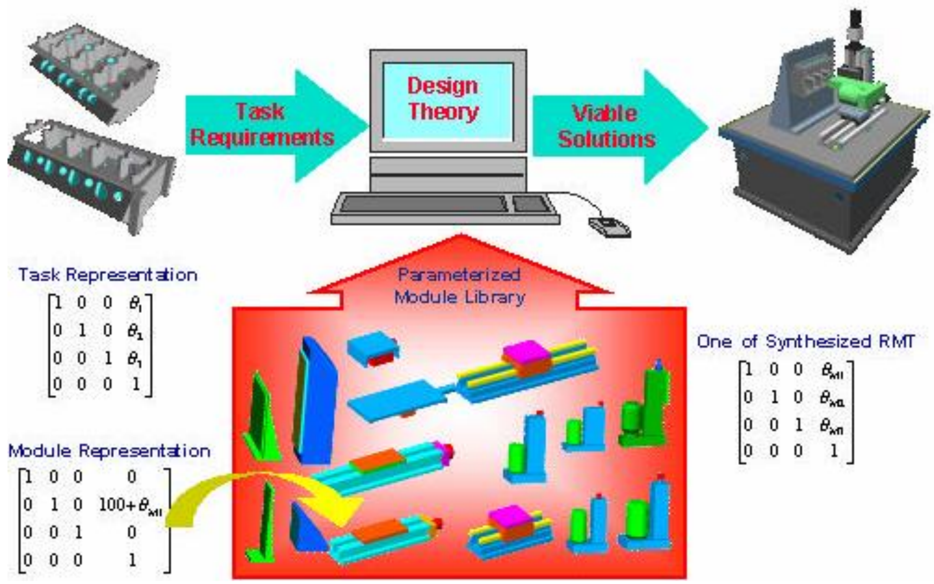


Fig. 2.19 An overview of the automated design methodology (Kota and Moon, 2000)

Kannan and Saha (2008) pointed out that reconfiguration of RMT can be classified into two types: reconfiguration with aids and self reconfiguration. No self reconfiguration has so far been attempted with reconfigurable machines because of the complex task-specification caused by spindle re-orientation, and they think the available configuration synthesis methodologies will be suitable for developing configuration alternates only. Therefore, they developed a methodology for RMT configuration synthesis, generic setup planning, which will be useful in developing configurations with self-reconfigurable capabilities.

Kannan and Saha (2008) used features to carry machining information as well as production information to define machine tool configuration such as number of axes, range and spindle orientation, which is different from Moon's screw theory based determination of motion requirements. The feature-based setup planning can then be used to capture configuration requirements and its variations. In this approach, machining feature groups are identified with an extended hybrid graph theory, and the making of machining feature groups and their sequencing for a given part orientation gives generic setup planning and forms the basis for configuration realization.

Except for the above two significant systematic design methods for the design of a RMT, there are other research works related to the design of RMTs. With the axiomatic design theory, Chen et al (2005) proposed a minimum yet sufficient module necessary to form a RMT for producing a part family. To provide designers with scientific guidance, Katz (2007) outlined general design principles and guidelines for reconfigurable machines. Yigit and ULsoy (2001) gave a general procedure to obtain and evaluate the dynamic stiffness of various alternative RMT designs from their modules including the effects of non-linear joint characteristics.

Recently, Young (2008) developed a co-evolutionary multi-agent approach for designing the architecture of reconfigurable manufacturing machines. The machine architecture represents a set of components that will be used to construct the manufacturing machine when the design of a part changes. The machine architecture can be obtained by co-evolution between agents which are located to different parts. Each agent continually sends its current configuration information to other agents and receives configuration information from other agents until certain criteria of a co-evolutionary algorithm can be fulfilled, making a machine tool configuration to be identified for each part. Upon removal of duplicated components between the various machine configurations, the architecture for the reconfigurable manufacturing machine can be identified.

Since RMT is a new type of the machine tool, there are many challenges in the design of RMT that need to be addressed before they can be used widely. The main challenges in the design of RMT include defining part families, mechanical design process, control system design, system integration and reconfiguration and calibration (Pasek, 2006).

2.4 Design methodologies

It is obvious that decisions made during design stage of product and process development will significantly affect the product quality and productivity (Yang and Zhang, 2000). The lack of scientific design knowledge has caused many problems because of poor design of products and process (Pahl et al, 2007). Therefore, the establishment of structured, scientific and systematic theories and methods for design is much needed and important.

Several scientific design methods have been established by researchers, such as quality deployment function (QFD), TRIZ, etc. Axiomatic design theory, developed by Suh (2001) in 1990s, is one of the useful design methodologies. It aims to establish a scientific basis for design and to improve design activities by providing the designer with a theoretical foundation based on logical and rational thought processes and tools (Suh, 2001).

2.4.1 Axiomatic design theory

2.4.1.1 The concept of domains

Axiomatic design is a design methodology which systematically processes information between and within four domains in the design world: the consumer domain, the functional domain, the physical domain and the process domain, as demonstrated in Fig. 2.20. The domain on the left relative to the domain on the right represents "what we want to achieve," whereas the domain on the right represents the design solution, "how we propose to satisfy the requirements specified in the left domain" (Suh, 2001).

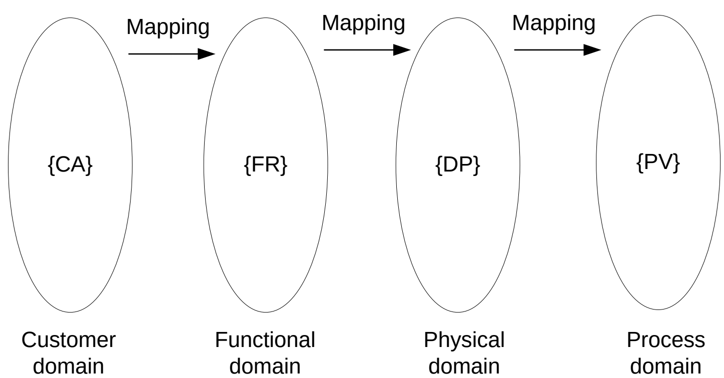


Fig. 2.20 Four domains in the design world

Customer needs are described in the customer domain by the vector {CAs}. In the functional domain, the customer needs are translated to functional requirements {FRs). To satisfy the specified FRs, design parameters {DPs} in the physical domain are conceived. Finally, to produce the product specified in terms of DPs, a process that is characterized by process variables {PVs} is developed in the process domain.

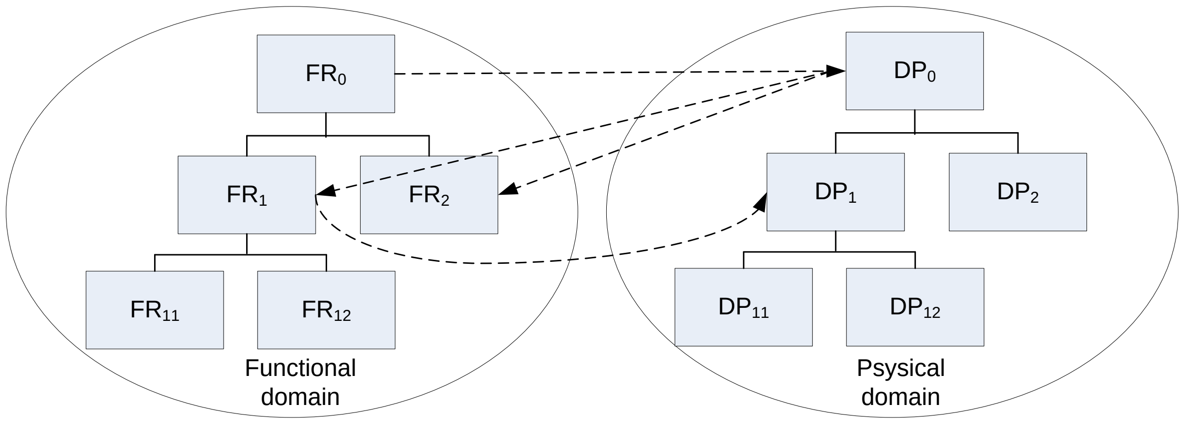


Fig. 2.21 Zigzagging to decompose FRs and DPs

Axiomatic design begins with the most general requirements, and then these highest-level requirements are decomposed into lower-level sub-requirements. As shown in Fig. 2.21, first go to the physical domain to conceptualise a design and determine its corresponding DP. Then we come back to the functional domain to create the next level FR_1 and FR_2 that collectively satisfies the highest level FR. FR_1 and FR_2 are the sub FRs characterizing the highest level DP. The decomposition process must proceed layer by layer until the design reaches the final stage, creating a design that can be implemented (Suh, 2001).This process of interaction between the functional and physical domains, and progressing from a general to detailed description, is called zigzagging. The design hierarchy linking a high-level conceptual design and a low-level detailed design is termed the system architecture.

The mapping process between the domains can be expressed mathematically in terms of the characteristic vectors that define the design goals and design solutions. The relationship between functional requirements {FR} and design parameters {DP} which satisfy the functional requirements, for example, can be written as:

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} A_{11} & 0 \\ A_{21} & A_{22} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix} \tag{2.1}$$

where A_{11} represents the effects of DP_1 on FR_1, A_{21} represents the effect of DP_1 on FR_2, etc. The matrix in Equation (2.1) is called design matrix. When the design equations describe conceptual design levels, the elements in the design matrix A_{ij} are normally to be replaced with an 'X' if there is an effect and with a '0' if there is no effect.

2.4.1.2 Two axioms in axiomatic design

Two axioms that govern the design process in axiomatic design are stated as:

- Axiom 1: The Independence Axiom. Maintain the independence of the FRs.
- Axiom 2: The Information Axiom. Minimize the information content of the design.

Independence axiom states that the independence of functional requirements must always be maintained. It means that when there are two or more FRs, the design solution must be such that each one of the FRs can be satisfied without affecting the other FRs.

The design matrix can be used to apply the independence axiom mathematically in a design. If a design satisfies the independence axiom, the design matrix must be either diagonal or triangular. When the design matrix is diagonal, the design is called an uncoupled design because each FR can be satisfied independently by means of one DP. When the matrix is triangular, the design is called a decoupled design because the independence of FRs can be guaranteed if and only if the DPs are determined in a proper sequence. Any other form of the design matrix is called a full matrix, resulting in a coupled design. Therefore, when several FRs must be satisfied, either a diagonal or a triangular design matrix must be created for designs.

Information axiom states that among those designs that satisfy the Independence Axiom, the design that has the smallest information content is the best design because it requires the least amount of information to achieve the design goals. Information content I for a given FR is defined in terms of the probability P of satisfying FR:

$$I = \log_2 \frac{1}{P} = -\log_2 P \qquad (2.2)$$

The information content for an entire system I_{sys} with m FRs is

$$I_{sys} = -\log_2 P_{\{m\}} \qquad (2.3)$$

where $P_{\{m\}}$ is the joint probability that all m FRs are satisfied.

In simple cases where the distributions can be approximated as uniform distributions, Equation (2.2) may be expressed as:

$$I = \log_2\left(\frac{System\,Range}{Common\,Range}\right) \tag{2.4}$$

where System Range and Common Range are defined in Fig. 2.22. The Design Range corresponds to the required tolerances.

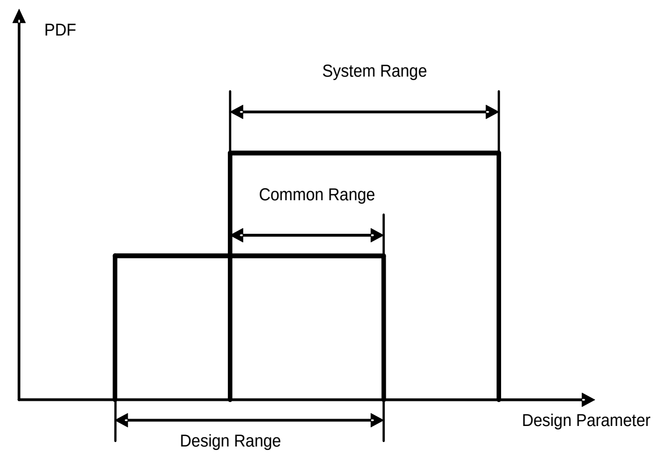


Fig. 2.22 Probability distribution of a system parameter

2.4.1.3 Representation of system architecture in axiomatic design

There are three different but equivalent ways of representing a system in axiomatic design including FR/DP/PV hierarchies, a module-junction diagram, and a flow diagram or flow chart. Although all these represent the same system, they emphasize the system from different aspects.

The hierarchical diagram shows the entire decomposition steps and all FRs and DPs. The module-junction diagram illustrates the hierarchical structure of modules, where a module is defined as the row of the design matrix. The flow diagram is created to show the design relationships of all modules at the leaf level and the implementation precedence based on design matrices of each level of design decomposition. The flow diagram is a concise and powerful tool that provides a comprehensive view of the system and a road map for implementation of the system design.

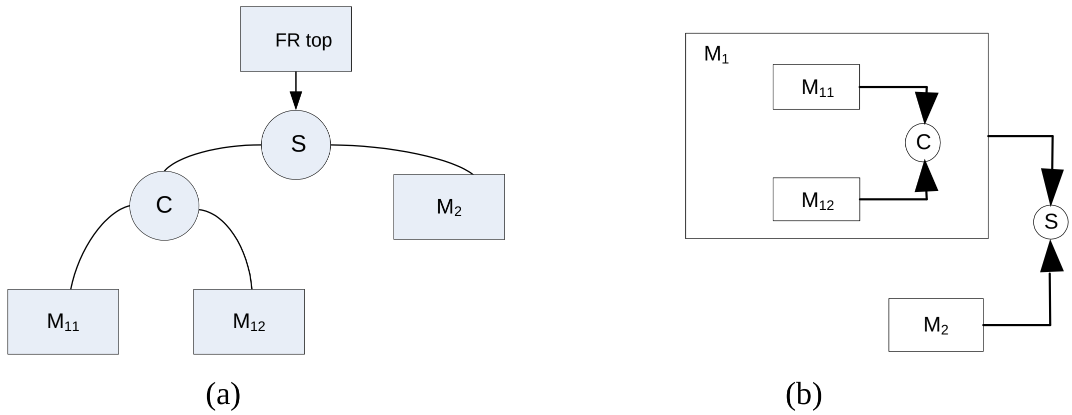


Fig. 2.23 Equivalent representations of system given in Fig. 2.21: (a) the module-junction diagram, and (b) the flow chart diagram

Fig. 2.21 demonstrates a system architecture using FR and DP hierarchies, and Fig. 2.23 shows the module-junction diagram and flow chart diagram of the same system. In Fig. 2.23, the circled S is used to represent a simple summation of FRs, and the circled C indicates that FRs are determined in a controlled sequence as suggested by the design matrix of the decoupled design.

As Suh has stated, axiomatic design is applicable to all designs. The main applications of axiomatic design can be summarised as the following topics:

- Software design; Yi and Park (2005) have developed a software system to aid an engineer to design an expanded polystyrene cushioning package in the conceptual design. Chen et al (2003) created a computer-aided quotation system to help designers to estimate quickly the cost of products they are designing. Similarly, knowledge-based design support system for design of energy absorbers was built (Zhu et al, 2008). The significant software developed with axiomatic is the Acclaro software systems which help designers to develop rational and correct design (Suh and Do, 2000).
- System design; Cellular manufacturing system, fixed manufacturing system and flexible manufacturing system have been developed based on axiomatic design (Kulark et al, 2005; Babic, 1999; Gu et al, 2001). In addition, design of fluid dispensing systems

(Chen et al, 2007) and machine control system (Lee, 2001) have been investigated using axiomatic design theory.

- Product design; Shin et al (2006) designed an automobile seat using axiomatic design and with axiomatic design, a spacer grid was designed by Park et al (2003). Also, with aid of axiomatic design, Melvin (2003) has built a chemical mechanical polishing (CMP) machine.

Moreover, axiomatic design can be used to design the process of selecting optimal sets of modules forming a reconfigurable machine tool (Chen, 2005) and office cells (Durmusogul and Kulak, 2008). Additionally, materials such as artificial skin (Gebala and Suh, 1992) and nanofluids (Bang and Heo, 2008) have been designed under guidance of axiomatic design.

2.4.2 Other design methods

2.4.2.1 Quality function deployment (QFD)

QFD, developed by Yoji Akao in Japan in 1966, is an overall concept that provides a means of translating customer requirements through the various stages of product planning, engineering and manufacturing into a final product (Zariri, 1993; Akao, 1990).

QFD provides the framework and techniques to capture the voices and needs of the customer and use them as key guidelines in all processes and operations. The QFD process starts with the customer requirements (emotional and physical), which are often difficult to measure, e.g. how it looks, how it feels, how does it compare to other products/services available. These requirements are then converted into suitable technical specifications or design requirements, which are usually measurable or quantifiable. The technical specifications or design requirements are further propagated into corresponding part characteristics at the next level. This process is repeated many times (hence deployment) generally by converting high-level quality requirements into low-level quality characteristics or elements. QFD typically covers product planning and design stages, but it can also be extended to process planning and operational activity stages.

The basic unit in QFD is what is referred to as the house of quality. It makes use of several matrices, with one in the shape of a roof (hence the name “house of quality”). Each house of quality charts a propagation process in QFD, typically giving information including customer needs and requirements, technical specifications/design requirements, target values, competitive ratings on products/services.

The relationship between the customer requirements and design requirements is the core of the house of quality. Their quantitative evaluations in terms of degree of importance, weighting and competitive ratings are possible. Competitive ratings take into account both quality competitiveness and technical competitiveness, whilst the weighting is used for highlighting critical attributes and/or strategic considerations. The target values in the “how much” matrix are generated to optimise the quality levels, given the critical attributes, market competitiveness and resources allocation.

2.4.2.2 Taguchi’s robust design method

Robust design aims to search for the set of conditions to achieve optimum behaviour. A robust product is one that works as intended regardless of variations in a product’s manufacturing process, variations resulting from deterioration, and variations in use. To achieve desirable product quality by design, Taguchi suggested a three-stage process: system design, parameter design and tolerance design.

System design is the process of selecting an appropriate technology to achieve the desired functions. Parameter design is the process of selecting the nominals of the system once the system technology has been chosen. Tolerance design is the process of tightening tolerance and up-grading materials to achieve a robust, high-quality system. Tolerance design is based on the concept of quality loss function (Peace, 1993).

The quality loss function is a continuous function that is defined in terms of the deviation of a design parameter from an ideal or target value. This function penalizes the deviation of a parameter from the specification value that contributes to deteriorating the performance of the product, resulting in a loss to the customer (Simpson, n.d.).

2.4.2.3 Comparisons with axiomatic design

QFD is similar to axiomatic design because of the matrix relating customer requirements to engineering requirements. From this matrix, the designer can see conflicts that need to be resolved. However, QFD is more subjective compared to axiomatic design. And, QFD does not show a mathematical relationship between a functional requirement and a design parameter, which axiomatic design does (Gould, n.d.).

Robust design aims to develop a product that would satisfy design requirements while ensuring that environmental variability would have the least effect on product performance. The use of axiomatic design theory generally leads to robust design. However, some robust designs may not be functionally independent; it normally focuses on only one requirement at a time (Gu et al, 2004).

2.5 XML

2.5.1 Features of XML

XML, standing for Extensible Markup Language, is recommended by World Wide Web Consortium (W3C). Unlike HTML (Hypertext markup language) which is deigned to display data, XML is used to transport and store data focusing on what data is. XML is extensible because it has no a fixed format. It is a meta-language (a language for describing other languages), rather than predefined markup language as HTML is. That means that XML allows the users to define new tags and structures for their own markup languages. It is the most common tool for data transmissions between all sorts of applications due to its portable, vendor-neutral and readable format, and has gained widespread popularity in the area of storing and describing information (Deitel, 2001; W3schools, n.d.). The main advantages of XML can be summarized as:

- XML can encode complex data, independent from any programming language.
- XML files are readable by both computer programs and by humans.
- XML- formatted data files can be changed easily.

2.5.2 XML related technologies

Document Type Definition (DTD) is used to define the legal building blocks of an XML file. DTD specifies a sequence of rules by defining tags, attributes and the relationship of tags that an XML file should have. Thus, the data received from outside can be verified with a standard DTD. Also, different groups of people can use a standard DTD to interchange data stored in XML files. A DTD can be combined with an XML document in two different ways, i.e. declaring the DTD inside the XML document or declaring the DTD as an external reference.

XML Document Object Model (XML DOM) is one of the key technologies related to XML. An XML document is analyzed as a hierarchical tree structure with DOM parser when it is loaded into the computer memory. XML DOM defines interfaces and methods to access and manipulate the hierarchical tree structure that represents the XML document. In the tree, everything in the XML document is represented by a node: the entire document is a document node; every element is an element node; the text in elements is a text node and every attribute is an attribute node. With programming languages, such as Java, and the programming interfaces to DOM defined by a set of properties and methods, every node in the tree structure can be accessed and modified or deleted, and new nodes can be added to the tree structure as well. Accordingly, all elements in the XML document can be changed or deleted, and new elements can be added to the XML document.

```
<?xml version="1.0" encoding="UTF-8"?>
<products>
      <product id="1">
           <price> 10.00 </price>
           <quantity> 6 </quantity>
      </product>
</products>
```

Fig. 2.24 An XML document

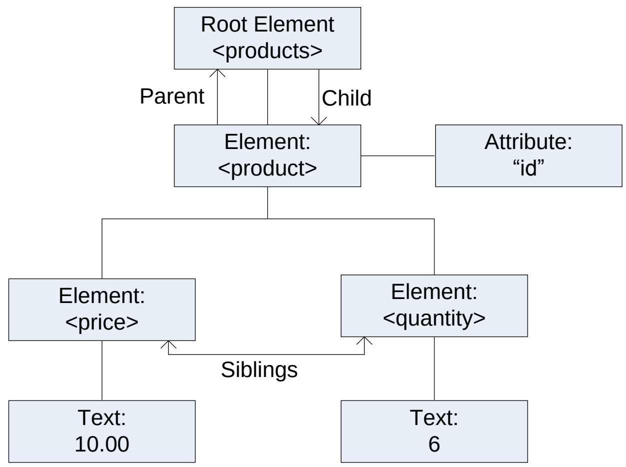


Fig. 2.25 The tree view of the document

Fig. 2.25 is the tree view of Fig. 2.24. Terms parent, child, and sibling are used to describe the relationships between nodes. The top node is root node. Every node can be accessed and manipulated using properties and methods provided by the DOM. The following Table 2.3 gives some typical XML DOM properties and methods, assuming x is a node object.

Table 2.3 Typical XML DOM properties and methods

XML DOM Properties	**Explanation**
x.nodeName	the name of x
x.nodeValue	the value of x
x.parentNode	the parent node of x
x.childNodes	the child nodes of x
x.attributes	the attributes nodes of x
XML DOM methods	**Explanation**
x.getElementByTagName(*name*)	get all elements with a specified tag name
x.appendChild(*node*)	insert a child node to x
x.removeChild(*node*)	remove a child node from x

x is a node object

XML is a text-based markup language, so XML documents can be created and edited with simple text editor. However, it is better to edit XML documents using professional XML editor than simple text editors because simple text editors can not provide assistance with editing. Professional XML editor can facilitate the editing of XML documents, such as adding closing tags to opening tags automatically, validating XML against DTD or Schema, colouring code the XML syntax, etc.

Currently, there are many professional XML editors including oXygen editor, XML Spy editor, and so on. In the current research, the oXygen editor is used as it has not only common functionalities of professional XML editors, it also has the Eclipse plugin version. The availability of Eclipse plugin version of oXygen editor allows the development of Java-based interface and editing of XML based component library in the same environment.

2.6 Design support system

Design support system is necessary because engineering design is generally a difficult problem. According to Simon (1973), design may be best characterised as an ill-structured problem to which a solution may not be fully and consistently specified until significant effort has been made to understand the structure of the design problem. As Alcantara (1995) pointed out, it is ill-structured with its initial specifications usually inconsistent, redundant and/or incomplete; it is an explorative and opportunistic task ranging from the routine to the creative; it is typically carried out by a team of engineers over a long period of time; and it covers several different tasks, such as synthesis, simulation, optimization, etc.

There have been many design support systems (DSSs) reported in the literature since 1970s. Some of these DSSs are relatively more focused, e.g. (Homann and Thornton, 1998; Qin, 2001). Homann and Thornton (1998) from MIT developed a precision machine design assistant (PMDA), which is essentially a design support system. The assistant comprises standard components in a hierarchy and the interface objects connecting the standard objects. Given a configuration defined manually by the user, the assistant is able to automatically perform the kinematic modelling and simulate the errors. In addition, the assistant can also evaluate the design constraints specified and report to the user if there is any violation.

Although the assistant can be a valuable tool for rapid design evaluation, it is mainly intended for conceptual design. It has a limited scope and focuses on the geometric error analysis and constraints evaluation.

Many DSSs have a rather more general approach, often as knowledge-based or intelligent DSSs (Moriwaki and Nunobiki, 1994; Tang, 1997; Chen, 2005; Zhang, 2008; Lorenzer et al, 2007), or more recently as web-based or Internet-based DSSs, e.g. (Pan et al, 2002).

Lorenzer et al (2007) developed an axis construction kit as a modelling and evaluation tool for supporting decisions on the design of reconfigurable machine tools. It may be viewed as a DSS, which covers the axis configuration, machine simulation and actual commissioning based upon both the physical and virtual predefined machine tool module library. However, whilst the use of predefined machine module has some obvious advantage (e.g. accurate data from manufacturer can be used in the simulation or analysis), the axis construction kit proposed can only consider the control aspect, thus limiting its use in the design of the complete machine tool. Secondly, since only the library modules of individual axes are available, the accuracy of the simulation results is limited since the relationships between axes are not predefined and they can play a significant role in terms of machine performance.

Moriwaki and Nunobiki (1994) analysed the machine tool design process through interviews with experienced designers and proposed an object-oriented DSS, which is essentially the design process model based upon the concept of design objects. The design process is decomposed into a number of steps, each of them corresponds to the components of a particular configuration and can be modelled as a design object or class. The specific design of a particular component is then the instantiation of the corresponding design class. The approach assumed the configuration and decomposition are already known and focused upon the design process.

Chen et al (2005) proposed a framework of knowledge-based design support system for hammer forging. Whilst the framework has some good key features and covers the whole design process, the framework is nevertheless narrow in scope and lacks a proper underpinning.

A knowledge-based DSS aims at combining design theory, artificial intelligence (AI) and computational techniques to assist designers to explore the design problems and find their solutions by combining human design expertise with domain and design knowledge, which can be stored in advance in a computer-based design system. Although the principle of knowledge-based DSS is well established, there are still many fundamental issues to be addressed, especially, the systematisation of design knowledge and the issue of exploring and maintaining multiple design contexts (Tang, 1997).

As Shim et al (2002) pointed out, "The use of AI is being replaced with intelligent systems and soft computing, which are emerging new technological platforms. In fact, rather than standalone AI modules, intelligent logic is now usually inherent in the processing of all decision support tools."

Other trends have also been identified in the development of DSSs, e.g. intelligent CAD approach, building block approach, prototype approach, constraint-based approach (Tang, 1997); model-based and web-based approach (Shim et al, 2002) .

2.7 Summary

This chapter has reviewed the state of the art and trends of micro manufacturing and, in particular, reconfigurable machine tools, together with key design methodologies and use of design support systems.

Micro manufacturing has some distinct characteristics and the literature review has established the clear trends of the related technologies. It has confirmed that the proposal of a generic modular reconfigurable platform (GMRP) is a novel approach with many advantages and great potentials, as given in chapter one. The existing reconfigurable machine tools tend to be limited to one specific product family and not intended for micro manufacturing applications. Although there are some interesting developments of microfactory applications, they have not been designed as reconfigurable machine tools. The combination of three key features, i.e generic, reconfigurable (which also implies modular) and micro machine tools, seem to offer great prospects. This is essentially the GMRP proposed in this research.

The difficult nature of engineering design plus the extra complexity of these GMRPs demand a practical and effective design support system to assist their successful development. An integrated framework as a general design support system should be developed using the latest technologies and sound methodology. These will be further discussed in the next chapter.

Chapter 3 A Framework for Developing Generic Modular Reconfigurable Machine Platforms

3.1 Introduction

According to the literature review in the previous chapter, although there have been several research efforts on reconfigurable machine tools intended to provide a cost effective solution to mass customisation and high-speed capability, the existing reconfigurable machine tools have been designed for a particular part family. However, the manufacturers of micro products face a volatile market in which the features of micro products are very difficult to forecast due to the highly personalized and continually emerging products. For this reason, the GMRPs as well as the proposed framework architecture are not intended for a known part family, and the GMRP must be able to be reconfigured, based upon the micro manufacturing processes needed at any moment of time. This has important implications for the architecture of the framework and the development of GMRPs.

It is also clear from the literature review that although there have been many design support systems (DSSs) published, most of them have limited applications in this research. A more practical and sound approach should be adopted and this is detailed in the following sections.

3.2 Framework development

3.2.1 Framework architecture

The fundamental limitation of a pure knowledge-based approach is the complexity and amount of work required in the acquisition and representation of domain knowledge and design knowledge, which are often underestimated. As a manifestation, most of the reported knowledge-based DSSs focused on simple parts, e.g. axisymmetric components, with few studies for complex components.

Since the GMRP is a very complicated machine, a more practical approach has to be adopted, especially at the early stage of its development.

Alcantara (1995) has critically analyzed the knowledge-based approach of DSS and further identified the following design support system requirements:

- Exploration
- Evolution
- Cooperation
- Integration
- Automation

Based upon the detailed review of the existing DSSs and in particular the above requirements for practical DSSs, a novel and practical framework for developing GMRPs has been proposed as shown in Fig. 3.1. It is composed of four parts including theoretical model of GMRPs, design support system (DSS) of GMRPs, micro/nano applications of GMRPs and extension interfaces. The whole framework could be regarded as a general design support system and also a practical tool for GMRP development and applications.

The theoretical model of GMRPs covers various machine tool elements, configurations and micro manufacturing processes. It can be in various forms, e.g. mathematical model, program model and ultimately a virtual machine. The design support system (DSS) of GMRPs, as the name suggests, assist the designer in the design process, and it focuses on the systematic design and analysis of GMRPs. Whilst the GMRP models may be separately developed, they can also interact with the DSS as both input and output. The modules used in the DSS for analysis and design, together with design database and knowledge base, are necessarily dependent upon the pre-establishment of the theoretical models of GMRPs. On the other hand, the GMRP models can also be generated (or designed) by the DSS.

