Development of Virtual Machine Tool for Simulation and Evaluation

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ABSTRACT

Machine tools play an important role in manufacturing, but it is not easy to ensure efficiency and low cost, for machine tools. A machine tool simulation and evaluation system is urgently required. This paper presents an integrated machine tool simulation and evaluation system, which incorporates 3-D motion simulation and collision detection. The evaluation system incorporates post-processor and volumetric error analysis, for the evaluation of preliminary manufacturability and cutting force simulation. Using integrated virtual machine tool technologies, a variety of engineering activities in the product cycle can be performed digitally, to assess the characteristics of the real machine tool.

Keywords: virtual machine tool, simulation, evaluation.
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1 INTRODUCTION

Machine tools play an important role in manufacturing. However, it is not easy to ensure efficiency and low cost, for a machine tool. Pre-evaluation helps smooth the manufacturing process, but it requires input from an experienced engineer. Related studies have resulted in the development of commercial software. Virtual machine tools can be used to evaluate machining processes and machine tools. The technologies for virtual machine tools, presented in this paper, consist of both 3-D vision-aided and evaluation technologies. The 3-D vision-aided technology includes motion simulation and collision detection. Engineering evaluation technologies in which vision technology is not essential include post-processor, manufacturing precision evaluation, PMES (Preliminary Manufacturability Evaluation System) and real-time cutting force simulation.

Motion simulation, for a machine tool, can check the tool path. Collision detection [1] can eliminate the huge expense incurred by a machine tool's collision with a fixture, or workpiece.

A post-processor transforms Cutter Location (CL) files to Numerical Controlled (NC) codes, for specific multi-axis machine tools. Reshetov and Portman [2] proposed the concept of a form shaping function, using homogeneous transformation matrices to describe tool position from the view of the workpiece. This is an important function in multi-axis machine tools and their post-processors. Cheng and She [3] developed a post-processor and reverse post-processor, for multi-axis machine tools.

In milling, cutting force is an important factor, which influences the surface finish of the workpiece, cutting temperature and tool life. Commercial CAM software provides functions that provide tool path and cutting geometry simulation, to enable the evaluation of machinability.

Koenigsberger and Sabberwal [4] proposed a force model, to calculate cutting force. The model used proportional coefficients, which depend on chip thickness to determine the cutting force. Using the local cutting force model, Yellowly [5] separated the cutting force into a shearing force and a ploughing force. Both of the forces have a specific cutting coefficient. This type of force model is called a Dual-mechanism Global Cutting Constants (DGCC) model.

There are many mechanical errors in machine tools. Ramesh [6] reviewed recent research and separated the error sources into geometric and kinematic errors, thermal errors, cutting-force induced errors and fixture-dependent errors. These errors influence the precision of the machining of the workpiece. In general, there are two ways to reduce errors; one is to avoid generating the error and the other is to compensate for the error. However, higher precision usually means higher cost, so a machine tool design engineer must conduct a careful analysis, to achieve balance between cost and quality. Lin and Shen [7] simplified the machine tool deviation model. Bohez [8] applied a motion chain to analyze a five-axis machine tool.

In process planning PMES involves providing appropriate suggestions, such as the configuration of the machine tool, a suitable cutter size, and the minimum tool orientation angle for surface machining. Balasubramaniam [9,10] proposed a method to generate a five-axis tool path, using the visibility cone to assess suitable cutter orientation and size. Lee et al. [11] incorporated the visibility cone into workspace analysis, to evaluate an appropriate machine tool configuration and workpiece orientation, for process planning. All of these studies used a CAD model as input information. The machine shop receives a CL file, for manufacturing.

This study uses the form shaping function and the spherical coordinates system. A CL file provides input information to calculate the travel and rotation angle of the workpiece and then the appropriate machine tool configuration, for manufacturing, is suggested.

2 3-D VISION AIDED SIMULATION

Simulation, using 3-D visual technology, is vital for a virtual machine tool, especially when dealing with graphic data, such as StereoLithography (STL). It can be used for motion simulation and collision detection. However, before performing these tasks, the virtual machine tool must first be constructed. A virtual machine tool database can be created, to collect machine tool information.

2.1 Virtual Machine Tool Construction and Motion Simulation

There are various types of machine tools. It is necessary to construct a different virtual machine tool for each type. A universal virtual machine tool construction system has been developed, based on a mechanical, topological matrix. By entering geometrical information and motion ability, for each component, virtual machine tools can be constructed. A virtual machine tool, constructed using the universal virtual machine tool construction system, is shown in Fig. 1. Screenshots of motion simulation are shown in Fig. 2. Another approach, by Lee and Lin [12], adopts D-H notation in universal virtual machine tool construction procedures. The user interfaces are designed to help users select the configuration of a machine tool. Once the configuration is decided, the motion directions between adjacent links can be known and the kinematic parameters are described using D-H notation. Postprocessor is also derived by D-H notation. Finally, the motion control simulation of the virtual machine tool is executed, using the D-H transformation matrix.

