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# EXPERT SYSTEM IN DESIGN AUTOMATION FOR CUSTOMIZED PRODUCT DEVELOPMENT - THREE DEGREE OF FREEDOM VERTICAL CNC MILLING MACHINE

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**Abstract**

New product has been emerging on the market faster and with better quality. There is a new emerging market, which is custom product development. The custom product development faces challenges such as time constraint and necessity for exploring customer view. In the concurrent engineering, more advanced CAD system is employed in the designing process such as virtual prototyping or AI. This article offers an alternative solution to enhance the design efficiency by using a formally defined expert system to automate designing process and generating 3D model, which is referred as design automation. One of the design automation being developed is the design of three degree of freedom vertical CNC milling machine. This system could boost the efficiency in designing and replaces the repetitive task in designing similar product.

**Keywords**: Design Automation, CNC Milling, Product Development

## INTRODUCTION

New products have been launching on the market faster than its predecessor also with better function, durability, and cheaper. These constraints are the challenges facing in the engineering design and that means there is a shorter period of time in developing process. Thus put the designer under the great pressure to produce results as quickly as possible and often skip the analysis process in early design [1]. One of the many analysis method is Design for Manufacture and Assembly. This method could increase the productivity, efficiency and reduce the production cost if it were done in early stage.

According to Dieter, design is a process that pulls together something new to arrange existing things in a new way to satisfy a recognized need of society [2]. Nowadays, design is not just only for mass production but there is a demand for a customized design, a unique design and it is referred as custom product development. The customized product mainly equipped with the same equipment and offer the same feature but it is made to be tailor suited into the customer specification.

The problem in the custom product development is limited amount of time and meanwhile the need to explore customer perception on the customized product. However, in current computer aided design (CAD) system, there is virtual prototyping, which enables designer to provide design definition and a tailored, scenario-based environment to meet the expectation of the customer [3]. Virtual prototyping could greatly reduce resource and time invested. However, it consumed a considerable amount of time to generate a virtual prototype, which is dependent to skill of designer.

It is expected the next generation of design and manufacturing system is autonomous and intelligent so it can shorten the process or even skip the design process. Early application of artificial intelligent (AI) in design system is the system called ‘EDISON’, used to generate simple mechanical devices described by Dyer, Flower, and Hodges [4]. Recent development of AI in design is the implementation of genetic algorithm in CAD system described by Renner [5]. These system offer a better flexibility

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application in CAD system and the compensation of it is the better understanding of the definition of design.

In any circumstances, the lack of understanding and expertise formulation somehow led the practitioners to re-use of previous solution in the development of AI in CAD system [6]. This approach offer more simplicity in the development of system and the processing logic is similar to rule based. One of the many in its kind is the expert system which is formally defined as described by the Whitley [7]. This article will explore a new way of the CAD system which uses design automation based on this formally defined expert system with a study case on three degree of freedom CNC vertical milling machine.

A Computer Numerical Control (CNC) machine tool is a machine tool that uses a set of instruction to automatically position of cutting tool relative to workpiece. A milling machine is a type of machine tool defined by a rotating tool with cutting edges which is used to mechanically remove materials in forms of chips, as defined by [8]. Thus a three axis of CNC milling machine consist of some compulsory mechanical electrical components, which are linear motion guide, linear system positioning, actuators in each respective axis and cutting spindle as well as the controller of CNC systems.

Machine structure is the essential factor in determining the performance of the machine tools itself since it is directly affecting the stiffness of the machine whether it is statically or dynamically. There are two common type of machine structure in the industrial, which are open frame and closed frame structures, described by Slocum [9]. Each kind of structures have their own pro and cons as well as application, which has been described by Wei Qin [10]. The structure of CNC milling machine in this article will adapt to the open frame structures, as shown as Figure 1.