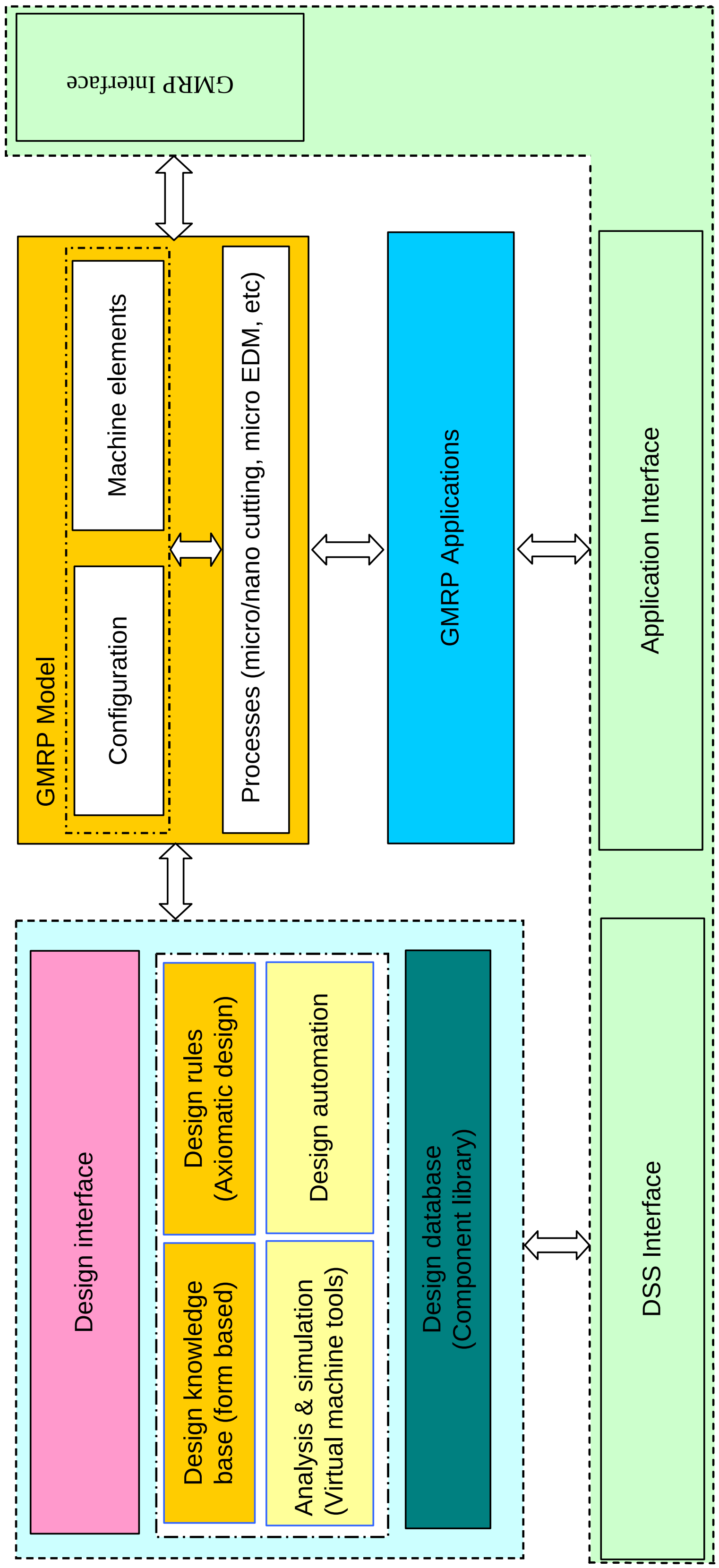


Fig. 3.1 The architecture of the framework for developing GMRPs

The framework also includes the micro/nano applications of GMRPs. GMRPs can be used to fabricate micro products, such as watches, automotive optics, medical devices, customer electronics, etc. A micro manufacturing system composed of GMRPs is capable of responding to the changing micro product markets quickly and cost effectively.

Further, the framework proposed also has several interfaces to extend its functionalities and connectivity. An open system philosophy has been adopted to enable the expansion and sharing of common modules and knowledge base.

Given the various components and modules in the proposed framework, it can be readily seen that the above requirements for a DSS have indeed been appropriately addressed.

Exploration allows the designer to consider more alternatives and assists in the management of those alternatives, i.e. their representation, control, evaluation and use. This is mainly built in the model of GMRPs, including configuration, components and manufacturing processes, each of them may have various alternatives. Together with the design rules in the design engine, the different alternatives can be displayed and evaluated in the user interface.

Evolution refers to the representation of the dynamic nature of the design process and of the evolution of the design object. In the proposed framework and DSS, the interactions between the GMRP model and the DSS can be continuously improved with the design object continually refined. The design and analysis function modules can perform a very important role in this function.

Cooperation needs to support the cooperation between multiple designers, allowing the sharing of data and knowledge, and the maintenance of consistency among the sub-designs. This can be achieved mainly through the DSS interfaces.

Integration aims to gather currently dispersed and isolated pieces of information, tools and techniques used in the design process. This requirement can be met in the proposed system because the framework itself provides exactly this integration function with all of the components including the interfaces.

Automation means the DSS not only models how the designed objects behave, but also represents explicitly the designers' intention, decisions, methods and assumptions, which are recorded, structured and related to the design object and the design process. The design automation module in the proposed DSS will be the key driver for achieving these functions.

3.2.2 The theoretical model of GMRPs

Precision machine tools are normally composed of several major components, so different components can be selected and arranged into a configuration providing necessary kinematic motions to the required micro manufacturing process. The theoretical model of a GMRP shall encompass two kinds of element, i. e. machine tool components and micro manufacturing processes, as shown in Fig. 3.2, which are also described in details in the sub-sections below.

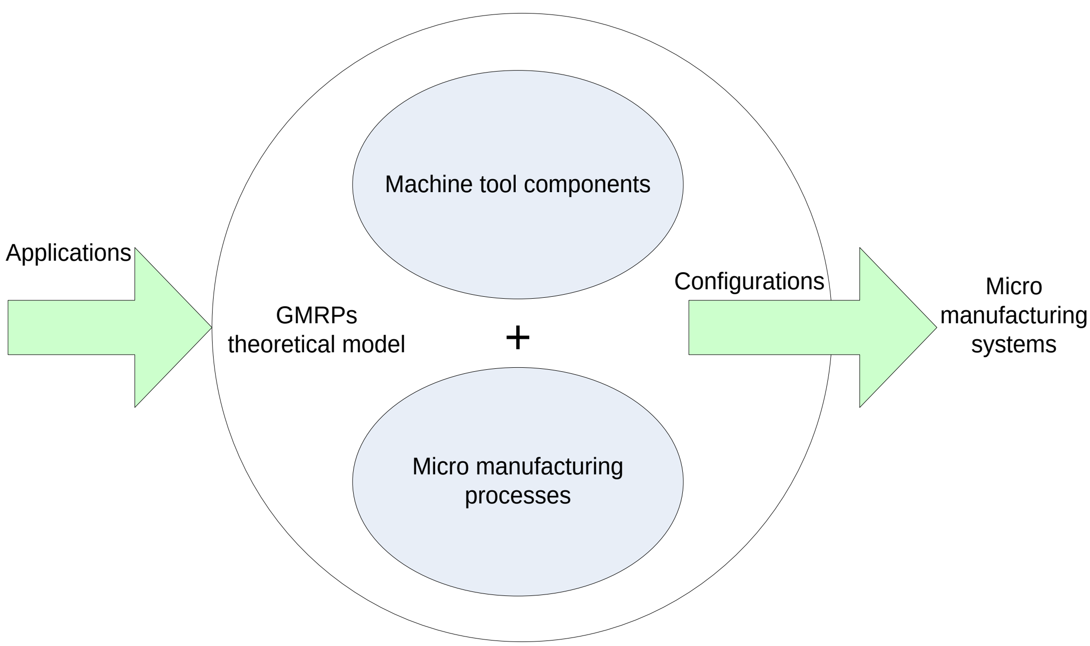


Fig. 3.2 The theoretical model of GMRPs

3.2.2.1 Components of precision machine tools

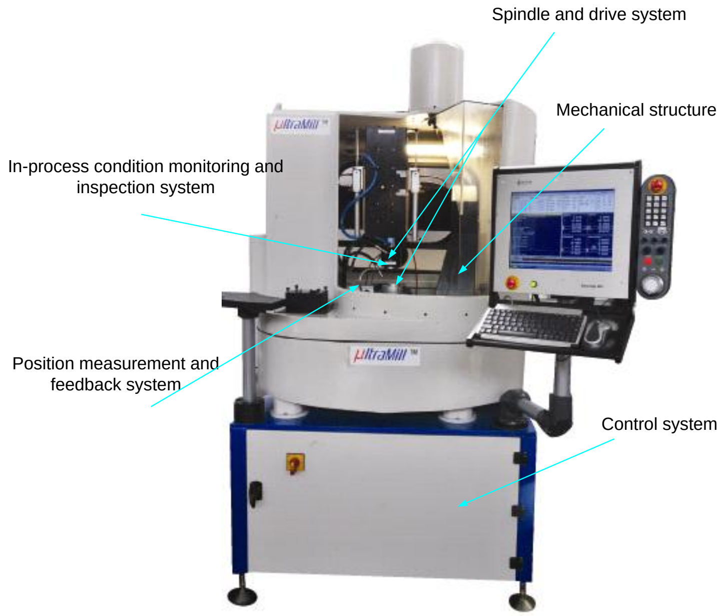


Fig. 3.3 Schematic figure of a 5-aixs micro milling machine (Huo and Cheng, 2008)

As shown in Fig. 3.3, a typical precision machine tool has five major sub-systems, including a mechanical structure, spindle and drive system, a control system, a position measurement and feedback system, and an in-process condition monitoring and inspection system. These sub-systems critically determine the overall machine tool system performance.

Mechanical structure

The mechanical structure provides a framework and mechanical support for all the machine components. It encompasses important components such as the machine base, column, worktable, slide, spindle cases and carriages. The major factors for machine design and selection include (Luo et al, 2005):

- Structural configuration
- Stiffness and damping
- Structural connectivity and interface
- Structure dynamics and associated performance

A robust design of mechanical structure should aim to achieve high structural loop stiffness, good damping properties, a symmetrical and closed loop structural configuration, minimization of heat deformation, long-term stability and isolation of environmental effects.

Material is also a key factor in determining final machine performance. Whilst cast iron and granite have been widely used for fabricating machine bases and slideways, polymer concretes have become popular for precision machine tools where light weight, high damping capacity and rigidity are required. Structural materials with a low thermal expansion coefficient and high dimensional stability have also been found applications, including super-invar, synthetic granite, ceramics and Zerodur.

Spindle and drive system

The spindle is a key component of a precision machine and it has significant impact on machined components in terms of form/dimensional accuracy and surface quality. Two types of spindles are most commonly used in precision machine tools, i.e. aerostatic bearing spindles and oil hydrostatic bearing spindles. They are capable of high rotational speed with high motion accuracy. Aerostatic bearing spindles usually have lower stiffness than oil hydrostatic bearing spindles, but they have lower thermal deformation than the latter. Aerostatic bearing spindles are widely used in machine tools with medium and small loading capacity, whereas oil hydrostatic bearing spindles are more suitable for large and heavily-loaded machine tools.

More recently, the groove technique has been used in the design of air bearings. A grooved hybrid air bearing combines aerostatic and aerodynamic design principles to optimise ultra-high speed performance.

Several drive mechanisms can be used for precision machine tools, including piezoelectric actuators, linear motor direct drives and friction drives. Piezoelectric actuators usually have a short stroke with high motion accuracy and wide response bandwidth. They have been employed in fine tool positioning so as to achieve high precision control of the cutting tool (e.g. diamond cutting tool).

Linear motor direct drives (AC or DC) usually have a long stroke and they do not need conversion mechanisms such as lead screws, and rack and pinions. They offer better stiffness, acceleration, speed, motion smoothness, repeatability and accuracy, etc, although their applications in the machine tools industry are still relatively new.

Friction drives also have a long stroke and usually consist of a driving wheel, a flat or round bar and a supporting back-up roller. They offer low friction force, smooth motion, and good repeatability and reproducibility due to elastic deformation induced by the preload.

Control system

Following the invention of Computer Numerical Control (CNC) in the early 1970s, many companies started to develop their control systems for machine tools. The control system typically includes motors, amplifiers, switches and a controller. High speed multi-axis CNC controllers play an essential role in efficient and precision control of servo drives, error compensation (thermal and geometrical errors), optimized tool setting and direct entry of the equation of shapes (Ikawa et al, 1991). Advanced PC-based control systems have achieved nanometer or even sub-nanometer level of control resolution for ultra-precision and micro manufacturing purposes, which are also commonly used by the majority of commercially available precision machines.

Position measurement and feedback system

Precision machine tools necessarily require a precision position measurement and feedback system. Laser encoders (laser interferometer based) are particularly suitable because interferometers have an intrinsically high resolution. Interferometers also have the ability to eliminate Abbe errors. They have a typical resolution of 20 nm (digital), and sub-nanometer resolution can also be achieved with an analogue system via external interpolation. The installation may be made simpler by means of fibre optics laser launch and integrated interferometer optics. Some laser holographic linear scales have a resolution of better than 10 nm.

Another alternative technique is to use ultra high resolution optical encoders. They can provide resolution close to the laser encoders, but in a simpler and more industrially feasible manner. There is a trend that more optical encoders are being adopted for precision and ultraprecision machines in industry.

In-process condition monitoring and inspection system

Intelligent and smart machine tools are an important development for precision applications. To meet these requirements, some sensors are generally required to monitor the operation of the machine tool and to enhance multi-functionality, reliability, sensitivity and accuracy. Monitoring the micro machining status during precision machining is usually difficult because of the associated very small energy emissions and cutting forces compared with the conventional machining processes. Thermal effects have been known to be the largest source of dimensional errors. It is therefore important to implement on-line temperature monitoring. Condition monitoring may be also applied to other parameters or variables, e.g. cutting force, chatter and vibration. It is desirable to use multiple sensors to realise the smart and intelligent machine tool. Furthermore, tool wear and tool breakage including its engaging process are very demanding of attention in micro/nano machining because of the high precision and fragile micro tools involved.

3.2.2.2 Micro manufacturing processes

Same with conventional manufacturing processes, micro manufacturing processes convert raw materials into desired parts to make usable and saleable products. Many different types of micro manufacturing processes have been developed, and these various processes vary in terms of their working principles and their material interactions. For micro manufacturing defined by WTEC, i.e. micro manufacturing is the creation of high-precision three-dimensional products using a variety of materials and possessing features with sizes ranging from tens of micrometers to a few millimetres, micro manufacturing processes can be subdivided into mechanical, electro physical and chemical, near net shape, energy beam and additive micro manufacturing processes (Ehmann et al, 2005; Masuzawa, 2000).

Mechanical micro manufacturing processes are naturally downscaled versions of the conventional processes. In these processes, the tools are in direct mechanical contact with the workpiece leading to a good geometric correlation between the tool path and the machined surface. They have a higher material removal rate and the ability to machine complex 2D and 3D micro features in a wide variety of materials. But, the machining accuracy may be influenced by the machining force and there is a limit of machinable size due to elastic deformation of the tool and/ or the workpiece. Typical mechanical methods are micro milling, micro turning, micro drilling, and micro grinding, etc.

Electro physical and chemical micro manufacturing processes have distinct advantages in micro manufacturing because there is no direct mechanical contact between the tool and the workpiece in these processes, avoiding problems such as elastic deformation, vibration and tool breakage. Micro electro discharge machining (EDM) and micro electro chemical machining (ECM) are typical electro physical and chemical micro manufacturing processes.

Near net shape micro manufacturing processes are generally based on plastic deformation of a wide range of materials, offering an efficient and economical choice when a large number of parts need to be produced. High production speed is one of most remarkable advantages of these processes. In many cases, the fabrication time is of millisecond order in principle, which indicates that these processes are suitable for mass production. Normally, the shape of the product is specified by copying the shape of a die or a mold. Micro extrusion and micro injection molding are two classic near-net-shape processes.

Energy beams are extremely precise tools for micro manufacturing because they can selectively remove materials from a substrate to create a desired micro feature by concentrating onto a small target of a few micro micrometers in diameter. The material is removed by melting/vaporization or ablation. By using finely focused point of beam energy, small feature sizes with tight dimensional tolerance can be obtained. Energy beam includes laser beam, ion beam, and electron beam. They have advantages of contactless machining without tool wear and the ability to machine a wide variety of materials.

Lamination and deposition are the two material addition types during material additive processes. Various rapid prototyping processes are lamination based, where 3D parts can be produced directly through layer by layer fabrication without using part-specific tools. Thus, inner side of parts can be easily shaped without a die or a mole. However, the narrow choice of the material is its major disadvantage. Except for micro productions with material lamination, electroforming which features atomic deposition is also a typical material additive process.

Table 3.1 gives the comparison of various micro manufacturing processes. It can be seen from the table, compared to other micro manufacturing processes, mechanical micro manufacturing processes have the overall advantage.

GMRPs may be very difficult, if not impossible, to be reconfigured to perform any arbitrary type of micro manufacturing processes, but they can be easily used for some micro manufacturing processes such as mechanical processes by reconfiguration of appropriate precision machine tool components. Furthermore, inspection and assembly functions theoretically could be obtained by selecting and configuring corresponding components.

Table 3.1 Comparison of micro manufacturing processes (Rajurkar et al, 2006)

	Geometric Complexity	Range of Materials	Proto-typing	Mass Production	Surface Quality	Afford-ability
Additive processes	+	-	+	o	o	+
Electro physical and chemical processes	+	o	+	-	o	+
Energy beam processes	o	+	+	-	o	o
Lithography	-	-	-	+	+	-
Mechanical processes	+	o	+	o	+	+
Near net shape processes	o	o	-	+	o	o

Legend + Good o Fair - Poor

3.2.3 Design support system and methodology of GMRPs

The design support system is the heart of the proposed framework and as such, it also reflects the underlying design methodology adopted. Whilst the DSS design will be detailed in Chapter 5, the design methodology is discussed here in this section.

The DSS essentially has a three tier architecture and the core (or maybe termed as design engine) includes modules for analysis and simulation, design rules, design knowledge base and design automation. Analysis and simulation modules are essential for the generation and evaluation of design. Advanced simulation, e.g. use of virtual machine tool, can provide virtual experience of interactions with the machine concerned, and it may be used for training operator and optimising the design performance. The design rules adopted for the DSS are based upon axiomatic design theory, which has been introduced in Chapter 2. The actual use of these design rules will be presented in Chapters 4 and 5 where they are used for the conceptual design of the proposed GMRP and the DSS, respectively. As a generic design methodology, axiomatic design theory offers great modularity and extensibility for GMRPs and DSS.

The design knowledge base generally facilitates the design generation and design process. It has been proposed as a basic module of the design engine in the business logic tier, although it may alternatively be located in the database tier. The knowledge base may be presented using various representation schemes, e.g. rules based, form based, etc. This may be implemented with external third party software (e.g. expert system shell) or internal built-in inference module. The latter is preferred as it allows for greater level of integration.

The design automation may be implemented at various levels. Fundamentally designs may be generated automatically based upon the use of design rules and design knowledge base. With the continuous development of the knowledge base and software modules, it is possible to automatically generate the design largely, if not completely. The automation will offer many benefits, e.g. speed, cost-effectiveness and other potentials.

The database will be used as a general support and library for design and analysis. Since a large number of components may be used in the design, a component library is essential to facilitate the design process. A database may be also used to provide other key information in the design, e.g. material properties and mechanical configurations, etc.

The proposed DSS for the GMRPs, together with its user-friendly interface, design engine, knowledge base and database, will serve as a practical tool (or toolbox) for designers throughout the design process, thus speeding up the design process and leading to better designed machine tools.

3.2.4 Applications of GMRPs

The GMRP concept has the potential to bring dramatic changes to the modern manufacturing industry due to its advantages in terms of low cost, reduction of space, diverse functionality, and industrial feasibility. GMRPs can not only deliver modular, reconfigurable, adaptive, reusable manufacturing facilities and methodology for supporting industries (SMEs in particular) to enter high value-added manufacturing, but also enable reconfigurable adaptive manufacturing systems for manufacturing industry to compete in the dynamic global marketplace. Furthermore, adopting a holistic approach, GMRPs provide exemplar pilot systems, implementation protocols and applications for enabling European manufacturing SMEs to engage in the global manufacturing in a highly innovative, responsive and productive manner.

The Application module in the proposed framework handles the configurations and integration at a high system level, where GMRPs are used as building blocks, which is essentially a micro factory approach. At this level both simulation and optimisation are generally required in terms of operation and system performance.

The two specific application areas of GMRPs may be indentified and discussed here, i.e. hybrid reconfigurable micro manufacturing machines and product-oriented micro manufacturing systems.

3.2.4.1 Hybrid reconfigurable micro manufacturing machines

Recently the emergence of "point-of-care" service systems has been proposed as a major model for the future of healthcare. Similarly, in the manufacturing domain, there is a swing back from the existing largely centralized manufacturing model to a more distributed manufacturing model that co-exits with the centralized model (Ehmann et al, 2007; Bateman and Cheng, 2002; Bateman and Cheng, 2006).

Moreover, micro manufacturing is a disruptive technology that will completely change our thinking as to know when and where products will be manufactured, e.g. on-site, on-demand in the hospital operating room or on-board a warship (Ehmann et al, 2007). That means manufacturing service location will move to the point of consumption from factories in the future. The proposed reconfigurable machine platforms for micro manufacturing have the ability to enable the micro manufacturing to take place at the "point-of-use" in a timely and economic fashion. A GMRP is able to perform many kinds of micro manufacturing processes on a site after it has been reconfigured, making the "point-of-use" practical and easy.

3.2.4.2 Product-oriented micro manufacturing system

The concept of product-service systems has been proposed for one decade or so as a possible solution to unlink environmental pressure from economic growth. Godekoop et al (1999) defined a product-service system as "a marketable set of products and services capable of jointly fulfilling a user's need and has a lower environmental impact than traditional business models". The key idea behind product-service systems is that consumers' specific needs can be met more properly by using service engineering to meet some needs rather than a merely physical object. Product-service systems respond more appropriately to the current demands than the conventional systems of mass production because of the flexibility of customers' demands in current vibrant market place. This is an evolution of the economic transition away from standardized and mass production towards flexibility, mass-customisation and markets driven by quality, innovative products and added value rather than cost (Mont, 2002; Kang and Wimmer, 2008; Williams, 2007; Morelli, 2006). Therefore, most advanced manufacturing companies are shifting their business strategy from traditional business model towards services-oriented or functionality-driven instead of merely products.

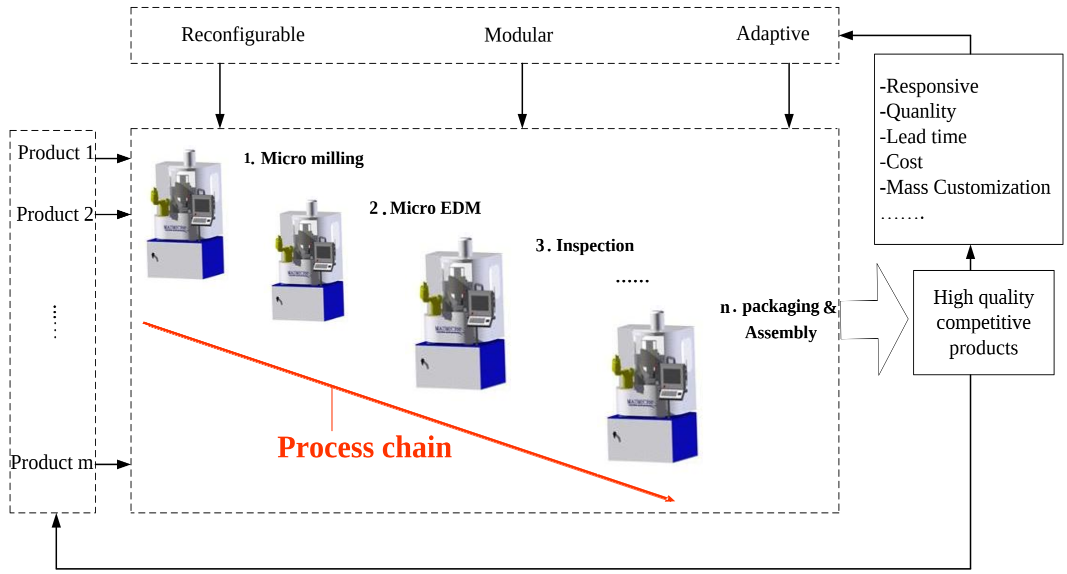


Fig. 3.4 Principle of a product-oriented micro manufacturing system

Fig. 3.4 shows that a product-oriented micro manufacturing system can be developed with GMRPs to fabricate various micro products, covering the full process chain from different machining operations (e.g. micro milling, drilling, EDM) through inspection (e.g. micro CMM) to the final assembly. Such a system can be used to produce high quality products competitively due to its reconfigurability, modularity and adaptivity, offering excellent responsiveness, short lead time, low cost and mass customisation. In this micro manufacturing system, each GMRP can be configured as a specified functional machine by choosing corresponding modular components from the library of modules, which greatly reduces the set up and the cost of the whole manufacturing system. The system is highly flexible and can be easily reconfigured and reused because of the adoption of GMRPs.

Such kind of machine platform will play as a basic but key modular unit to provide the functionalities and flexibility required by the product-oriented production systems.

3.2.5 Extension interfaces

In addition to the design interface in the DSS, the framework has provided functional extension interfaces, including DSS interface, GMRP interface and application interface. These interfaces will generally expand the functionalities of the framework and facilitate the access to external software modules, knowledge bases and databases. They will also provide the important scalability and upgradability required for the cost-effective development and maintenance of the design support system.

Although the DSS has built-in modules for generating, analysing and evaluating designs with design knowledge base and database support, they are undoubtedly limited to the micro manufacturing process models and functionalities which have already been developed. In order to further expand the design knowledge base and functionalities of the DSS, an open system architecture will be desirable for sharing and accessing external functional modules, knowledge bases and databases. Specifically the DSS Interface will allow the importing and exporting of design data and design knowledge with external system. Additional software or software modules for design and analysis (including simulation, e.g. ProE, ANSYS, Simulink) can also be integrated through the DSS Interface, which may well be web-based applications or services over the Internet.

The GMRP Interface may be used to interact with other systems, either software or hardware based. Partial or complete machine models may be exported or imported through this interface. The partial models are typically those of specific machine elements or a manufacturing process. In addition, it is also possible to directly link the GMRP model to external real GMRP machine tools. For example, reconfiguring control routines may be first optimised in the virtual machine tool module and then exported to the real GMRP to test or evaluate the performance.

The Application Interface plays a similar role to the GMRP Interface, but at a higher system level. It facilitates the exchange of the data with external systems and applications, including those applications discussed in the previous section, i.e. hybrid reconfigurable micro manufacturing machines and product-oriented micro manufacturing system.

3.3 Summary

The framework and the underlying methodology for developing GMRPs have been presented in this chapter. The proposed framework consists of four modules or parts, i.e. theoretical model of GMRPs, design support system, applications and interfaces. The key parts of the framework are the theoretical model of GMRPs and the design support system. The former is the basis and the aim of latter, whilst the latter is the tool and methodology to generate the GMRP deign required according to the intended application.

GMRPs have the ability to enable the micro manufacturing to take place at the “point-of-use” in a timely and economic fashion. In addition, GMRPs can be used to form a product-oriented micro manufacturing system, providing excellent responsiveness, short lead time, low cost and mass customisation.

Chapter 4 Conceptual Design and Analysis of GMRPs

4.1 Introduction

The general GMRP Model has been discussed in Chapter 3. This chapter applies the axiomatic design approach to the conceptual design of GMRPs. The discussion focuses on the general methodology, i.e. use of different design axioms (or design rules). The error analysis (or error budget) of a GMRP is also presented, which is followed by the characteristics of GMRPs.

Fig. 4.1 highlights the main topics presented in this chapter in relation to the whole framework, shown in red rectangle.

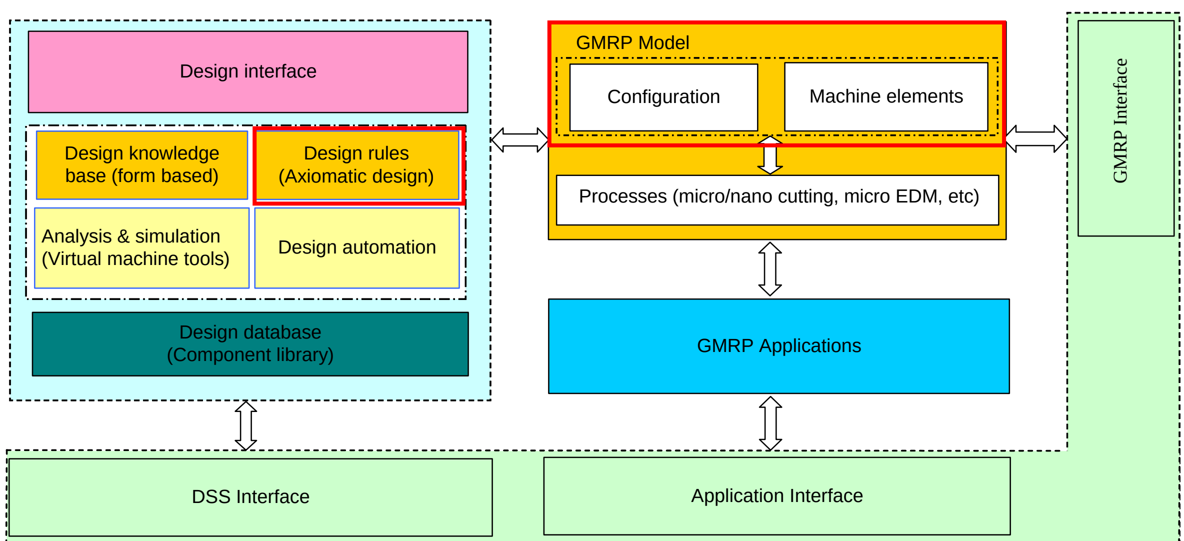


Fig. 4.1 Main topics addressed in this chapter

4.2 Conceptual design of GMRPs with axiomatic design theory

A number of corollaries can be derived from the two axioms of axiomatic design theory and some of them are very relevant to the conceptual design of GMRP, i.e.

Corollary 2: Minimisation of FRs.

Corollary 3: Integration of physical parts.

Corollary 4: Use of standardisation.

Corollary 6: Largest tolerance.

Corollary 7: Uncoupled design with less information.

They can be directly used to guide the design process. A typical design process based upon the axiomatic design theory is as follows (Babic, 1997):

Step 1: Establishment of design goals to satisfy a given set of perceived needs.

Step 2: Conceptualisation of design solutions.

Step 3: Analysis of the proposed solution.

Step 4: Selection of the best design from among those proposed.

Step 5: Implementation.

