DESIGN AND ANALYSIS OF MECHANICAL MATING INTERFACES FOR RECONFIGURABLE MACHINE TOOLS

NORMARIAH BINTI CHE MAIDEEN

UNIVERSITI SAINS MALAYSIA
2010

DESIGN AND ANALYSIS OF MECHANICAL MATING INTERFACES FOR RECONFIGURABLE MACHINE TOOLS

by

NORMARIAH BINTI CHE MAIDEEN

Thesis submitted in fulfilment of the requirements for the degree of Master of Science

November 2010

ACKNOWLEDGEMENT

The author would like to express her thanks to:

- Associate Professor Dr. Zaidi Mohd Ripin for permitting this work to be carried out in the School of Mechanical Engineering.
- Her supervisor, Associate Professor Dr. Indra Putra Almanar for his thoughtful supervision, steady support, guidance, and critics throughout the completion of the research work.
- Dr. Mohd Salman Bin Abu Mansor, Dr. Amir Yazid Bin Ali, Assoc. Prof. Ir. Shuib Bin Sahudin, and Dr. Zuhailawati Hussain for their comments to improve the dissertation and content of the research work.
- Universiti Sains Malaysia for the financial support given under fellowship scheme.

Finally, special thanks to my family and colleagues for their support and motivations.

TABLE OF CONTENTS

APPENDIXES

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

θ_{ic}	Angle of non-vertex inner cone
θ_{oc}	Angle of non-vertex outer cone
a	Face clearance between male and female at initial assembly
d_m	Depth of penetration of the male interface into the female interface
F_i	Bolt preload
A_t	Tensile stress area
S_p	Proof strength
t_g	Tolerance for gap value
d_g	Mean gap value of the clearance
n	Number of dimensions involve in the stackup
a_i	Sensitivity
d_i	Nominal value of the *i*th dimension in the loop diagram
t_{rss}	Assembly tolerance using RSS method
t_i	Tolerance value of the dimensions in the loop diagram
P	Proportionality factor
t_{fn}	Tolerance value that has *n* fixed property
t_{vn}	Tolerance value that has *n* variable property
t_n	New tolerance value of particular dimension

LIST OF ABBREVIATIONS

RMS	Reconfigurable Manufacturing System
FMS	Flexible Manufacturing System
RMTs	Reconfigurable Machine Tools
METEOR	***ME**hr **TE**chnologie **O**rientierte **R**ekonfigurierbare*
DMT	Dedicated Machine Tools
CNC	Computer Numerical Control
MIT	Massachusetts Institute of Technology
PREMADE	**P**rogram for **RE**configurable **M**achine tool **De**sign
FEM	Finite Element Method
CAD	Computer Aided Design
MDO	Multidisciplinary Design Optimization
HSK	Hollow Shank Kegel
PERG	Precision Engineering Research Group
PSDAM	Precision Systems Design and Manufacturing Group
DOF	Degree of Freedom
FEA	Finite Element Analysis

LIST OF APPENDIXES

LIST OF PUBLICATIONS

1. An Improved Mechanical Mating Interface Apparatus for Reconfigurable Machine Tool
2. Mating Interface Methods of Assembled Modules in Reconfigurable Machine Tool
3. Ergonomic Assessment Factors in Reconfigurable Assembly Workplace
4. Mechanical Assemblies Design of Underwater Electric Motor
5. Tolerance Allocation for Mechanical Assemblies of AC Brushless High Speed Electric Mini Motor

REKABENTUK DAN ANALISA

PERTEMUAN MEKANIKAL ANTARA MUKA BAGI

ALATAN MESIN BOLEH UBAH

ABSTRAK

Alatan mesin boleh ubah yang direkabentuk mengikut konsep bermodul adalah merupakan kaedah baru di dalam teknologi alatan mesin. Mempunyai ciri-ciri yang spesifik tetapi fleksible, menjadikan kaedah baru ini mampu untuk menyediakan kehendak pengeluaran semasa. Ia membenarkan perubahan konfigurasi fizikal mesin apabila diperlukan. Konsep alatan mesin ini masih lagi di bawah fasa pembangunan. Walaupun terdapat beberapa kaedah rekabentuk telah di cadangkan, tetapi masih belum ada kaedah rekabentuk yang menjelaskan bagaimana setiap modul yang terlibat perlu disambungkan bersama. Menggunakan kaedah rekabentuk berstruktur, rekabentuk baru bagi pertemuan antara muka secara mekanik dicadangkan. Dua kon tanpa bucu bersama aturan pin-lubang alur telah dikenalpasti sebagai konsep yang terbaik. Menggunakan kaedah unsur takterhingga, rekabentuk terperinci dapat diketahui melalui kombinasi optimum bagi pembolehubah di dalam rekabentuk. Kekakuan sambungan yang baik dapat diperolehi apabila nisbah kedalaman kemasukan kon terhadap tebal keseluruhan antara muka adalah 0.6. Sudut 1/10 adalah nilai yang terbaik bagi kon dan 0.15 mm nilai bagi kelegaan-muka di antara pertemuan antara muka telah menjamin nilai pemasangan gangguan sebanyak 5µm. Menggunakan simulasi model, prestasi rekabentuk baru bagi pertemuan antara muka telah dikaji dan dibandingkan dengan kaedah lama antara muka. Hasil perbandingan menunjukkan bahawa prestasi

rekabentuk baru bagi pertemuan antara muka adalah lebih baik berbanding kaedah lama. Akhir sekali, analisa had-terima dilakukan dan nilai had-terima yang paling sesuai diberikan kepada rekabentuk. Dengan ini, pemasangan gangguan yang dikehendaki di dalam sambungan tercapai.