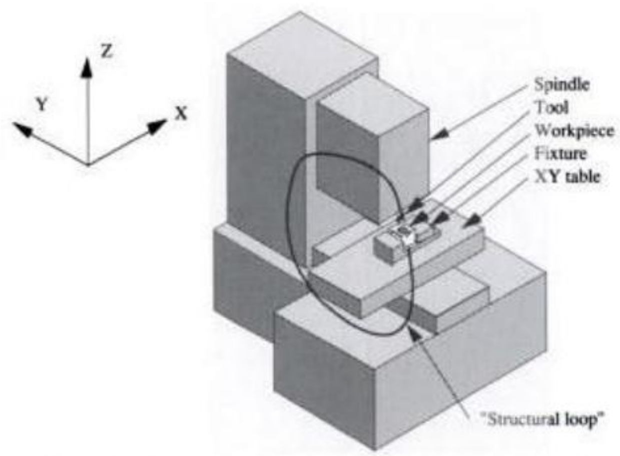


Figure 1. Open frame machine tool structure vertical tool position [9]

## LINEAR MOTION GUIDE

Linear motion system used in this design of vertical CNC milling is linear guideways, which consist of rail and blocks. Linear guideways in milling machine is used as an element for distributing the load such as cutting force or any acting forces from the system to the machine structure while maintaining the system precision. The linear guideways used in this milling machine is commercially available HIWIN linear guideways and the selection of it is based on the maximum acting load distributed at each block which the value must be lower than the dynamic load specified in the manufacturer specification. The distribution of load in a vertical milling machine could be modeled as Figure 2.

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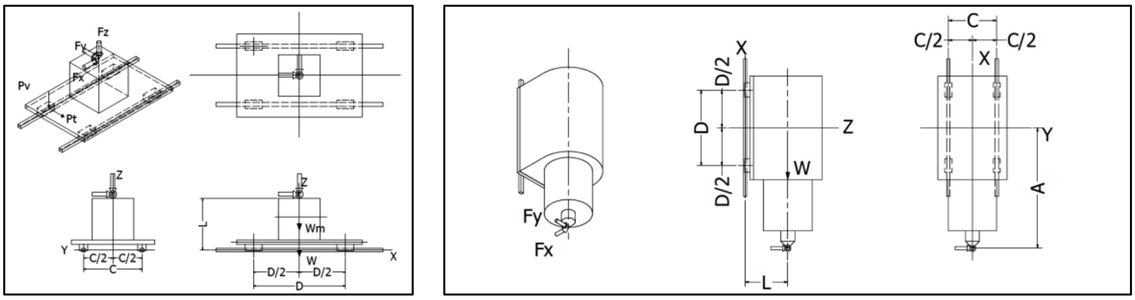

Figure 2. Load distribution in XY table (left) and spindle (Right)

Maximal load distribution is the sum of vertical load distribution $(F_{LV})$ and tangential load distribution $(F_{LT})$ of block, which is given by

$$F_{LG} = (F_{LT} + F_{LV})F_{SL} \quad (2)$$

Where $F_{LG}$ is the maximum distributed load of block, $F_{SL}$ is the safety factor load for linear guideways, which the value is about 5 with operating condition in presence of impact and vibrations [11]. Vertical load distribution and tangential load distribution of table XY in Figure 2. are given by

$$F_{LV} = \frac{W_K}{4} + \frac{W_m}{4} + \frac{F_z}{4} + \frac{F_x.L}{2D} + \frac{F_y.L}{2C} \quad (3)$$

$$F_{LT} = \frac{F_y}{4} \quad (4)$$

Where $W_k$ is the system loads, $W_m$ is material weight loads, $F_z$ is axial cutting force, $F_x$ is x-axis cutting force and $F_y$ is y-axis cutting force. Vertical load distribution and tangential load distribution of spindle in Figure 2. are given by

$$F_{LV} = \frac{W.L}{2D} + \frac{F_x.L}{2D} \quad (5)$$

$$F_{LT} = \frac{F_y.A}{2C} \quad (6)$$

Where $W$ is spindle and mounting weight loads.

## LINEAR MOTION POSITIONING

Linear motion positioning used in this design of vertical CNC milling is ball screws, which consist of screw and nuts. Ball screw in vertical milling is used as a mechanical device that translates rotary motion into a linear motion as well as position the nut along the screw. The ball screw used in this milling machine is commercially available HIWIN ball screws and the selection of ball screw is based on the maximum dynamic load acting on the screw. The maximum dynamic load is given by

$$C_{BS} = F_a\left(\frac{L_b}{10^6}\right)^{\frac{1}{3}} \quad (7)$$

Where as $C_{BS}$ is the maximum dynamic load, $F_a = F_b + F_{PR}$ is axial force of ball screw, $L_b = 5 \times 10^6 / \, l_e$ is travel distance of ball screw in rotation, and $l_e$ is lead value of screw. Axial force of ball screw consist of axial operating load $(F_b)$ and preload force $(F_{PR})$, which is present to maintain the system precision. The axial operating load and preload force are given by

$$F_b = F_{x,y,z}.f_p \quad (8)$$

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$$F_{PR} = \frac{F_b}{2.8} \quad (9)$$

Where $f_p$ is factor of ball screw operation condition. The factor of $f_p$ is about 3 with operating condition in presence of impact and vibration [12]. The dynamic load specified in the ball screw catalogue must be more than calculated maximum dynamic load.