4.2.1 Conceptual design of a GMRP

In accordance with axiomatic design theory, the design process for GMRPs begins with the establishment of FRs in the functional domain to satisfy a given set of needs. For the design of a GMRP, the customer needs can be therefore identified as:

CA=fabricate various micro products quickly with high accuracy

Level 1

The need can be further translated into functional requirements:

FR_1=perform nano/micro manufacturing

FR_2=respond to market quickly

FR_3=perform different machining functions with high accuracy

Corollary 2, which highlights the minimization of number of FRs, is considered in the next step to perform the joining of related FRs. The final FRs in the functional domain are as follows:

FR_1=respond to the market quickly

FR_2= perform different micro machining functions with high accuracy

The functional requirements can be each related to a design parameter:

DP_1=short set-up time

DP_2=reconfiguration of the high precision machine tool

Short set-up time only has effects on the response of the GMRP to the market, while micro machining functions are just related to the reconfiguration of GMRP. Therefore, it is possible to determine the mathematical relationship between the functional requirements and design parameters as:

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix} \tag{4.1}$$

The independence axiom has been satisfied in the generation of the design parameters due to characteristics of the design matrix of Equation (4.1), i.e. the design matrix is diagonal.

Second Level Decomposition: FR_1-Respond to market quickly

FR_1, FR_2, DP_1 and DP_2 are defined at the highest level. The next step in axiomatic design is to go back to the functional domain from the physical domain if the DP_1 and DP_2 cannot be implemented without further detailed design. For the DP_1, FR_1 can be decomposed as

FR_{11}=Apply the modularity concept

FR_{12}=Standardise the interface

FR_{13}=Change machine elements quickly

The corresponding set of DPs may be chosen as

DP_{11}=Modularity of major components (e.g. structural elements, controls, toolings)

DP_{12}=Standard interface

DP_{13}=Convertibility

The GMRP will be designed to meet modularity concepts to allow efficient and quick reconfigurability of the machine, such as applying unified fasteners and connectors, modular structural elements, modular software. In addition, standard electrical, mechanical, control and software interfaces should allow rapid integration of modularized elements or "building blocks" which were designed or selected in advance (Katz, 2007). Convertibility is another factor which can reduce the set-up time, allowing easy and fast change of machine elements, rapid addition or removal of elements. In this step, the standardization and modularity is based on the application of Corollary 4 which states the use of standard or interchangeable parts.

After $\{FR_{1x}\}$ and $\{DP_{1x}\}$ are determined for DP_1, the design matrix must be created to determine whether the proposed design satisfy the Independence Axiom. The design equation and design matrix are given as:

$$\begin{Bmatrix} FR_{11} \\ FR_{12} \\ FR_{13} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP_{11} \\ DP_{12} \\ DP_{13} \end{Bmatrix} \tag{4.2}$$

This design matrix is decoupled and thus satisfies the Independence Axiom.

Second Level Decomposition: FR_2- perform different micro machining functions with high accuracy

FR_{21}=Clarify task requirements

FR_{22}=Design the structural configuration

FR_{23}=Design/select components

FR_{24}=Evaluate the generated machine tool

The corresponding set of DPs may be chosen as

DP_{21}=Definition of requirements

DP_{22}=Structural configuration synthesis method

DP_{23}=Development of a component library

DP_{24}=Analysis of the generated machine tool

The reconfiguration of a machine tool aims to enable the machine tool to meet new micro product requirements. So the new task requirements have to be clarified firstly, generating configuration and selecting key components are essential subsequent steps to form a machine tool. Evaluation has to be performed to ensure that the generated conceptual machine tool has the capability of fabricating required products. In this design step, selection of key components such as spindle, slideway, etc. is based on Corollary 3, which requires the reduction of the number of physical components. Therefore, the design equation and matrix can be shown as:

$$\begin{Bmatrix} FR_{21} \\ FR_{22} \\ FR_{23} \\ FR_{24} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ X & 0 & X & 0 \\ X & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_{21} \\ DP_{22} \\ DP_{23} \\ DP_{24} \end{Bmatrix} \tag{4.3}$$

The design matrix is decoupled, satisfying the Independence Axiom. Configuration generation, development of component library and analysis of generated machine tool are detailed in the conceptual design of a GMRP, there is no further decomposition.

Level 3 Decomposition: FR_{21}-Clarify the task requirements

FR_{211}=Remove the material effectively
FR_{212}=Achieve the required geometry
FR_{213}=Get the required accuracy and surface quality

The corresponding set of DPs may be defined as
DP_{211}=An appropriate machining process
DP_{212}=Number of the axes
DP_{213}=The machine accuracy

The efficient removal of the material is greatly affected by the used micro machining process, while the capability of manufacturing the required geometry is not only related to micro machining process, but also the number of the axes of the machine tool. Regarding the required accuracy, it is normally related to the micro machining process, the number of axes and the accuracy of the machine tool. During the specification of the required accuracy and surface quality, Corollary 6 (application of the largest possible tolerance) should be taken into consideration (Babic, 1997). Thus, the design equation and matrix can be obtained as:

$$\begin{Bmatrix} FR_{211} \\ FR_{212} \\ FR_{213} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP_{211} \\ DP_{212} \\ DP_{213} \end{Bmatrix} \tag{4.4}$$

The design matrix is diagonal, which indicates that the design is a decoupled design and satisfies the Independence Axiom, and DP_{211}, DP_{212} and DP_{213} are therefore adopted. Since the three DPs are clear, there is no need of any further decomposition.

4.2.2 Representation of the design architecture

After finishing mapping between functional domain and physical domain, with the design matrices, the hierarchies of FRs and DPs can be used to represent the design architecture for the conceptual design of GMRPs clearly. The FR/DP hierarchical diagrams shown in Fig. 4.2 and the design matrices given in Equations (4.2~4.4) illustrate the entire decomposition steps and all FRs/DPs in the conceptual design of GMRPs.

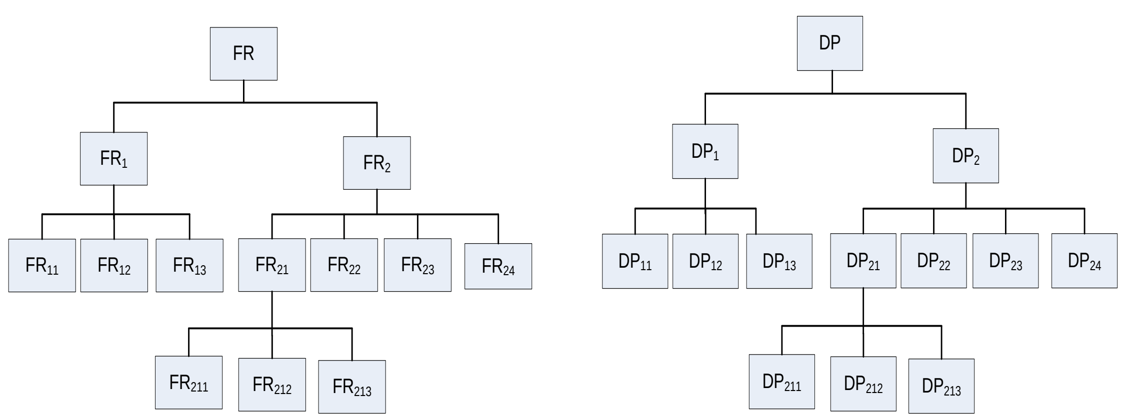


Fig. 4.2 The FR and DP hierarchies

In the conceptual design of GMRPs, the first layer is an uncoupled design, while the second and third layers are decoupled designs according to the design matrices. The decoupled designs must be controlled by following the sequence dictated by the design matrices, and then the design is an acceptable design since there is no coupling in this design.

FR_1 and FR_2 can be simply combined to obtain the highest level because they are uncoupled with respect to each other. Other design matrices in this design are triangular matrix, so the lower level FRs must be satisfied in the sequence given by the corresponding design matrix to satisfy the higher level FR.

4.2.3 Selection of components using Information Axiom

Selection of components for GMRPs is an important step in the design of GMRPs. When selecting a component, there are normally a set of function requirements have to be satisfied at the same time. The Information Axiom, which is a powerful tool for selecting the best set of DPs when there are many FRs to be satisfied, can therefore be used in the selection of components to get the most suitable components.

In the following, the selection of a slideway for a GMRP is shown as an example to explain how to use axiomatic information to choose the best components for the design of GMRPs. Suppose that a slideway with the following three functional requirements is needed for a GMRP, and there are three Aerotech slideways, i.e. ALS130-25, ALS130-50 and ALS10010, in the component library. The relevant specifications of the three slideways are shown in Table 4.1.

FR_1= resolution of the slideway must be 0.003~0.05 μm

FR_2= accuracy of the slideway must be ±1.5 μm

FR_3= straightness of the slideway must be ±1.25 μm

Table 4.1 Specification of the three slideways

Slideway	**FR_1=Resolution (μm)**	**FR_2=Accuracy (μm)**	**FR_3=Straightness (μm)**
ALS130-25	0.0025~1.0	±2.0	±1.0
ALS130-50	0.0025~1.0	±2.0	±1.5
ALS10010	0.005~1.0	±1.0	±4.0

The FRs of the required slideway specify the design ranges, and the system ranges of the design are given in the above table. Using these design and system ranges, the information content for each FR for each slideway can be calculated using Equation (2.4). Fig. 4.3 and Fig. 4.4 illustrate the overlap between the design range and the system range for FR_1 and FR_2, respectively, of slideway ALS130-25. According to the information content Equation (2.4), the information content for FR_2 and FR_3 of slideway can be calculated as:

$$I_2 = \log_2\left(\frac{SystemRange}{CommonRange}\right) = \log_2\left(\frac{4.0}{3.0}\right) = 0.415 \text{ bits}$$

$$I_3 = \log_3\left(\frac{SystemRange}{CommonRange}\right) = \log_2\left(\frac{2.0}{2.0}\right) = 0 \text{ bits}$$

Thus, the information content for FR_2 and FR_3 of slideway ALS130-25 is 0.415 bits and 0 bits, respectively. The information contents for the FRs are shown in Table 4.2.

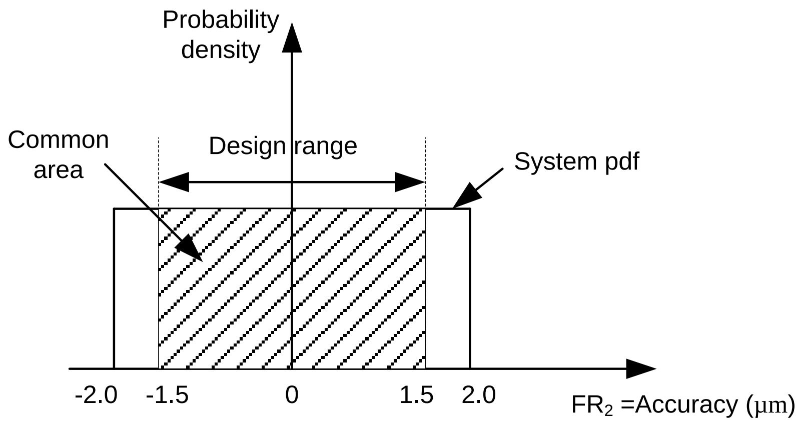


Fig. 4.3 Probability distribution of accuracy

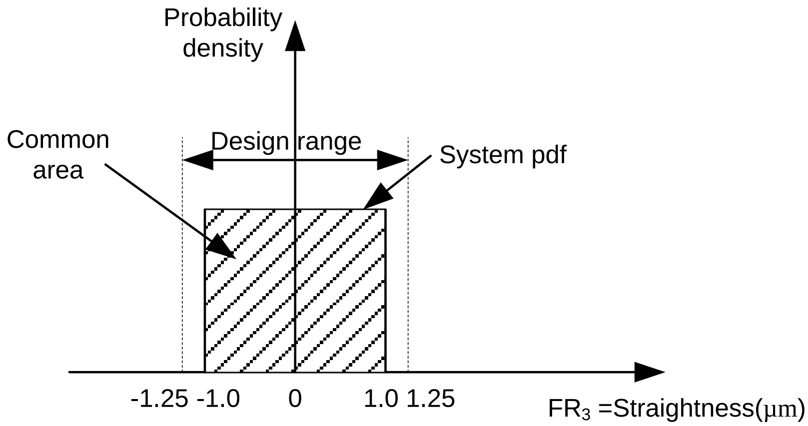


Fig. 4.4 Probability distribution of straightness

Table 4.2 Information content of FRs for three slideways

Slideway	I_1 (bits)	I_2 (bits)	I_3 (bits)	$\sum I$ (bits)
ALS130-25	4.327	0.415	0	4.742
ALS130-50	4.327	0.415	0.2630	5.005
ALS10010	4.467	0	1.6781	6.145

Note: I_1 is the resolution information content; I_2 the accuracy information content; I_3 the straightness information content.

The information contents associated with resolution and accuracy in ALS130-25 and ALS130-50 are the same, but ALS130-50 has higher straightness information content and is thus more difficult to satisfy the required straightness than ALS130-25. On the other hand, ALS10010 can easily satisfy the needed accuracy than other two slideways, however, it has difficulty to satisfy the resolution requirement. According to Table 4.2, the slideway that best satisfies the three requirements efficiently is ALS130-25 because it has the least total information contents. ALS130-25 should therefore be selected for the GMRP concerned.

4.3 Error analysis of a reconfigured machine tool

The source of the error of a machine tool includes geometrical errors, dynamic errors and thermal errors. This section focuses on the geometrical errors. In order to determine the geometrical errors of a machine tool, the spatial relationship between the tool tip position and the workpiece must be defined in a common reference coordinate system. Homogeneous transformation matrices (HTMs) are typically used to represent the relative position of a rigid body in three-dimensional space with respect to a given coordinate system.

The HTMs corresponding to the six degrees of freedom of a rigid body are as follows:

$$T_x = \begin{bmatrix} 1 & 0 & 0 & a \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4.5) \quad T_y = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & b \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4.6) \quad T_z = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & c \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4.7)$$

$$T_a = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_x & -\sin\theta_x & 0 \\ 0 & \sin\theta_x & \cos\theta_x & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4.8)$$

$$T_b = \begin{bmatrix} \cos\theta_y & 0 & \sin\theta_y & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\theta_y & 0 & \cos\theta_y & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4.9)$$

$$T_c = \begin{bmatrix} \cos\theta_z & -\sin\theta_z & 0 & 0 \\ \sin\theta_z & \cos\theta_z & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4.10)$$

where a, b and c are the translations along x, y and z axis, respectively; θ_x, θ_y and θ_z the rotations about x, y and z axis, respectively;

The combined HTM of six HTMs (i.e. six degrees of freedom) is given as:

$$T = T_x T_y T_z T_a T_b T_c =$$

$$\begin{bmatrix} \cos\theta_y \cos\theta_z & -\cos\theta_y \sin\theta_z & \sin\theta_y & a \\ \sin\theta_x \cos\theta_z \sin\theta_y + \sin\theta_z \cos\theta_x & -\sin\theta_x \sin\theta_z \sin\theta_y + \cos\theta_z \cos\theta_x & -\cos\theta_y \sin\theta_x & b \\ \cos\theta_z \cos\theta_x \sin\theta_y + \sin\theta_z \sin\theta_x & -\cos\theta_x \sin\theta_z \sin\theta_y + \cos\theta_z \sin\theta_x & \cos\theta_y \cos\theta_x & c \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4.11)$$

For a rigid body, there are three rotational errors ε_X , ε_Y , ε_Z and three translational errors δ_X , δ_Y , δ_Z associated with their motions. After submitting these errors into Equation (4.11), with negligible second-order term and small-angle approximations, the actual HTM for the linear motion carriage with errors can be written as follows:

$$T_{error} = \begin{bmatrix} 1 & -\varepsilon_z & \varepsilon_y & a+\delta x \\ \varepsilon_z & 1 & -\varepsilon_x & b+\delta y \\ -\varepsilon_y & \varepsilon_x & 1 & c+\delta z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.12}$$

The actual HTM for a rotary table revolving about X, Y, Z axis with errors can be presented as Equations (4.13), (4.14) and (4.15), respectively.

$$T_{aerror} = \begin{bmatrix} 1 & -\varepsilon_z & \varepsilon_y & \delta_x \\ \varepsilon_y \sin\theta_x + \varepsilon_z \cos\theta_x & \cos\theta_x & -\sin\theta_x & \delta_y \\ \varepsilon_y \cos\theta_x + \varepsilon_z \sin\theta & \sin\theta_x & \cos\theta_x & \delta_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.13}$$

$$T_{berror} = \begin{bmatrix} \cos\theta_y & -\varepsilon_z \cos\theta_y & \sin\theta_y & \delta_x \\ \varepsilon_x \sin\theta_y + \varepsilon_z & 1 & -\varepsilon_x \cos\theta_y & \delta_y \\ -\sin\theta_y & \varepsilon_z \sin\theta_y + \varepsilon_x & \cos\theta_y & \delta_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.14}$$

$$T_{cerror} = \begin{bmatrix} \cos\theta_z & -\sin\theta_z & \varepsilon_y & \delta_x \\ \sin\theta_z & \cos\theta_z & -\varepsilon_x & \delta_y \\ \varepsilon_x \sin\theta_z - \varepsilon_y \cos\theta_z & \varepsilon_x \cos\theta_z + \varepsilon_y \sin\theta_z & 1 & \delta_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.15}$$

In the following section, the 5-axis milling machine tool developed at Brunel University will be taken as an example to explain how to evaluate the machine errors. The 5-axis machine tool has three linear axes X, Y, Z and two rotary axes B, C, as shown in Fig. 4.5

A machine structure may be modelled as a series of relative motions between the axes. Since each axis can be represented as a homogeneous transformation matrix, the overall transformation matrix can then be obtained simply by multiplying the individual HTMs, starting from the tip and working all the way down to the base reference coordinate system. Suppose the actual position of tool tip in the workpiece coordinate system is (X_a, Y_a, Z_a) after movement of every slideway and rotary table; the nominal movement of x, y, z slideway is X, Y, Z; and the position of tooltip in coordinate system of the component on which tool is installed is X_t, Y_t, Z_t. For the 5-axis machine tool shown in Fig. 4.5, we have:

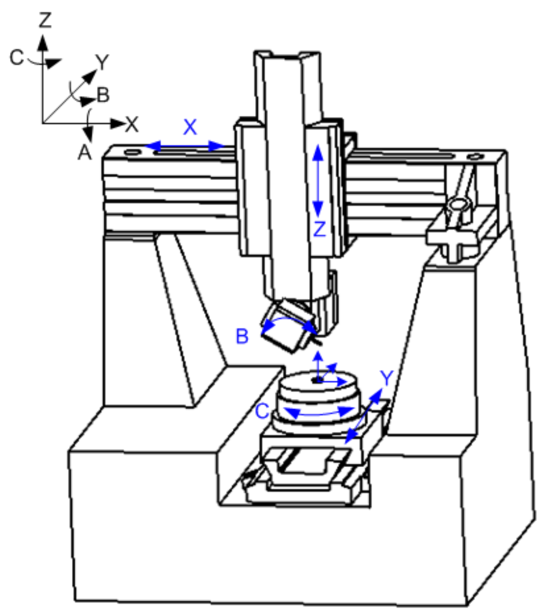


Fig. 4.5 Schematic of the 5-axis milling machine tool

$$ {}^{f}T_{y}\,{}^{y}T_{c}\begin{bmatrix} X_a \\ Y_a \\ Z_a \\ 1 \end{bmatrix} = {}^{f}T_{x}\,{}^{x}T_{z}\,{}^{z}T_{b}\begin{bmatrix} X_t \\ Y_t \\ Z_t \\ 1 \end{bmatrix} \tag{4.16} $$

where ${}^{f}T_{y}$, ${}^{y}T_{c}$, ${}^{f}T_{x}$, ${}^{x}T_{z}$ and ${}^{z}T_{b}$ are transformation matrices:

$$ {}^{f}T_{y} = \begin{bmatrix} 1 & -\varepsilon_z(Y) & \varepsilon_y(Y) & \delta_x(Y) \\ \varepsilon_z(Y) & 1 & -\varepsilon_x(Y) & -Y-\delta_y(Y) \\ -\varepsilon_y(Y) & \varepsilon_x(Y) & 1 & \delta_z(Y) \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$
{}^{y}T_{c}=\begin{bmatrix}
\cos(\theta_z) & -\sin(\theta_z) & \varepsilon_y(C) & \delta_x(C)\\
\sin(\theta_z) & \cos(\theta_z) & -\varepsilon_x(C) & \delta_y(C)\\
\varepsilon_x(C)\sin(\theta_z)-\varepsilon_y(C)\cos(\theta_z) & \varepsilon_x(C)\cos(\theta_z)+\varepsilon_y(C)\sin(\theta_z) & 1 & \delta_z(C)\\
0 & 0 & 0 & 1
\end{bmatrix}
$$

$$
{}^{f}T_{x}=\begin{bmatrix}
1 & -\varepsilon_z(X) & \varepsilon_y(X) & X+\delta_x(X)\\
\varepsilon_z(X) & 1 & -\varepsilon_x(X) & \delta_y(X)-\alpha X\\
-\varepsilon_y(X) & \varepsilon_x(X) & 1 & \delta_z(X)\\
0 & 0 & 0 & 1
\end{bmatrix}
$$

$$
{}^{x}T_{z}=\begin{bmatrix}
1 & -\varepsilon_z(Z) & \varepsilon_y(Z) & \delta_x(Z)-\beta_1 Z\\
\varepsilon_z(Z) & 1 & -\varepsilon_x(Z) & \delta_y(Z)-\beta_2 Z\\
-\varepsilon_y(Z) & \varepsilon_x(Z) & 1 & Z+\delta_z(Z)\\
0 & 0 & 0 & 1
\end{bmatrix}
$$

$$
{}^{z}T_{b}=\begin{bmatrix}
\cos(-\theta_y) & -\varepsilon_z(B)\cos(-\theta_y) & \sin(-\theta_y) & \delta_x(B)\\
\varepsilon_x(B)\sin(-\theta_y)+\varepsilon_z(B) & 1 & -\varepsilon_x(B)\cos(-\theta_y) & \delta_y(B)\\
-\sin(-\theta_y) & \varepsilon_z(B)\sin(-\theta_y)+\varepsilon_x(B) & \cos(-\theta_y) & \delta_z(B)\\
0 & 0 & 0 & 1
\end{bmatrix}
$$

where $-\delta_x(X)$, $\delta_y(Y)$, $\delta_z(Z)$ are the positional errors along X, Y, Z direction, respectively.

$-\delta_x(B)$, $\delta_y(B)$, $\delta_z(B)$ are radial errors and axial error when the axis of rotation revolves around X axis of the reference coordinate frame.

$-\delta_x(C)$, $\delta_y(C)$ and $\delta_z(C)$ are radial errors and axial error when the axis of rotation revolves around Y axis of the reference coordinate frame.

$-\delta_y(X)$, $\delta_z(X)$ are straightness errors of X axis on y, z direction, respectively.

$-\delta_x(Y)$, $\delta_z(Y)$ are straightness errors of Y axis on x, z direction, respectively.

$-\delta_x(Z)$, $\delta_y(Z)$ are straightness errors of Z axis on x, y direction, respectively.

$-\varepsilon_x(X)$, $\varepsilon_y(X)$, $\varepsilon_z(X)$ are rotational errors of X axis around x, y, z direction, respectively.

$-\varepsilon_x(Y)$, $\varepsilon_y(Y)$, $\varepsilon_z(Y)$ are rotational errors of Y axis around x, y, z direction, respectively.

$-\varepsilon_x(Z), \varepsilon_y(Z), \varepsilon_z(Z)$ are rotational errors of Z axis around x, y, z direction, respectively.

$-\varepsilon_x(B), \varepsilon_z(B)$ are rotational errors when the axis of rotation revolves around Y axis of the reference coordinate frame.

$-\varepsilon_x(C), \varepsilon_y(C)$ are rotational errors when the axis of rotation revolves around Z axis of the reference coordinate frame.

$-\alpha, \beta_1, \beta_2$ are squareness errors between the XY, XZ, YZ axes, respectively.

The volumetric error is the difference between tool tip's actual position $(X_a, Y_a, Z_a)^T$ and nominal position. The actual position $(X_a, Y_a, Z_a)^T$ can be obtained from Equation (4.16) with all the error components in each axis. In fact, the nominal position of the tool tip can be also determined from Equation (4.16), but assuming all the error components are zeros. They can be shown as follows:

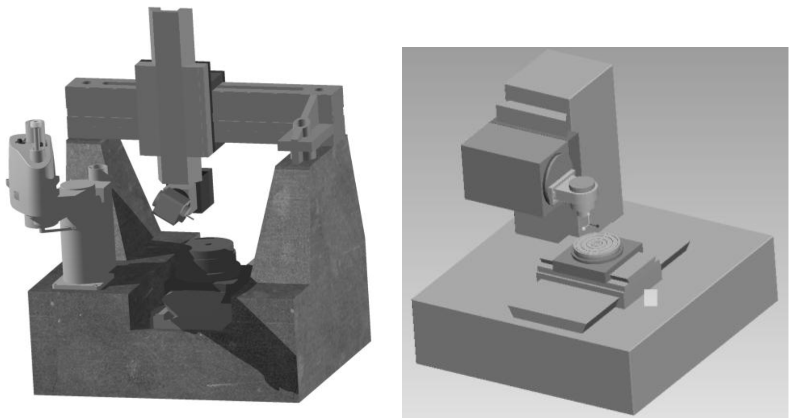
$$\begin{cases} X_n = \cos\theta_z(X + X_t\cos\theta_y + Z_t\sin\theta_y) + \sin\theta_z(Y_t + Y) \\ Y_n = -\sin\theta_z(X + X_t\cos\theta_y + Z_t\sin\theta_y) + \cos\theta_z(Y_t + Y) \\ Z_n = Z - X_t\sin\theta_y + Z_t\cos\theta_y \end{cases}$$

The final errors $(\Delta X, \Delta Y, \Delta Z)^T$ can therefore be determined and can be expressed as follows:

$$\begin{cases} \Delta X = X_a - X_n = X_a - [\cos\theta_z(X + X_t\cos\theta_y + Z_t\sin\theta_y) + \sin\theta_z(Y_t + Y)] \\ \Delta Y = Y_a - Y_n = Y_a - [-\sin\theta_z(X + X_t\cos\theta_y + Z_t\sin\theta_y) + \cos\theta_z(Y_t + Y)] \\ \Delta Z = Z_a - Z_n = Z_a - Z + X_t\sin\theta_y - Z_t\cos\theta_y \end{cases} \quad (4.17)$$

4.4 Characteristics of GMRPs

As shown in Fig. 4.6, two GMRP configurations are proposed. Each GMRP is a bench-top hybrid processing machine designed for industrial feasible micro/nano manufacturing, especially for manufacturing SMEs. The base of each platform is generic, and manufacturers can add, change, or remove modular components such as spindles, slideways, tool holders, etc., forming a specified micro/nano hybrid machine as new components/ products manufacturing is required. Furthermore, as a GMRP is modular and reconfigurable in structure, it can thus be used as a generic machine unit for forming a micro manufacturing system at low cost. The unit can have adaptive, associative and intelligent capability, e.g. remembering the past machining experience and configuration setup, etc, which is essential for the rapid and responsive setup of the system in an intelligent way.



(a) (b)

Fig. 4.6 Virtual models of two GMRP configurations

4.4.1 Hybrid manufacturing capability

Micro components/products are normally integrated products with different materials and diverse micro features, which make it necessary for manufacturers to possess hybrid micromachining ability to cope with varied features and materials. For example, micro grinding has been widely applied for machining pins and grooves with small dimensions on hard or brittle materials, but deep micro holes or deep, narrow cavities are not promising for micro grinding. On other hand, micro-EDM is one of the most powerful methods for fabricating micro holes in metals and other electrically conductive materials.

The GMRP has hybrid manufacturing capability aiming to broaden the limit of its applications and to improve the product manufacturing quality. As illustrated in Fig. 4.7, the GMRP may integrate many micro processes such as micro EDM, micro grinding, micro milling, micro drilling, etc. because of their similar kinematic configurations. The seamless integration of micromachining processes on a GMRP will lead to predictability, producibility and productivity of micro/nano manufacturing, which is essential in the current competitive global market place.

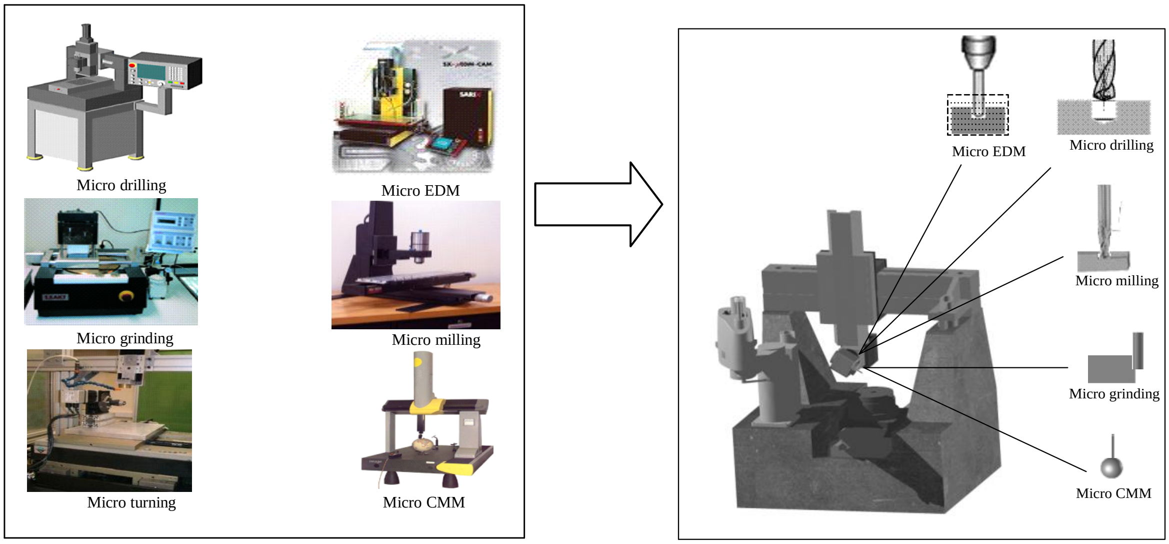


Fig. 4.7 Hybrid manufacturing capability of a GMRP

4.4.2 Machine platform and modularity

Modular structure and reconfiguration are required for micro manufacturing in the current market climate where variations of micro products occur at shorter and shorter intervals. Modularity is one solution for micro manufacturing systems to outlive the products they were originally designed for. The GMRP is designed as a modular system. The manufacturer can easily configure the platform and later reconfigure it to meet customer's future needs (Heilala, 2006). Modularity is also a cost-efficient solution, and makes later upgrades or modifications to the platform easier. The manufacturers can therefore respond to customers or other market changes rapidly without building or buying new machines.

