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STRUCTURE MODELING OF MACHINE TOOLS AND INTERNET-BASED IMPLEMENTATION

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ABSTRACT

Reconfigurability of machine tools is one of the critical factors to realize the responsive manufacturing systems to satisfy the mass-customization production. This paper presents the methods to model and simulate the machine tools on Internet in response to change in the machining requirements. Specifically, a set of module combination rules and a modeling method of the structure of machine tools using connectivity graph are developed. In response to the user requirements, kinematic relations and structures of machine tools can be derived using the module combination rules and connectivity graph relationships. Internet-based simulator of machine tools is implemented and presented. The developed machine tool simulator can be used to verify the structure of machine tools derived from the user requirements.

1 INTRODUCTION

Under the mass-customization paradigm which requires flexibility to produce the variety of products as well as the volume responsiveness, design of modular machine tools are necessary (Mehrabi, Ulsoy, and Koren 2000; `http://www.opengl.org`; `http://erc.engin.umich.edu`). To increase the responsiveness of machine tools to the required production volume and product variety, it is useful to model and simulate the changed functionality of machine tools through Internet.. This research is to present the method to model and simulate the structure of machine tools in response to the required changes.

Since the structure of machine tools has close relations with the other properties of machine tools, machine tools are designed based on their structures (Koenigsberger and Tlusty 1970). Vragov presents the notation to represent the machine tools using logic operation and multiple-factor theory (Vragov and Yu 1972). Shinno and Ito develop a series of methods to generate the structure of machine tools through introduction of modular components of machine tools (Shinno and Ito 1984, Shinno and Ito 1986). Kitajima and Yoshikawa (1984) propose a structure model to relate the components of machine tools in hierarchy, and develop a designing system of machine tools using the proposed method. Chaar et al.(1998) present the relational model to decompose and combining the module components of machine tools in a virtual environment and implement their model to develop commercial simulation software, ADAMS (Chaar *et al.* 1998). Ehmann et al.(1997) at MT-AMRI pointed out that simulation of machine tools is necessary to minimize the trial errors to design and implement the machine tools and present the framework of virtual machine tools (Ehmann *et al.* 1997). Suh et al. (2003) propose the web-based machine tool (WVMT) to model and simulate machining centers on Internet. Seo et al. (2005) develop a web-based CAM system to dynamically show the machining process on user's applet through Internet.

In this paper, we propose structure modeling method to generate various types of initial structure corresponding to user requirements that are composed function and structure element of machine tool.

2 STRUCTURAL MODEL OF MACHINE TOOLS

To systematically generate the structure of machine tools in response to user requirements, definitions of component modules and the relations between them are required. The structure of machine tools is represented by a connectivity graph. In the connectivity graph, the nodes represent the component modules of machine tool, while the arcs mean the contact and kinematics relations between them. In this section, three modeling elements of machine tool's structure are defined: component modules, contact and kinematics relations.

Component modules of machine tool contain the information on size, motion, motion type, etc. and are stored in a module library. Functional and shape characteristics of component module are utilized to visualize machine tools on computer and to derive contact and kinematics relations. Contact relations show the linkages between adjacent component modules. Various types of feasible machine tools' structure can be derived by applying module combining rules, which regulate the mating feasibility of two component modules. Finally, kinematics relations required to show the motions of machine tools can be derived by using functional characteristics of modules and connectivity relations. Figure 1 shows the relationships between the modeling elements of machine tools' structure.

2.1 User Requirements

Inputs submitted by user to define structure are summarized in Table 1 Modules containing function elements required by user are selected and the range of initial alternatives is restricted with inputs. Structure types of machine tool to be satisfy structure elements required are also provided. And the size of each module is adjusted for simulation that a volume of workpiece is considered.