## ACTUATOR

There are a lot of commercially available type of actuator could be used in this design of vertical CNC milling, which are servo motor and stepper motor. Each type of actuator has it pro and cons as described by Wei Qin for this design [10]. The actuator used is servo motor and the selection of servo motor for axis motor and spindle motor are based on the torque required to prevent from any malfunction or defect on cutting process. The torque required $(T_{Ma})$ for spindle motor is obtained from cutting force calculation. The torque required for axis motor is obtained from equation given by

$$T_{Ma} = T_a + T_d + T'a \quad (10)$$

Where $T_a$ is torque require for axial load, $T_d$ is torque required for preload, and $T'a$ is torque required for accelerating work piece. Torque for axial load, preload and acceleration are given by

$$T_a = \frac{F_a.l_e}{2.\pi.\eta_1} \quad (11)$$

$$T_d = \frac{K_p.F_{PR}.l_e}{2\pi} \quad (12)$$

$$T'a = \frac{l_e}{2\pi\eta_1}\left(\frac{W.a_b}{9.81\ m/s^2} + F_{f_{LG}}\right) \quad (13)$$

Where $\eta_1$ is mechanical efficiency from converting rotation to translation, $K_p$ is preload torque coefficient, $W$ is system weight loads, $a_{bs}$ is acceleration, $F_{f_{LG}}$is friction force from linear guideways. Mechanical efficiency of the ball screw is about 0.9 to 0.95 and preload torque coefficient is about 0.1 to 0.3 [12]. Torque required for axis motor is dependent on the lead value of ball screw.

## WORKFLOW OF THE SYSTEM

The work flow of this formally defined expert system in three degree axis of CNC milling machine begin with estimating the cutting forces. The estimation of cutting forces then are used to process a set of rules pre-defined for selecting main components such as linear guideways, ball screws and servo motor. The system then is to draft a selection of all components that will be awaiting the approval from the user. The approved components then will be used along with the other parameter to generate three dimension (3D) model. The whole process is illustrated in Figure 3.

The 3D modeling software used in this system is Autodesk Inventor 2013, the software has the parametric based 3D modeling feature as described in Mastering Autodesk 2012 [13]. This feature allows this pre-modeled CNC milling machine structure in this design to update instantaneously according to the parameter linked to Autodesk Inventor by using a third party interchangeable format. This interchangeable format is the essential tool for establishing one way communication between the expert system and the 3D modeling software. This system terminates at the point where the model has been updated to the desired model generate from the expert system.