Standardization of key modular components makes it simple and economic to reconfigure a new platform just by adding or changing components or modules. It is possible to produce different micro products on a single platform due to the flexible combination of different modular components or modules.

The key components or modules that can be integrated include:

- spindle units
- drive and actuation units
- tool holders
- micro toolings
- fixtures
- machine structure or frame
- measure elements and inspection units
- control system

Fig. 4.8 illustrates the major modular components of a GMRP.

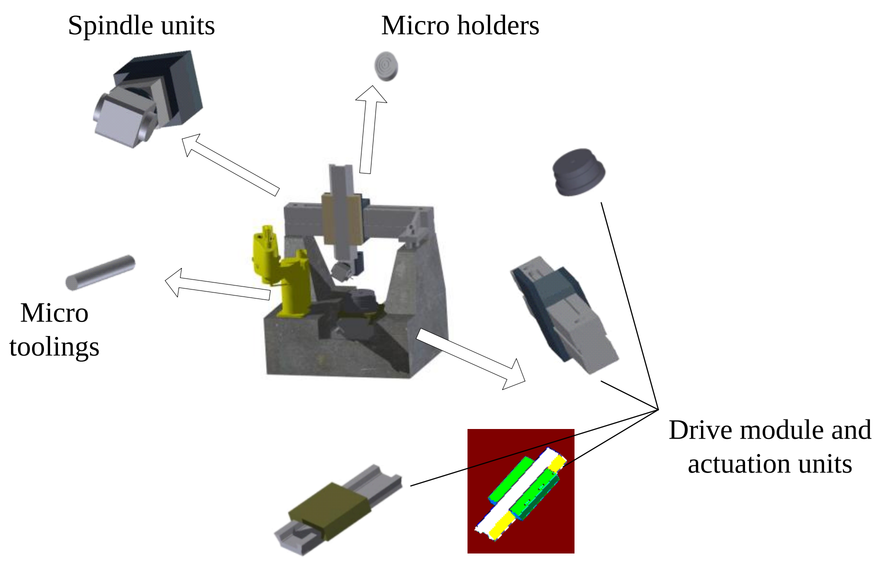


Fig. 4.8 Modular components of a GMRP

Taking a spindle unit as an example, it has different speed ranges, powers and rotational accuracy requirements for various micromachining processes. For slideways, different strokes and positioning accuracies may be required with linear or rotary motors depending upon applications. Standardized interfaces enable the use of different drive systems. Moreover, micro tools can be a micro electrode, a micro milling tool or a micro driller according to the micro processes operated. The selection of these modules is decided by customer requirement, technical requirement and/or according to the price of the final product. Similar to machine modules, the control systems on a GMRP can also be modular in terms of software, algorithms and controller, etc.

4.4.3 Machine platform and reconfigurability

Reconfigurability is an important characteristic of modern manufacturing systems (Koren et al, 1999; Mehrabi, 2000). GMRP is designed highly reconfigurable in order to be adaptive to the introduction of new technologies, manufacturing changes and mobility requirements.

Mechanical reconfigurability

GMRP is able to be easily reconfigured for changes due to its modular components and modules. For example, reconfigurability for changes of products and processes is achieved by changing machine modules, such as spindle units, rotary tables, and linear slideways, with different sizes, accuracy and functionalities.

In addition to changing modules, as shown in Fig. 4.9, one or more spindle units can be added to the existing platform to improve the productivity as needed.

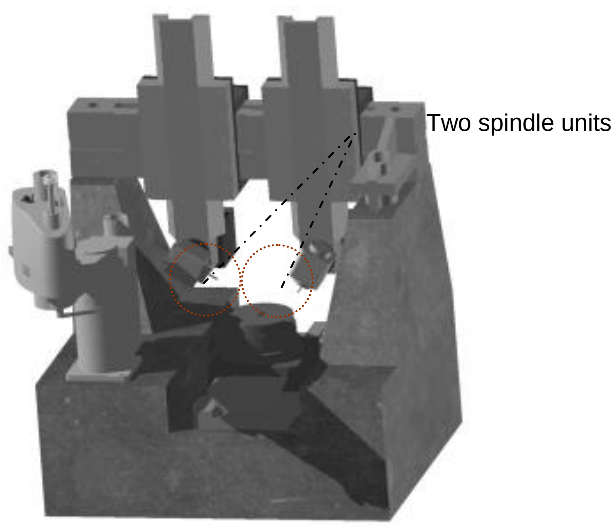


Fig. 4.9 The reconfigured GMRP

Electrical reconfigurability

Electrical installation on the GMRP can be reconfigured by choosing modules from the library of electrical components and hardware. This library should include rotary or linear motors with diverse specifications, encoders and amplifiers. Rotary motors, for example, can be replaced with linear motors to get better motion performance and neat design of the drive and actuation system. Different types of encoders can also be selected to reconfigure the system for different levels of performance requirements.

Control system reconfigurability

Similar to reconfiguring machine modules and electrical systems, control systems are also capable of being reconfigured by selecting suitable software modules (e.g., servo control algorithms, interpolators) and hardware modules (controllers) in the development of open-ended control architecture. Selection of control modules is directly influenced by the electrical components.

4.5 Summary

The axiomatic design theory has been applied and demonstrated in this chapter to develop the conceptual design of the GMRP. Together with the error analysis module, it is the fundamental basis for the design of overall machine tool configuration or structure. This is one of the key steps (usually the first step) in the machine tool design process, which closely corresponds to the system design of Taguchi's robust design. The key characteristics of the GMRP have been identified and discussed. It should be pointed out that these characteristics apply to various aspects of GMRPs, namely mechanical, electrical and software modules. The rapid and successful development of these modules relies critically upon the underpinning of a user-friendly and yet reliable design support system, which will be detailed in the next chapter.

Chapter 5 Design Support System for GMRPs

5.1 Introduction

This chapter presents the design and implementation of a design support system for GMRPs. The architecture of this design support system is determined with the axiomatic design theory, using the same set of the principles and methodologies of axiomatic design that were presented for GMRPs in the previous chapter. The implementation of the proposed design support system is based on the programming languages JAVA, Matlab and XML.

The main topics presented in this chapter in relation to the whole framework are highlighted in Fig. 5.1 as those in the red rectangle.

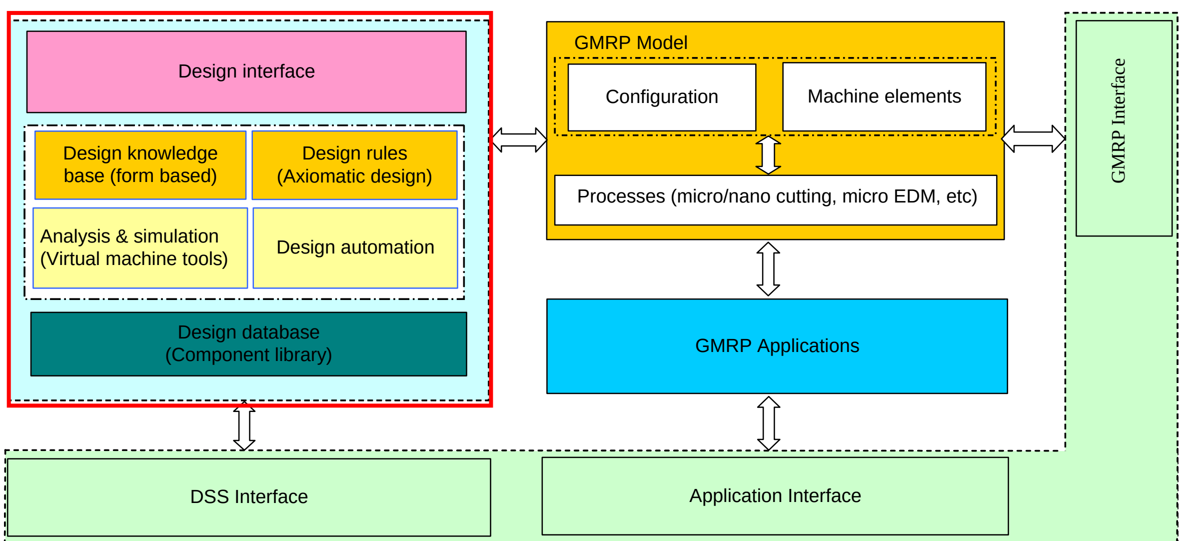


Fig. 5.1 Main topics covered in this chapter

5.2 System design based on the axiomatic design theory

Software design based upon axiomatic design theory is self-consistent, provides proper interrelationship and arrangement among modules, and it is easy to change, modify and extend (Suh, 2001).

The highest level FR and mapping in the physical domain

The aim of the design support system is to assist designers to design and evaluate machine structure variants, so the following FRs of the system are established to meet the user's needs:

FR_1 Generate a recommended GMRP

FR_2 Evaluate the recommended GMRP

FR_3 Support easy use of the support system

To satisfy the above requirements, the DPs can be written as

DP_1 Development of GMRP generation module

DP_2 Development of GMRP evaluation module

DP_3 Graphical user interface

The design matrix at this level is a triangular matrix that indicates the design is a decoupled design, that is:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix}$$

The independence axiom can be met if the DPs are determined in the proper sequence: $DP_1 \rightarrow DP_2 \rightarrow DP_3$.

Second level decomposition

Decomposition of FR_1—Generate a recommended GMRP

The highest level DPs are not detailed enough, so the highest level FRs must be decomposed. Because the generation of a GMRP is based on the structure configuration and key components, FR_1 can be decomposed as:

FR_{11} Select an optimal configuration with knowledge base

FR_{12} Select key components for GMRP

FR_{13} Assist the selection of configurations and components

The corresponding DPs may be chosen as:

DP_{11} Development of configuration selection module

DP_{12} Development of key component selection module

DP_{13} Sub-graphical user interface

Thus, the relationship between FRs and DPs are presented by

$$\begin{Bmatrix} FR_{11} \\ FR_{12} \\ FR_{13} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP_{11} \\ DP_{12} \\ DP_{13} \end{Bmatrix}$$

The design matrix in the obtained equation is diagonal, satisfying the independence axiom.

Decomposition of FR_2—Evaluate the recommended GMRP

The evaluation module of the support system may include the following functions: demonstrating the generated GMRP virtually, calculating dynamic/static stiffness and calculating natural frequencies. As a result, the FR_2 can be decomposed as:

FR_{21} Demonstrate virtual GMRP

FR_{22} Calculate dynamic/static stiffness

FR_{23} Calculate natural frequencies

The corresponding DPs are selected as:

DP_{21} Development of virtual GMRP demonstration module

DP_{22} Dynamic/static stiffness calculation

DP_{23} Natural frequency calculation

The relationship between FRs and DPs at this level can be described as:

$$\begin{Bmatrix} FR_{21} \\ FR_{22} \\ FR_{23} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_{21} \\ DP_{22} \\ DP_{23} \end{Bmatrix}$$

From the obtained equation, it can be seen that the design matrix is diagonal and the independence axiom is thus satisfied.

Third level decomposition

Decomposition of FR_{11}— Select an optimal configuration with knowledge base

Selection of an optimal configuration for a GMRP involves the management of all structure configurations and the selection rules. So FR_{11} may be decomposed as:

FR_{111} Manage configurations for GMRPs

FR_{112} Select optimal configuration by rules

To satisfy the FRs, the corresponding DP_{11} should be decomposed as the following DPs

DP_{111} Building up a configuration database for GMRPs

DP_{112} Development of configuration selection sub-module

Accordingly, the design equation for this design is:

$$\begin{Bmatrix} FR_{111} \\ FR_{112} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{111} \\ DP_{112} \end{Bmatrix}$$

The triangle design matrix indicates that this design satisfies independence axiom if DP_{111} is determined firstly, and then determine DP_{112}.

Decomposition of FR_{12}— Select key components for GMRP

Similarly to FR_{11}, FR_{12} can be decomposed as:

FR_{121} Manage key components

FR_{122} Select key components for optimal GMRP by rules

And the DP_{11} can be decomposed as:

DP_{121} Building up key component virtual library for GMRPs

DP_{122} Development of components selection sub-module

$$\begin{Bmatrix} FR_{121} \\ FR_{122} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{121} \\ DP_{122} \end{Bmatrix}$$

The design matrix in above design equation is triangle, so this design meets the independence axiom.

Decomposition of FR_{21}— Demonstrate generated virtual GMRP

Instead of creating a method for structural configuration synthesis, all virtual configurations with default dimensions can be stored in a library. After the physical configuration and components have been selected, the corresponding virtual configuration with dimension of selected components can be called to show the virtual generated GMRP. Thus, FR_{21} can be decomposed as:

FR_{211} Develop a virtual 3D configuration model library

FR_{212} Change default dimensions with dimensions of selected components

The DPs can be selected as:

DP_{211} Development of a virtual 3D configuration model library

DP_{212} Change of default dimensions with dimensions of selected components

So the relationship between FRs and DPs is shown as:

$$\begin{Bmatrix} FR_{211} \\ FR_{212} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{211} \\ DP_{212} \end{Bmatrix}$$

From the design equation, this design satisfies independence axiom because of the decoupled design matrix.

Now, the decomposition process comes to an end since all the branches of the DPs tree form the terminal nodes and each node represents one module of software that can be coded into a program.

According to the hierarchical tree structures of FRs and DPs, the flow chart of the design support system is given in Fig. 5.2. The system is composed of 10 modules which represent ten FR terminal nodes, and eight junctions that represent their integration of child modules into a parent module. The sequence of software development begins at the lowest level, which is defined as the leaves. To achieve the highest level FRs, which are the final outputs of the software, the development of the system must begin from the innermost modules, then go to the next higher level modules following the sequence indicated by the system architecture; that is, go from the innermost boxes to the outermost boxes (Suh, 2001).

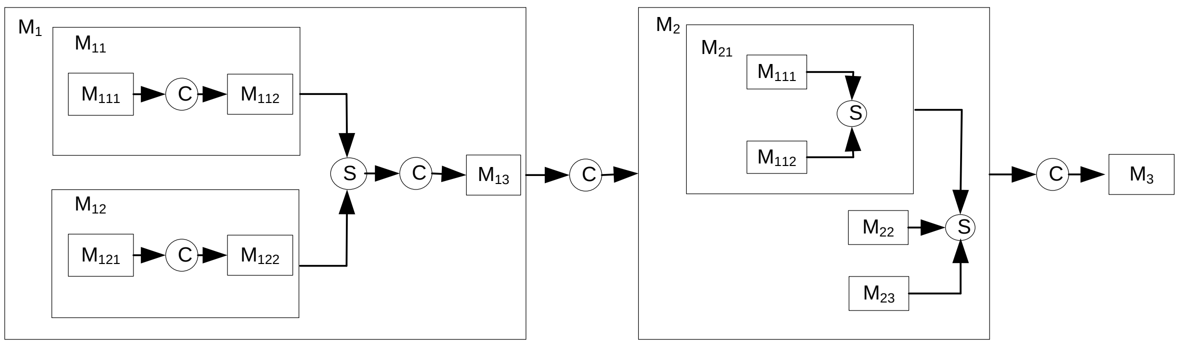


Fig. 5.2 Flowchart of the design support system

5.3 Implementation of the design support system

According to the axiomatic design results of the design support system, there are 10 modules that need to be implemented in the system, as shown in Fig. 5.3. Components and an optimal configuration can be selected via the Java-based interface from the components library and knowledge base stored in XML files, and the detailed information of the selected components and configuration will be shown in the Matlab-based main user interface.

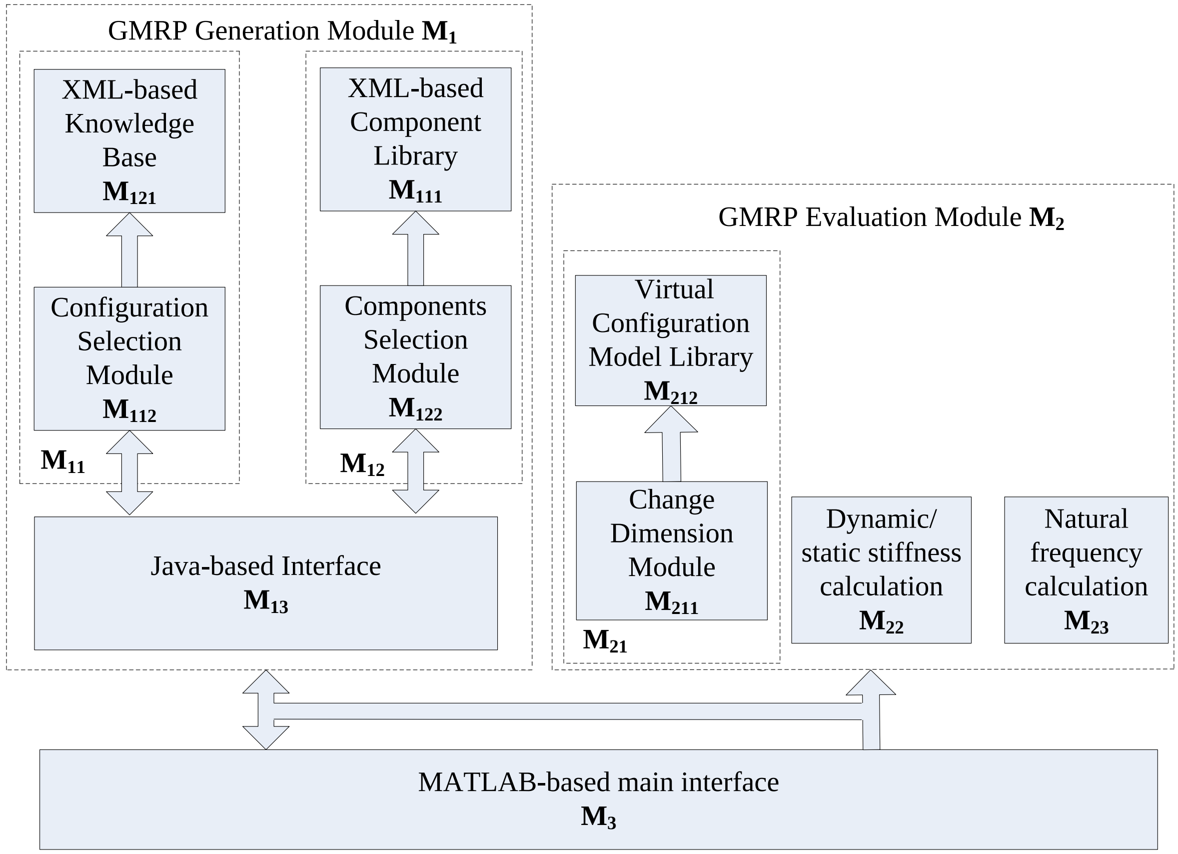


Fig. 5.3 The implementation framework of the design support system

With selected components and configurations, the 3D virtual demonstration of generated GMRP can be represented in a virtual reality viewer integrated in Virtual Reality Toolbox. Signals generated in Simulink are used to control the movements of every axis in the 3D virtual reality model. In the following, the implementation of the system will be introduced in detail.

5.3.1 XML-based database

5.3.1.1 XML based component library

The component library is basically a database to support the design process. The detailed information of the components will be used for analysis and evaluation of different design configurations. They will also be directly used in the representation and display of actual designed modules or systems.

All components of GMRPs are organized into a library, as shown in Fig. 5.4, which can be described by a XML document according to component types, that is, all spindles are grouped together, slideways are grouped together, etc. The information of components such as manufacturer, model, performance and size is also structured. Obviously, the current component library has limited components, but it can be expanded by adding more machine tool elements. All aspects of the component are described with XML tags. By navigating the components in the library, the designer can locate the appropriate component for a particular required function on the basis of the description of the detailed information of the component's performance.

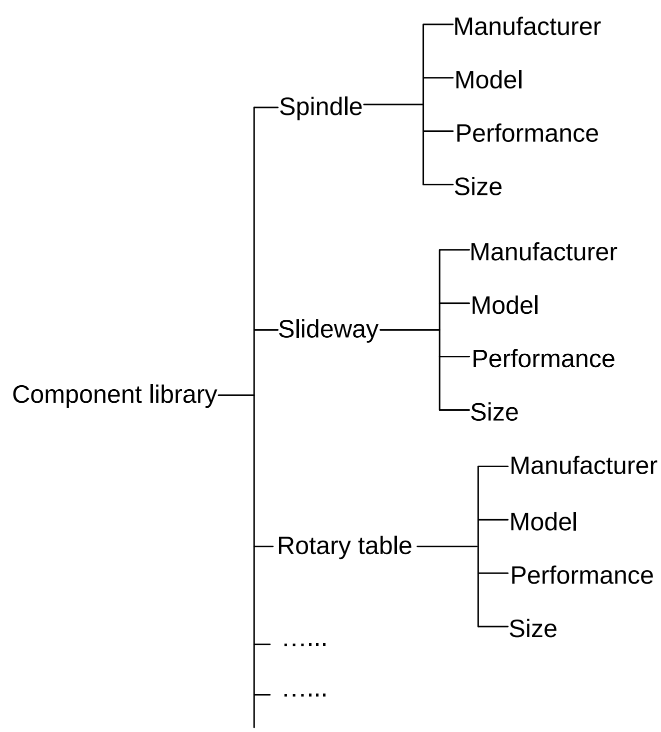


Fig. 5.4 Structure of the component library

XML tags, internal and operational, define the two abstract aspects of the information of components in the component library which is stored in the XML document. The internal elements are used to declare inner or intrinsic information of components, while operational elements are used to introduce information about the operation of components. For example, the declaration for a spindle would be as follows:

```
<Spindle Model="Diamond Turing Spindle">
    <internal>
      <Manufacturer>Loadpoint Bearings</Manufacturer>
      <Model>Diamond Turing Spindle</Model>
      <Performance>
          <Resolution>256-2048 lines/rev </Resolution>
          <TotalErrorMotion>0.0 5µm</TotalErrorMotion>
      </Performance>
      <MaxRotSpeed>15000 rpm with air cooling or 25000 rpm with water
cooling</MaxRotSpeed>
    </internal>
    <operational>
       <DriveSys> AC Induction Motors </DriveSys>
    </operational>
</Spindle>
```

5.3.1.2 XML based knowledge base

The knowledge base stores the knowledge of selecting GMRPs' configuration. The overall structure of the knowledge base in XML is shown in Fig. 5.5. Given the design requirements, the recommended configurations can be retrieved using the XML DOM technology.

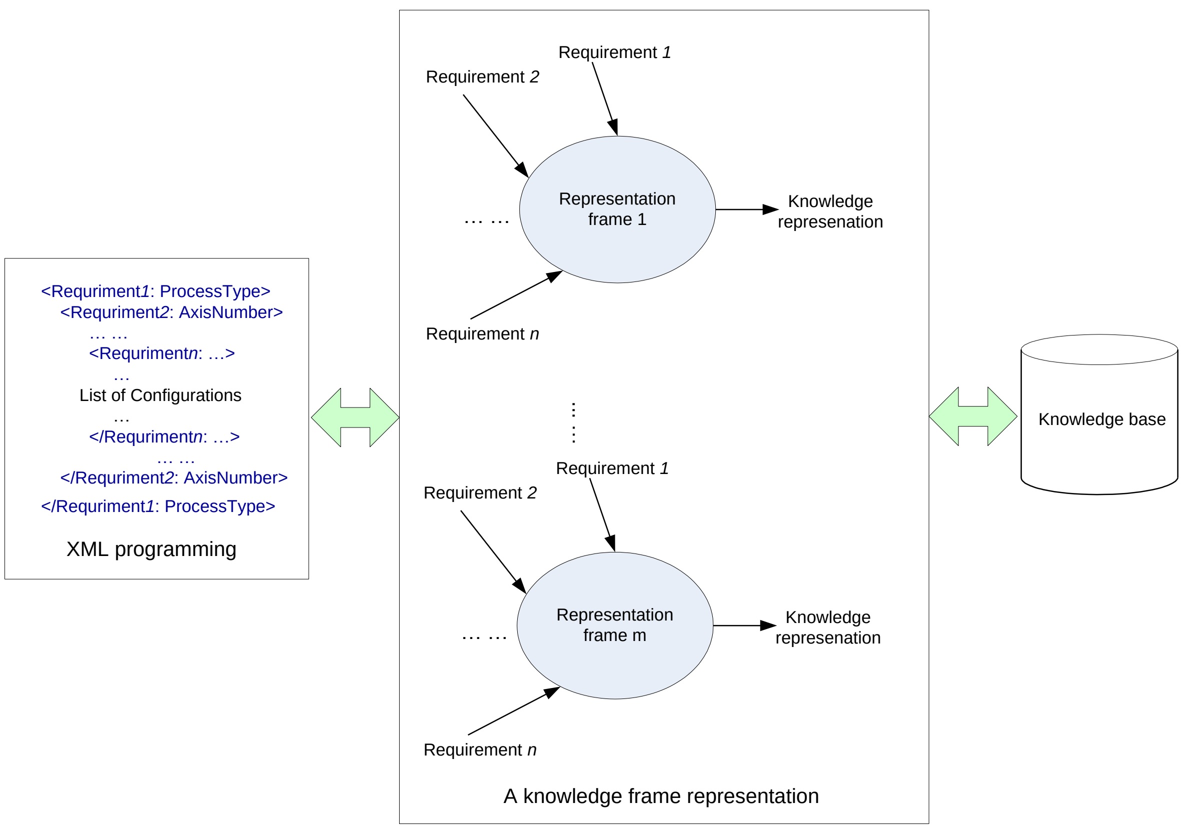


Fig. 5.5 Overall structure of the knowledge base

Design requirements, including type of micromachining process and the number of axis, are declared using process tags and axis tags, respectively, in the XML document. Given the attribute of process tags and axis tags, the only information of GMRP's configuration can be obtained. The following gives an example segment of the knowledge base XML document for the micro EDM process:

```
<process type="micro EDM">
      <axis number = "3" >31 32 33</axis >
      <axis number = "4" >41 42 43</axis >
      <axis number = "5" >51 52 53</axis >
</process>
```

5.3.2 Java-based graphical user interface

A graphical user interface (GUI) has been developed for the selection of appropriate components from the component library and search proper configuration from the knowledge base for desired GMRPs. The use of a GUI allows user-friendliness of the view and the search of the information stored in XML documents, so making the use of XML based information easier for the user. Moreover, changes of XML document can be reflected by the graphical user interface instantly. This is accomplished by using a Java-based GUI. Advantages of using Java include the cross-platform capability and the object-oriented development paradigm (Horstmann, 2006; Ward et al, 1999). New components and knowledge rules can be written into the XML documents directly, and the added information can be reflected by the Java graphical user interface.

5.3.2.1 Features of Java

Java is an object-oriented programming language designed by Sun Microsystems in 1990s. Since its first emergence, Java has gained enormous popularity as a computer language due to its design and programming features. As stated by Sun Microsystems, Java is a simple, object-oriented, distributed, interpreted, robust, secure, architecture neutral, portable, multithreaded, and dynamic programming language. Java was chosen as the programming language for the user interface of the XML documents because of the following advantages in particular:

- Simplicity

Programs are easy to write, compile and debug for the reason that Java eliminates the use of pointers and replaces multiple inheritance in C++ with a simple structure called interface. In addition, the clean syntax makes Java programs easy to write and read. Besides, Java provides the bug free system due to the strong memory management, which also ease the use of Java. What is more, it is easier to learn Java when compared to other programming languages.

- Portability: write once, run anywhere (platform independence)

Portability is one of Java's key advantages. The same java program will run, without having to be recompiled, on most major hardware and software platforms, including Windows, the Macintosh, and several varieties of UNIX. The dependencies of Java program on hardware and operating system are removed, which makes the Java program instantly compatible with these software platforms.

- Java API

XML is a standard part of Java. Java provides Java API for XML processing offering the capability of validating and parsing XML document. Also, Java Swing API which can provide a more sophisticated set of GUI components would make the implementation of graphical user interface easier and simpler.

Except for the features above, the good match of Java and XML is another important reason to choose Java to implement the user interface for the view of XML documents. XML provides platform-independent data representation offering a flexible method of exchanging data, and Java provides platform-independent code for processing the XML data. In addition, Java has intrinsic hierarchical APIs to support the hierarchical representation of XML data, making the two technologies very compatible for representing each other's structures. The majority of XML development is focused on Java, which is emerging as the language of choice for processing XML, while there are many XML tools and libraries based on other languages (Falco, n.d.).

The code development of Java for the current research has been done in a Java Integrated Development Environment (IDE), Eclipse. Eclipse is a software development platform consisting of an IDE and a plug-in system to extend it. It is not only used to develop applications in Java, it can also be employed to develop applications in other languages as well by using various plug-ins. At the moment, Eclipse is one of the most popular Java IDEs because of its features, such as:

- It is an extensible, free and open-source IDE.
- It has lots of available plug-ins for free.
- It is fast and easy to use.

5.3.2.2 Java based user interface

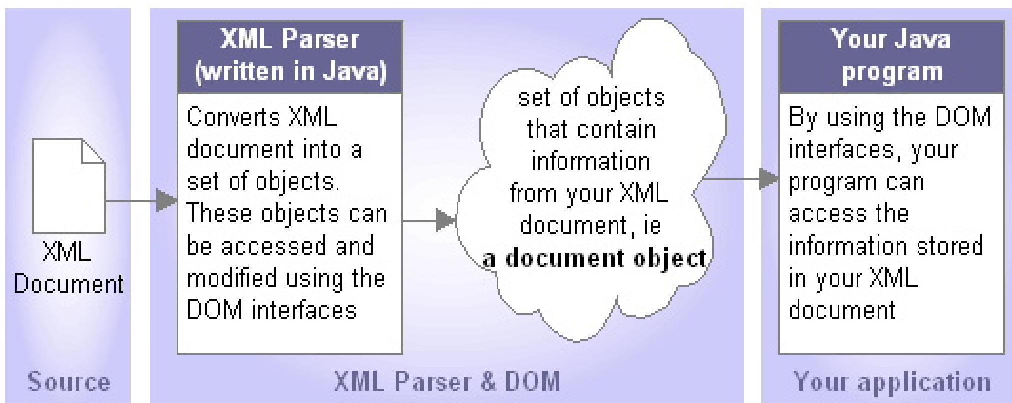


Fig. 5.6 XML parser and DOM layer

Fig. 5.6 demonstrates how the information in XML documents can be displayed using Java user interface, i.e. the principle of Java rendering a XML document to a graphical user interface. As Fig. 5.6 shows, XML Parser converts a XML document into a set of objects which contain information from the XML document. By using the DOM interfaces, Java program can access and modify these objects to manipulate the information stored in the XML document. After the Java program gets the content of the XML document, then it maps the content to a Java object model which can be viewed and modified using a Java Swing application.