DESIGN AND ANALYSIS OF MECHANICAL MATING INTERFACES FOR RECONFIGURABLE MACHINE TOOLS

ABSTRACT

Reconfigurable Machine Tools (RMTs) which are designed under modularity concept are a new approach in machine tools technology which is characterized by customized flexibility to serve current production requirements. It allows changes in machine physical configuration whenever required. This concept of machine tools is still under development stage. Even though there are numbers of design methodologies proposed, there is no method specifically mentioned on how each module would be assembled together. Using a structured design approach, the newly design of mechanical mating interface method is proposed. Two non-vertex cones with pin-slot arrangement were found to be the best concept. Using Finite Element Method (FEM), the detail design on the optimum design variables was determined. The stiffer assembly was assured when the ratio of depth of penetration to the total mating interface thickness used is 0.6. The 1/10 tapered angle was the best value for the cones and 0.15 mm of the face clearance between mating interfaces ensured 5μm of interference fit. Using simulation modelling, the performance of the newly designed mating interface was investigated and compared with conventional interface method. The newly designed mating interfaces were confirmed to perform better compared to conventional method. Finally, the tolerance analysis was conducted and appropriate tolerance values were allocated. The intended interference fit of the assembled modules was achieved.

CHAPTER 1

INTRODUCTION

First chapter is written and structured in six sections as to provide general information about the work that has been conducted. In the first section of the first chapter, the theoretical foundations of this work are presented and further elaborated subsequently in the sections that discuss the role of reconfigurable machine tools and their performance requirements as the machine in a new manufacturing environment called Reconfigurable Manufacturing System (RMS). The necessity of having suitable mechanical mating interfaces are stated in the problem statement section, followed by the establishment of research objectives. An overview of the structure of the thesis is given in the final section.

1.1 Background

Today's manufacturing system has to deal with turbulent and quickly changing business environment, which are manifested in shorter product life cycles, unpredictable demand, and customized products that have forced manufacturing systems to operate more efficiently and effectively. However, traditional manufacturing systems, such as job shops and flow lines, cannot handle this kind of environment because they are not flexible enough for the changes. Only Flexible Manufacturing System (FMS) is suitable for this kind of environment, but the high initial capital cost is considered as the disadvantage. For that reasons a new approach in manufacturing system called Reconfigurable Manufacturing System (RMS) was introduced at the Engineering

Research Center of the University of Michigan in the mid 1990s (Koren, 2006). The characteristics of the proposed system are: modularity, integrability, convertability, diagnosability, customization, and scalability. The more of these characteristics are possessed by a manufacturing system, the more reconfigurable it becomes.

Over the last few years, considerable efforts have been made to develop and implement the RMS that is believed could provide a cost effective answer to the new business environment. This new system provides the functionality, which is available when it is needed. This could be achieved through rapid scaling of capacity and functionality, in response to new requirements, by rearranging or changing its components. The RMS components could be classified as physical components (machine, tooling, fixture, etc) and logical components (programs, control, plan, etc) (Mehrabi et al., 2000). Out of those components, machine tools are the key principle for the reconfiguration of the manufacturing systems (Wiendahl et al., 2007). As illustrated by Abele et al. (2007), a typical RMS consists of a number of Reconfigurable Machine Tools (RMTs). Until today however, there are two prototypes of RMTs that have been developed: the Arch Type RMT and ***ME****hr* ***TE****chnologie* ***O****rientierte* ***R****ekonfigurierbare* (METEOR). Both RMTs are still under research and development and there are no commercial reconfigurable machine tools available yet.

1.2 Roles of Reconfigurable Machine Tools (RMTs) in RMS

Common type of machine tools in large manufacturing industries today is the Dedicated Machine Tool (DMT). This type of machine is specifically designed for a single part that would be mass produced. It can perform a unique operation with high reliability, high repeatability and high productivity. As the result, its structures are relatively simple and its cost is always less expensive. However it is not cost-effectively converted when parts to be produced are changed. To address this challenge, flexible CNC machine tools has been developed and used in many industries. The machine should perform multiple operations with high reliability, repeatability and productivity as dedicated machine do. Due to the reason of redundant flexibilities and over capabilities, they often have wasted resources that make users pay for features they do not need. These challenges left the option to adopt the DMT approach and design the machine that can be reconfigured around part family or a set of parts (rather than a specific part), so conversion by rapid reconfiguration of the machine can be made possible. To drive the machine, CNC technology is used. This hybrid type of machine, which is known as Reconfigurable Machine Tool (RMT), has therefore a customized flexibility that makes it less expensive than general-purpose CNCs.

1.3 The Construction of RMTs

To achieve the goals set in RMS (modularity, integrability, convertability, diagnosability, customization, and scalability), modularity should be the key characteristic for the construction of RMTs. Although modular machine tools have been on the market for several years, they do not satisfy the modularity required by RMTs, because the configuration of the modules have already been predetermined during the design stage. However, some theory in published articles on modular machines, modular robots and assemblies are relevant to the modularity concept of RMTs. For example, Ito (2008) demonstrated how the modularity concept is implemented in designing a modular machine tool. However he did not discuss how the modularity of machine tool structure could be re-configured. Research on modular robot and assemblies conducted by Massachusetts Institute of Technology (MIT) introduced kinematic coupling concept to improve the technology in precision assembly of modular robot, instrumentation structures, and engine's assembly process (Culpepper, 2000; Culpepper, 2004; Willoughby et al., 2005 and Hart et al., 2004). However, the modularity is only applicable for the modification of structural dimension of wrist and relocation of the robot base where the robot itself is not re-configurable.

In general, RMTs are made up of various exchangeable modules that can be configured and reconfigured to performed functions as required. Thus, in order to perform the intended function, RMTs undergo topological changes, i.e. size, type and number of modules and their interconnections (Moon and Kota, 2002). The degree of modularity is measured by the ability of the modules to be integrated (integrability), to be modified due to the system's functionality (convertibility), to be adapted to other functional modules (scalability), and to be dedicated for a given part family (customization) (Abele et al., 2007). As a whole, the mentioned degree of modularity is meaningless if the performance of the developed RMTs is worse than existing types of DMTs or FMSs.