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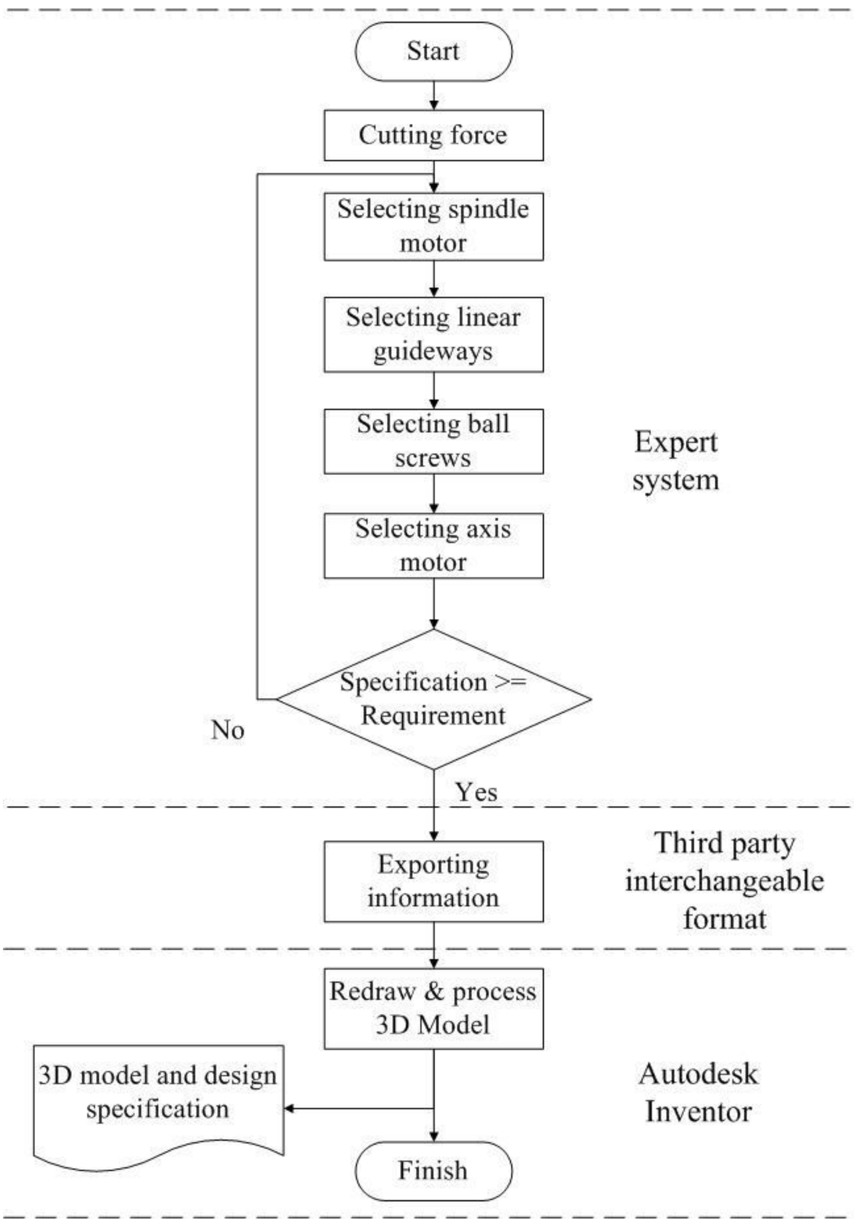


Figure 3. Work Flow of Expert Systems.

**STUDY CASE**

The expert system will generate a 3D model vertical CNC milling machine based on a study case with following input or constraints:

1. Maximum length of work piece is 600 $mm$.
2. Maximum width of work piece is 400 $mm$.
3. Maximum height of work piece is 300 $mm$.
4. Material of work piece is mild steel.

The acting working forces in a vertical milling machine consist of the work piece's material weight, the machine components itself and the cutting forces. The working forces are divided into several and limited milling operations. The cutting condition is then inputted into the systems and it will process to derive a rough estimation of cutting forces in each axis. The cutting conditions for each specific milling operations of this study case are tabled into the following Table 1.

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Table 1. Cutting conditions of study case

| Parameters | Drilling | Face Milling | Slitting | Shouldering | Slotting |
|---|---|---|---|---|---|
| Diameter $(mm)$ | 16 | 250 | 200 | 25 | 25 |
| Tooth | - | 12 | 10 | 6 | 6 |
| Axial depth of cut $(mm)$ | - | 4 | 50 | 20 | 25 |
| Radial depth of cut $(mm)$ | - | 175 | 9.5 | 10 | 10 |
| Feeding speed $(mm/rev)$ | 0.2 | 0.15 | 0.2 | 0.1 | 0.1 |

The maximal cutting forces processed by the expert system from the cutting conditions of several milling operation in Table 1. are tabled in Table 2.

Table 2. Maximal cutting force of study case

| Maximal specification | Value |
|---|---|
| Radial cutting force, $(N)$ | 2953.74 |
| X & Y-Axis cutting force, $(N)$ | 2517.19 |
| Axial cutting force, $(N)$ | 2758.54 |
| Cutting torque, $(N.mm)$ | 157 645.40 |

The expert system drafted up a selection of main components as tabled into the following table based on the maximal cutting forces in Table 2. The component listed in draft by the expert system could be changed by the user to another specification provided by the database if necessary and the system will make sure that the specification of changed component is still above the machine's requirement.