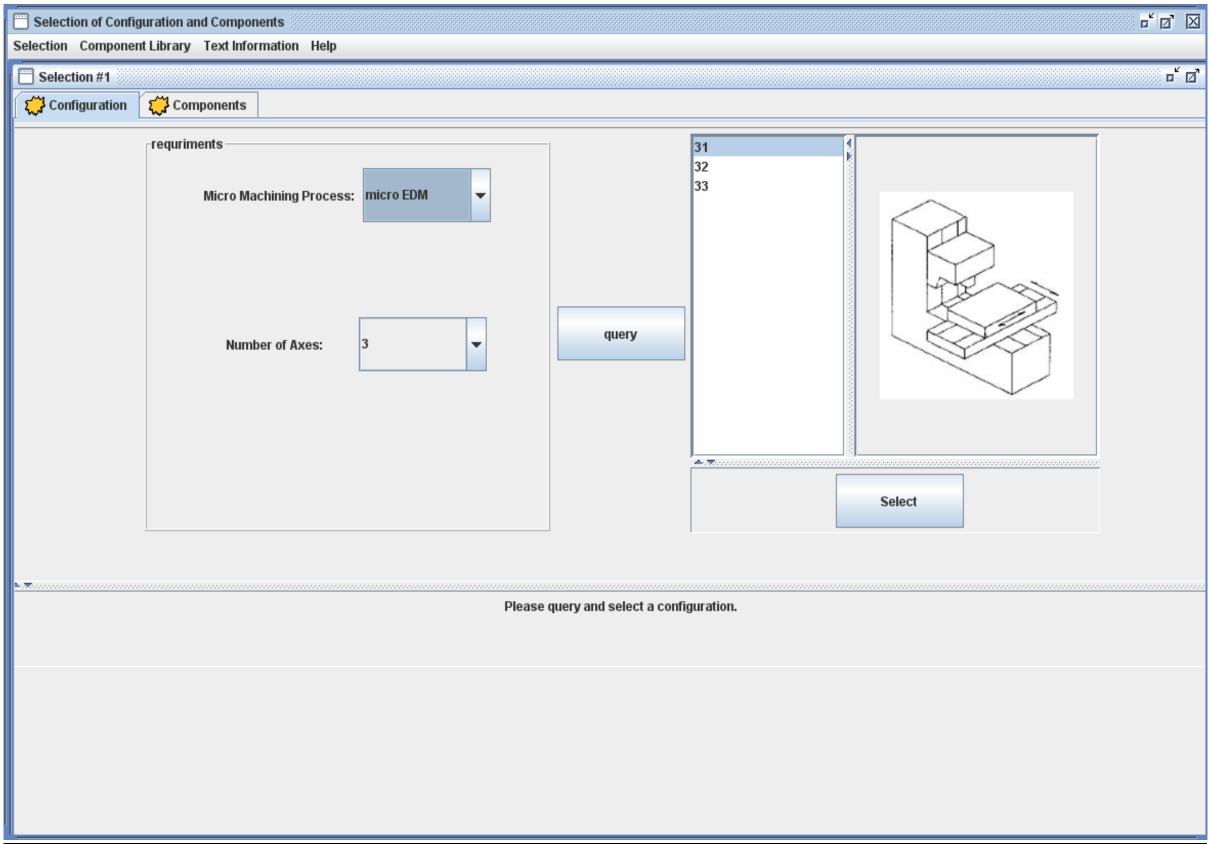


Fig. 5.7 Design requirements and recommended configurations interface

The Java based user interface provides a user-friendly HCI for accessing different modules and functionalities, i.e. configuration selection module and component selection module. Fig. 5.7 is the interface for accessing configuration selection module. Through the interface, the designer will be able to specify the design requirements according to the customer needs such as the type of machining, the number of axes of the machine tool, etc. The system will use the knowledge base to display relevant design suggestions and/or solutions for the designer to choose suitable design options or parameters. The representation of configurations of machine tool in this research is based on the configuration code of machine tools proposed by (Chen, 2001). The name of the selected configuration will be shown at the bottom of the interface giving a reminder to designer. The interface presents an integrated platform for the interactive design process.

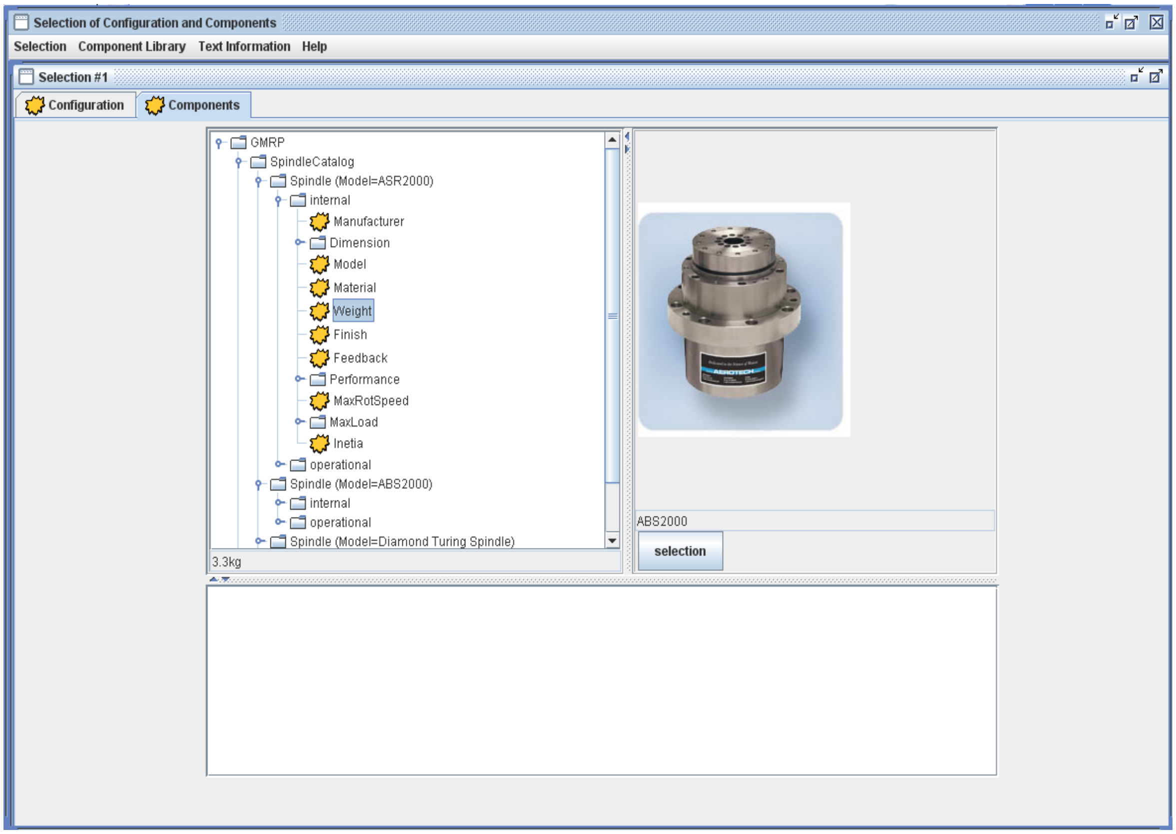


Fig. 5.8 Detail information of components

Fig. 5.8 is the interface for the view and selection of components for desired GMRPs. All information of components is rendered from the XML based component library to the Java Swing component with a tree structure, providing a clear organization for the user. When moving from the top to the bottom of the hierarchy, more information can be found. At the top, the components are abstract and represent its families, such as SpindleCatalog; at the bottom, the leaf nodes of the hierarchy represent completely specified physical components.

After clicking selection button on the interface, the highlighted component is selected, and all information of this component is at the same time written to a new XML document which will be used to present the virtual model of generated GMRPs later. Similar to configuration selection interface, all the selected components will be shown in the bottom text area giving a summary to the user.

5.3.3 Virtual demonstration

The design support system has the function of demonstrating the created GMRP after configuration and components are selected via Java user interface. The demonstration module of the design support system is realized using Matlab and Simulink. Particularly, Virtual Reality Toolbox provides functions to connect the GMRP defined by the VRML to Matlab and Simulink, simplifying the visualization and manipulation of the virtual GMRP.

5.3.3.1 VRML

Virtual Reality Modelling Language (VRML) is a standard file format for representing 3-dimenional interactive graphics and defining the layout and content of a 3D world. VRML is not a general purpose programming language like C++, a script language like Java script or a mark-up language like HTML. It is a modelling language that demonstrates the geometry and behaviour of a 3D scene. Instead of being compiled from source code, VRML files are parsed, rendered and finally displayed by a VRML viewer (Zhao, 2000). A VRML file is a plain text file, so it can be created, viewed, and edited in any plain text editor.

5.3.3.2 Main features of Virtual Reality Toolbox

Virtual Reality Toolbox extends the capabilities of Matlab and Simulink to the virtual world, created with VRML, by offering a flexible Matlab interface and a Simulink interface to a virtual reality world. Virtual Reality Toolbox has also VRML viewer and VRML editor to provide a complete working environment (Matlab, n.d.).

The Matlab interface includes functions and methods for associating Matlab objects with a virtual world. It has capability of manipulating the virtual world by retrieving and changing the virtual world properties.

Virtual Reality Toolbox provides blocks to directly connect Simulink signals with virtual worlds. Once these blocks are included in a Simulink diagram, Simulink signals can be connected to a selected virtual world. And then Virtual Reality Toolbox automatically scans a virtual world for available VRML nodes that Simulink can drive.

5.3.3.3 Virtual demonstration of GMRPs

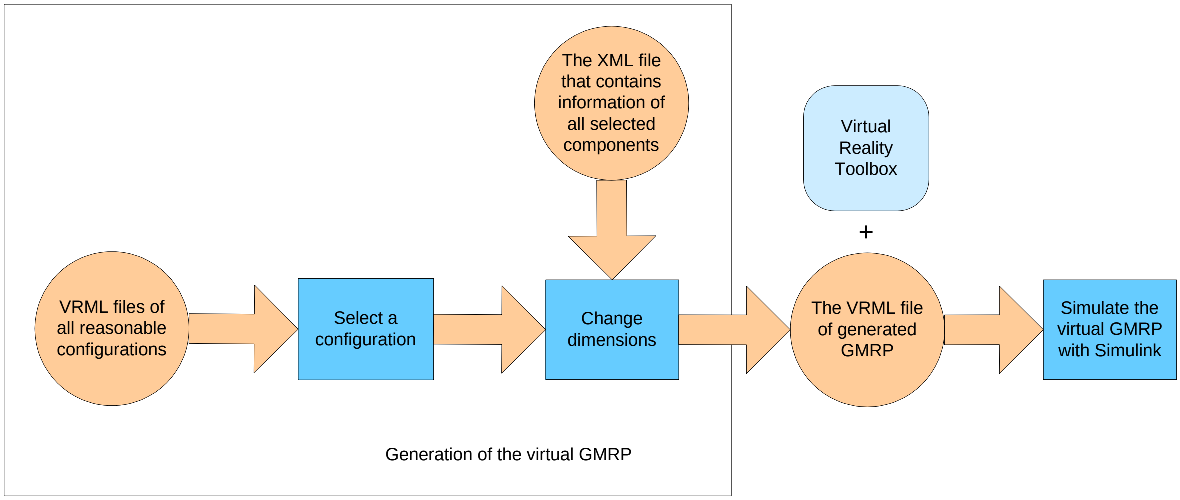


Fig. 5.9 The GMRP generation and demonstration process

The process of creating the VRML file of the generated GMRP and demonstrating it in Simulink is shown in Fig. 5.9. The VRML file of selected configuration is located and called from the library of VRML files of all suitable configurations after the configuration is determined from previous steps. With functions provided by Virtual Reality Toolbox, the Matlab program can modify default dimensions in the virtual model according to the properties of the selected components which are stored in an XML file, forming a VRML file of the GMRP required by the designer. Connecting the VRML file and Siminluk signals is allowed with Virtual Reality blocks to visualize the virtual GMRP as a three-dimensional animation.

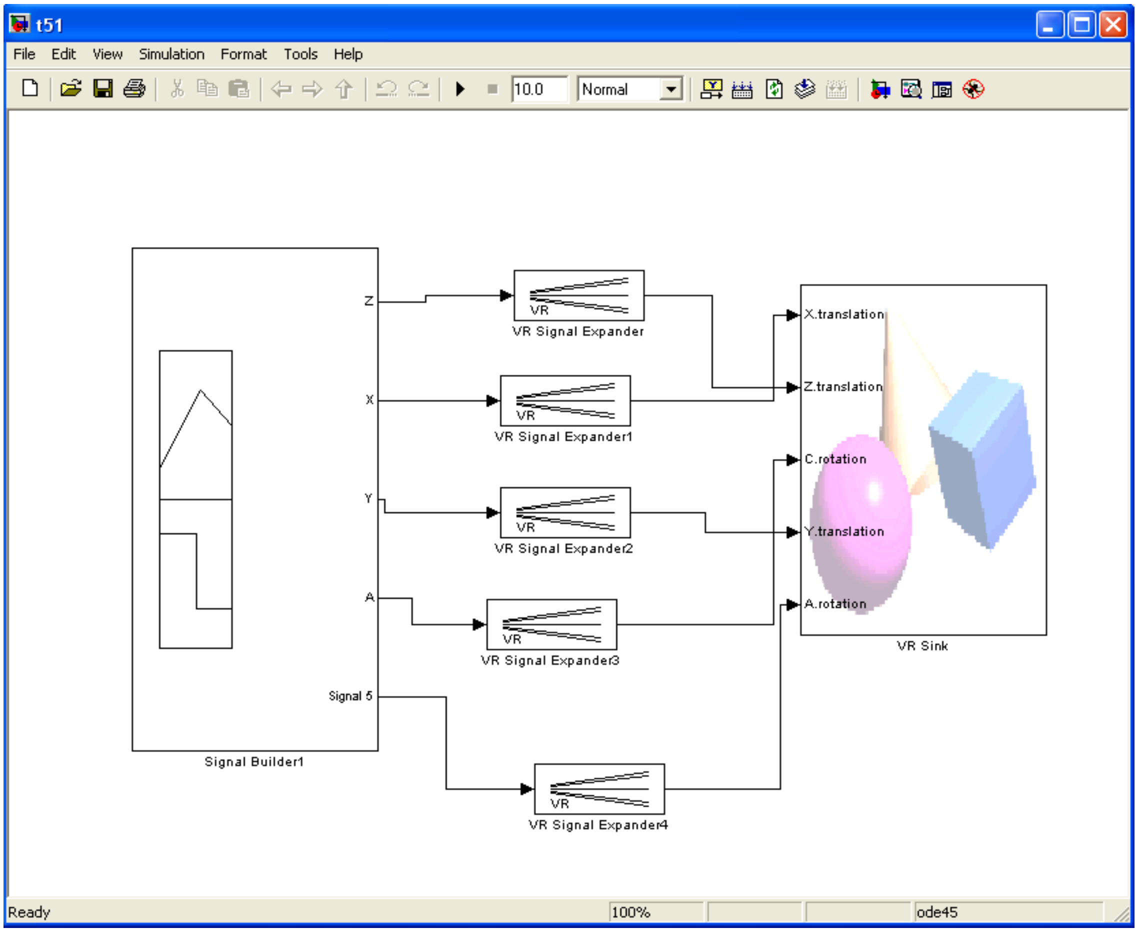


Fig. 5.10 The Simulink model of a virtual 5-axis GMRP

Fig. 5.10 is the Simulink model of a virtual 5-axis GMRP. The VRML file of the 5-axis GMRP is imported into the VR Sink which is a block provided by Virtual Reality Toolbox. After the VRML file is scanned by Virtual Reality Toolbox, all VRMR node properties are listed in a hierarchical tree-style viewer, and five degrees of freedom of the GMRP, i.e. three translation freedom X, Y, Z and two rotary freedom A, C are selected to be controlled by the signals from Simulink blocks.

Double click the VR Sink in the Simulink model, a viewer window containing the GMRP's virtual model appears, as shown in Fig. 5.11. The final position of the 5-axis GMRP at the end of the simulation is shown in Fig. 5.12.

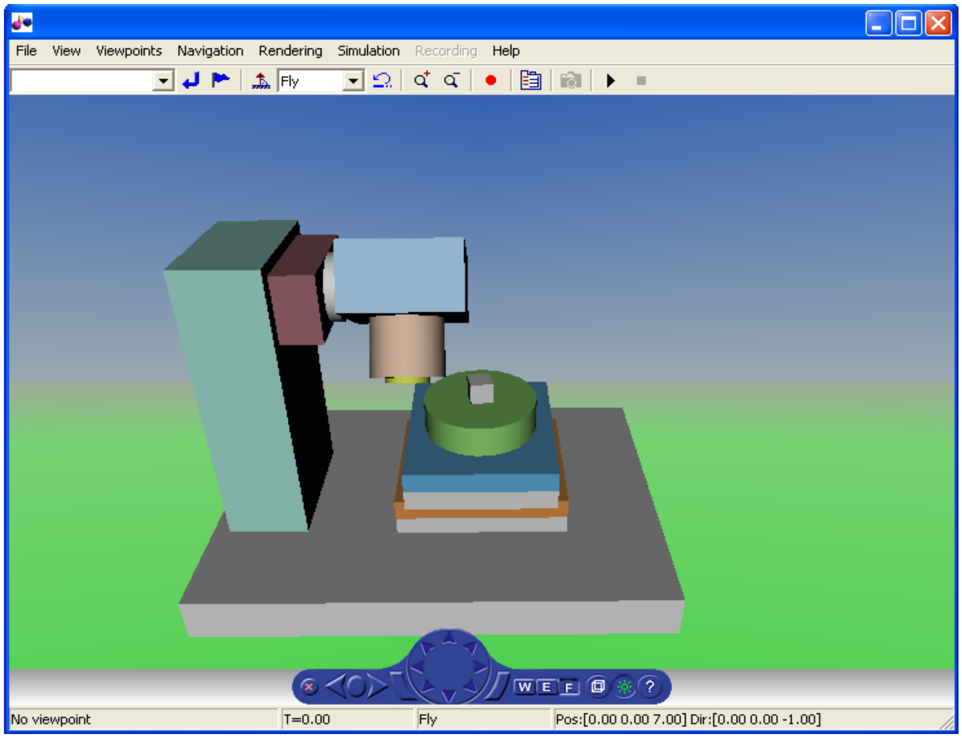


Fig. 5.11 A virtual 5-axis GMRP at the initial position

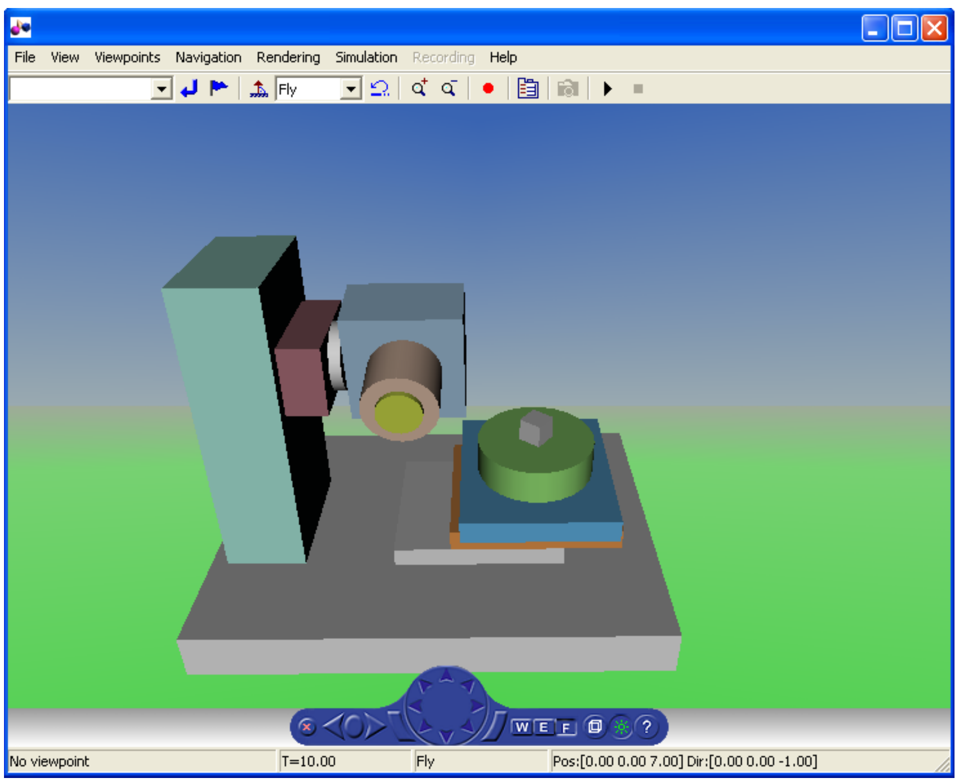


Fig. 5.12 A virtual 5-axis GMRP at the final position

5.3.4 Matlab based main interface

To provide a user-friendly, interactive and integrated design environment for designers, a main user interface integrating the above three main modules is provided in the design support system. The main user interface of the design support system is created in Matlab GUIDE, a graphical user interface development environment, which provides a set of tools for creating graphical user interface. Although the user-interface components and devices in GUIDE are limited compared to Java or VB GUI library, GUIDE makes the call of Matlab or Simulink functions more easily.

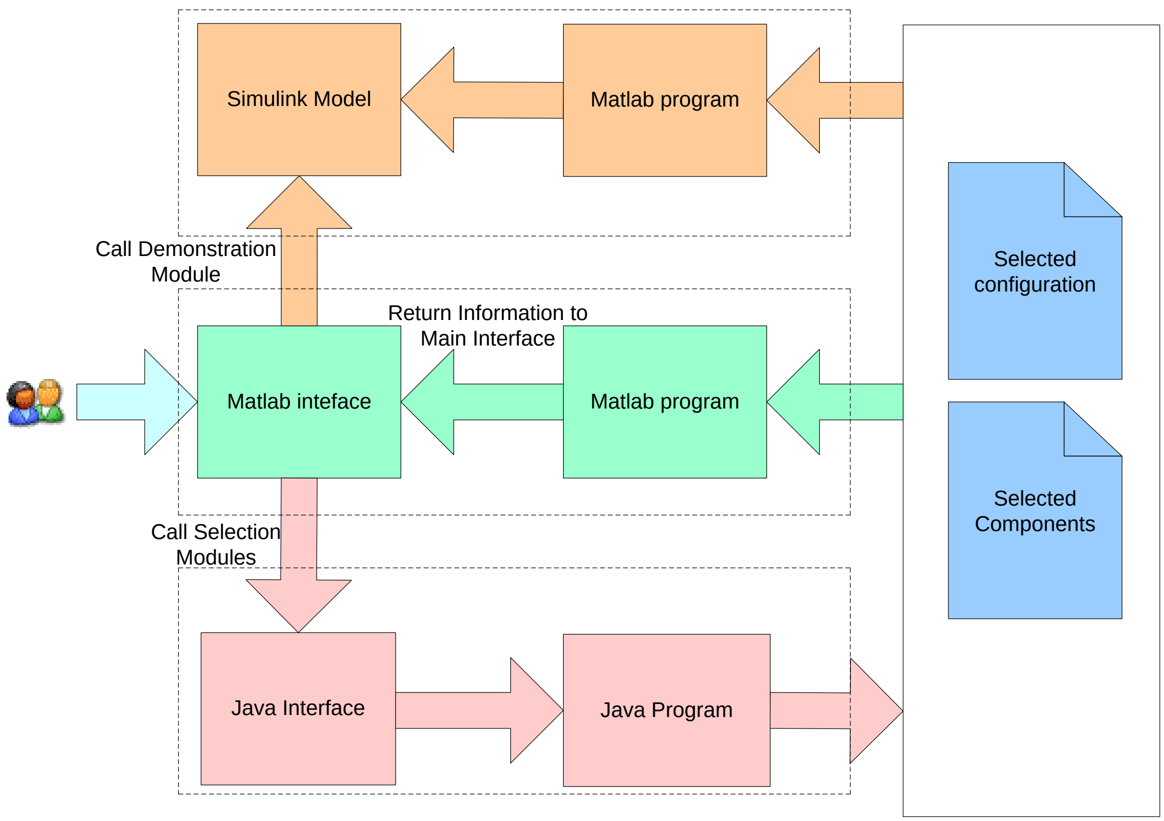


Fig. 5.13 The structure of Matlab main user interface

The brief structure of MATAB user interface combining the three modules is illustrated in Fig. 5.13. The Java based user interface can be called from the main Matlab interface, and then the Java program generates the files about the selected configuration and the components, which are displayed on the Matlab user interface. Moreover, the files will be needed to create the virtual GMRP Simulink model which can be called from the main user interface as well.

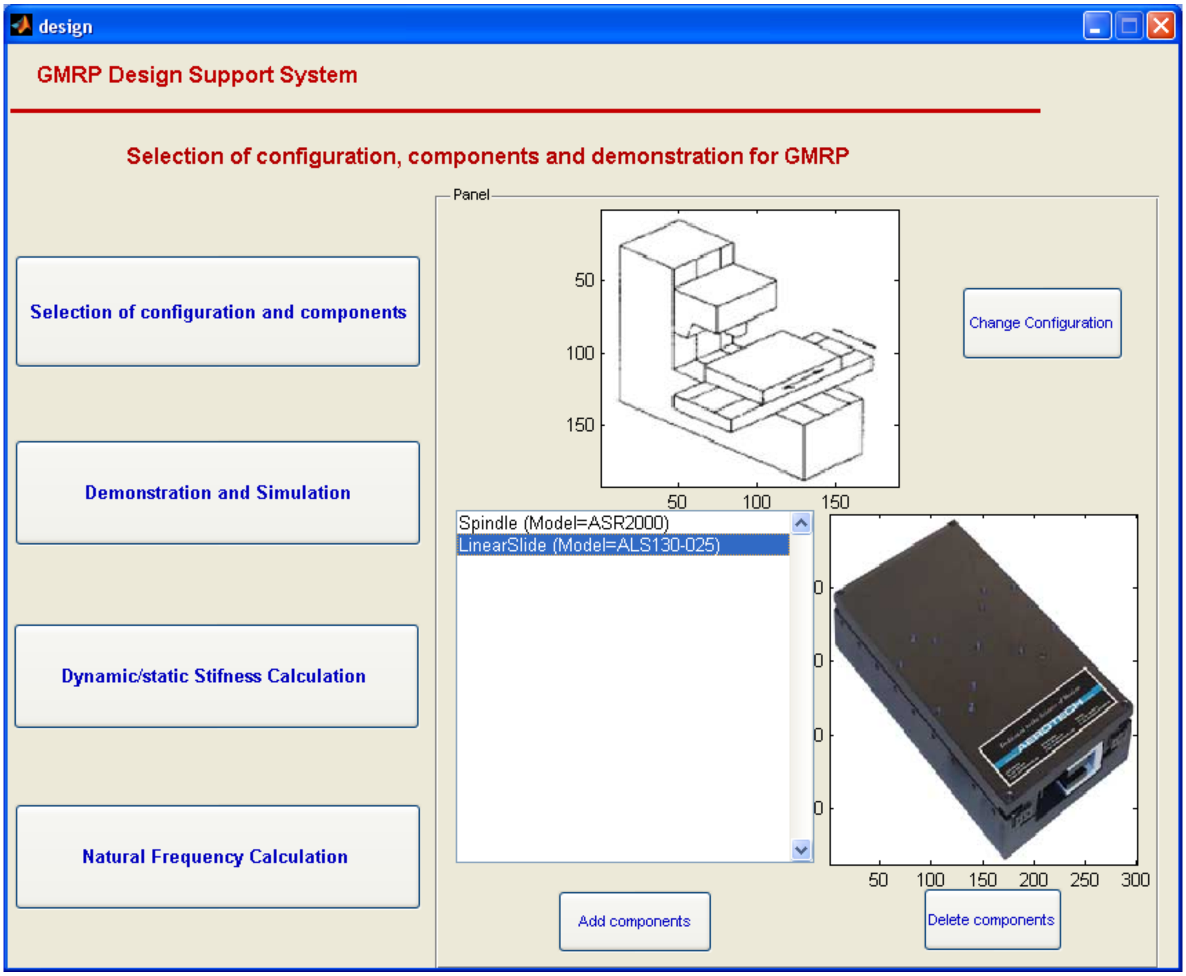


Fig. 5.14 The Matlab graphical user interface

Fig. 5.14 presents the actual Matlab graphical user interface. The configuration and components selection module and demonstration module can be called by clicking the Selection of Configuration and Components button and Demonstration and Simulation button respectively. The right side of the interface gives brief information of the selected configuration and selected components. In addition, changes of the configuration and components are possible on the interface by clicking corresponding buttons to call individual functions, making the design process more flexible because there is no need to recall the entire configuration and components selection model.

Dynamic/static Stiffness Calculation module and Natural Frequency Calculation module are not integrated in the design support system at the moment because of the complexity, but links to external modules are provided. The system also provides the interface connection to a commercial analysis software ANSYS.

5.4 Summary

This chapter has detailed the design and implementation of the design support system for the GMRP. The architecture of the design support system has been designed using the axiomatic design theory and its implementation with several software technologies, i.e. Java, Matlab and XML. The user interface in Matlab functions as the main interface for the design, linking all the design functional modules (or objects). Additional design interface is also provided in the Java program to facilitate the generation of configurations and selection of components. The Java and Matlab programs can query and search information from the component library and knowledge base stored in the XML documents. The design support system also encompasses several tools for the evaluation and optimisation of the design solution.

The architecture of the DSS allows these modules to be easily upgraded and scaled since it has a layered structure. Additional modules can also be integrated through the DSS interface, e.g. through the Internet connection. This will be a very useful feature when cooperation and integration are required in the design process.

Chapter 6 Modelling and Simulation of Micro/Nano Machining Processes

6.1 Introduction

The modelling of various machining processes of the GMRP is a very important part of the proposed framework (as discussed in Chapter 3), partly because the GMRP will integrate different processes together, which has practical significance in the applications of the GMRP, and partly because the knowledge base used in the design support system will be based upon these models, thus also of theoretical importance.

Whilst the mechanisms of conventional manufacturing processes are well established, the mechanics and the associated intricate issues in micro/nano scale manufacturing are less well understood. It is therefore necessary to closely examine the micro manufacturing processes and understand the key influencing parameters.

As discussed in Section 3.2, mechanical micro manufacturing processes have overall advantages over other micro manufacturing processes in terms of geometrical complexity, range of materials, surface finish, etc. In order to develop in-depth insight and knowledge about mechanical micro manufacturing processes, the multiscale modelling and simulation of nano cutting process is first presented in this chapter.

The micro EDM process, as a good example of non-traditional micro manufacturing process, will then be investigated in this chapter to provide a good guidance for choosing the appropriate process parameters in the manufacturing process.