Since RMTs were introduced, a number of relevant researches have been conducted, initiated with the study on the performance requirements of RMTs that were discussed by Landers et al. (2001). Researches grow with the establishment of principles and structured design methodologies (Katz and Moon, 2000; Moon, 2006; Riba et al., 2005; Ahuett et al., 2005; Abele et al., 2007; Katz, 2007; Jang et al., 2008;

Mpofu et al., 2008; and Bi and Wang, 2009) together with the optimization on the RMTs design as introduced by Liang and Lie (2007). They established a method to optimize the design by using modified fuzzy-Chebyshev programming approach. Lorenzed et al. (2007) introduced a modeling and evaluation tools for supporting decisions of the design. A year later, Xing et al. (2008) introduced the application of mechatronic design approach in design and optimization of RMTs. However, the most challenging task in developing RMTs is to ensure that the dimensional and geometric accuracies are maintained each time a new configuration takes place, so that the lengthy and expensive setting up and re-calibration procedures could be avoided. Since the RMTs are made in modular forms, the most critical factor that will influenced the machine tools accuracy is the mechanical interfaces between two or more assembled modules. The failure to accurately position the RMTs modules relative to each other will affects the positioning accuracy of the tool relative to the work piece. As discussed by Abele et al. (2007), the positioning error is caused by static and dynamic stiffness. Previously, Yigit and Ulsoy (2002) have developed a systematic methodology to evaluate the RMT structural stiffness.

In modular machine tools, each module is developed and fabricated separately and will be assembled according to the predefined function and specification at the predefined dimensional and geometric accuracies. Every time a set of machine's modules are assembled to its predefined configuration, a set of predefined dimensional and geometric accuracies must be achieved. It is a lengthy and expensive process especially when a precision machine is built since a lot of fine adjustments and calibrations should be carried out by highly qualified technicians using highly accurate instruments. Once the machine is assembled, any disturbances on the setup will require another fine adjustment and re-calibration. This is an uneconomical task to perform.

One invented method in machine tools re-configuration was made by Koren et al. (1997) published in US patent as US-5943750A: Reconfigurable Machine Tool. They proposed a method that allows rapid changes in the machine structure and rapid transformation of the machine function by relocating its basic building blocks to the required new configuration. In the patent, workpiece is secured onto a table that includes support units that can carry at least one unit of single-axis spindle. The re-configuration is achieved when the spindle units can be mounted and re-mounted easily from one support to another. However, they did not explain how repeatable accuracies of the spindle mounting could be achieved when it is moved from one support to another. They also did not mention what type of mounting interface they are using to achieve various repeatable configurations. In other publication, Katz (2007) mentioned about the positioning block that are attached to the arch plate and bolted joint to have better structural rigidity and precision. However, the information about the repeatability of dimensional and geometric accuracies of the positioning block and the joints are not specifically disclosed.

1.4 Problem Statement

The dimensional and geometric accuracies are the important factors in order to gain the predefined accuracies of the reconfigurable systems when they are assembled into one of possible available configurations, or re-assembled into a different possible available configuration.

The most important performance requirement of modular RMTs are the repeatability of squareness, parallelity and concentricity of functional axes of the machine modules that support the tool axis in its relationship with the axes of table module that is used to carry the workpiece or vice versa. Moreover, in modular RMTs, there is a need to ensure that all possible factors that contribute to the alignment errors are eliminated.

Since the RMTs consist of modules that should be assembled or reassembled, there is a probability that errors occur if the properties of the assembly are wrong. The stiffness of the machine will be lost and the tool/module's chatter will destroy the quality of finished product. As the assembly of the machine modules is usually involving two flat surfaces tightened by bolts, there is a possibility that the two bolted flat surfaces will be slipping due to the separation of deformed flat surfaces. Figure 1.1 shows an example of the separation that occurs in spindle - gear box assembly due to static loading. However, the problem can be solved by increasing the contact area between two mating surfaces. It will make the joint becomes stiffer.

Although bolt-and-nut is a common method to join modules, the setup to attain a required geometric accuracy is difficult to achieve because the modules will be deformed when the bolts and nuts are tightened. Also, when cantilever assembly is made, the weight of the cantilevered module will create positional inaccuracy of the assembly since tolerance must be given to the bolts and their corresponding mounting holes. Thus, suitable mating interface between the two assembled modules should be provided. They should be able to provide accurate repeatable and interchangeable mating interfaces. Without the capability to provide a repeatable configuration and reconfiguration, the concept of modular RMTs is not achieved. Apart from that, the mating interfaces should provide good stiffness to ensure the stability of the machine structure. Also, a quick change of modules can make to RMTs become more efficient and economical.

