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ORIGINAL ARTICLE

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An integrated inference architecture for machine tools design involving complex knowledge

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Abstract This paper describes the inference architecture of an intelligent CAD system that is to be used for the design of machine tools in which a complex and large amount of knowledge is used. In order to investigate the issue of handling huge and complex knowledge, the design knowledge for the machine tools design is categorised into four types and inference methods for them are identified respectively; original design problems are decomposed into several modules of design processes and finally into sub-problems with the four types of knowledge as the basic elements in a top-down manner. We demonstrate the implementation of the architecture with the result on the machining centre design.

Keywords Inference system · Design knowledge · Intelligent CAD · Decomposition

1 Introduction

Developing efficient ways to infer and manage design knowledge for intelligent CAD systems is one of the challenging problems in the area of computer-aided design [1,2,3,4]. Difficulties in solving the problem result from characteristics of the intelligent CAD systems: since the intelligent CAD systems are to support the entire engineering design process, the design knowledge involved in the systems is quite large and diversified [3,4]. In addition to the characteristic mentioned, since the intelligent CAD systems are to support the design processes by interactions between the designer and the computer, the inference processes involved in the systems are supposed to be capable of modifying the form of the design knowledge as the designer chooses the options [3,4].

This paper is an attempt to propose an architecture for an intelligent CAD system that manages the design of machine tools. Since the machine tools we are to design consist of several sub-units involving a large amount of conditions and data to consider [5,6,7,8], the knowledge used in the processes to design is of various kinds and complex [9,10,11,12]. Thus, for the architecture to be efficient and reliable, the interdependent knowledge for the design processes is decomposed into a level in which the knowledge and processes can be managed systematically.

Four types of knowledge about the design objects of machine tools are classified to define the level of decomposition and four types of inference procedures for them each are also proposed and identified in this paper. The four types of knowledge are equations, the rules for production systems, the rules for multi-criteria decision making and formalised data such as tables and graphs. The four types of inference procedures are a constraint network based inference, a rule inference, multiple attribute decision making and table data retrieval. The inference procedures are from our successive pieces of previous work [4,5,6,13,14]. Based on the architecture proposed, an intelligent CAD system is implemented and a machining centre, one of the machine tools, is designed with the system as a case study to show the efficiency of the system.

2 A basic approach: decomposition

The main issue that arises from designing the architecture of inference engines for machine tools design is how to deal with the complex and massive amount of knowledge involved in the design tasks [9,10,11]. This is the key issue for the inference architecture of the

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knowledge integrated CAD system to be proposed in this paper. In this section, an outline of the approach is given to show how the architecture works.

Basically, in this study, we use a top-down approach that decomposes a design problem into smaller, known sub-problems as shown in Fig. 1, since a design is a set of processes in which a many pieces of knowledge are modified and used to satisfy a design specification [15,16]. More specifically, we can model a design with some sets of knowledge and processes to manage them. Design knowledge can be divided into the knowledge of design objects and the knowledge of design processes. A catalogue of standard and existing parts, knowledge of the design and manufacturing, industrial standards, etc., belong to the former. A knowledge of the previous design, evaluation and selection knowledge, and the experience of engineers belong to the latter.