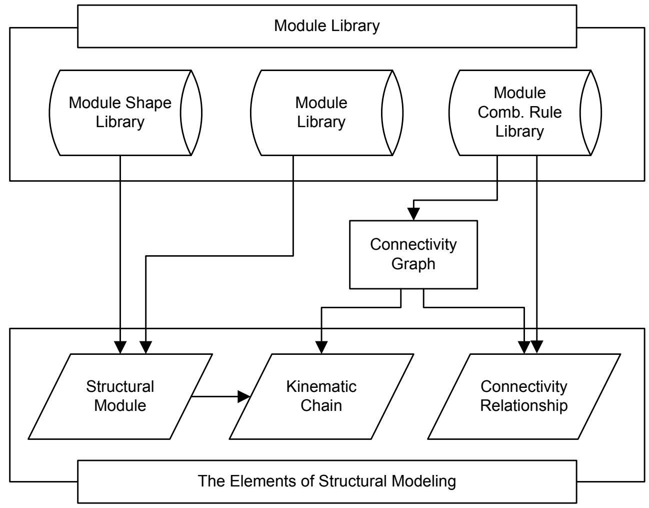

Figure 1: Relationships Between Modeling Elements

2.2 Module Library

Module library contains information on component modules in terms of input fields classified into functional and shape element. Function elements contain module name, module type, moving or static module and motion type, while shape elements include size, initial shape, guideway position, contact surface, mirrored shape and offset. Shinno and Ito (1986) defines nine basic components of machine tools as spindle, single slide, swivel slide, cross-slide unit, column, rotary table, base, column base and bed and provides 15 combining patterns between components using directed graph. Beside basic component modules by Shinno and Ito (1986), new component modules for recent-developed machine tools are defined and stored in module library (<http://mtamri.me.uiuc.edu/>). Also, user interface is provided to define and register new structure modules. Table 2 shows an example of modules in module library.

Table 1: User Inputs and Required Processes

Types	User Inputs	Required Processes
Functional elements	Types of module	Select a set of modules using module combining rules.
	Axis of motion (*x, y, z, a, b, c*)	Define the motions of selected modules.
	The number of tools in ATC	Determine the number of tools for displaying ATC.
Structural elements	Tool approach direction (vertical, horizontal)	Confine the machine tools with the tool approach direction specified.
	Types of machine tools (vertical, horizontal, gantry etc.)	Confine the feasible range of machine tool's structures with the type specified.
	Workpiece volumes	Determine the feasible range of machining volume for machine tools designed.

Table 2: Example of Input Field for Module

Function elements				Shape elements					
Module name	Type	Move	Motion type	Size	Basic Shape	Guide-way position	Contact surface	Mirrored shape	Offset
Wall-type column	Column	false	none	(3, 3, 10)	Block	s1	s2, s4	true	(0, 0, 0)
Swivel Slide	Slide	true	rotary	(3, 3, 1)	Cylinder	none	s3, s4	false	(0, 0, 0)

2.3 Module Combining Rules

Module combining rules regulate the feasibility of topological relations between two modules. Also, to represent the overall shape of machine tool on computer, the contact surfaces between modules and their orientations in the combination are required to be precisely specified. To express the contact relation between two modules, a node (*i.e.*, module) in connectivity graph follows the notations below.

$(m_i, s_{i-1}/s_{i+1}, o_i)$,

where m_i = the number of *i*th module in connectivity graph, s_{i-1} and s_{i+1} = contact surfaces of *i*th module with previous (*i.e.*, (*i*-1)th) and followed (*i.e.*, (*i*+1)th) module respectively in connectivity graph and o_i = orientation of *i*th module. The orientation of a module means rotation around y-axis in Cartesian coordinate system. Figure 2 and 3 respectively illustrate examples of surfaces and its 4 orientations. For instance, a part of connectivity graph '(0, -/s2, OT1) → (1, s1/s4, OT1) → (2, s3/-, OT1)' means that the surface s2 of spindle module with module number 0 and orientation OT1 contacts with the surface s1 of the head module of number 1 with orientation OT1, and the surface s4 of the head module with orientation OT1 contacts with the surface s3 of slide of module number 2 with orientation OT1.