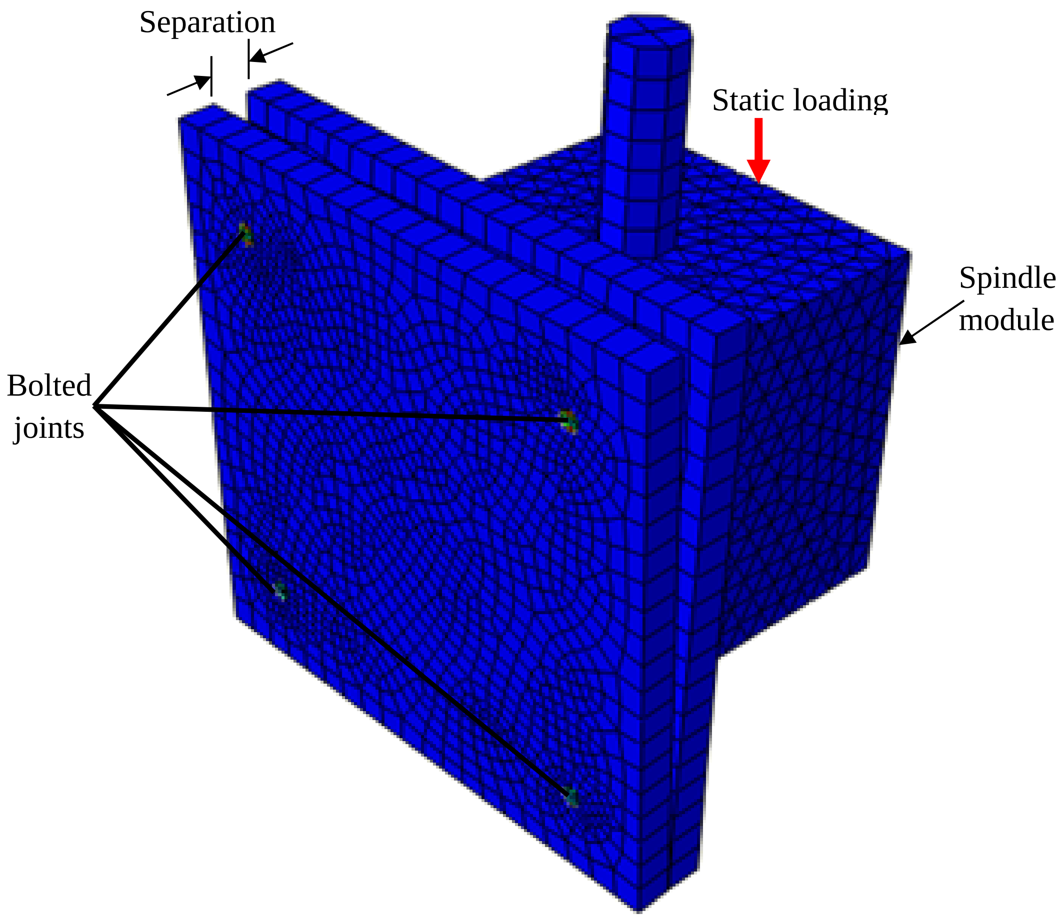

Figure 1.1: Separation of two bolted joint flat surfaces of spindle – gear-box assembly due to static loading

1.5 Research Objectives

To provide solutions on the problems stated in the previous section, a series of objectives is established. The series contains steps as follows:

1. To establish the conceptual design by using Functional Analysis System Technique (FAST) followed by design matrix for mating surfaces,
2. To develop detail design from the conceptual design followed by performance verification,
3. To allocate the design tolerance of newly designed mating interfaces method for fabrication process.

1.6 Thesis Outline

The thesis contains of five chapters. Chapter 1 provides the overview of the current scenario in manufacturing industries that require a new type of machine tools that are called Reconfigurable Machine Tools (RMTs). Then, the existing researches on RMTs were briefly reviewed to show the importance of this research. Problem statement section provides an explanation on the performance requirements of mechanical mating interfaces in RMTs and the problems with conventional method, which are not relevant anymore for RMTs applications. Chapter 2 provides the reviews on the available literatures which encompass development, ideas and methods of RMTs from researchers in machine tool area. This chapter also provides information on tools and techniques that are relevant to designing suitable mating interface for RMTs.

Chapter 3 discusses the design methodology and theoretical analysis that has been conducted in this research in order to produce the most suitable design for mechanical mating interface in RMTs applications. Subsequently, Chapter 4 demonstrated a case study on the spindle-gear-box assembly modules and the performance of newly designed mechanical mating interface. The spindle-gear-box assembly modules were then verified by comparative study with the conventional method.

Finally, Chapter 5 summarizes the whole work and provides recommendations for future work in RMTs.

CHAPTER 2

LITERATURE REVIEW

This chapter reviews published literatures related to the development of reconfigurable machine tools (RMTs). Their performance requirements are reviewed. Special attention is given to the reported studies on the performance requirements for mechanical mating interface of assembled modules for stationary joints. Then, the available designs similar to the performance requirement mentioned above are reviewed. Finally, evaluation methods on the performance of mechanical mating interface of the assembled modules for reconfigurable machine tools are also reviewed.

2.1 Developed Reconfigurable Machine Tools (RMTs)

As introduced in Chapter 1, Reconfigurable Machine Tools (RMTs) is a new form of machine tools that is characterized by customized flexibility for current production requirements. It allows changes in machine configuration whenever there are changes in production requirements. The RMTs are designed under modularity criteria that consists of a set of modules or building blocks that is reconfigurable by assembling predetermined modules. As described by Landers et al. (2001), RMTs is custom-designed for a given range of operation requirements and can be economically converted to meet new requirements.

According to Moon (2006), there are two ways of making a machine tool reconfigurable; the first one is to replace machine modules and the second is to use a machine tool's integrated reconfigurable functions. However, in order to fully optimize the RMTs performance, Moon (2006) suggested using both ways simultaneously.

Based on the patent invented by Koren and Kota, (1999), the first RMTs has been developed in the Engineering Research Centre for Reconfigurable Machining System at the University of Michigan. As shown in Figure 2.1, the machine is named Arch-Type RMT where it is designed to provide customized flexibility, easy and rapid convertibility. This machine employed the first way of making machine tool reconfigurable by changing the position of the spindle from one angle to another by means of a motorized mechanism and by fixing it at a precise location. It is capable of performing milling operations on an inclined surface. It is capable of performing drilling or tapping processes (Karts, 2007). The detailed design and construction of the machine is described in Dhupia et al. (2008) where this type of RMTs successfully demonstrates the concept of reconfiguration and its dynamic performance.

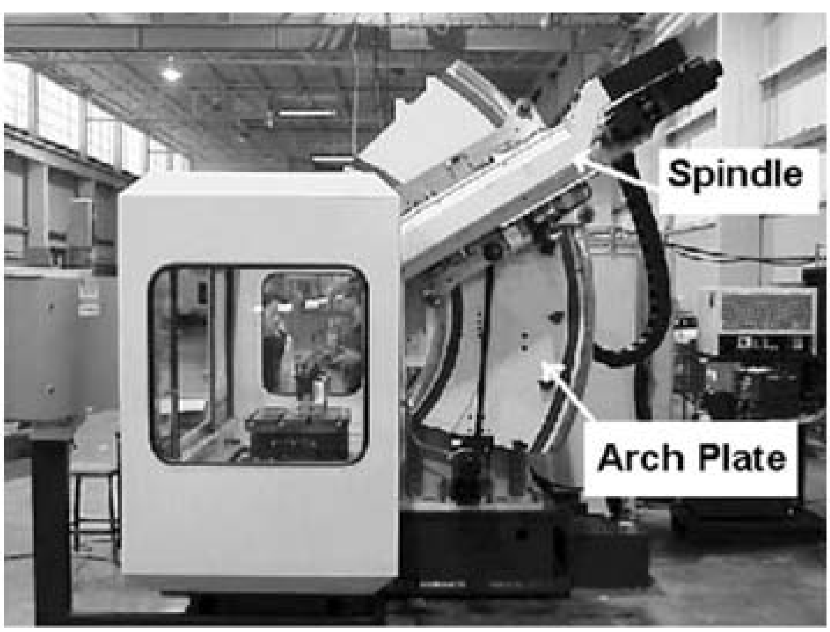

Figure 2.1: Full scale prototype of Arch-Type RMT (Katz, 2007)