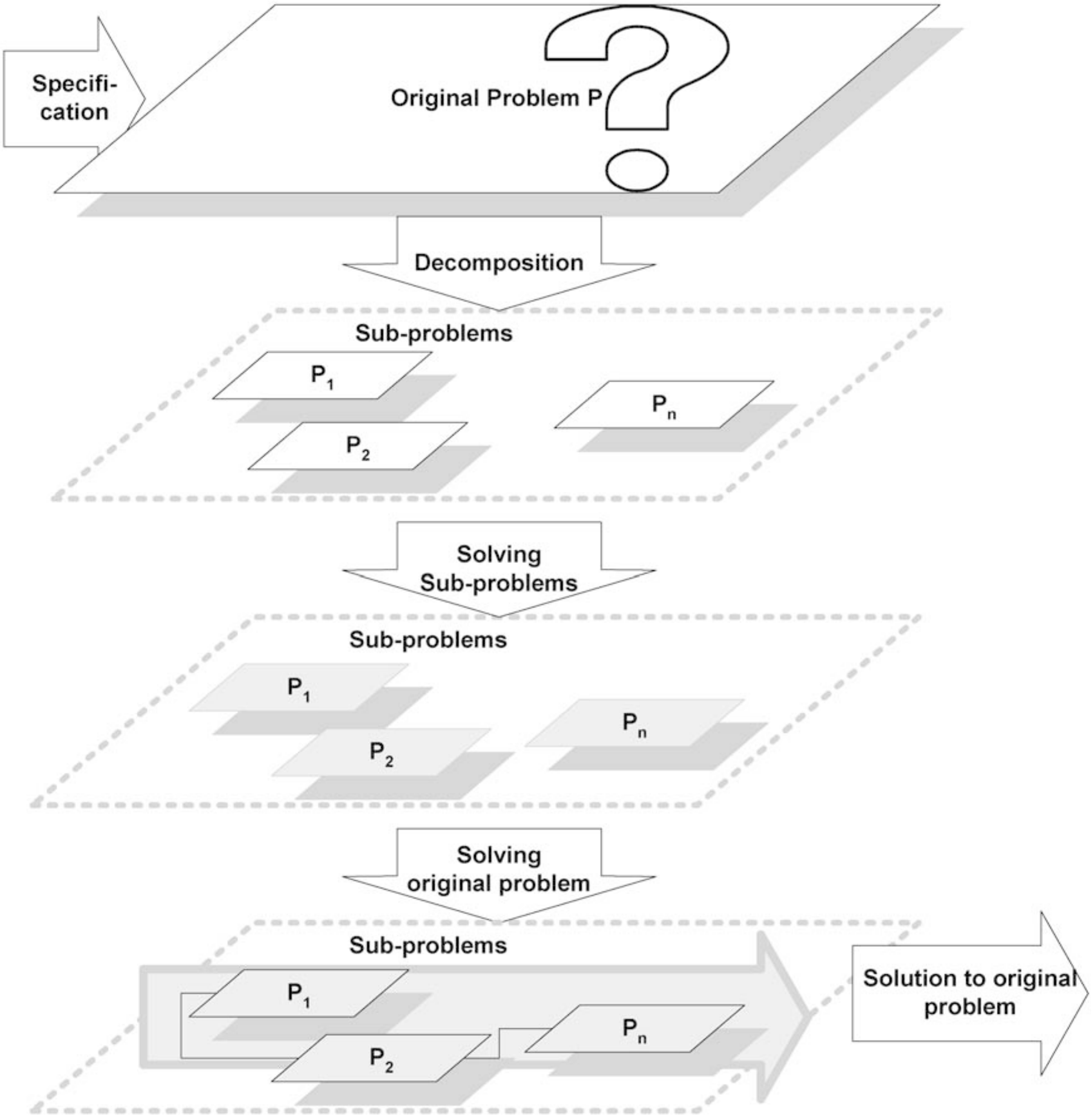
Since there are many types of knowledge in a design task, a set of knowledge types should be identified according to the design object in advance. One of the key issues in designing the architecture we are to propose is to define a concrete set of the types of knowledge to represent sub-problems effectively [9,10,11,12,15,16]. In addition to defining the types of knowledge for the assembling processes of the sub-problems so that they are fully systematic several modules consist of currently available pieces of sub-problems which are also used in the decomposition process.

3 The machining centre design

3.1 Design modules

As a first step, the machine tools design, as with so many other designs, can be decomposed into several design

Fig. 1 A top-down approach



modules, which are groups of physically or conceptually dependent design processes. Thus, a design module can be represented with several sets of more dependent pieces of knowledge and used to manage the overall flows of the complex processes involved in machine tools design in a consistent manner. From the practical design experience of the area of machine tools design, the processes of the machining centre we designed is roughly composed of the following four modules [5,6,7,8]:

- Configuration design module: in the module, key outer dimensions of sub-units consisting machining centres are decided, appropriate types of machine structure are selected and the goal specifications are set on the reception of the design requirement.
- Spindle unit design module: in the module, key dimensions of the main spindles and housings and details of spindle units such as drive mechanisms, types of auto-chucking, approximate dimensions, specification and arrangement locations of main bearings, etc., are decided.
- Feed drive unit design module: in the module, the parameters of ball screws are decided, the geometric details of guideways and the drive mechanisms are designed, and appropriate servomotors are chosen.
- Constructional elements design module: in the module, detailed size and shape of columns, beds, carriages etc. are determined and ribs for reinforcing the mainframe are also defined and allocated.