The main topics presented in this chapter in relation to the whole framework are highlighted in Fig. 6.1 as those in the red rectangle.

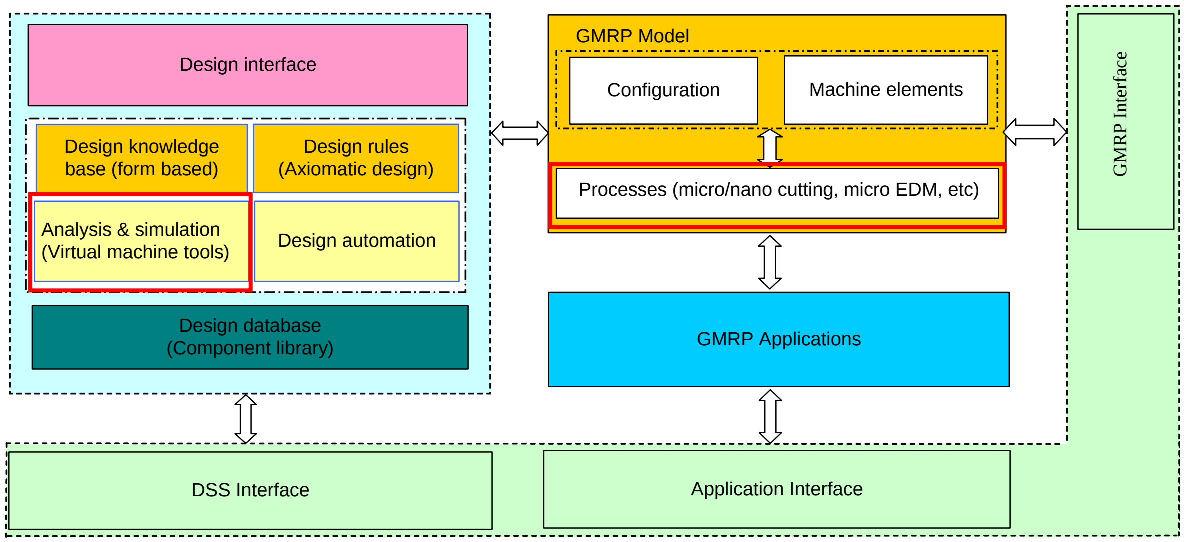


Fig. 6.1 Main topics presented in this chapter

6.2 Multiscale simulation of nano cutting process

As discussed in Chapter 2, MD simulation and FE method have been successfully applied in the simulation of machining processes. However, the two methods have their own respective limitations. For example, the MD simulation can only cover the phenomena occurring at nanometric scale because of the physical dimension, the computational cost and the scale, while FE method is suited to model meso and macro scale machining and to simulate macro parameters such as the temperature in the cutting zone, the stress/strain distribution and cutting forces, etc. A natural approach to the simulation of multiscale processes is to combine a MD simulation for the critical regions within the system with a FE method for continuum coverage of the remainder of the system. The hybrid approach provides an atomistic description near the interface and a continuum description deep into the substrate, increasing the accessible dimensional scales, and greatly reducing the computational cost while increasing the modelling accuracy and capacity.

In this section, Quasicontinuum (QC) method is used to model and simulate the nano cutting process to investigate the nano cutting mechanisms and the effect of rake angle on cutting force and internal stress.

6.2.1 Quasicontinuum (QC) method

QC method originally proposed by Tadmor et al in 1996 is an outstanding multiscale simulation approach (Tadmor et al, 1996). The idea underlying this method is that atomistic calculation resolution is required only in regions with high gradients, but the description of regions with slowly varying gradients follows well-established continuum finite element theories. Thus, the degrees of freedom and computational requirement are reduced significantly without losing atomistic detail in interested regions. Furthermore, the fully atomistic, critical regions can evolve with the deformation during the simulation (Shan, 2005). Generally, the QC method consists of the following three main components:

(1) A FE method on an adaptively generated mesh, which is automatically refined to the atomistic level near defects;

(2) A kinematic constraint by which representative atoms are selected;

(3) The Cauchy-Born rule that computes an approximation to the total energy of the system by visiting only a small subset of the atoms.

Ideally, in order to calculate the total energy, one needs to visit all the atoms in the domain:

$$E_{tot} = \sum_{i=1}^{N} E_i(x_1, x_2, ..., x_N) \tag{6.1}$$

where E_i – the energy contribution from site x_i.

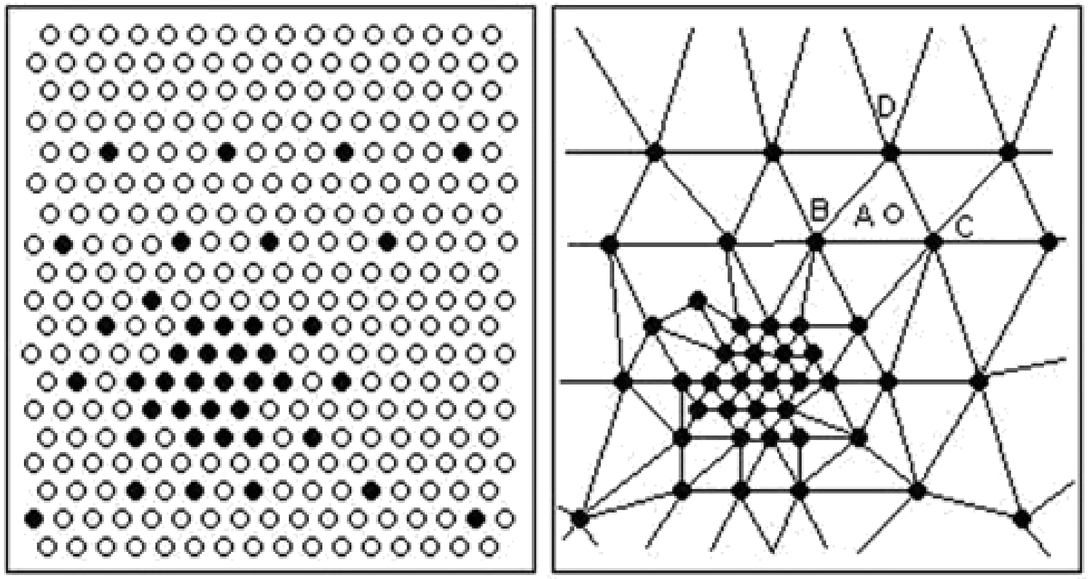
The precise form of E_i depends on the used potential function. In the region where the displacement field is smooth, keeping track of each individual atom is unnecessary. Therefore, some representative atoms (repatoms) can be selected to reduce the computational cost. After selecting repatoms, the displacement of any atoms in the system is obtained from a finite element mesh which is constructed with repatoms as nodes. The approximate displacement of non-representative atoms can be obtained by interpolation:

$$u_j = \sum_{\alpha=1}^{N_{rep}} S_\alpha(x_j^0) u_\alpha$$

where the subscript α identifies the representative atoms;

S_α – an finite element shape function;

N_{rep} – the number of repatoms involved.



(a) (b)

Fig. 6.2 Selection of repatoms (Miller and Tadmor, 2002)

Fig. 6.2 (a) illustrates the selection of repatoms from all the atoms near a dislocation core, and the selected repatoms are then meshed by linear triangular elements in (b). The density of the repatoms varies according to the severity of the variation in the deformation gradient.

In Fig. 6.2, the displacement of atom A is determined entirely from the sum over the three repatoms B, C, and D defining the element in which atom A is contained:

$$u^h(X_A) = S_B(X_A)u_B + S_C(X_A)u_C + S_D(X_A)u_D$$

Though this step reduces the number of degrees of freedom to be calculated, it still need to visit every atom. To reduce the computational complexity involved in obtaining the total energy, several simplified rules are introduced. One of these rules, namely that the Cauchy-Born rule assumes that the deformation gradient, A, is uniform within each element. The strain energy in the element Ω_k can be approximately written as $\varepsilon(A_k)|\Omega_k$ in terms of the strain energy density $\varepsilon(A)$. With these approximations, the evaluation of the total energy is reduced to a summation over the finite elements:

$$E_{tot} \approx \sum_{k=1}^{N_e} \varepsilon(A_k)|\Omega_k| \tag{6.2}$$

where N_e – the number of elements.

This formulation is called the local version of QC. In the presence of material defects, the deformation tends to be non-smooth. Therefore, the approximation made in local QC will be inaccurate. A non-local version of QC has been developed in which the energy is expressed as:

$$E_{tot} \approx \sum_{\alpha=1}^{N_{rep}} n_\alpha E_\alpha(u_\alpha) \tag{6.3}$$

where n_α – a suitably chosen weight;

E_α – the energy from repatom α .

E_α can be obtained by visiting its neighboring atoms whose positions are generated by the local deformation. Practical implementation usually combines both local and non-local version of the method, and a criterion has been proposed to identify the local/non-local regions, so that the whole procedure can be applied adaptively.

6.2.2 Multiscale simulation of nano cutting of single crystal aluminium

6.2.2.1 Multiscale simulation model

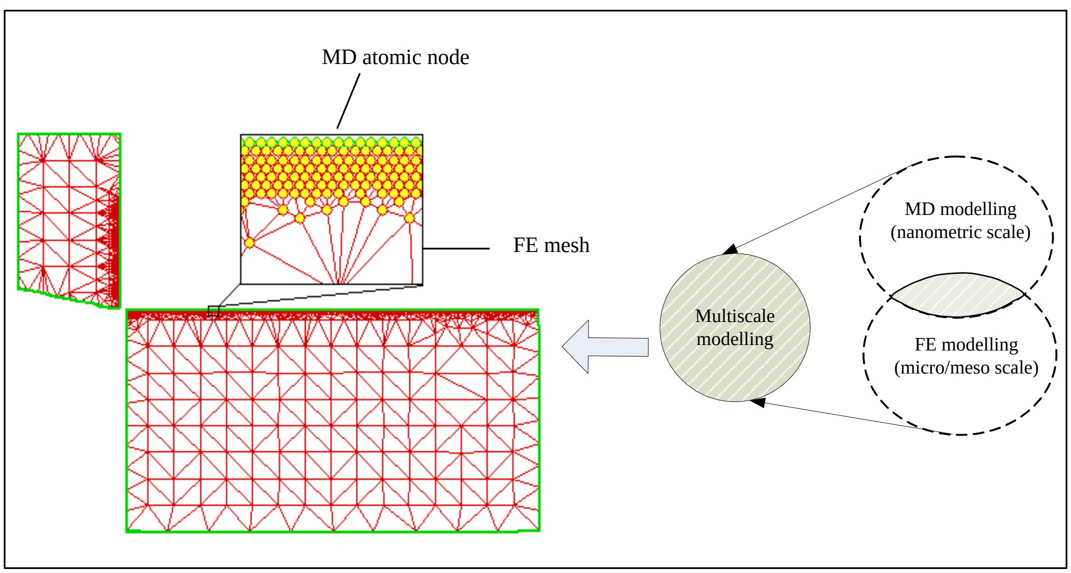


Fig. 6.3 Multiscale model for nano cutting of single crystal Aluminum

Fig. 6.3 presents the multiscale simulation model applied to the nanometric cutting of single crystal Aluminium. To investigate the workpiece material behaviour, formation of chip, generation of machined surface during cutting process, atomistic calculation resolution is performed along the workpiece surface, while the region away from the interested tool-workpiece interaction is estimated based on the finite element theory. So it can be seen from the multiscale model of cutting that the atom density becomes larger upwards, and the material is represented exactly with atoms at the material upper surface. The size of the work material is 0.2×0.1 μm, and the number of material atoms in the initial model is 10, 263. At the 50th step time the number of material atoms is no more than 20, 000, which is much less compared to 1.25×10^{7} atoms included in its MD model. The computational intensity is greatly reduced by using the QC method.

The simulation is conducted on the single crystal aluminium along the crystal orientation <001> and cutting direction [100] with the depth of cut 1 nm. For convenience, an infinitely hard diamond tool is used in the simulation because tool wear is hardly a problem at machining pure aluminium. The constitutive law for aluminium is chosen as the embedded atom method (EAM) potential for the simulation. The nano cutting is performed by gradually moving the tool relative to the workpiece with each step of 0.3 angstrom. Table 6.1 lists the computational parameters used in the simulation.

Table 6.1 Parameters used in the multiscale simulation of nano cutting of single crystal aluminium

Configuration	2D
Workpiece material	Single crystal aluminium
Potential function	EAM
Workpiece dimensions	0.2×0.1μm
The number of work atoms (initial value)	10263
Tool rake angle	0°
Tool clearance angle	10°
Depth of cut	1nm

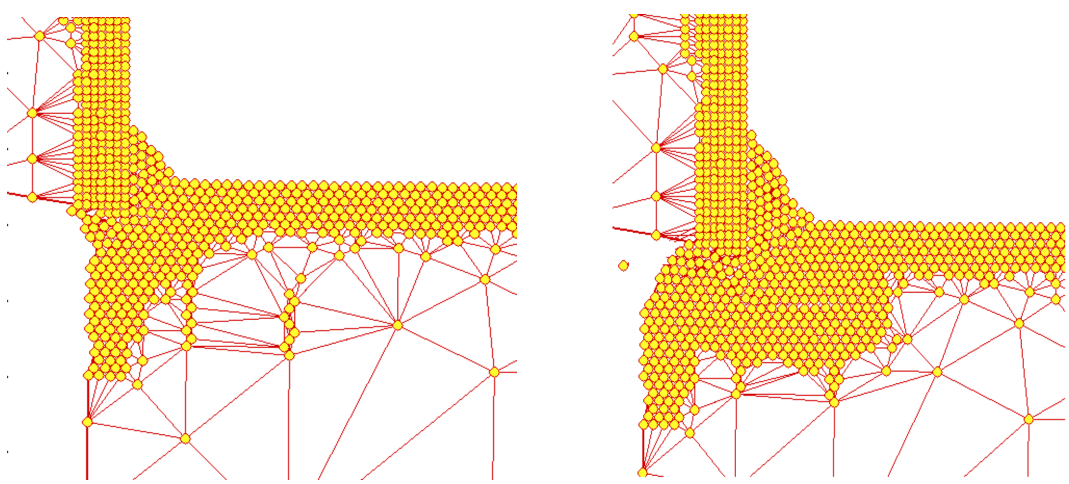
The advantages of combining the MD and FE methods together in the context of multiscale modelling and simulation of the cutting process are:

(1) The modelling and simulation can cover a large surface area machined with comprehensive surface integrity information including surface roughness, microhardness, microstructure changes at subsurface, residual stress and fatigue, etc.

(2) The application of FE method for the continuum description of the non-critical area within the system is able to eliminate the atomistic degrees of freedom and thus improve the computation efficiency.

(3) The combination of MD and FE can preserve atomistic details, such as atom dislocation, in the surface generation area and continuum information, such as residual stress, at the workpiece subsurface.

6.2.2.2 The simulation of the nano cutting process



(a) (b)

Fig. 6.4 The atom snapshot with motion of the tool:
(a) at the 20th time step, and (b) at the 43rd time step

Although the QC method can describe larger volumes with fewer atoms, its efficiency depends on the performance of computer hardware because it is not a high-speed algorithm.

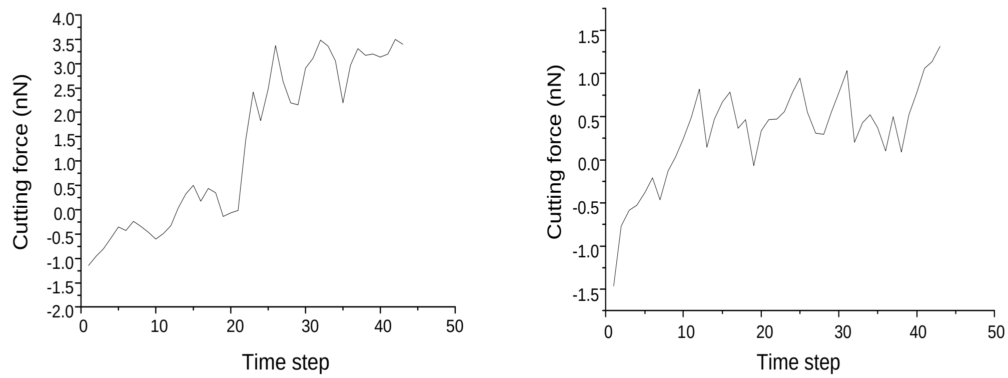
In the multiscale simulation, we only obtained 43 time step results due to time consideration. Fig. 6.4 shows the atom snapshot at the 20th time step and the 43rd time step of the cutting process simulation.

At the start, the uncut material in the workpiece seems to be little affected by the motion of the tool because little meshes beneath the tool are refined to atomic level (Fig. 6.4 (a)). As the cutting progresses, not only the material ahead of the tool is deformed, but several layers below the uncut material ahead of the tool tip is also affected (Fig. 6.4 (b)) since meshes of the deformed material are refined to the atomic level.

Under the effect of the cutting tool, the workpiece atoms are piled up along the front face of the cutting tool as the atom cluster (Fig. 6.4 (a)), and with the progress of the cutting they are removed in the form of chips (Fig. 6.4 (b)). As the tool passes the machined surface, partial elastic recovery of the deformed subsurface region takes place and the remained deformation results in the subsurface deformation beneath the machined surface (Fig. 6.4 (b)). It can be seen obviously that the generation and propagation of dislocations into the workpiece material at an angle of 0°~45°. All phenomena mentioned above are very similar to the results obtained by the MD simulation (Shimada, 1993), which means the application of multiscale QC to nano cutting is feasible.

6.2.2.3 The effect of rake angle on cutting force and internal stress

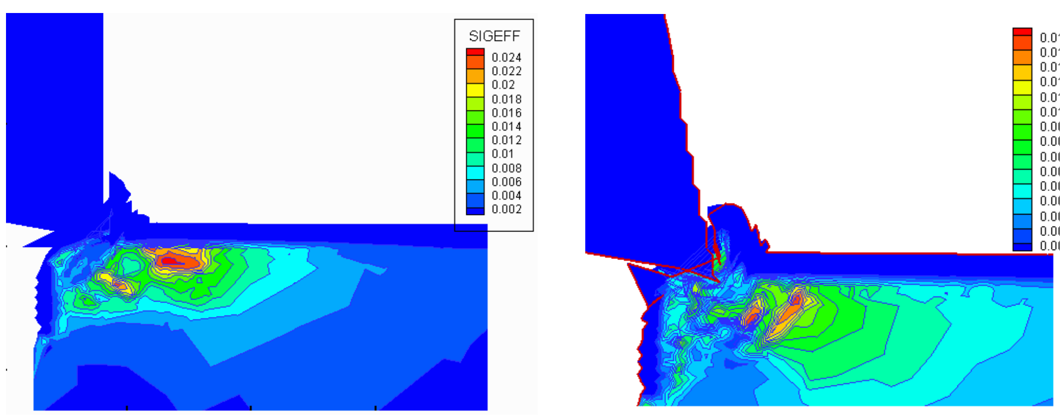
Fig. 6.5 shows the cutting forces obtained with two different rake angles, 0°and 30°. It can be seen that cutting force decreases when the rake angle increases. The mean cutting force during the machining process is 1.65 nN with a rake angle of 0°, and it is reduced to 0.54 nN when the rake angle is set at 30°. These multiscale simulation results of nano cutting force are very close to the MD simulation results produced by Luo (2004).



(a) Rake angle at 0^o (b) Rake angle at 30^o

Fig. 6.5 The variation of cutting force during machining process

The internal stress in the workpiece at the 43rd time step is depicted in Fig. 6.6 for different rake angles. The maximum stress in the workpiece is 2.4 MPa and 1.5 MPa when the rake angle is 0^o and 30^o, respectively. The results indicate that smaller rake angle results in greater internal stress.



(a) Rake angle at 0^o (b) Rake angle at 30^o

Fig. 6.6 The stress contour in the workpiece at 43rd time step

6.2.3 Environment of multiscale modelling and simulation

Whilst the application of QC method to nano cutting is successful, the procedure of the simulation and results analysis are more complex. For example, parameters such as material properties, potential function, model parameters, cut-off radius, step time and other simulation parameter in parameter inputs file have to be defined separately by the user. The geometrical model in the simulation is also expressed in the text format, which is not intuitive to users. To provide users with a user-friendly and highly productive integrated environment for the QC simulation of nanometric cutting, a Matlab-based simulation system has been developed.

The system provides tool and workpiece geometrical parameters description, simulation conditions, implementation of QC, simulation results analysis within a unified visual environment and can execute on Windows operation system. This system has significantly simplified and speeded up the modelling and simulation steps. The integration of modelling, simulation and analysis can enable the QC simulations of nano cutting to behave as a virtual nano cutting system.

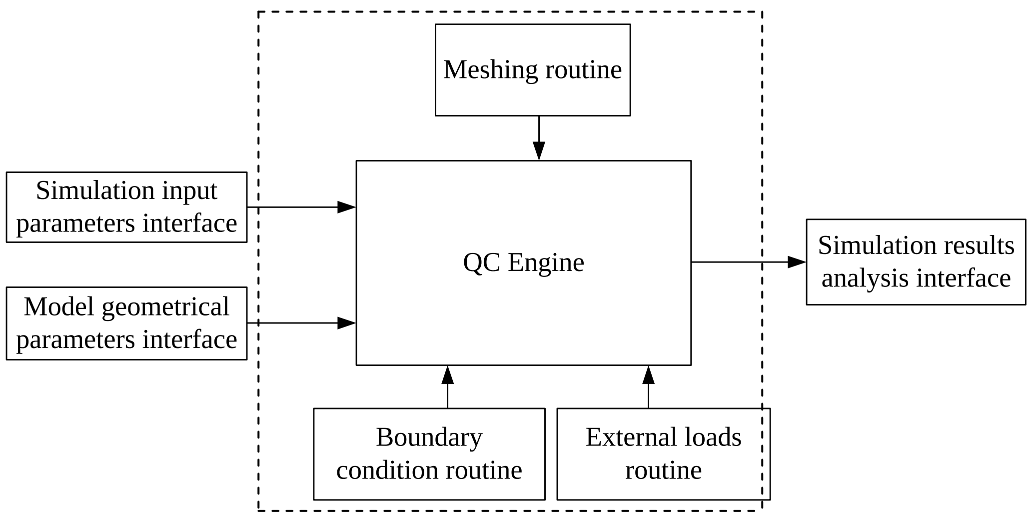


Fig. 6.7 Architecture of the simulation system

The architecture of the simulation system is illustrated in Fig. 6.7. The meshing routine, boundary condition routine and external loads routine are compiled by the QC engine with an executable file generated in advance. Given the data defined through the simulation parameters input interface and the model geometrical parameters interface, the executable file can perform the required cutting simulation. Simulation results can be obtained from simulation results analysis interface.

The screen copy of the system main interface illustrated in Fig. 6.8 provides the interactive selection access for different functions of the system, each with a prompt message. The functions buttons are listed in the typical order of the simulation process, but each of them can be chosen and run independently. If necessary, default parameters can be used in the simulation.

In the Model Geometrical Parameters interface (Fig. 6.9), the standard cutting configuration is shown with both the tooling and the workpiece. A number of geometrical parameters have been defined with default values displayed, such as the size of the workpiece, the shape of the tool, etc.

Fig. 6.8 The main interface of the simulation system

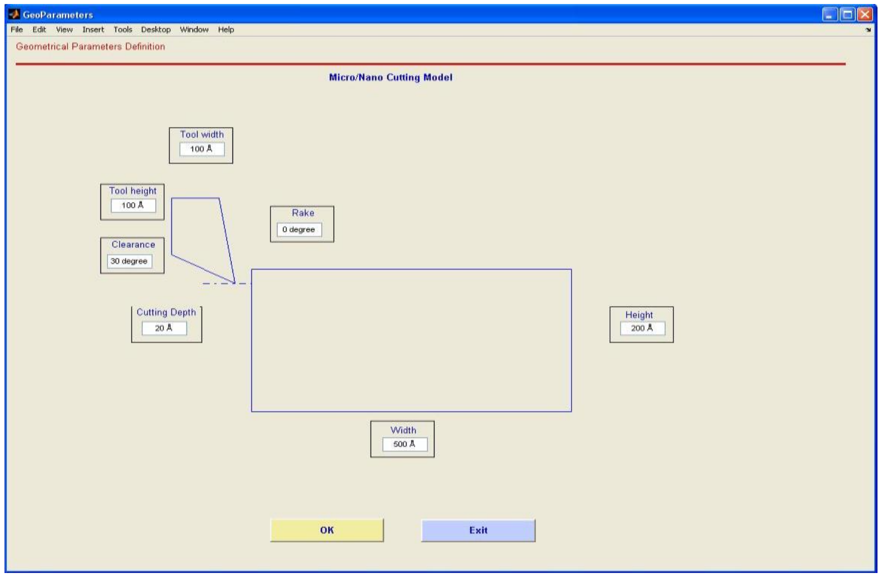


Fig. 6.9 Geometrical Parameters input interface

Through the interface, the user can edit and change the values of these parameters according to the needs of each particular application. When the OK button is clicked, all the changes made will be saved and subsequently used in the simulation. If EXIT is clicked, the changes will be discarded and the default values will be used instead in the simulation.

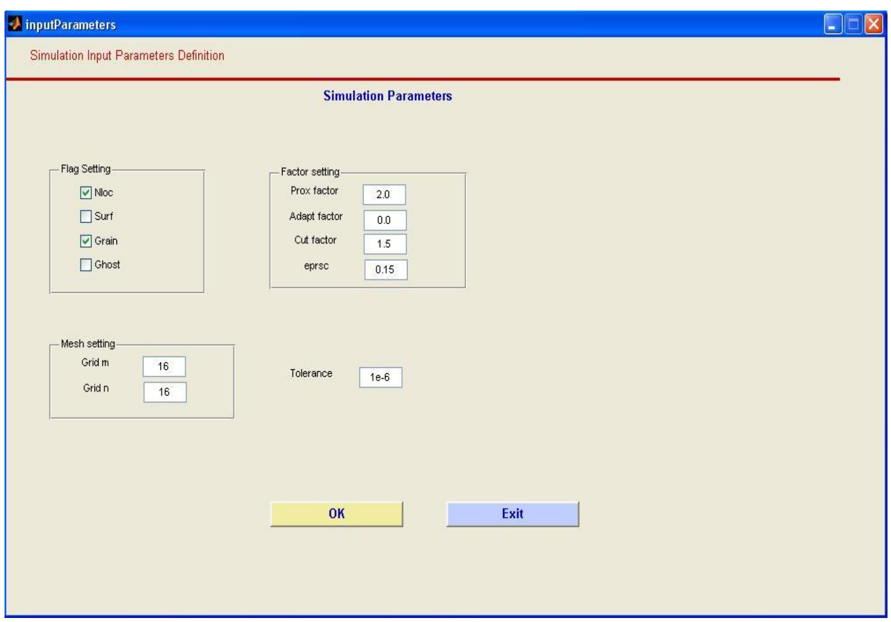


Fig. 6.10 Simulation Input Parameters interface

The Simulation Input Parameters interface (shown in Fig. 6.10) has several groups of controls, i.e. a group of check boxes for simulation flag settings, a group of text boxes for simulation factor settings, a pair of text boxes for mesh setting and a text box for simulation tolerance setting. Again, each of the settings has a default value, but the user can freely change the settings according to the requirements. The changes can also be saved or discarded by clicking the OK or EXIT button.

One example of the simulation results analysis is shown in Fig. 6.11, in which the roughness of the machined surface is calculated. The results are generated in four steps:

1) The results analysis module firstly displays the initial distributions of the atoms of both the tooling and workpiece.

2) The atoms of machined surface are displayed.

3) The user defines the beginning and the finishing atoms of the surface to be evaluated.

4) The program then calculates the R_a value according to its definition based upon the distribution of the atoms concerned. More analysis functions can be similarly performed, e.g. cutting force in the cutting process and residual stress at the machined surface.

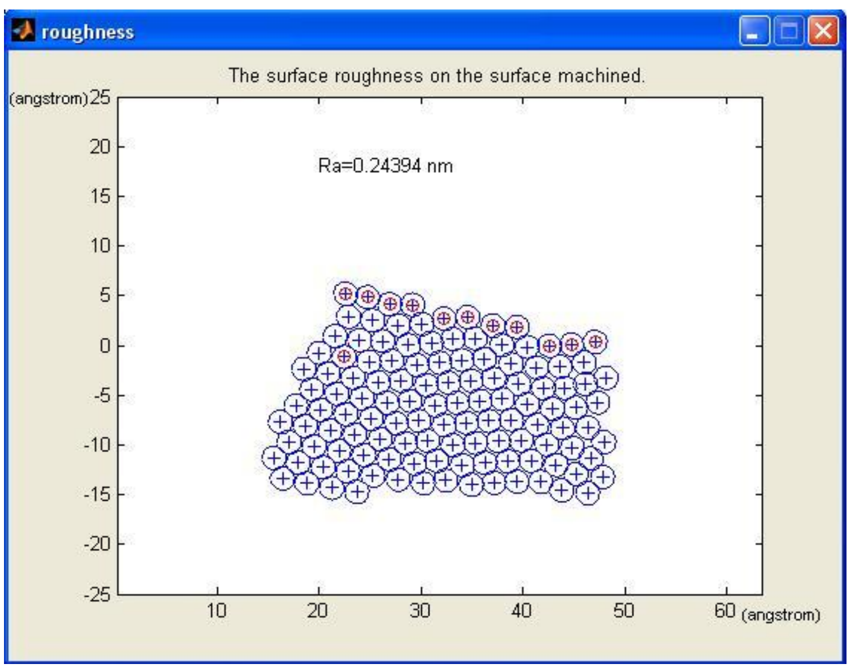


Fig. 6.11 The roughness of the machined surface

6.3 Modelling of micro EDM process

Micro EDM is a non-traditional micromachining process that is capable of fabricating miniature, complex and 3D features down to micrometers and nano scales regardless of their hardness. It is a variation of EDM, so the work principle of micro EDM is essentially the same as that of EDM. Due to its unique features of machining electrically conductive parts regardless of hardness and applying no pressure on workpieces, micro-EDM has been considered a very successful micromachining process to machine micro structures with high quality on difficult-to-cut materials.

In micro EDM process, a spark occurs within a gap between the anode and the cathode submerged in a dielectric liquid environment, and then the spark generates a large amount of heat over a small area of the anode and the cathode. The heat generated by the spark is divided into three portions: a portion conducted through the cathode, a portion conducted through the anode, and the rest is dissipated by the dielectric. A plasma channel between the two electrodes is formed within spark duration where electron and ions move rapidly towards anode and cathode respectively, as shown in Fig. 6.12. The anode melts firstly due to absorption of fast-moving electrons at the start of the pulse, resulting in a larger molten area compared with the cathode, which normally happen in micro EDM. However, after a few microseconds, the anode will begin to resolidify because of the expansion of the plasma radius at the anode, while the plasma radius at the cathode is much smaller because it emits electrons. The phenomenon results in smaller molten areas at anode than at cathode, which are prevalent in conventional EDM (Yeo et al, 2007; Dhanik et al, 2005).