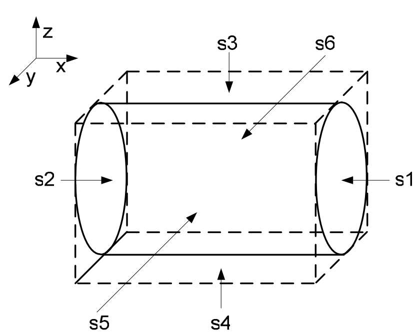

Figure 2: Example for Definitions of Surfaces

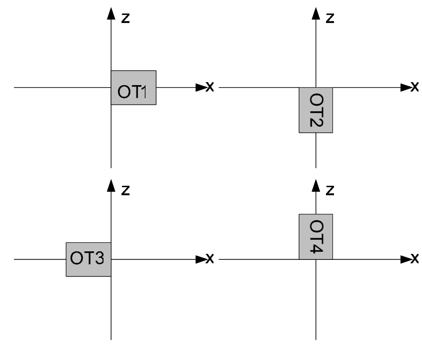

Figure 3: Definitions of Orientations

The module combining rules in the module combination rules library regulates the feasible combination of two modules. New rules are able to added. For example, the head with module number 1 can be connected to #2 slide, #3 swivel slide, #6 cross-slide or # 7 base. The contact surface of the head is the only s4. Each module is defined to some contact surfaces. Among these surfaces, particular surfaces can be made use of connecting surface for other modules. Table 3 provides a part of module combining rules.

Table 3: Example of Module Combining Rules

No.	Module name	Module Combination Rules
0	Spindle	(0, -/s2, OT1) → (1, s1/-, OT1)
1	Head	(1, -/s4, OT1) → (2, s3/-, OT1) (1, -/s4, OT1) → (3, s3/-, OT1) (1, -/s4, OT1) → (6, s3/-, OT1) (1, -/s4, OT1) → (7, s3/-, OT1)
2	Slide	(2, -/s4, OT2) → (4, s1/-, OT1) (2, -/s4, OT1) → (9, s3/-, OT1)
3	Swivel Slide	(3, -/s4, OT1) → (2, s3/-, OT1) (3, -/s4, OT1) → (7, s3/-, OT1)
4	Column	(4, -/s4, OT1) → (6, s3/-, OT1) (4, -/s4, OT1) → (8, s3/-, OT1)
…	…	…
13	Wall-Type Column	(13, -/s4, OT1) → (F, s3/-, OT1)
14	Cross-Bar	(14, -/s4, OT1) → (9, s3/-, OT1) (14, -/s4, OT4) → (13, s1/-, OT1)

2.4 Connectivity Graph Representation

A unidirectional graph can be used to model the structure of a machine tool, *i.e.*, topological relations between the components of the machine tools. The nodes are used to represent the components of machine tool, while the arcs the connectivity relation between the components. The direction of arc is reflected by the flow of forces of a machine tool (Mehrabi, Ulsoy, and Koren 2000, Chaar *et al.* 1998). The flow of forces, which is used to obtain the functional decomposition of the machine, takes into account all the different forces that are present in the machine tool. The main flow of forces goes from the cutting tool to the base, while the secondary flow of forces is the one transmitted from the piece-holder to the base. Both flows of forces join in the piece-holder and the basement. Thus, the arrows of the directed graph for representing the machine tool are heading for the basement of the machine tool from the cutting tool and the workpiece-holder respectively. A vertical machine tool and its directed graph representation are illustrated in Figure 4 and 5.

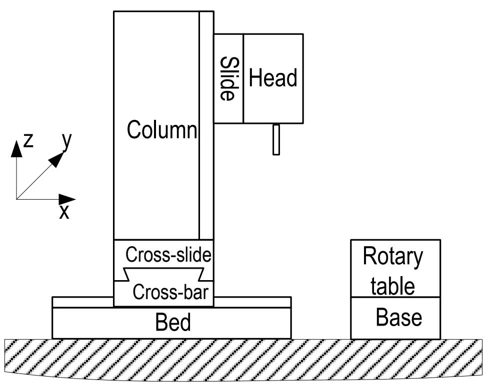

Figure 4: Schematic Diagram of a Vertical Machine Tool

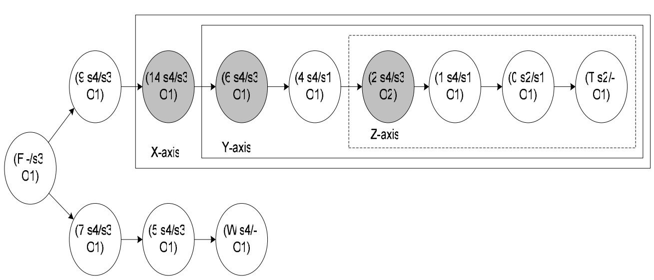

Figure 5: Connectivity Graph for Vertical Machine in Figure 4

2.5 Derivation of Kinematics Relations

Homogeneous transformation matrix (HTM) is used to express the kinematics relations of a machine tool. Let $T_{x\chi}$, $T_{y\psi}$ and $T_{z\omega}$ be used to respectively express the translation of χ, ψ, ω along x-, y-, z-axis, and $R_{x\alpha}$, $R_{y\beta}$, and $R_{z\gamma}$ be respectively the rotation of α, β, and γ degree about x-, y-, z-axis. Kinematics relation of each component module is derived based on functional elements of the module defined in connectivity graph. The HTM K^R_i of module i along reference system R is expressed as product of HTM K^R_{i-1} of previous module and the HTM A_i of module i.