3.2 Design activities

The design modules can also be decomposed into several design activities that are represented with a specific knowledge type. To give proper representations to the design activities, the activities involved in the design should be identified first.

Design activities can be categorised, though they are not precisely fixed, into three design types, i.e., original design, adaptive design and variant design. The original design is a type of design involving elaborating an original solution principles for a system with the same, a similar or a new task; adaptive design is a type of design involving adapting a known system to a changed task and variant design is a type of design which involves varying the size and arrangement of certain aspects of the chosen system [17].

Since, in the majority of cases, the design of machine tools is performed by adaptation or variation, the design system takes only adaptive design and/or variant design into consideration. Considering the definition of adaptive design (to adapt a known system according to a changed task or a condition) it can be expected that actual cases of adaptive design are designed with comparatively less formalised knowledge such as changing parts, types of modules and types of machine tools with specific decision-making knowledge.

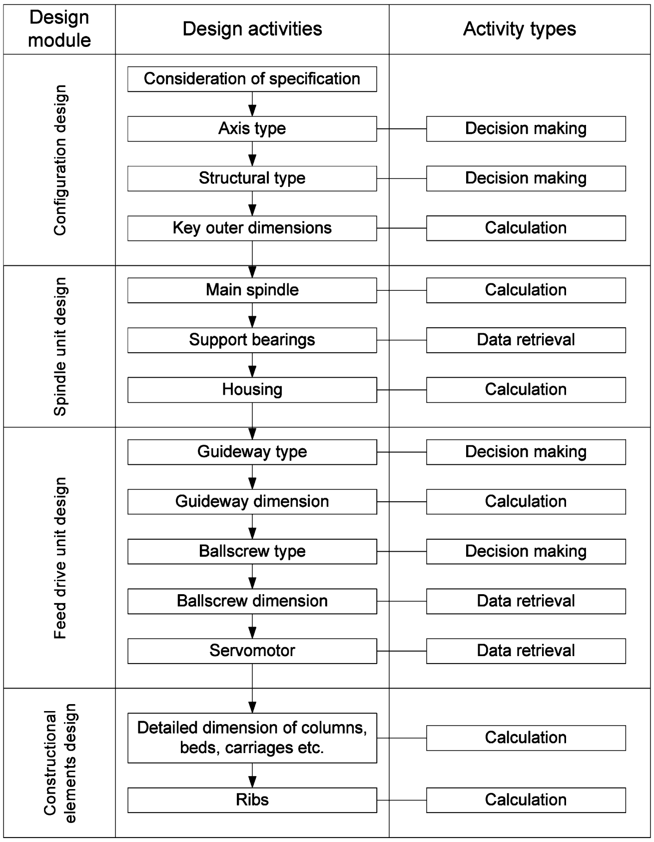


Fig. 2 Design activities and types

Considering the definition of variant design (to vary several parametric values according to a changed task or condition) it can be expected that actual cases of adaptive design are designed with comparatively more formalised knowledge such as calculating something from specific equations and referring to data from a graph or a table.

The actual machining centre design activities and their types are illustrated in Fig. 2. As shown in the figure, the design processes are represented as activities of specific types. It can also be seen that the activities of decision are performed in the early stages of the design of each module, as compared to the activities of calculation or data retrieval.

4 Knowledge types and inference

4.1 Four types of knowledge

In the previous section, each module of machining centres was divided into sub-problems and represented by several types of manageable activities. Now that decision making activities can be performed with if-then rules and multi-criteria decision making rules according to the properties of the rules involved, the design knowledge used in the machine tools design is classified into next four categories: equations, if-then rules, multi criteria decision-making rules and a series of data such as graphs or tables. The categories have their own representation methods for their specific forms and their own problem-solving methods for their specific representation methods.