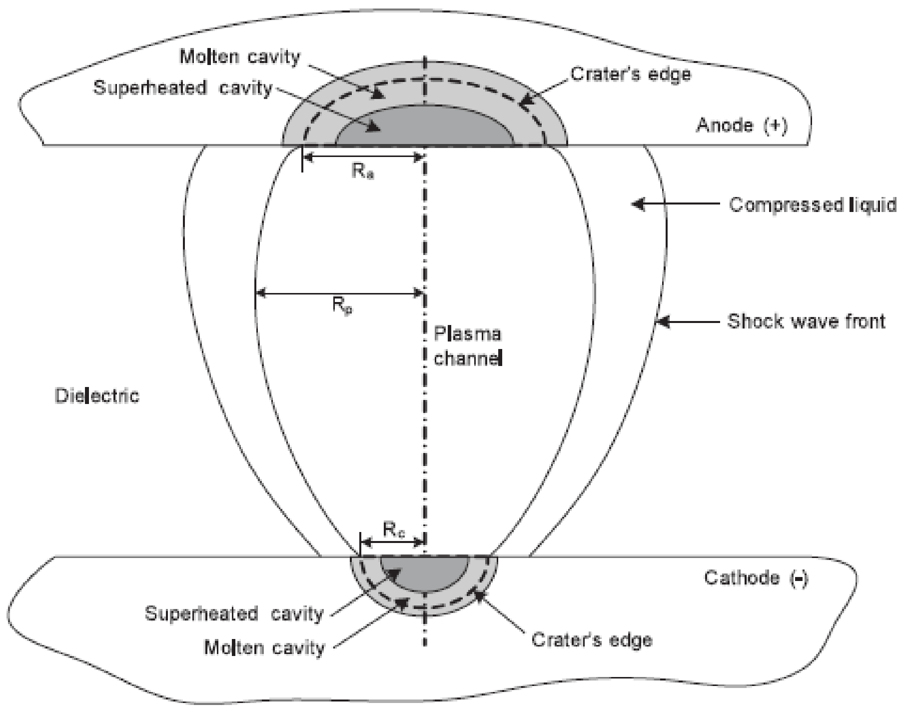


Fig. 6.12 Schematic diagram of the micro EDM process (Yeo et al, 2007)

The plasma channel has a high pressure holding the molten material in its place, therefore the molten and vaporized material will be ejected from the electrode surface as soon as the spark duration time is over, and leaving small craters at locations where material has been removed. Although the quantity of material removed per discharge is small, a serious of successive electrical discharges results in removal of the desired amount of material.

There are two main stages in EDM, i. e. dielectric breakdown process and thermal process, and the two processes are closely related. However, almost all the simulation and modelling efforts focus on either dielectric breakdown process (Dhanik and Joshi, 2005; Eubank et al, 1993) or thermal process (DiBitonto et al, 1989; Patel et al, 1989; Murali and Yeo, 2005; Wang et al, 2002; Singh and Ghosh, 1999; Das et al, 2003; Allen and Chen, 2007). Furthermore, few among these works is about micro EDM although a number of research efforts have been undertaken to simulate the conventional EDM.

A systematic approach for modelling and simulation of micro EDM is proposed in this research. According to the micro EDM process, the proposed simulation model incorporates two submodels including the model of pulsed dielectric breakdown and the model based on heat transfer principles. The pulsed dielectric breakdown model provides initial conditions accurately for the heat transfer model. The model aims at getting better understanding of the effect of process parameters on the surface micro EDMed.

6.3.1 Sub-microsecond breakdown model for micro EDM process

The breakdown in micro EDM involves conversion of liquid dielectric into a high temperature gaseous ionized medium (Dhanik and Joshi, 2005). In general, the models of dielectric breakdown are based on thermal mechanism or electronic mechanism. It is normally assumed that the thermal mechanism is associated with dielectric breakdown of liquids subjected to electric field stresses of microsecond duration, and that the electronic mechanism is associated with breakdown for pulse of shorter duration. However, the models that combine thermal and electronic mechanism to explain breakdown in sub-microsecond time scales and that are suitable for micro EDM, have been proposed (Jones and Kunhardt, 1995).

The dielectric breakdown model based on the combination of thermal and electronic mechanism consists of three phases including emission of prebreakdown current, nucleation of a bubble and formation of embryonic plasma channel.

6.3.1.1 Emission of prebreakdown current

The dielectric liquid in the interelectrode gap (dielectric liquid near asperity in particular) is heated by a current once the pulse on-time begins. The current is a result of the emission of electrons from the cathode surface, and it can be calculated by (Dhanik and Joshi, 2005)

$$j = CE_p^2 \exp(-\frac{D}{E_p}) \qquad (6.4)$$

where E_p – the electric field at asperity given by

$$E_p = \frac{E}{r_i \ln(2\times(b/r_i))} \qquad (6.5)$$

C and D – constants;

For metals, $C = (1.54\times10^{4.52\phi^{-0.5}})/\phi$ and $D = 6.53\times10^{9}\phi^{1.5}$, where ϕ the work function of metal is $4.5\,eV$.

r_i – radius of an asperity;

E –applied voltage;

b – interelectrode gap.

6.3.1.2 Nucleation of a bubble

With the prebreakdown current heating, an asperity forms a nucleation site. The nucleation rate per unit volume S is given below (Jonest and Kunhardt, 1995)

$$S = N\exp(\frac{-\lambda}{iT})(\frac{2\sigma}{\pi m})^{-\frac{1}{2}}\exp(\frac{-16\pi\sigma^3}{3iT(P_v - P)^2}) \tag{6.6}$$

where N – the number of molecules per unit volume;

λ – heat of vaporization per molecule;

σ – surface tension;

m – mass of one molecule;

$P_v(T)$ – pressure in the bubble at temperature T;

P – external pressure;

i –Boltzmann constant.

The value for the nucleation time, τ_{nuc}, can be obtained from by setting (Jonest and Kunhardt, 1995);

$$Sr_t^3\tau_{nuc} = 1 \tag{6.7}$$

The bubble pressure is calculated via the Clausius-Clapeyron equation in the form

$$P_v(nuc) = P + (T_{nuc} - T_{sat})\frac{\rho_v h_{fg}}{T_{sat}} \tag{6.8}$$

where P – external pressure;

T_{nuc} – temperature at which nucleation occurs;

T_{sat} –saturation temperature;

ρ_v – density in the bubble;

h_{fg} – latent heat of vaporization.

In addition, a relationship between the applied voltage E and the nucleation time τ_{nuc} is given by (Jonest and Kunhardt, 1995);

$$jE\tau_{nuc} = 10^9 J/m^3 \tag{6.9}$$

Therefore, the nucleation time τ_{nuc}, bubble pressure $P_v(nuc)$ and bubble temperature T_{nuc} finally can are obtained by solving Equations (6.4~6.9).

6.3.1.3 Formation of embryonic plasma channel

After the bubble temperature T_{nuc} is known, the initial radius of the nucleated bubble r_0 can be calculated by

$$r_0 = \frac{2\sigma T_{sat}}{(T_{nuc} - T_{sat})\rho_v h_{fg}} \tag{6.10}$$

Electron impact ionization of water molecules can take place when the density of water vapour reaches 2.99 (Kg/mm^3). That means, bubble reaches an active growth criterion and expands quickly towards anode forming an embryonic plasma channel.

Also, the following two expressions are known (Jonest and Kunhardt, 1995)

$$t_c = \left\{ [2.4 jE\Delta r + (320 jE\tau_{nuc} - 67P)^{\frac{3}{2}}]^{\frac{2}{3}} - 160 jE\tau_{nuc} + 67P \right\} (160 jE)^{-1}$$

$$t_c - \tau_{nuc} < 1 \ ns$$

where Δr – the difference between the initial radius and active radius r_0 and r_{active};

t_c – the time at which bubble reaches an active growth criterion.

Suppose $t_c = \tau_{nuc}$ because the time associated with the expansion of initial bubble to active bubble is very short, so the radius of bubble reaching active growth can be achieved by combining the above two equations:

$$r_{active} = r_0 + ((160\times 10^{-15} jE_p + 160 jE_p\tau_{nuc})^{3/2} - (320 jE_p\tau_{nuc} - 67)^{3/2}) / 2.4 jE_p \tag{6.11}$$

As the bubble reaches the electron impact criterion, the bubble begins to grow. The time of growth τ_g can be calculated by

$$\tau_g = 3 \times b/v \tag{6.12}$$

where v – the velocity of electron drift;

b – distance between anode and cathode.

Assume initial radius of the embryonic plasma is r_{active}, thus

$$R(t) = r_{active} \text{ at } (t_0 = \tau_{nuc} + \tau_g) \tag{6.13}$$

where $R(t)$ – plasmas radius at time t.

6.3.2 Mathematical thermal model for micro-EDM process

The material removal process from electrodes is primarily a complex and random thermal process, so in order to simplify the mathematical model the following assumption were made in this study:

- The workpiece is homogeneous and isotropic
- The discharge channel is a uniform cylindrical shape
- The material properties of workpiece is temperature-independent
- The heat transfer to the workpiece is by conduction
- Materials with temperature higher than melting point are completely removed.
- The analysis is done for a single discharge

6.3.2.1 Governing equation

The governing equation of the heat transfer for the workpiece heated by a single spark is

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{\rho c}{k} \frac{\partial T}{\partial t} \tag{6.14}$$

where ρ – material density;

c – specific heat capacity;

k – thermal conductivity;

x, y and z – the coordinate axes.

6.3.2.2 Heat flux

Currently, three types of heat flux have been used for heat input model, i.e. concentred point heat load, uniform heat flux distribution, Gaussian heat flux distribution.

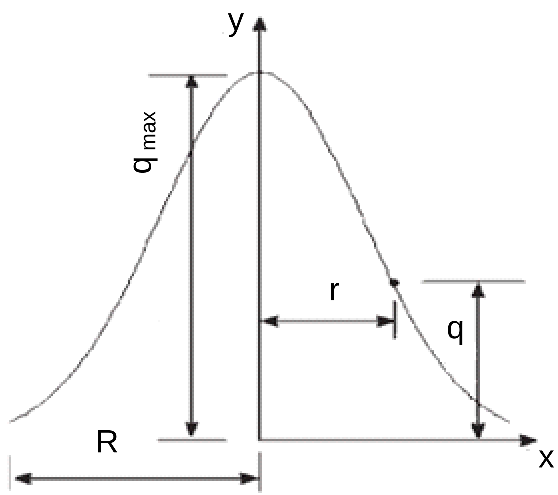


Fig. 6.13 Gaussian distribution

With a well-accepted track record, the Gauss heat flux distribution given in Fig. 6.13 is assumed here. According to the Gaussian function, the heat flux at radius r can be obtained as

$$q(r,t) = \frac{4.55 P_w U I}{\pi R(t)^2} \exp(-4.5(\frac{r}{R(t)})^2) \tag{6.15}$$

where P_w – the energy partition to the workpiece; For micro EDM, P_w is 0.39 (Yeo, 2007)

U – discharge voltage;

I – the current.

6.3.2.3 Boundary conditions

Considering the workpiece is a block shown in Fig. 6.14, energy is transferred to the top surface Γ_1 within the area covered by the spark radius $R(t)$ located at the centre of the surface. In the area beyond this spark zone, the heat is lost to the dielectric liquid. For other five surfaces ($\Gamma_2, \Gamma_3, \Gamma_4, \Gamma_5, \Gamma_6$) no heat transfer occurs because they are too far from the heating region.

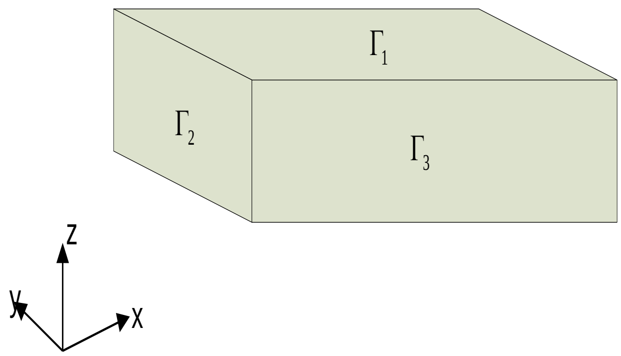


Fig. 6.14 The block workpiece

That is, on Γ_1:

$$\left.\begin{aligned} &k\frac{\partial T}{\partial z}=0 \text{ for spark off time} \\ &k\frac{\partial T}{\partial z}=q \text{ if } r\le R \\ &k\frac{\partial T}{\partial z}=h_c(T-T_0) \text{ if } r\ge R \end{aligned}\right\} \qquad (6.16)$$

On other five surfaces:

$$\frac{\partial T}{\partial n}=0 \qquad (6.17)$$

where q – the quantity of heat flux entering into the workpiece;

h_c – heat transfer coefficient;

n – direction that is normal to the surface;

T_0 – room temperature.

6.3.2.4 Initial conditions

The initial temperature T_i of the workpiece is equivalent to the ambient temperature T_0 of the dielectric liquid in which the workpiece is submerged, thus:

$$T_i = T_0 \quad (t=0)$$

The spark radius varies with time according to (Eubank et al, 1993):

$$R(t) = K_p t^{3/4} \tag{6.18}$$

where K_p is a constant.

Thus, K_p can be obtained by combining Equations (6.13, 6.18).

Once the heat flux, boundary conditions and initial conditions are known, the governing equation of the heat transfer for the workpiece (Equation (6.14)) can be solved to get the thermal distribution in x, y, z direction. The material with temperature higher melting temperature is assumed to be removed.

6.4 Summary

QC-based multiscale model and simulations have been presented in this chapter to investigate the nano cutting of single crystal aluminium. A Matlab-based simulation system has been developed to facilitate and perform the multiscale modelling and simulation steps. From the simulation results, the following conclusions can be drawn:

(1) The QC method characterized by the combined MD-FE technique can be effectively applied to the simulation of nano cutting to overcome the limitations of MD simulation.

(2) The mean cutting force during the machining process and internal stress in workpiece material decreases when the rake angle increases.

This chapter has also presented a detailed mathematical model for micro EDM process. The developed systematic model includes two sub-models, i.e. dielectric breakdown model and thermal model. The dielectric breakdown model describes the formation of plasma between two electrodes, from which a various plasma radius with time can be obtained. The thermal model presents the material removal process from the anode. The heat conduction equation, the heat flux with Gaussian distribution and the various plasma radiuses achieved from the dielectric breakdown model are used in the thermal model. As part of the framework proposed for developing GMRP, the evaluation and validation of the developed mathematical model of the micro EDM will be carried out in the next chapter.

Chapter 7 Application Case Studies and Discussions

7.1 Introduction

This chapter presents the evaluation of the framework proposed for developing GMRP through two case studies. Since the framework includes a number of aspects, only partial evaluations are considered in this chapter.

The first case study is concerned with modular reconfigurable three-axis machines and the second case study is a five-axis milling/drilling/grinding machine tool.

This chapter also presents the validation of the mathematical models developed in the previous chapter for micro EDM process using the FEA and experimental results.

7.2 GMRP case study one

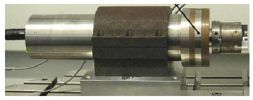
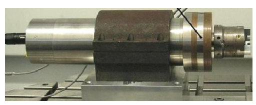
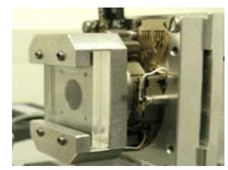
Three-axis machine tools have first been selected to evaluate the proposed framework. For simplicity, only mechanical reconfigurability of the GMRP is considered here since it is relatively easy to reconfigure the machine using modular components and modules.

Each machine tool consists of a spindle, slideways and a tool holder, as shown in Table 7.1. Given the standard three-axis configuration, the machine tool may be reconfigured in two different ways:

1) selecting components with different specification to achieve different machining performance;
2) Selecting different types of components to perform different machining operations.

Table 7.1 has shown three different machine tools reconfigured using two spindles, four slideways and 3 tool/workpiece holders.

Table 7.1 The components used in three different machine tools.

	Spindle	**Slideway**	**Tool/workpiece holder**
Machine A	Loadpoint spindle 1 	 manual slideway  Loadpoint slideway	Tool holder 1 
Machine B	Loadpoint spindle 2 	 Aerotech slideway  Loadpoint slideway	Tool holder 2 
Machine C	Loadpoint spindle 1 	 manual slideway  PI slideway	Workpiece holder 

The two spindles have the following key specifications:

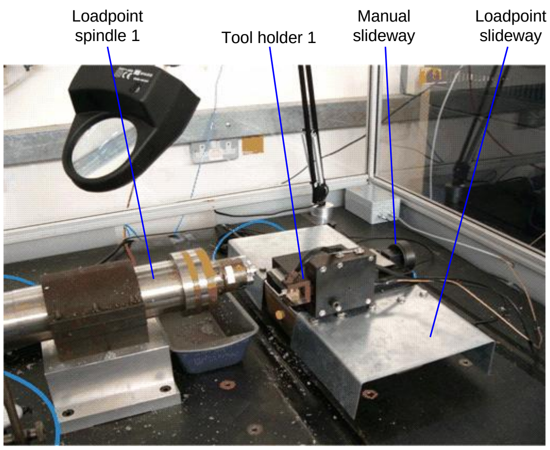
Table 7.2 Comparison of two spindles

	Maximum spindle speed (rev/min)	**Run out (nm)**	**Stiffness (N/µm)**
Spindle 1	100000	50	3
Spindle 2	120000	50	30

The three machine tools have different combinations of the components. Machines A and B use tool holders 1 and 2, respectively, and they perform micro diamond turning operations. With different spindles and slideways, they offer different turning accuracy because spindle 2 has much higher stiffness which has significant influence on the machined surface finish. The Aerotech slideway used in Machine B also has better performance than the manual slideway used in Machine A.

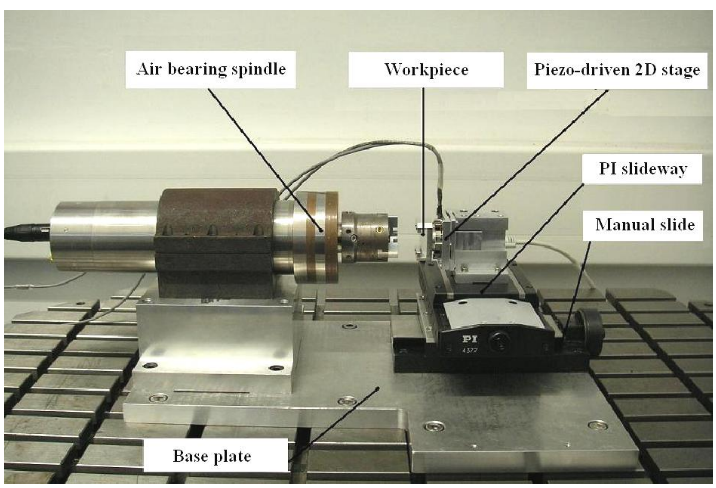
Machine C performs vibration assisted milling operation with the tool installed in the spindle and workpiece held with a piezo-driven stage. It can be used to produce fine surface finish on brittle materials.

The three assembled machines A, B and C are shown in Fig. 7.1.



(a) 3-axis turning

(b) 3-axis turning



(c) Vibration assisted micro milling process

Fig. 7.1 Three assembled meso machine tools

The above designed machine tools can be further evaluated using experiments. Machine A and B are used to conduct micro turning on Aluminium, generating two mirror surfaces with different roughness, as shown in Fig. 7.2. The surface roughness was measured using Zygo surface profiling machine, Zygo New View 5000. The measurement results are shown in Fig. 7.3. It can be seen from the measurement results that the surface produced by Machine B has a R_a of 9 nm whereas the surface by Machine A has a R_a of 20 nm. This confirms that Machine B has a much better performance than Machine A. Fig. 7.4 shows the measurement results of a machined surface on Machine C, and the surface roughness is 1.6 µm.

(a) (b)

Fig. 7.2 Machined mirror surfaces: (a) the mirror surface machined on Machine A, (b) the mirror surface machined on Machine B.

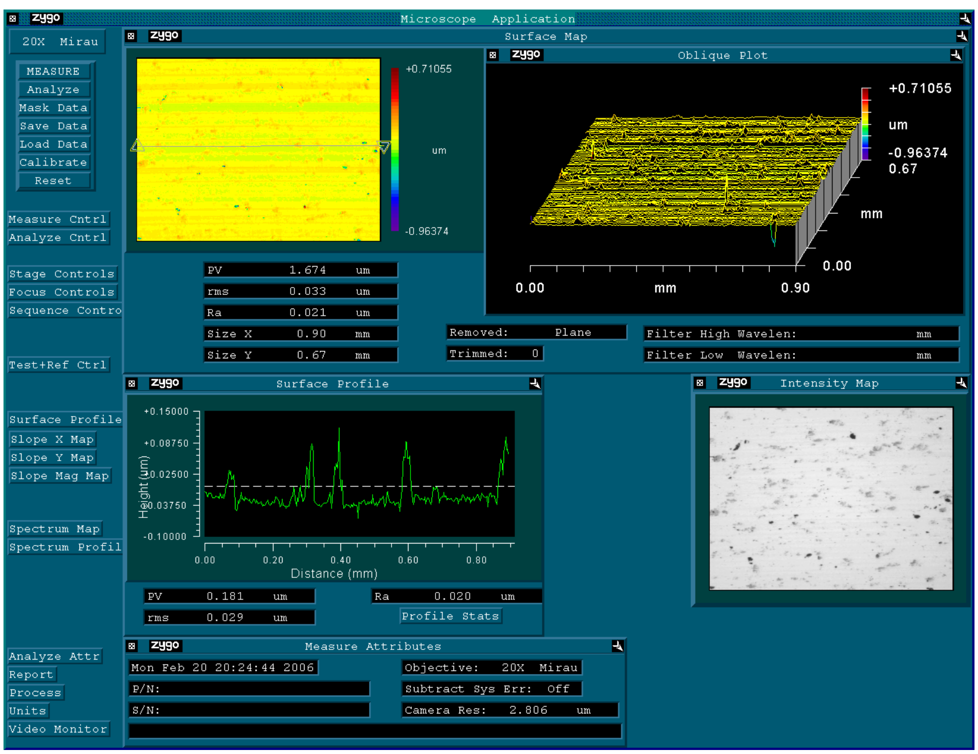


Fig. 7.3a Surface roughness of the mirror surface machined on Machine A

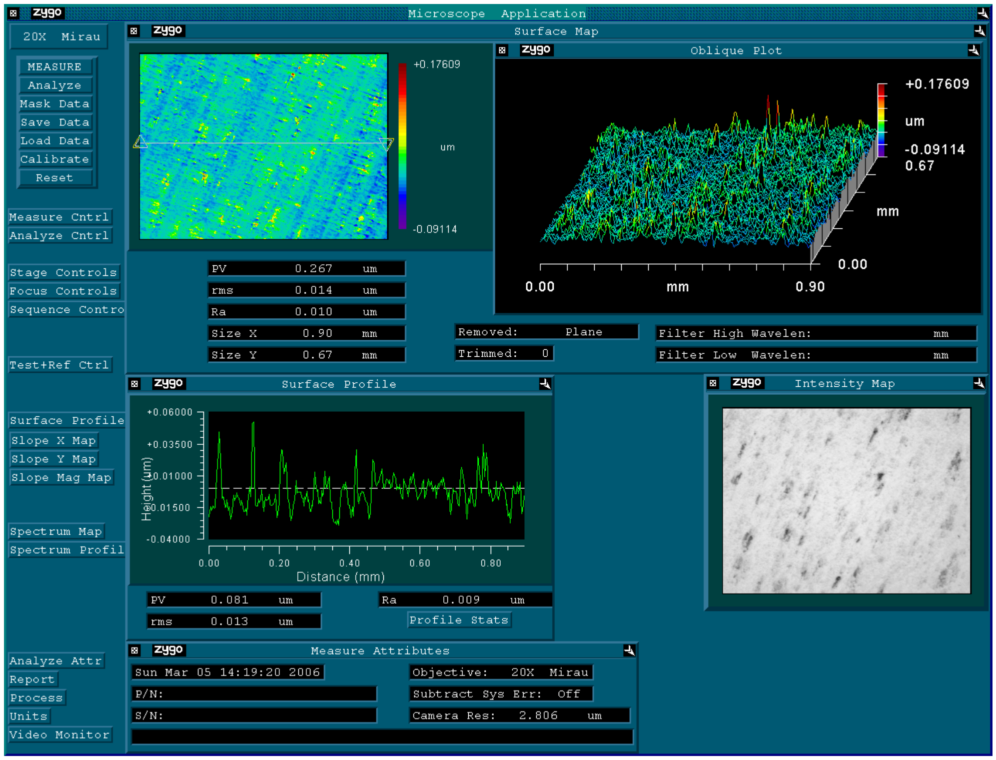


Fig. 7.3b Surface roughness of the mirror surface machined on Machine B

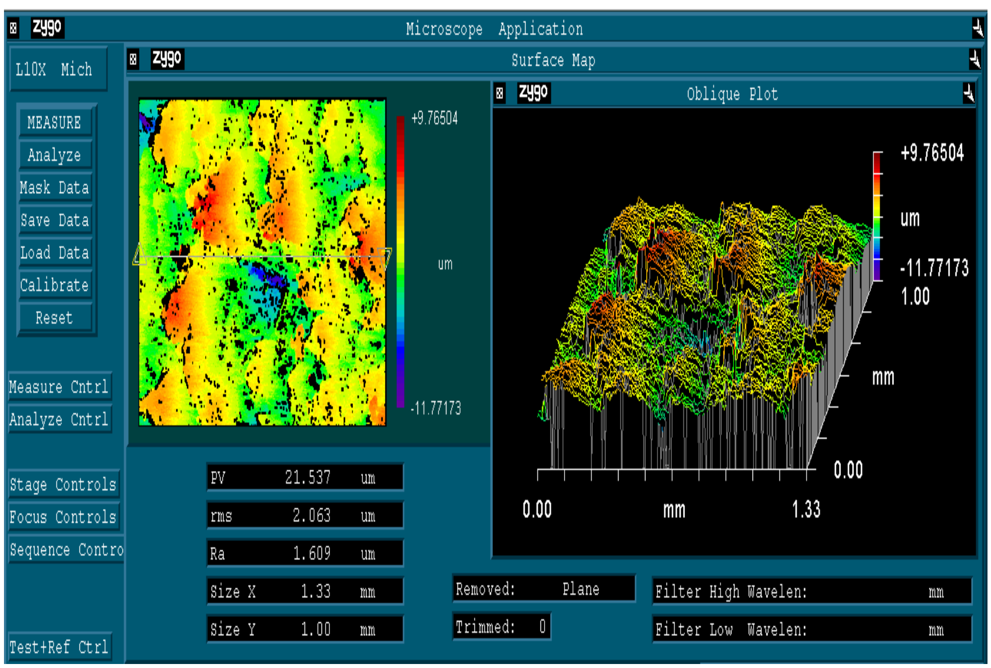


Fig. 7.4 Surface roughness of the machined slot on Machine C

Of course, the machining accuracy is not only dependent upon the individual components or modules; it is also determined by the relative arrangement of the modules and the combined motions of tool and the workpiece. The complete evaluation will require the use of additional analytical tools, e.g. determination of dynamic stiffness and FEA modelling.

Thus one practical solution is to perform the design evaluation at two levels in the design support system of the framework. At the basic component level, the specification and parameters of individual components will be considered. At the higher system level, the overall performance of the complete designed machine tools can be determined.

7.3 GMRP case study two

The concept of modular reconfigurable platforms for micro manufacturing has been, to some extent, applied to a 5-axis ultraprecision micro milling machine tool developed at Brunel University (as shown in Fig. 7.5), although the embodiment of the concept onto this micro milling machine tool is limited. Some key components of the machine tool are modular, so the machine tool can perform different micro machining processes, such as micro milling, drilling and grinding, when corresponding components are used.

Fig. 7.5 5-axis micro milling machine tool

The concept of modular reconfigurable platform can be further incorporated into the next generation machine tools for micro manufacturing through the modular design of mechanical components/elements/structures and use of wireless actuation and control communication mechanism, etc, which will help achieve full reconfigurability through the reconfigurable control systems working with mechanical systems. It will undoubtedly make the micro manufacturing system more efficient and practical, but this will have to be tested and verified by the next generation of the micro machines to be developed. The envisaged further development would lead to step change which impacts as illustrated in Fig. 7.6.

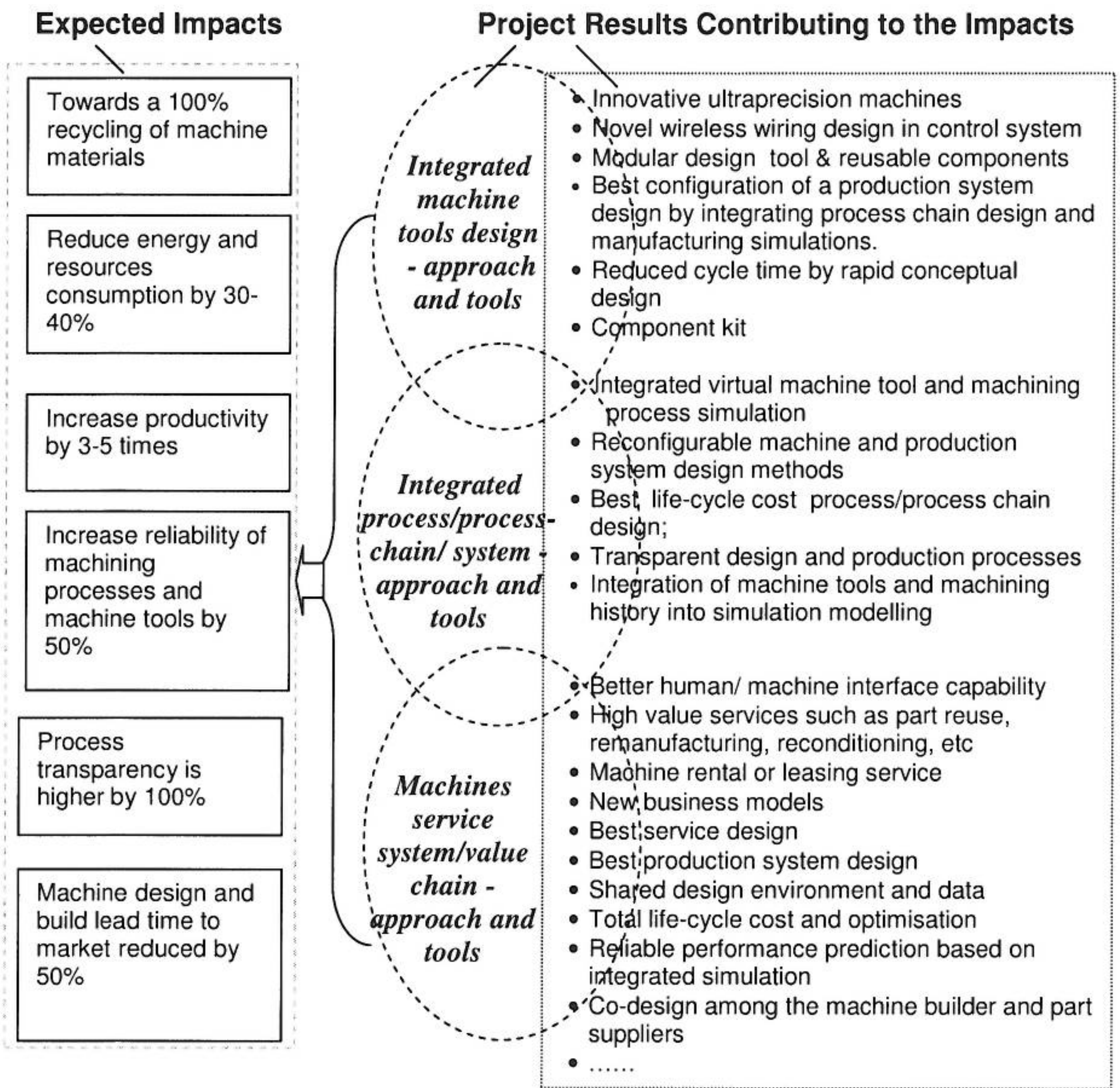


Fig. 7.6 The expected impacts from the development of next future generation machining systems/tools

7.4 Evaluation of the proposed systematic model for micro EDM process

In this section, modelling and simulation of micro EDM on molybdenum is presented to validate the mathematic models developed in the previous chapter. The dielectric is deionised water. At first, the initial plasma radius and the relationship between various plasma radius and time can be obtained using the dielectric breakdown model, which can then be used in the thermal model to investigate the crater size and the material removal rate (MRR).