Another RMT prototype is the machine tool named METEOR, an acronym for (***ME**hr **TE**chnologie **O**rientierte **R**ekonfigurierbare*) that was developed by Abele and Worn (2009), enables the integration of multiple machining technologies in one machine workspace. It is shown in Figure 2.2. Based on a platform, METEOR consists of modules that can be reconfigured by means of construction kit. This machine employs the both ways of making machine tool reconfigurable as suggested by Moon (2006) where the modules can be economically adapted through addition, substitution or structural changes. However, up till today, there are only two machines that have been developed and both are still under research and development stages. Thus, there are no reconfigurable machine tools available yet. Over the past few years, a number of researchers have started to introduce the design principles and methodology in order to contribute in the development of reliable and functional RMTs. The next section will further discuss the design methods developed.

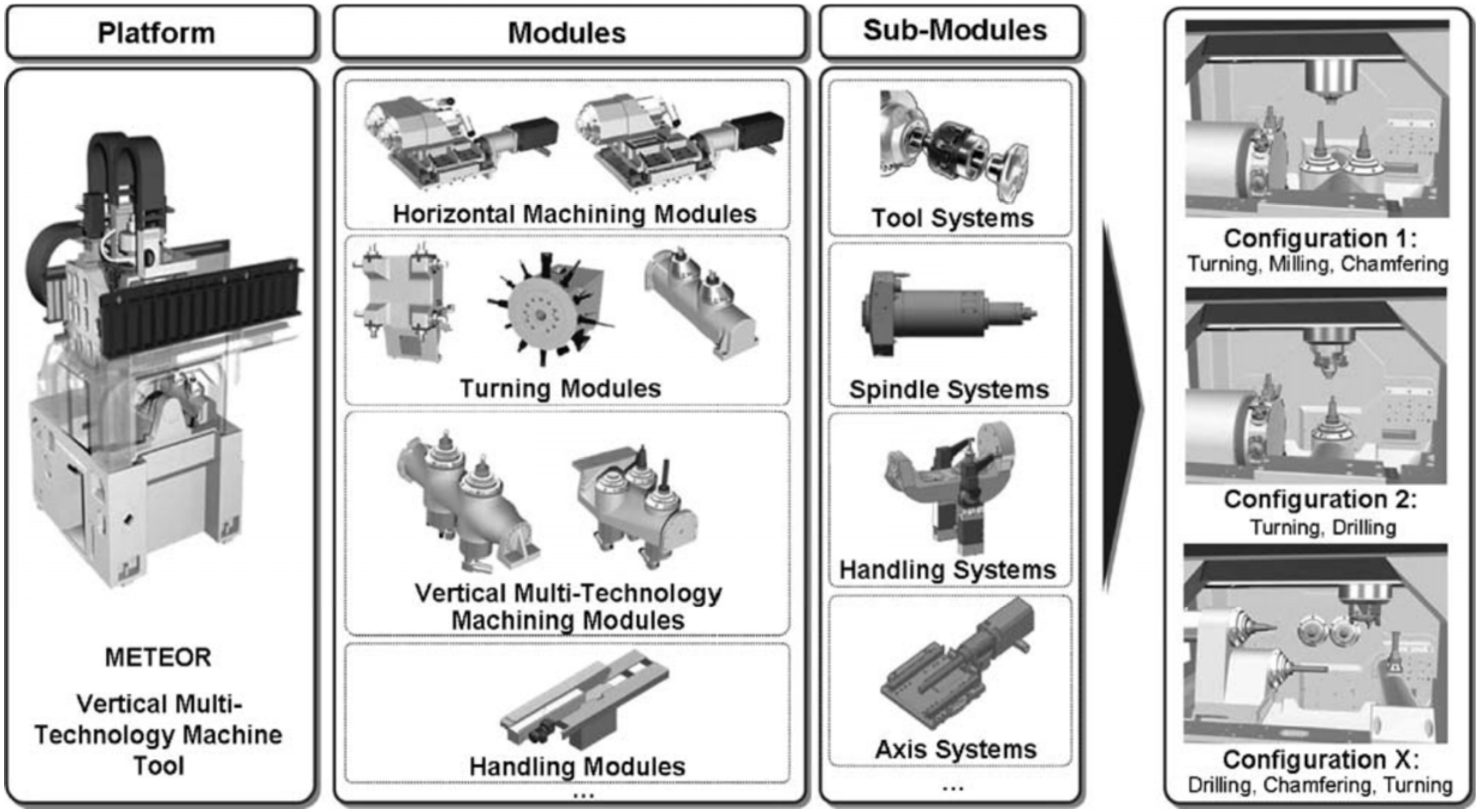

Figure 2.2: Full scale prototype of METEOR (Abele and Worn, 2009)

2.2 Design Principles and Methods of RMTs

Katz and Moon (2000) publish their research work which demonstrates the principles and methodology to designing a virtual arch type RMTs. This method is developed to support the invention that has been patented by Koren et al (1997). The design starts with the analyses on the principles and characteristics (Koren et. al., 1999) of RMTs that basically serve the modularity, convertability, customization, intergratibility and diagnosability functions of Reconfigurable Manufacturing System (RMS). The process continues with the generation of six concepts. Then, the design steps continued using RMT design software **P**rogram for **RE**configurable **M**achine tool **DE**sign (PREMADE). This software consists of four modules that represent another four major steps in design stage which are:

Task clarification,

Structure design,

Supplier selection and,

Module selection.