4.1.1 Equations

Equations are a type of knowledge representing relationships between parameters in the forms of mathematical statements. A set of knowledge described with equations involves accurate and exact information about the properties and relations of parameters in very compact and efficient ways. Since a physical mechanical design is a much more complex process than just the specification of geometry, equations are used in a basic form to describe complex design knowledge that can be even nonlinear and can contain either equalities or inequalities.

Constraint networks are used to effectively represent and solve the equations. Since constant networks represent knowledge in declarative forms, the knowledge represented with constraint networks is compact, highly modifiable and easily manageable to deal with. Therefore, we can expect to manage knowledge at a comparatively low cost [1,2,3,4].

Equations that are represented with constraint networks are resolved based on several methods from our previous work on constraint satisfaction algorithms. These are the variable elimination and constraint propagation method for closed loops [4], and the constrained network based simulated annealing (SA) for under constrained conditions [14].

4.1.2 If-then rules

If-then rules are a type of knowledge that is composed of independent rules represented as 'IF condition-THEN process' [16]. If-then rules are a method to define a series of simple but powerful relationships that denote logical connections between facts such as if, then, and, or, etc. If-then rules have several specific merits in the representation of knowledge. Since they are in a form of a common language, it is comparatively easy to understand and use them; since a rule is dependent on other rules, it is easy to use empirical fragmentary knowledge; since they are represented in simple ways, it is easy to represent vague knowledge in an if-then statement like empirical data [13,15]. If-then rules are one of the two primary types of design constraints together with equations and there are many different tools developed in AI fields to cope with the representation and inference of rule-based information.

4.1.3 Rules for multi-criteria decision making

There are great many cases when we have to select one option among some alternatives during design tasks. The multi-criteria decision-making is a powerful way to choose one best solution among possible options: when there are a large numbers of items to be considered, it is effective to represent the knowledge of the decision-making processes by the relative importance of the criteria and the impacts of the alternatives [18].

Multivariable reasoning is one of the multiple criteria decision-making approaches [6]. It is a method that considers various and complex conditions simultaneously by several numerical measures such as expectation values, the weight factors for comparative importance, the evaluation values of performance, etc. The preference P_i of alternatives is calculated according to the following formula [18]:

$$p_i = \sum_{j=1}^{N} a_{i,j} W_j \tag{1}$$

where,

P_i = *preference*

$a_{i,j}$ = *evaluation value of performance*

W_i = *weight factor*

4.1.4 Table and graph data

A table is a set of knowledge that is arranged in columns and rows and a graph is a mathematical diagram that shows the relationship between two or more sets of numbers or arguments. As design knowledge, table data and graphs are used when the design processes are highly formalised and fixed through a great number of design cases. Since machining centre design is also a highly formalised process, a large part of the knowledge is used in the form of table and graph data throughout the design processes. In practical terms, the design knowledge condensed in the forms of tables and graphs is very efficient at a low cost. In the case of using graphs, it is quite efficient to transform curves in graphs into parametric curves like NURBS curves [13,15].

4.2 The integration of inference processes

To summarise the types of knowledge categorised, we have presented four different forms of knowledge and the approaches for processing them. The four basic pairs are proposed in this paper to be used in machine tools design. The relations between the four types of knowl-

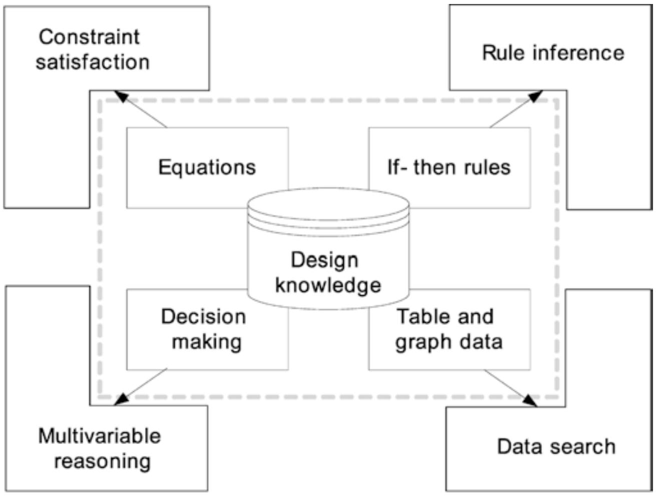


Fig. 3 Knowledge representations and solutions

edge and their respective approaches can be seen in the diagram in Fig. 3.