7.4.1 Simulation of sub-second breakdown

Substitute parameters r_t=0.15 μm, E=120 V, b=3.5 μm, p=1.01×10^5 N/m^2 into Equations (6.4~6.9), then τ_{nuc} is calculated as 5.9483×10^{-9} s and T_{nuc}=588 K. The radius of active bubble is calculated using Equations (6.10~6.11) as 0.1285 μm. v is considered as $4.5\times10^3 m/s$ in Equation (6.12), so t_0 can be determined from Equations (6.12~6.13) as 4.7157ns. Further, constant K_p=7.1390 can be obtained by submitting r_{active}=0.12847 μm, t_0=4.7157 ns into Equation (6.18). Hence, the initial conditions of plasma for FEM have been achieved.

7.4.2 FEA of material removal process

The thermal analysis of micro EDM on molybdenum is conducted as a 3D thermal transient analysis with commercial software ANSYS^{TM}. In the FEA model of the micro EDM process, various plasma radii were used. The simulation parameters and relevant material properties of molybdenum for thermal analysis are shown in Table 7.3 and Table 7.4, respectively.

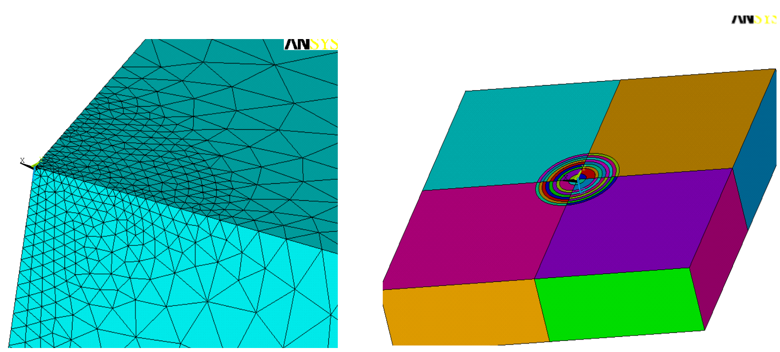
Table 7.3 Simulation parameters

Analysis type	3D thermal transient
Spark radius	$7.1390\times t^{3/4}$ (t=0.005, 0.105, 0.605, 1.605, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0)
Load step	11
Subload step	20
Work material	molybdenum
Spark on time	5 μs
FEM region size	$150\mu m\times 150\mu m\times 30\mu m$
Discharge Energy	30 W
Open voltage	120 W

Table 7.4 Relevant material properties of molybdenum for thermal analysis

Density (Kg/m^3 **)**	10.220×10^3
Melting temperature (K **)**	2896
Thermal conductivity (W/mK **)**	138
Specific heat (J/KgK **)**	276

There are 11 time-load steps applied to the FE model of the workpiece shown in Fig. 7.7 (a). Fig. 7.7 (b) demonstrates 11 corresponding circular areas on which heat flux is applied.



(a) FE elements (b) FE areas

Fig. 7.7 FE model of micro EDM process

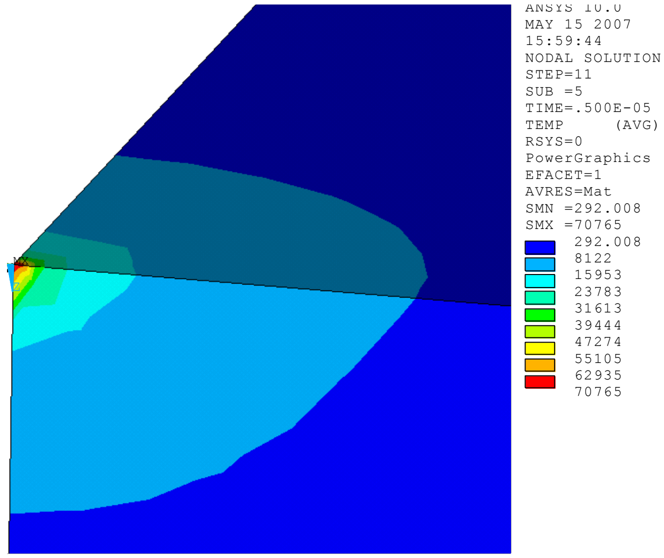


Fig. 7.8 Temperature distribution at pulse duration 5 μs

Fig. 7.8 illustrates the temperature profile after a heat flux is applied for a single pulse duration of 5μs. The maximum temperature is 70765K, so the material with temperature higher than 2896K is removed.

7.4.3 Effects of pulse duration on crater size

The size of crater varies with the pulse duration as shown in Fig. 7.9. It can be seen that the crater size is big at long pulse duration. And calculated crater radii are very close to experimental crater radii (Allen and Chen, 2007). The sources of the discrepancy between calculated and experimental crater radii may be due to FE calculation errors and the assumptions made for the model.

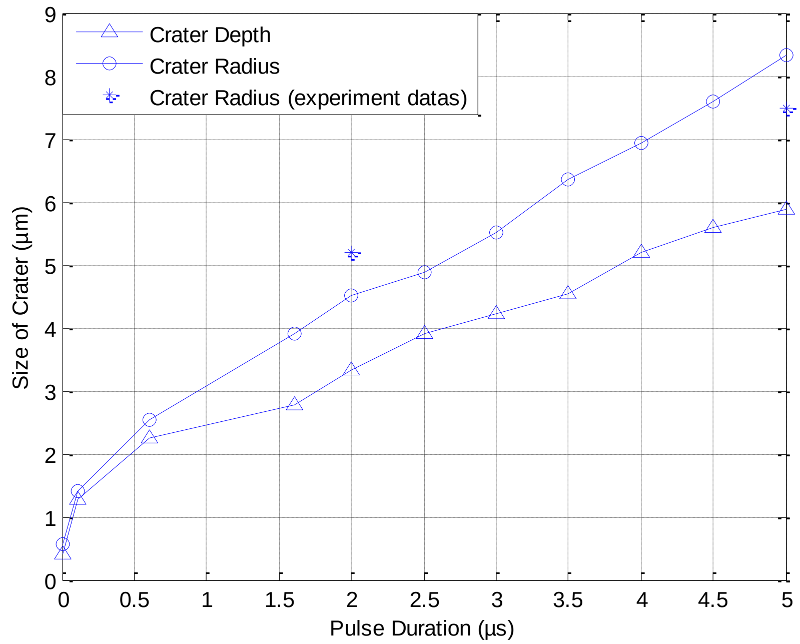


Fig. 7.9 Size of crater vs. pulse duration

7.4.4 Effect of open voltage on MRR

The effect of open voltage on machining performance has been investigated. With Equations (6.4~6.13), initial plasma radii r_{active} and the time to form the embryonic plasma t_0 can be obtained for open voltages E=80 V, 110 V, 120 V, respectively (as given in Table 7.5).

Table 7.5 t_0 and r_{active} for different E

$E(V)$	$t_0(ns)$	$r_{active}(\mu m)$	K_p
80	16.882	0.12847	2.7430
110	6.158	0.12847	5.8439
120	4.716	0.12847	7.1390

Table 7.5 demonstrates that at higher open voltage, the time to form the plasma is shorter, but the initial plasma radius is independent of open voltage.

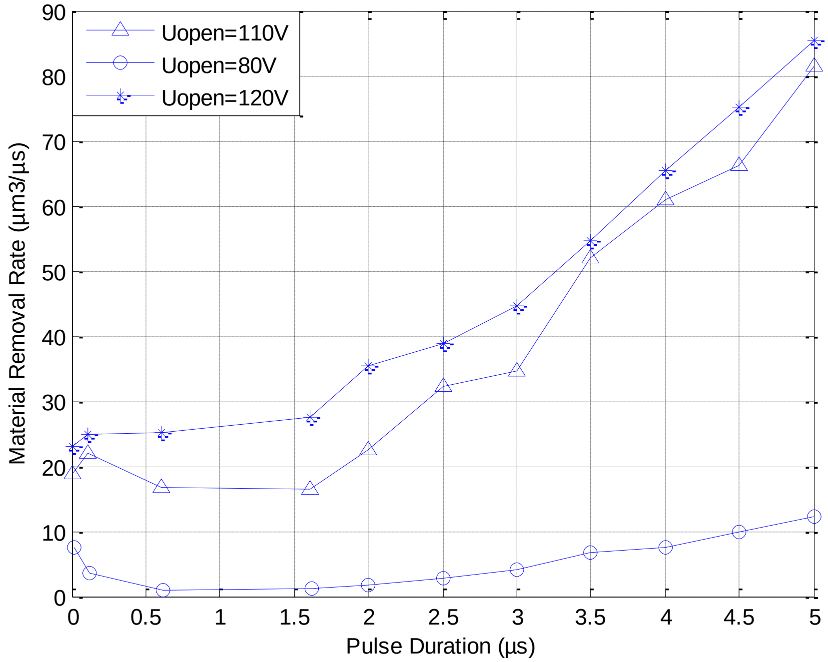


Fig. 7.10 MRR vs pulse duration

$$MRR = \frac{\text{volume of melted material}}{\text{machining time}} \quad (7.1)$$

Material removal rate (MRR) is defined in Equation (7.1). MRR at different pulse durations can be evaluated with calculated crater size. It can be seen from Fig. 7.10 that the MRR increases with open voltage. Fig. 7.10 also shows that at longer pulse duration, the MRR is higher.

7.5 **Summary**

The feasibility of modular reconfigurable platform has been demonstrated with two case studies, although there are still long way to go to develop machine tools with full reconfigrability because there are also electrical reconfiguration and control system reconfiguration. The case studies have only validated the mechanical reconfigurability.

The mathematical models for micro EDM process have been successfully validated using FEA and experimental results.

Chapter 8 Conclusions and Recommendations for Future Work

This chapter draws important conclusions of the investigations, highlights the contributions to knowledge, and recommends the work for future studies.

8.1 Conclusions

Based upon the discussion in the previous chapters and the results from the investigations, the following conclusions can be drawn:

1) Under the great impact of the MEMS revolution and globalisation, the continuing development of manufacturing in the direction of miniaturisation and mass customisation has made it necessary and possible to develop a generic modular and reconfigurable platform (GMRP). The proposed GMRP demonstrated potentials to offer hybrid manufacturing capabilities, modularity, reconfigurablity and adaptiveness for both individual machine tools and a micro manufacturing system.
2) In order to scientifically organise and manage the complexities involved in GMRPs, an integrated framework has been proposed to support its development. The framework incorporates a theoretical model of the GMRPs, a design support system, micro/nano machining applications of a GMRP and extension interfaces.
3) Among various design theories and methodologies, the axiomatic design theory has been selected because of its power and coherence based upon a limited number of design axioms. It can be used for the objective and optimised design of systems of multiple requirements. The axiomatic design theory has been applied to the conceptual design of a GMRP and its design support system.
4) An integrated design support system has been developed to assist in the design process of the GMRP. As a three-tier model, it includes a user-friendly interface, a design database and a design engine including design rules, analysis and simulation, design knowledge base and design automation.

5) The dynamic simulation of machine tools has been demonstrated using the Virtual Reality toolbox and Matlab. The simulation provides useful feedback to the design process.
6) The multiscale QC simulation has also been applied to and demonstrated in a fundamental and key micro manufacturing process – micro mechanical cutting. An integrated toolbox has been developed for the modelling, simulation and results analysis in Matlab. A number of different cutting parameters can be studied and the machining performance can be evaluated subsequently.
7) The mathematical models for a non-traditional micro manufacturing process – micro EDM, have been developed with the simulation performed using FEA. The results have been compared with other researchers' work. These models are incorporated in the proposed framework as part of the design knowledge base.

8.2 Contributions to knowledge

The research has resulted in a number of contributions to knowledge which are summarised as follows:

1) A novel generic modular and reconfigurable platform (GMRP) has been proposed and an integrated framework and methodologies have been established, designed and demonstrated.
2) For the first time, axiomatic design theory has been applied to the conceptual design of the GMRP and its design support system.
3) A new design support system including user-friendly interface, design engine and component library has been developed using a number of software technologies (Java, Matlab and XML).
4) A novel kinematic simulation of machine tools has been performed and demonstrated to evaluate the design using the Virtual Reality toolbox in Matlab.
5) An integrated toolbox for the multiscale QC simulation of the micro mechanical cutting process has been developed.
6) The mathematical models for the micro EDM process have been developed and validated with experimental results.

8.3 Recommendations for future work

Since the research covers a range of the aspects related to the development of generic modular reconfigurable platforms, there inevitably exist some relevant areas unexplored fully. The following areas are thus recommended for future investigations:

1) Since the design support system has been designed as three-tier architecture, each tier can be independently scaled and managed. The component library currently has only a small number of components. A significantly large amount of data could be added, preferably based upon manufacturers' commercial information. The knowledge base can be also expanded.
2) The functionality of the kinematic simulation using VR toolbox can be enhanced, e.g. allowing imports of the machine models created in other software packages. Ultimately full virtual machine tools can be developed.
3) The multi-scale QC modelling can be applied to other micro manufacturing processes. The results can be used to expand the knowledge base for future GMRP characterisations and applications.
4) The current generation of the GMRP has limited reconfigurability. The future generations of the GMRP should aim to improve on this using possibly new configuration concepts and/or machine components.
5) The design support system may be deployed over the Internet as a web-based application. This will allow much wider utilisations and generate more practical applications.

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Appendices

Appendix I

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Publications Resulting from the Research

Publications Resulting from the Research:

1. X. Sun, K. Cheng. Book Chapter: Micro/Nano cutting, in the Book: Micro-manufacturing Engineering and Technology, Elsevier, 2009 (Accepted).

2. X. Sun, K. Cheng. Multiscale simulation of the nanometric cutting process. International Journal of Advanced Manufacturing Technology, 2009 (In press).

3. X. Sun, S. Chen, K. Cheng, D. Huo, W. Chu. Multiscale simulation on nanometric cutting of single crystal copper. Proceedings of the IMechE, Part B: Journal of Engineering Manufacture, July, 2006, V220, pp.1217-1222.

4. X. Sun, K. Cheng. Design of generic modular reconfigurable platforms (GMRPs) for a product-oriented micro manufacturing system, Proceedings of the 6th International Conference on Manufacturing Research, Brunel University, UK, 9-11September, 2008.

5. X. Sun, K. Cheng. Design of generic modular reconfigurable platforms (GMRP) for future micro manufacturing, Proceedings of the 4M2007 Conference on Multi-Material Micro Manufacture, Borovets, Bulgaria, 3-5 October, 2007.

6. X. Sun, K. Cheng. Modelling and Simulation of Micro EDM Process: A Systematic Approach, Proceedings of the 5th International Conference on Manufacturing Research, De Montfort University, 11-13 September, 2007.

Appendix II

Part of Programmes for QC Simulation

The QC Input file

```
head nano-tribology
25000,50000
% initialize flag settings
flag,Nlocon,T
flag,Surfon,F
flag,Grainon,T
flag,Ghoston,F
% initialize factor settings
fact,PROXFACT,0
fact,ADAPFACT,0
fact,CUTFACT,1.5
fact,epscr,0.15
% read in material definitions
mate,,1,../../Potentials/cu_fbd3
% read in grain information
grains,file,fric2
% read in constitutive information
cons,func,1,../../Potentials/cu_fbd3
% generate a simple coarse mesh
mesh,,16,16
end
macros
tole,,1e-006
proportional,,2,,0.,0.,1000.,1000.
plot,disp,shear0,0,1.,1.
% compute local/nonlocal status and automatically
% refine nonlocal regions
status
plot,disp,shear0,0,1.,1.
plot,repatom,repatom
dtime,,4.7d0
time
dtime,,0.2d0
loop,time,1000
bcon
loop,,200
tang
solve,nr,1.0,10000,1
status,update
convergence,force
next
plot,disp,shear,0,1.,1.,1
plot,stre,shear,0,1.,1.
report
pdel,,p-delta
```

```
restart,write,shear
time
next,time
end
stop
```

Matlab program for QC simulation environment

```
function varargout = QCSim(varargin)
% QCSIM Application M-file for qcsim.fig
%    FIG = QCSIM launch qcsim GUI.
%    QCSIM('callback_name', ...) invoke the named callback.

% Last Modified by GUIDE v2.5 05-Mar-2008 11:29:17

% gui_Singleton = 1;
% gui_State = struct('gui_Name',       mfilename, ...
%                    'gui_Singleton',  gui_Singleton, ...
%                    'gui_OpeningFcn', @QCSim_OpeningFcn, ...
%                    'gui_OutputFcn',  @QCSim_OutputFcn, ...
%                    'gui_LayoutFcn',  [] , ...
%                    'gui_Callback',   []);

global GeoDefined
%GeoDefined=0;
global InDefined


if nargin == 0  % LAUNCH GUI

   fig = openfig(mfilename,'reuse');

   % Use system color scheme for figure:
   set(fig,'Color',get(0,'defaultUicontrolBackgroundColor'));

   % Generate a structure of handles to pass to callbacks, and store it.
   handles = guihandles(fig);
   guidata(fig, handles);

   %%  picture
      set(gca,'Position',[0.6 0.55 0.41 .4])
      [x,map] = imread('machine','jpg');
      image(x)
      set(gca,'visible','off')

   if nargout > 0
```

```
    varargout{1} = fig;
  end

elseif ischar(varargin{1}) % INVOKE NAMED SUBFUNCTION OR CALLBACK

  try
    if (nargout)
      [varargout{1:nargout}] = feval(varargin{:}); % FEVAL switchyard
    else
      feval(varargin{:}); % FEVAL switchyard
    end
  catch
    disp(lasterr);
  end

end


% --------------------------------------------------------------------
%function varargout = pushbutton1_Callback(h, eventdata, handles, varargin)
function varargout = pushbutton1_Callback(hObject, eventdata, handles)


figure(GeoParameters);
uiwait;


global GeoDefined

th=findobj(gcbf, 'Tag','statusGeo');

if GeoDefined==1
  set(th,'String','! Updated geometrical parameters are used for simulation.');
else
  set(th,'String','? You have not entered geometrical parameters.');
end


% --------------------------------------------------------------------
function varargout = pushbutton2_Callback(h, eventdata, handles, varargin)

figure(inputParameters)
uiwait;

global InDefined
```

```
in=findobj(gcbf,'Tag','statusIn');

if InDefined==1
     set(in,'String','! Updated input parameters are used for simulation.');
else
    set(in,'String','? You have not entered input parameters.');
end

% --------------------------------------------------------------------
function varargout = pushbutton3_Callback(h, eventdata, handles, varargin)
%figure(TransformerEqImp)
%wgeo;
%test2;
global GeoDefined
if GeoDefined==0
    uiwait(msgbox('You have not entered geometrical parameters.','Error','modal'))
   %disp('You have not entered geometrical parameters.');
    return;
end

global InDefined
if InDefined==0
    uiwait(msgbox('You have not entered input parameters.','Error','modal'))
    return;
end

%disp('Start simulation');
sim=findobj(gcbf,'Tag','statusSim');
set(sim,'String','! Simulation is in progress... ...');

cd Cutting\Shear
!..\fric <fric_shear2.in >out

finish=findobj(gcbf,'Tag','finish');
set(finish,'String','! Simulation is finished.');

%disp('after' )
cd ..
cd ..

% --------------------------------------------------------------------
function varargout = pushbuttonInfo_Callback(h, eventdata, handles, varargin)

%figure(lbox2)
figure(roughness)
% --------------------------------------------------------------------
```

```
function varargout = pushbutton4_Callback(h, eventdata, handles, varargin)
%finish
close all
```

Part of the caluation of surface roughness

```
clear;clc;
load s49a.txt -ascii;
x=s49a(:,1);
y=s49a(:,2);

x0=10;  % the left side of component
x10=-400;y1=100;
x20=-10;y2=0;
x30=-10;y3=800;
d=min(x)-x10;
x1=x10+d;
x2=x20+d;x3=x2;
hold off;plot([x1,x2],[y1,y2],'r');hold on;
plot([x2,x3],[y2,y3],'r');hold on;
plot(x,y,'b*');title('Complete tool and the workpiece');
%disp('Press any key to continue');pause;

uiwait(msgbox('Press OK to continue.                                  ','message','modal'));
%pause;

X1=x(find(x<x2 & x>x0)); %between left side of workpiece and right side of tool
Y1=y(find(x<x2 & x>x0));
%plot(X1,Y1,'g*');axis([-500 2000 -1000 800]);
%title('Region between the left workpiece edge and the right edge of tool');
%disp('Press any key to continue');pause;

Y1t=(y1-y2)/(x1-x2).*(X1-x2)+y2;  %
Y2=Y1(find(Y1<Y1t));
X2=X1(find(Y1<Y1t));%below the tool bottom surface
%plot(X2,Y2,'y*');axis([-500 2000 -1000 800]);
%title('...and below the tool bottom surface');
%disp('Press any key to continue');pause;

Y3=Y2(find(Y2>-15));
X3=X2(find(Y2>-15));
[X,I]=sort(X3);
Y=Y3(I);
plot(X,Y,'r*');axis([-500 2000 -1000 800]);
title('Selected region');
```

```
%disp('Press any key to continue');pause;hold off;

uiwait(msgbox('Press OK to continue.                    ','message','modal'));
%pause;
hold off;

for i=1:length(X)
u0=-1.18:0.05:1.18;
v0=(1.18^2-u0.^2).^.5;
u=u0+X(i);
plot([u,X(i)-u0],[Y(i)+v0,Y(i)-v0]);axis([10 60 -25 25]);axis equal;hold on;
end
plot(X,Y,'+');title('The selected region for roughness evaluation. Select 4 points and press
ENTER to finish');

%disp('Select 4 points from the plot and press ENTER to finish');

uiwait(msgbox('Select 4 points from the plot and press ENTER to
finish.','message','modal'));
```

Appendix III

-

Part of the Program of the Design Support System

Matlab main interface program

```
function varargout = design(varargin)
% DESIGN M-file for design.fig
% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
                   'gui_OpeningFcn', @design_OpeningFcn, ...
                   'gui_OutputFcn',  @design_OutputFcn, ...
                   'gui_LayoutFcn',  [] , ...
                   'gui_Callback',   []);
if nargin && ischar(varargin{1})
   gui_State.gui_Callback = str2func(varargin{1});
end
 if nargout
   [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
   gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT
 % --- Executes just before design is made visible.
function design_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% Choose default command line output for design
handles.output = hObject;
% Update handles structure
guidata(hObject, handles);
% UIWAIT makes design wait for user response (see UIRESUME)
% uiwait(handles.figure1);
```

```
% --- Outputs from this function are returned to the command line.
function varargout = design_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% Get default command line output from handles structure
varargout{1} = handles.output;

% --- Executes on selection change in listbox1.
function listbox1_Callback(hObject, eventdata, handles)
% hObject    handle to listbox1 (see GCBO)
%        contents{get(hObject,'Value')} returns selected item from listbox1
index_selected = get(hObject,'Value');
list = get(hObject,'String');
item_selected = list{index_selected};
fida=fopen('model.txt');
tln=0;
Var={};
while tln~=-1
    tln=fgetl(fida);
    if tln~=-1
    Var=[Var tln];
    end
   end
 fclose(fida);
 pic=Var{index_selected};
%picstr=num2str(pic)
axes(handles.axes2);
 set(handles.axes2);
[x,map] = imread(pic,'jpg');
image(x);
set(handles.axes2,'visible','on');
```

```
% --- Executes during object creation, after setting all properties.
function listbox1_CreateFcn(hObject, eventdata, handles)
% hObject    handle to listbox1 (see GCBO)
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
 % --- Executes on button press in pushbutton1.
function pushbutton1_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton1 (see GCBO)
!selection.exe
 load configuration.txt -ascii;
c=configuration(1,1);
s=num2str(c);
 axes(handles.axes1);
 set(handles.axes1);
[x,map] = imread(s,'jpg');
image(x);
set(handles.axes1,'visible','on');

fid=fopen('comselection.txt');
ln=0;
V={};
while ln~=-1
    ln=fgetl(fid);
    if ln~=-1
    V=[V ln];
    end
end
 fclose(fid);
```

```
V{1}
set(handles.listbox1,'String',V);
 axes(handles.axes2);
set(handles.axes2);
[x,map] = imread('blank','jpg' );
image(x);
set(handles.axes2,'visible','on');
 %--- Executes on button press in pushbutton2.
function pushbutton2_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton2 (see GCBO)
load configuration.txt -ascii;
c=configuration(1,1);
s=num2str(c);
t='.wrl'
o='t'
l='.mdl'
n=[o s t]
f=[o s l]
myworld=vrworld(n);
open(myworld);
open(f);
view(myworld);
% --- Executes on button press in pushbutton3.
function pushbutton3_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton3 (see GCBO)
!add.exe
 fid=fopen('comselection.txt');
ln=0;
V={};
while ln~=-1
    ln=fgetl(fid);
```

```
   if ln~=-1
   V=[V ln];
   end
end
 fclose(fid);
V{1}
set(handles.listbox1,'String',V);
axes(handles.axes2);
 set(handles.axes2);
[x,map] = imread('blank','jpg' );
image(x);
set(handles.axes2,'visible','on');
 % --- Executes on button press in pushbutton4.
function pushbutton4_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton4 (see GCBO)
selected = get(handles.listbox1,'Value');
prev_str = get(handles.listbox1, 'String');
len = length(prev_str);
if len > 0
  index = 1:len;
  prev_str = prev_str(find(index ~= selected),1);
  set(handles.listbox1, 'String', prev_str, 'Value', min(selected, length(prev_str)));
end
 xDoc=xmlread('component.xml');
root_element=xDoc.getDocumentElement;
child_nodes=root_element.getChildNodes;
remove_node=child_nodes.item(selected-1);
root_element.removeChild(remove_node);
xmlwrite('component.xml',xDoc);
% edit('component.xml');
```

```
 % display blank picture in axes2
axes(handles.axes2);
 set(handles.axes2);
[x,map] = imread('blank','jpg' );
image(x);
set(handles.axes2,'visible','on');
 %create new model.txt file
fid=fopen('model.txt');
ln=0;
V={};
while ln~=-1
    ln=fgetl(fid);
    if ln~=-1
    V=[V ln];
    end
end
L=length(V);
fclose(fid);
kk=selected;
fid=fopen('model.txt','w');
NV={};
for i=1:L
line=char(V{i});
NV=[NV line];
if i~=kk
fprintf(fid,'%s\r\n',NV{i});
end
end
 fclose(fid);
```

```
%create new comselection.txt file
fid=fopen('comselection.txt');
ln=0;
N={};
while ln~=-1
   ln=fgetl(fid);
   if ln~=-1
   N=[N ln];
   end
end
 L0=length(N);
fclose(fid);
 kk=selected;
 fid=fopen('comselection.txt','w');
V0={};
for i=1:L0
 line0=char(N{i});
V0=[V0 line0];
 if i~=kk
 fprintf(fid,'%s\r\n',V0{i});
 end
 end
 fclose(fid);

% --- Executes on button press in pushbutton5.
function pushbutton5_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton5 (see GCBO)
% eventdata  reserved - to be defined in a future version of Matlab
% handles    structure with handles and user data (see GUIDATA)
!changeconfig
```

```
load configuration.txt -ascii;
c=configuration(1,1);
s=num2str(c);
 axes(handles.axes1);
 set(handles.axes1);
[x,map] = imread(s,'jpg');
image(x);
set(handles.axes1,'visible','on');
```

Part of the JAVA program for reading XML file and get recommended configurations

```
package components;
org.w3c.dom.*;
import org.xml.sax.*;
import javax.xml.parsers.DocumentBuilder;
import javax.xml.parsers.DocumentBuilderFactory;

public class DOMPlanner {
    private JTextArea display;    // for displaying output
   private InputSource input;    // for reading the XML document
   private Document document;    // document node object
     private ImageIcon icon;
   private StringTokenizer tokens;
   private String str = " ",t,type;
   private JList list;
   private int axis;
     public DOMPlanner(JList output)
   {
     type =  "";
     axis  =0;
```

```
    list=output;
     try {
      // obtain the default parser
      DocumentBuilderFactory factory =
        DocumentBuilderFactory.newInstance();
      factory.setValidating( true );
      DocumentBuilder builder = factory.newDocumentBuilder();
      // set error handler for validation errors
      builder.setErrorHandler( new MyErrorHandler() );
      // obtain document object from XML document
      document = builder.parse( new File( "planner.xml" ) );
    }
    catch ( SAXParseException spe ) {
      System.err.println( "Parse error: " +
        spe.getMessage() );
      System.exit( 1 );
    }
    catch ( SAXException se ) {
      se.printStackTrace();
    }
    catch ( FileNotFoundException fne ) {
      System.err.println( "File \"planner.xml\" not found." );
      System.exit( 1 );
    }
    catch ( Exception e ) {
      e.printStackTrace();
    }
  }
```