The task clarification module involves identification of machining information and machining feature of family data. These data are used to determine the required motions for machining features. The configuration changes of the machining features imply reconfigurations of a machine tool which can be achieved either by active motion or passive motion. The required motions use a screw dual number form which is developed to represent the motions of tool. The method is explained in details by Moon and Kota (2002) and Moon (2006). In structural design, graph theory is employed to show the machine tool's functional and structural topology.

Then in module selection, PREMADE which has the functionality to access the network and review the available modules information to select all the candidate modules is used. When the candidate modules are selected, a number of possible machine configurations are generated to meet the functional and structural requirements for the set of machining features. In this step, a solution graph is generated. But since PREMADE software is still under development, the module selection and performance evaluation is not fully functional yet. Therefore, an existing process selection from other people's work was employed.

For performance evaluation, finite element simulation using I-DEAS 6 software is used. Using Finite Element Method (FEM), static and dynamic characteristic of virtual arch RMT are determined. During simulation studies, all the interfaces are assumed to be rigid thus the natural frequencies are estimated higher than its real values. Publication by Dhupia et al. (2008) validated the performance of the virtual arch type machine design through its experimental studies. From the experimental results, the designed machine is found to be satisfactory and comparable to other standard machine tool alternatives.

In other research work, Riba et al. (2005) demonstrated a concurrent approach to design RMTs to process bamboos. The methodology is shown in Figure 2.3. The method starts with building up a Reference Model. This model is used to identify the specific issues in the customer's company such as market opportunities, technological constraints and declared goals. This information helps to establish the requirement's layer which is a simple representation of the machine tools builder intentions on the reconfigurability function. Then functional structures domain is developed to provide a clear methodological procedure for the definition of the ideal sub-functions for a given set of requirements. All functions are decomposed to a certain levels with the last layer represent the sub-function that is more related to the final structure of the machine. The final structure is selected through decision making process. Once the final structure at each function is selected, the layer of the modular structure is obtained and finally, the machine tool with reconfigurable function is produced in the final step.

Extension from Riba's work, Ahuett et al. (2005) has proposed a directed evolution modularity framework in designing RMTs. The design methodology proposed by Riba et al. (2005) has been enhanced by providing machine tool builder's checklist as shown in Figure 2.4. In the enhanced methodology, upgradeability and adaptability are used as important drivers for the RMT. Compared to the proposed method by Katz and Moon (2000) and Riba et al. (2005), these two factors are additional factors to be considered. Thus, they provide upgradeability which refers to the ability of the manufacturer to establish improved technology into the machine.

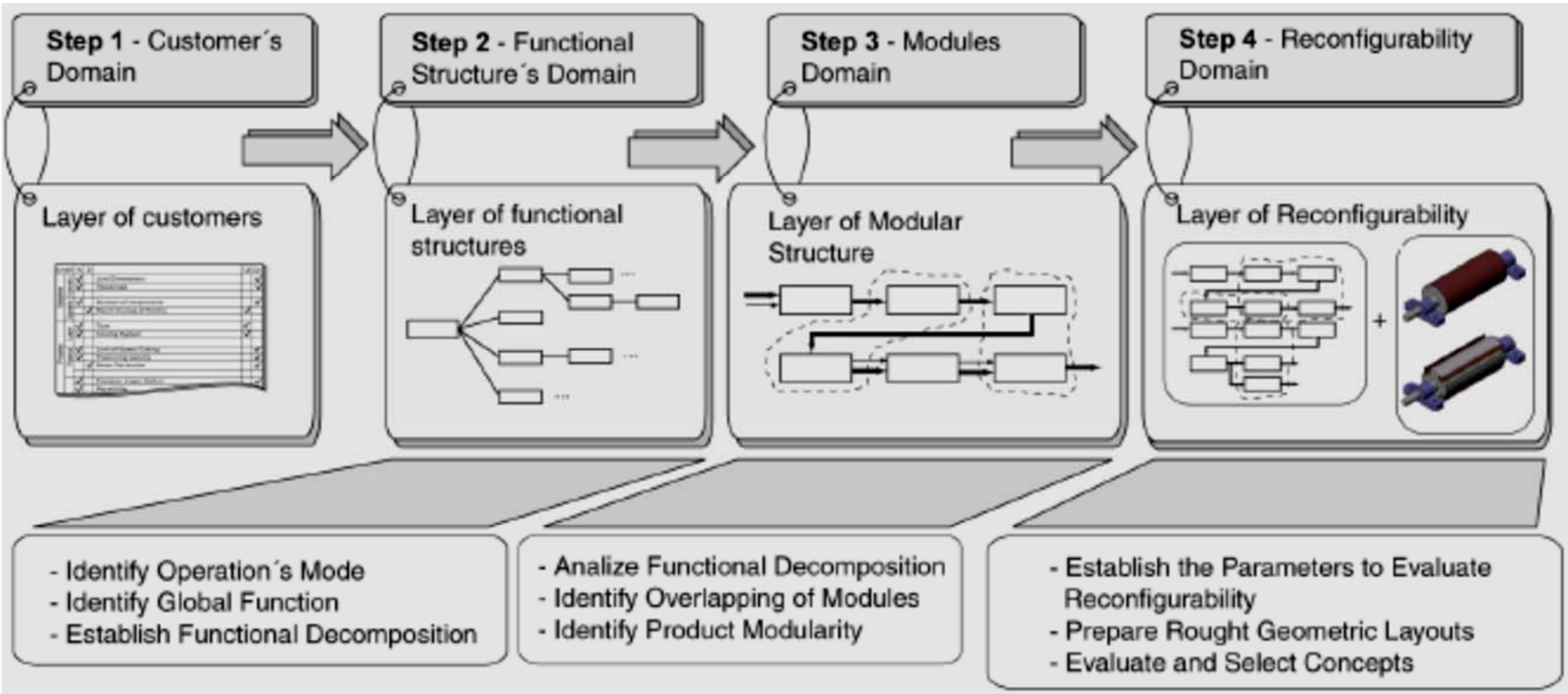

Figure 2.3: Concurrent design methodology (Riba et al., 2005)