$$K^R_i = K^R_{i-1}.\ \ A_i$$

For instance, The HTM K^9_2 of slide module # 2 along reference system of the bed of module number 9 is represented to the product of the HTM K^9_4 of previous module # 4 and the HTM $T_{z¥ø}$ about motion of module # 2 along reference system 9.

$$K^9_2 = K^9_4\ .\quad A^9_2 = K^9_4\ .\quad T_{z¥ø}$$

Tool path (TP) represents a path from shop floor to tool, while workpiece path (WP) means a path from shop floor to workpiece. Therefore, kinematics chains of the machine tool shown in Figure 6 can be obtained by chaining the HTMs as shown in Table 4 and Figure 6.

Table 4: Example of Kinematics Chain's Derivation

Kinematic chain of TP	Kinematic chain of WP
Bed(9) $K^9_9 = I$ Cross-bar(14) $K^9_{14} = K^9_9 \cdot T_{x¥ö}$ Cross-slide(6) $K^9_6 = K^9_{14} \cdot T_{y¥÷}$ Column(4) $K^9_4 = K^9_6 \cdot I$ Slide(2) $K^9_2 = K^9_4 \cdot T_{z¥ø}$ Head(1) $K^9_1 = K^9_2 \cdot I$ Spindle(0) $K^9_0 = K^9_1 \cdot I$	Base(7) $K^9_7 = I$ Rotary table(5) $K^9_5 = K^9_7 \cdot R^5_{z¥ã}$

3 INTERNET-BASED MACHINE TOOL STRUCTURAL MODELER(IMSM)

In this paper, Internet-based Machine tool Structural Modeler (IMSM) is implemented using OpenGL and VC++ based on the proposed modeling method of machine tools (Seo *et al.* 2005). It can generate easily and quickly initial alternatives of machine tools which satisfies the functions and structures required by user. Consequently, IMSM can automate the routine processes needed to design machine tools. Also, to consolidate expert knowledge for structural design into IMSM, initial alternatives can be modified by adaptation process followed. In Figure 7, flow of logics for IMSM is illustrated.