Based upon the classified four types of knowledge and the approaches for processing them, an inference engine of an intelligent CAD system is proposed. The hybrid engine is composed of four sub-engines for the four types of knowledge as shown in Fig. 4. The hybrid engine performs practical inference tasks of processing sub-problems represented according to their types, and assembles the sub-solutions into the original design problem.

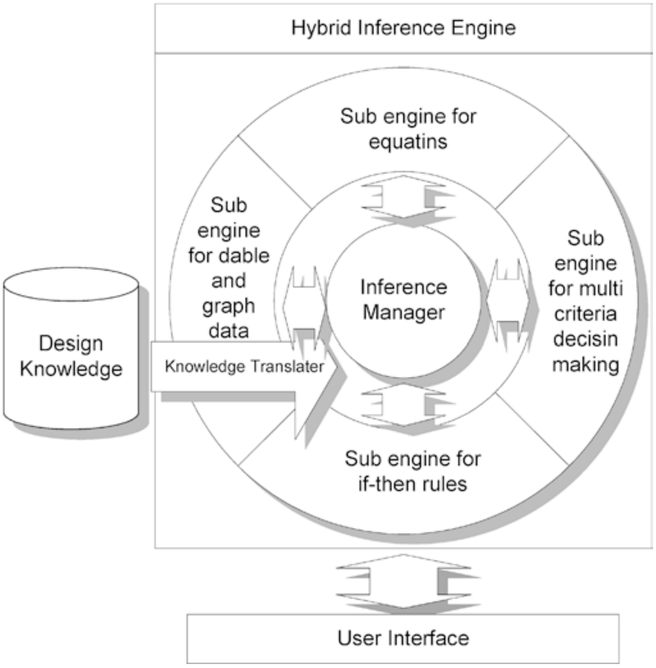


Fig. 4 The architecture of the hybrid inference engine

5 Case study: a machining centre design

In this section, a machining centre is designed with given specifications. The design flow can be seen in Fig. 5. In