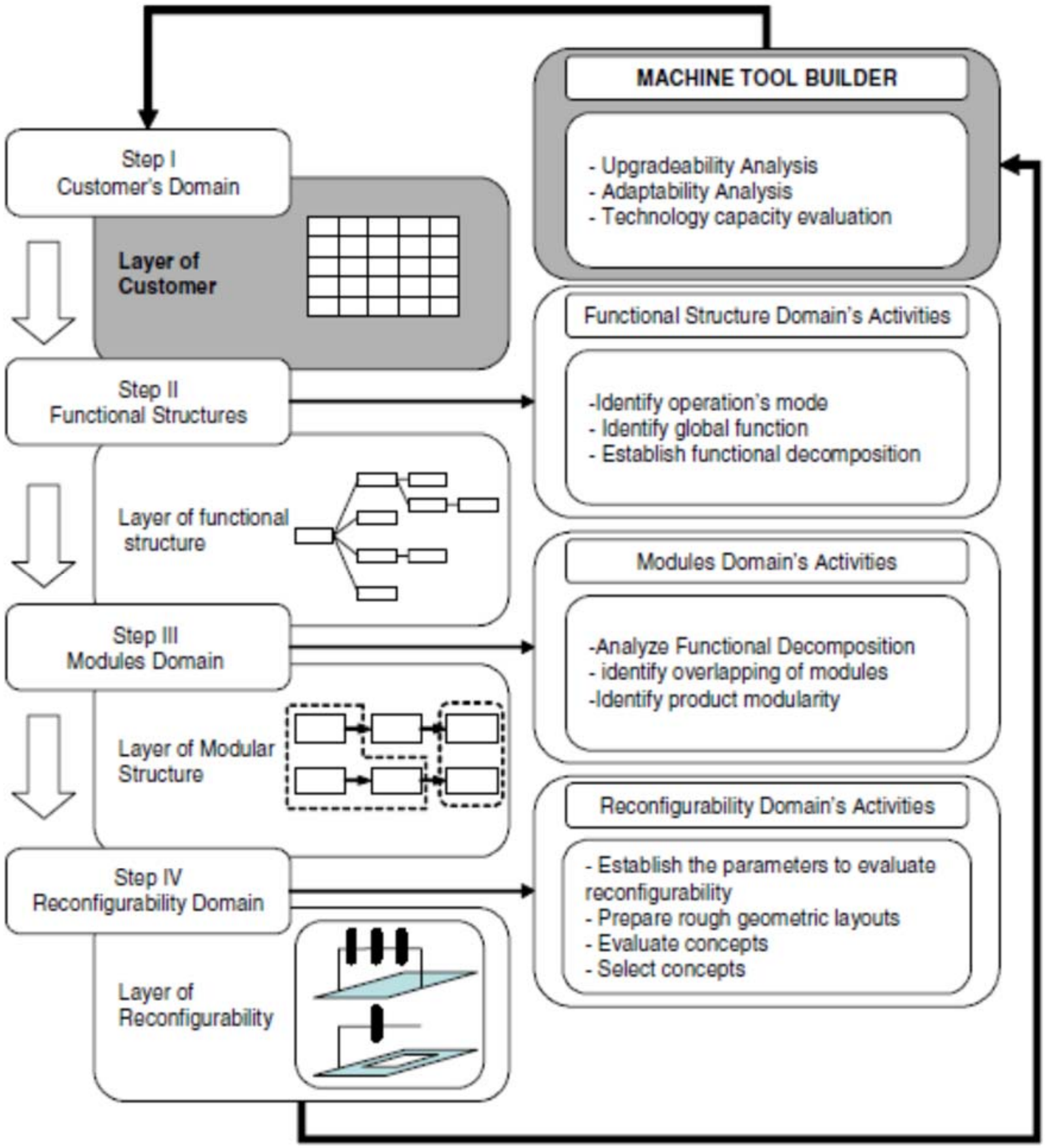

Figure 2.4: Modular reconfigurability design methodology (Ahuett et al., 2005)

On the other hand, adaptability refers to the capacity of the RMT to suit customer's desires. The relevance of this method is to ensure that the machine tool is manufactured based on customer requirements. Business environment such as financial condition, competitiveness issues, and labour concern are the influential factors to user's demand of the machine tool. Ahuett et al. (2005) have discussed the steps conducted on their case study of metal cutting machine. Four machine versions have been developed and the performance measures for selection are total cost to produce the machine, fatigue reduction, increment in productivity, and value added.

Zhang and Zhuming, (2005) employed modular design approach in the development of reconfigurable parallel kinematic machines. Compared to existing industrial robots that already in modular configuration, reconfigurable robots introduced a new dimension to flexible automation in terms of hardware flexibility. It consists of standard units such as joints and links, which can be efficiently re-configured into the most suitable arm geometry for its required task. The design approach proposed in their work was divided into two categories which are (1) identification of possible joints that suitable for modular architecture of the robots and (2) using Computer Aided Design (CAD) system for rapid formulation of a suitable configuration through a combination of these modular joints and links.

From the employment of step (1), there are five variations of reconfigurable parallel kinematic machines available. In step (2), kinematic analysis model is developed using forward or inverse model. The use of the model depends on the type of information acquired. In their research they use actuated joint motions or end-effectors motion. Later, the developed kinematic model is used to optimize the structural parameter. Optimization involves maximizing the rotational motion of the end-effectors. The result from optimization gives a larger workspace without void or empty space, and it has no interference among the system components.

Bi and Wang (2009) introduced an advanced method in optimization of reconfigurable parallel machining system by proposing a Multidisciplinary Design Optimization (MDO). The MDO is an approach that includes design analysis in all of the disciplines including kinematics, dynamics, and control. An integrated toolbox has been developed to process the analysis. The tool not only provides the information on workspace manipulability, but also stiffness of the structure, joint forces, tolerances, optimal structure, graphic simulation and monitoring process.