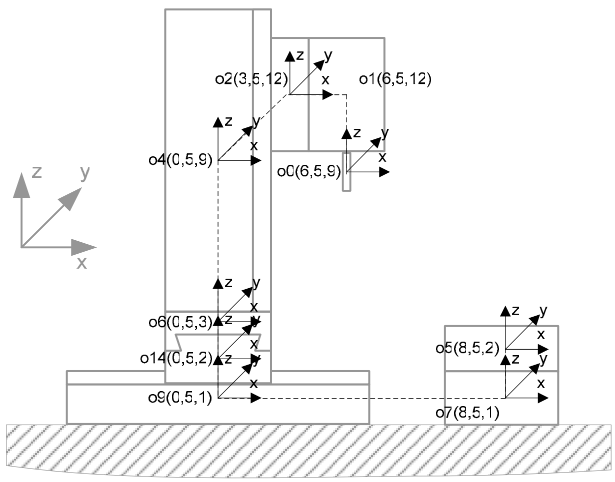

Figure 6: Example of Kinematics Chain

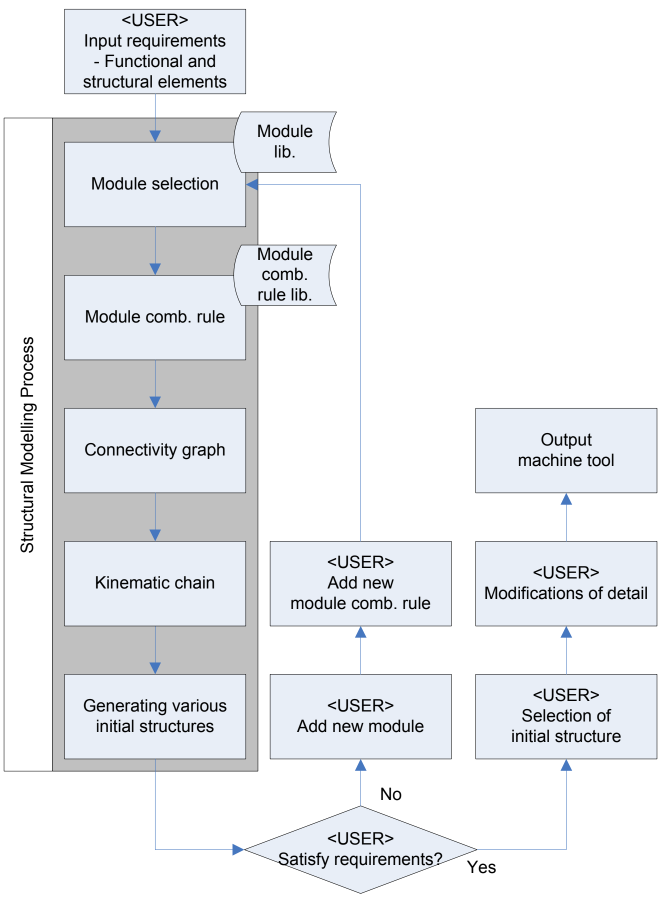

Figure 7: Flowchart Representation of IMSM

In this research, module and structure library contains various subordinated libraries as shown in Figure 8: module library contains component modules, module shape library includes the complicated module shapes, module combination rule library for combination rules, structure library stores the complete machine tools. The library is useful for information sharing, reusability and standardization of modules or machine tool's structures.

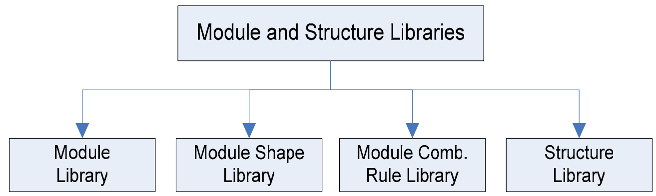

Figure 8: Types of Libraries in IMSM

Among initial alternatives automatically generated to meet the user requirements, the user can select one structure and modify the structure configurations in detail level. After modification, users can control and simulate the machine tool generated on computer monitor with keys or control buttons. If user does not satisfy with the initial alternatives, user can regenerate them after adding new modules or new module combination rules. The IMSM supports the modification process by providing user interfaces to edit module specifications, contact relations between modules, accessory modules, etc.

In Figure 9, various types of machines tools are presented to show the proposed medeling methods. A vertical and a horizontal machine tool are presented in the top row of Figure 9, and new structures of machine tools developed as test bench are also generated and shown in the bottom row of Figure 9.

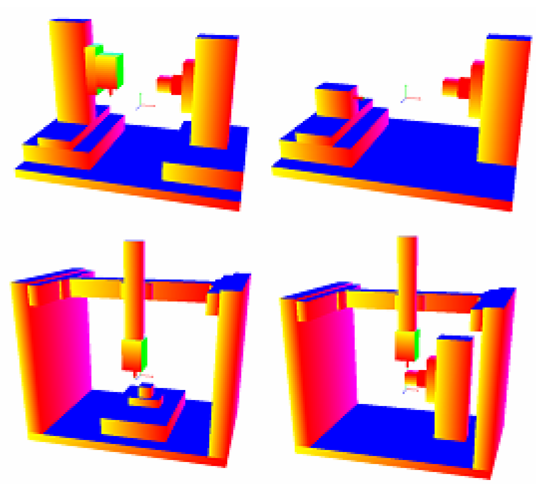

Figure 9: Various Machine tools Generated in IMSM

4 CONCLUSION

In this paper, a machine tool modeling method is presented to generates automatically the structures of machine tools in response to the functional and structural requirements by user. The proposed method automates the machine tools' structure generation using the module combining rules and connectivity graphs and automatically derives kinematics chain using functional elements of modules and connectivity graph. Based on proposed modeling method, the Internet-based Machine tool Structural Modeler is implemented. The proposed method can be utilized for rapid constructing the large-scale virtual plant and be applied to CAD/CAM system for machine tools which support the reconfigurable manufacturing system.

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