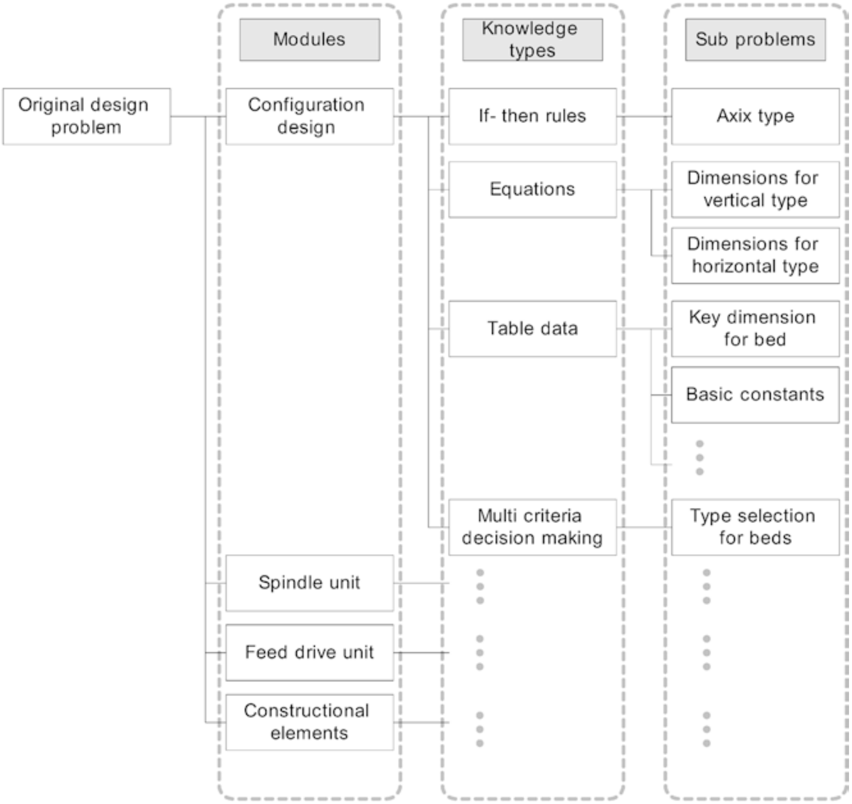


Fig. 5 The architecture of the knowledge for machining centres

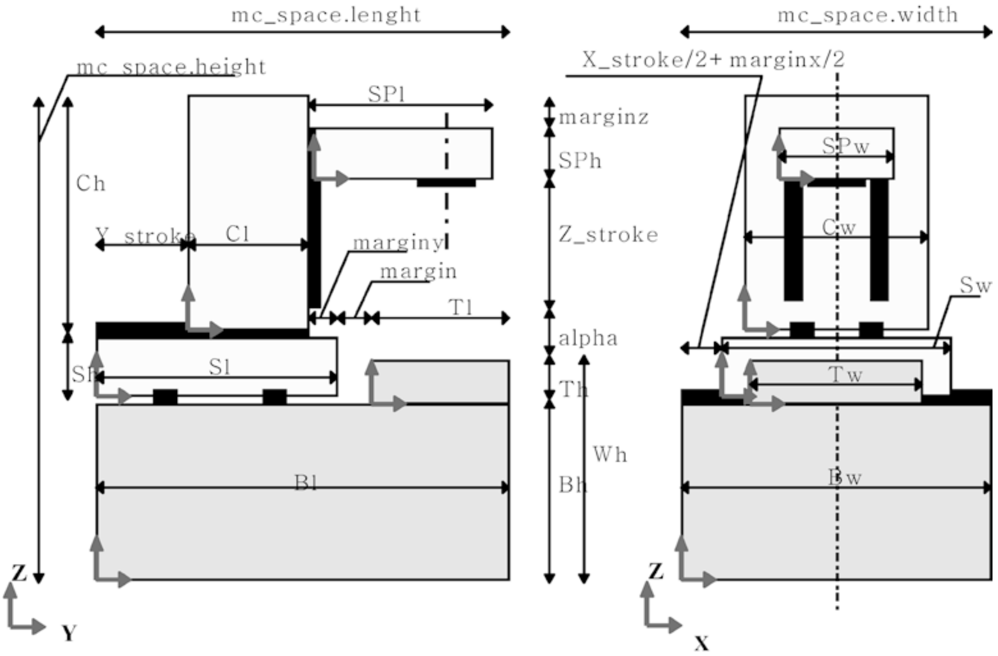


Fig. 6 The outline feature of a machining centre

the four modules, there are several cases that show us how the knowledge is used.

In the configuration design module; if-then rules are used for the type selection process where the types of machining centres are chosen. A set of rules is to choose one type mostly satisfying the requirements given by the engineer.

In the configuration design module, there are also processes that are highly regularised. Table data is used in the process to determine several parameters of, for example, beds and tables, i.e., particular parts of a machining centre. The key parameters to determine the outlined features of the machining centre are shown in Fig. 6 and the parameters listed in the table data are shown in Table 1.

Equations are also used to determine some parameters of beds and tables: unlike table data, equations are used for the case when there are some numerical relations between parameters. There is a set of equations for these relations in Fig. 7.

Table 1 The table data for the configuration design module

Table grade	Tl	Th	Wh	Margin y	Margin z	Alpha	Beta
400	400	100	850	20	20	200	0
500	500	125	900	20	20	200	0
600	600	150	950	20	20	200	0
700	700	175	1000	20	20	200	0
800	800	200	1050	25	25	250	0
900	900	225	1100	25	25	250	0
1000	1000	250	1150	25	25	250	0
1100	1100	275	1200	25	25	250	0
1200	1200	300	1250	25	25	250	0

A decision-making process is shown in the guideway type selection process in which suitable guideways for movement of beds are selected. In the selection process,

OBJECT
Configuration design module
MODULE
DimensionX
CONSTRAINT
MarginTx=Tw- XStroke
SPw=SPwMin
SSw=SPw*2.0*SS
Cw=SPw*2.0*(1- SS)+(SSw+XStroke+Marginx)*SS
:
:
Lw2=Lw1
CSw=(Cw+Marginx)*CS*(1- SS)
TSw=(Tw+XStroke+Marginx)*TS*(1- SS)
BCw=Cw+Marginx*(CS+1)+XStroke*XC
BTw=(Tw+Marginx+XStroke*XT)*(1- SS)+BCw*SS
Cframedistance=SPw*H