Katz R. in 2007 published the design principles of reconfigurable machines. There are five principles which are stressed out. These principles can be used by machine designer as a checklist to ensure that RMTs requirements are embedded into the machine. The highlighted principles are divided into two categories (1) necessary principle and (2) primary principles. The necessary principle is to design a reconfigurable machine around a specific part family of products, while primary principles which consist of five criteria, are used to design a better performance of RMTs (customized flexibility, easy and rapid convertibility, scalability, reconfiguration at several location, and modularity). The more items integrated in the design of machine tools, the better the reconfigurability of the machine.

As an example, Arch type RMT has been assessed with the proposed principles. From the six principles, Arch type fulfilled only three of them which are customized flexibility, easy and rapid convertibility, and reconfiguration at several locations. From the findings by Katz (2007), it can be concluded that they still unable to introduce modularity features to the Arch type RMT to enable spindles exchangeability which is the case of mating interfaces characteristic between the modules. In order to further understand the interfaces characteristic between assembled modules, next section will review the performance requirements of modules.

2.3 Functional Requirements of Machine Modules in RMT

The performance of every mechanical interface in mechanical assemblies of the machine modules determines the level of repeatability, interchangeability, and stability of the machine, especially in reconfigurable environment. It is strongly influenced the overall system's performance in the operating mode where the ability of the assembled modules to transmit forces and moments is a necessity (Abele et al. 2007). In general, mechanical assemblies in machine tools are classified into stationary and moving joints. Stationary joints include the machine base, column, and spindle housing. These stationary joints usually support the moving joints such as worktables, slides, spindles and carriages.

In reconfigurable environment, there are special requirements for the mechanical assembly interfaces compared to existing machine tools such as Dedicated Machine Tools (DMT) and Flexible Manufacturing System (FMS). Moon (2006) and Abele et al. (2007) stated that, the fast and accurate interfacing method should be developed for reconfigurable machine modules. This is to support the ability for the RMT users to frequently change the modules. Katz (2007) proposed to automate the assembly process in order to speed it up and keep it precise. To provide shorter assembly time, Abele and Worn (2009) suggested to specifically designing the geometry of interfaces between modules to facilitate the functional interactions and simplify the assembly and disassembly operations as they named the interface as SST-60. SST-60 which employs a plug and play modularity features is designed in order to ease spindle exchangeability. SST-60 is the design of spindle interfaces for machine tools to serve the requirement for reconfigurable machine tool named METEOR.

Another important requirement is to maintain the accuracy of the machine tools each time reconfiguration takes place. The explanation of accuracy is that once the module is re-assembled, then the geometric accuracy is assured Pasek (2006). This is to avoid the calibration process that will force the production to stop for setup, aligning functional axis and re-calibrate the machine. This process is time consuming and costly. The requirement to assemble the modules accurately was also mentioned by Abele et al. (2007) and Abele and Worn (2009). They discussed the importance of the mechanical modules to be aligned precisely in order to reduce positioning error of the tool relative to the work piece.

The misalignment of assembled modules will give an effect on static and dynamic components. The static component will produce dimensional deviations on the work piece while dynamic component will affect its surface quality. Generally, assembly interfaces are often the weakest chain in the whole mechanical structural system (Lin and Chen, 2002). This makes the stiffness at the module assembly is lower compared to its integral part. Therefore, even a small misalignment is not acceptable which will ruin the accuracy as well stiffness of the machine structure.

Thus, the assembled modules should be able to give the desired stiffness along its life time (Landers, 2001 and Pasek, 2006). Insufficient stiffness will cause static deflection and chatter to the machine tool structure. In order to achieve this requirement, an evaluation method on structural stiffness should be conducted during design stage (Yigit, 2002; Moon, 2006; Lorenzer, 2007; Katz, 2007; Abele et al., 2007, Wiendahl et al., 2007). Reliability upon the sensitivity of the locking mechanism for stationary joints to failure during assembly process also requires an assessment (Abele et al., 2007). This is to certify that the rigidity of the stationary joints is assured. Lin and Chen (2002) stated that the working performance of the interface between two assembled modules in stationary joints depends on the form of the mating interface, surface roughness and the number and distribution of the fixing bolts used in joining the two modules.

Standardization of machine modules is also an important requirement to allow interchangeability between different machine builders. Therefore, Moon (2006) proposed a standard for the machine tool named as ANSI B5.43. However the standard is for modular machine tool and the standard for reconfigurable machine tool is not yet available. Abele et al. (2007), Katz (2007), and Abele and Worn (2009) also discussed the interface standardization where it is believed that it can increase the degree of interchangeability for the assembly of a maximum variety of module type.

From all the reviews conducted, the summary of the literatures on the functional requirements of the machine modules in RMTs is tabulated in Table 2.1. Aside from Abele et al. (2007) and Abele and Worn (2009) that proposed SST-60 design for spindle module interfaces, there is no other design have been published. The mating interfaces that applicable to any modules that served the stationary joints in reconfigurable application is also unavailable. Thus, in the next section, mechanical mating interface design that is similar to the functional requirements that have been listed in Table 2.1 is reviewed.

Table 2.1: Summary of the functional requirements of the machine modules in RMTs

Num	Required function	Source of literature
1	Positional accuracy	Abele and Worn (2009) Abele et al. (2007) Moon (2006) Pasek (2006)
2	Quick change by easy for assembly and disassembly	Abele and Worn (2009) Katz (2007) Abele et al. (2007) Moon (2006)
3	Sufficient stiffness between interface	Abele et al. (2007) Lorenzer (2007) Katz (2007) Wiendahl et al. (2007) Pasek (2006) Moon (2006) Lin and Chen (2002) Landers (2001)
4	Standardized interfaces	Abele and Worn (2009) Katz (2007) Moon (2006)

2.4 Relevant Design for Mechanical Mating Interface

As reviewed, the functional requirements of mechanical mating interface are to have standardized interfaces and able to provide quick change that provides sufficient stiffness under predetermined accuracy. There are a number of other research fields that serve those functions. Modular machine tool is one of them. Before RMTs being introduced, a machine tool is already made in modular form. The machine tool is built up from many elementary parts to simplify their machining operation (Tsutsumi, 1979). Research in modular machine tool has already started since 1960’s and the findings can be used as starting point in the development of RMTs.