## RESULT AND DISCUSSION

Table 3. Milling machine specification of study case

| Desgination | | Specification |
|---|---|---|
| Maximum size of work piece | Length, $(mm)$ | 600 |
| | Width, $(mm)$ | 400 |
| | Height, $(mm)$ | 300 |
| Maximum payloads $(kg)$ | | 1130 |
| Stroke | X-axis, $(mm)$ | 800 |
| | Y-axis, $(mm)$ | 550 |
| | Z-axis, $(mm)$ | 550 |
| Spindle | | FM7-A220 |
| Spindle maximum speed, $(min^{-1})$ | | 8000 |
| Maximum feed rate | X-axis, $(m/min)$ | 48 |
| | Y-axis, $(m/min)$ | 48 |
| | Z-axis, $(m/min)$ | 24 |
| Motor | X-axis | FXM 54 |
| | Y-axis | FXM 54 |
| | Z-axis | FXM 14 |
| Linear guideways | X-axis | HGH-45CA |
| | Y-axis | HGH-45CA |
| | Z-axis | HGH-45HA |
| Ball screws | X-axis | 32-12B2 |
| | Y-axis | 32-12B2 |
| | Z-axis | 32-6B2 |

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The draft of the selected component by the expert system from the input of this particular study case is presented in Table 3. The system will do the iteration for the components from the available database, thus the component that meet the minimum requirement of the system will be selected. The model generated by the system according to the components in Table 3. is presented in the Figure 5. The model generated is the general purpose models that are still need the verification and additional equipment if necessary.

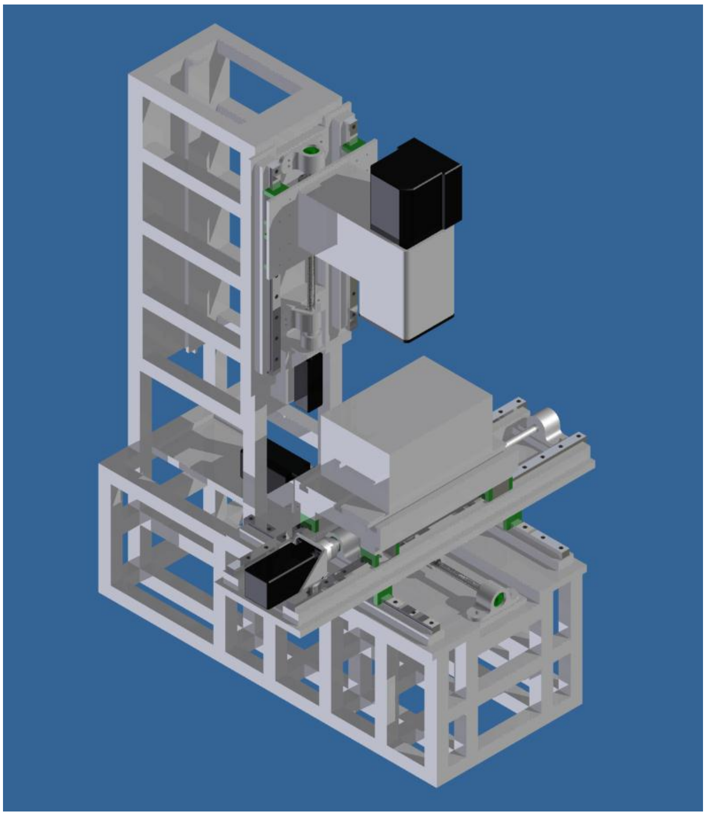

Figure 4. 3D model of three axis CNC milling machine generated by expert system

The pre-drawn 3D model has about 879 parameters, $(n)$ and if the time needed to manually modify each parameter  taken to manually modify each parameter is averagely 15 second, $(t)$ thus the time needed, $(T)$  to accustom this 3D model to design specification is about,

$$T = n \times t \quad (14)$$

$$= 879 \times 15\, s = \ 13\,185\, s \ \approx 219\, min$$

The subjective assumption of time needed for the expert system, $(T_{ES})$ to modify the parameter is about 5 minutes thus the overall subjectivity efficiency,$(\eta_{ES})$ of the system is shown as following,

$$\eta_{ES} = \frac{T - T_{ES}}{T} \times 100\% \quad (15)$$

$$= \frac{219\,\text{min} - 5\, min}{219\, min} \times 100\% = 95{,}4\ \%$$

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**CONCLUSIONS**

More advanced CAD system has been integrated in the designing process. Basically these CAD systems act as a catalyst in the designing process. This system developed uses the formally defined expert system to automate design by re-using the existing design. The case study of this expert system is the design of vertical CNC milling machine. The system starts with estimating the cutting forces, selecting the machine's component and generating 3D model of the machine instantaneously. it is worth mentioning that this system could qualitatively increase the efficiency in the design process and delivering the design on schedule. The design generated only served as general purposes and the verification of design is needed. Possible future development of the system is to establish a framework that could simplify the design of the system so it could be used by more people and also a platform for sharing the design.

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