Fig. 7 Equations for a vertical-stroke type machining centre

Table 2 The evaluation value matrix for the slide guideways

	SQ1	SQ2	SQ3	SQ4	VF	DB	HM
Stiffness-vertical	5	5	3	3	3	3	3
Stiffness-horizontal	3	3	3	3	3	3	3
Stability	3	3	3	3	1	4	4
Manufacturability	2	2	3	5	2	3	3
Chip removability	3	2	3	5	2	3	3
Size	5	5	3	4	2	3	3

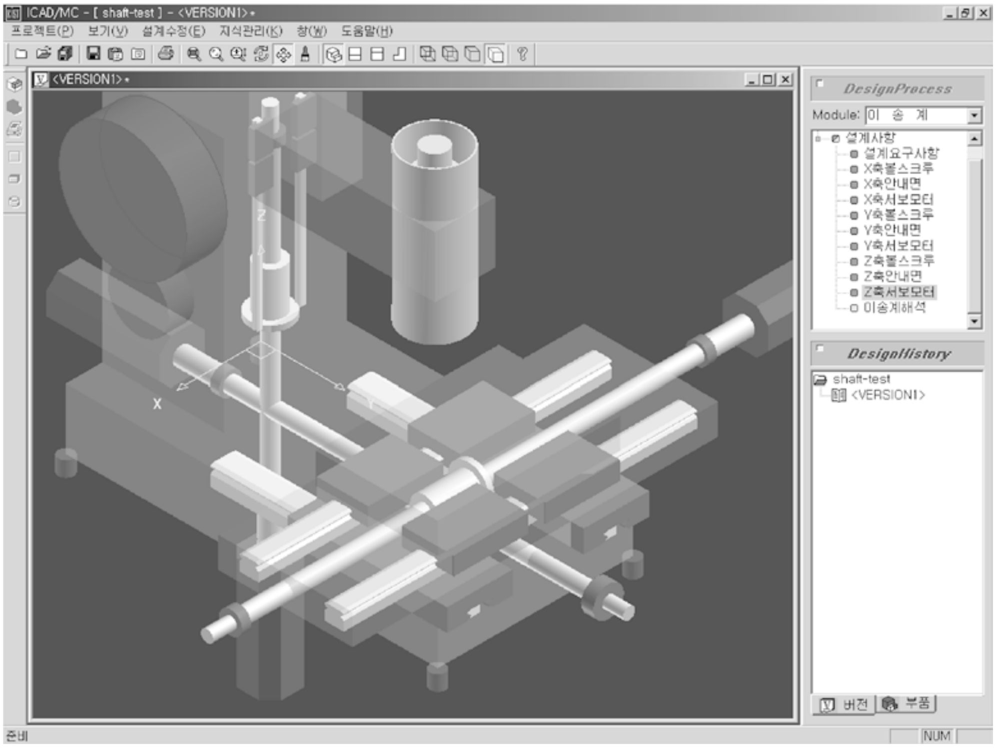


Fig. 8 Three-dimensional renderings of the design results

several properties of the guideways such as strength, manufacturability, cost, etc., are considered at the same time. Table 2 shows the evaluation value matrix for a slide guideway: the rows are terms of criteria and the columns are alternatives.

With the design processes, involving several processes shows as examples, a machining centre was finally designed. Three-dimensional renderings of the design results are shown in Fig. 8.

6 Conclusions

In this paper, an integrated inference architecture for machine tools design was proposed. The architecture makes inference processes of design, especially for machine tools in which huge and complex knowledge is involved, effective and manageable. The important issue was to manage the design knowledge for complex and large design objects. The decomposition of the original problems, based on a top-down manner, was used as the approach. Through the decomposition, the original problems were divided into several modules and finally sub-problems represented by different types of knowledge. By accessing those types of knowledge, four of them were specifically classified and the appropriate methods for processing them were identified. With the architecture proposed, an inference engine was developed and an intelligent CAD system was implemented with the inference engine. As a case study, a machining centre was designed conceptually in this paper as well.

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