The construction of virtual machine tools takes time, but it is a necessary step for simulation. Yan and Chen [13] proposed several types of common machine tools. Based on these types, a rapid construction system for a common virtual machine tool has been developed, in this study. As shown in Fig. 3, a common, virtual, multi-axis machine tool can be constructed rapidly, using its stroke and configuration code. The system can generate the STL geometries for each component in the virtual machine tool.

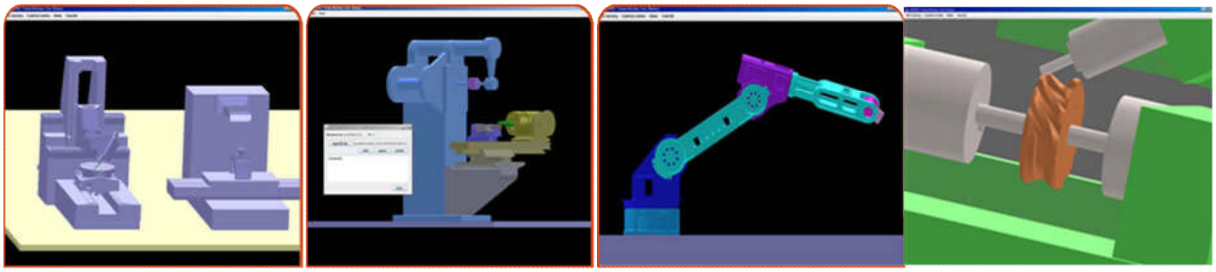


Fig. 1: Virtual machine tools, constructed using the universal virtual machine tool construction system: (a) Two virtual, five- axis machine tools constructed in the same environment, one of which is milling a workpiece with free surface, (b) Virtual five- axis horizontal machine tool, (c) Virtual robot arm, with 6 degrees of freedom, (d) A roller gear cam milling simulation, for a virtual five- axis machine tool.

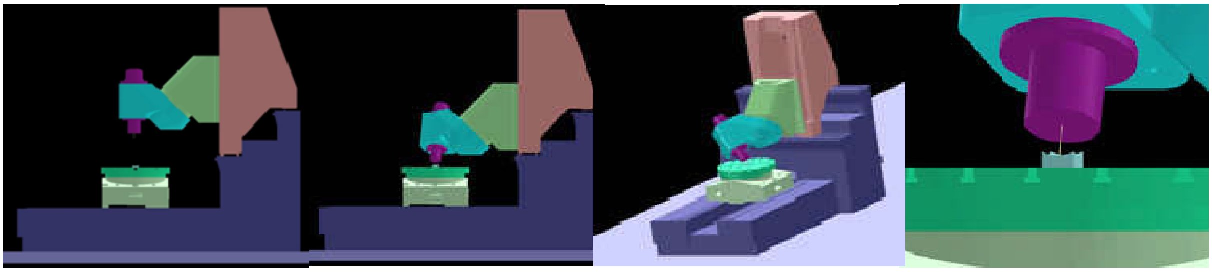
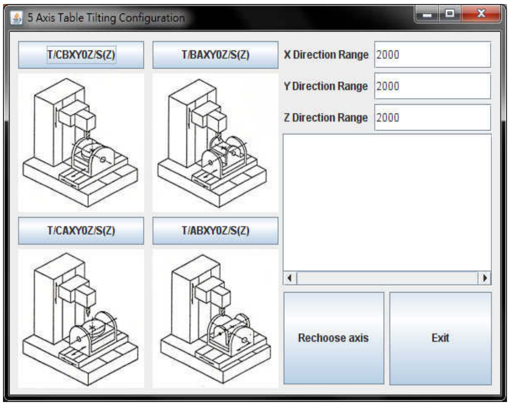


Fig. 2: Motion simulation for a five-axis virtual machine tool milling a workpiece with free surface: (a) The virtual machine tool stops, to establish machine origin, (b) The virtual machine tool begins to mill the workpiece, (c) Full view of milling process, (d) Close-up view of workpiece milling.



5 Axis Table Tilting Configuration

X Direction Range 2000

Y Direction Range 2000

Z Direction Range 2000

Fig. 3: Common virtual machine tool construction interface.

2.2 Universal Virtual Machine Tool Database

Virtual machine tools have various specific types. The universal constructing system has been developed, based on a mechanical, topological matrix. In response to the general construction system, a universal machine tool database [15] has also been developed. The universal machine tool database implements object-oriented ideals and is designed to deal with a mechanical topological matrix. The XML format for a virtual machine tool is defined using the Entity-Relation (ER) diagram in the database. Several virtual machine tools, shown in Fig. 1, were built, using the XML format.

2.3 Collision Detection

A collision detection module was developed, by checking vertex overlap, as shown in Fig. 4. The overlapping points are marked with bright color. A hollow and continuous shell of point clouds defines the surface of each component. Each point is a detection object. A collision signal is produced, if the detection objects overlap.

The computation of point clouds is a massive task for a CPU, so the program is implemented using OpenCL GPU architecture. Through normalization, points can be sorted and checked for overlap. Bitonic Sort is used for parallel computation. As opposed to traditional CPU computation, GPU is able to handle massive amounts of data requiring minimal computation for each element. GPU allows this method to be used, with acceptable efficiency.

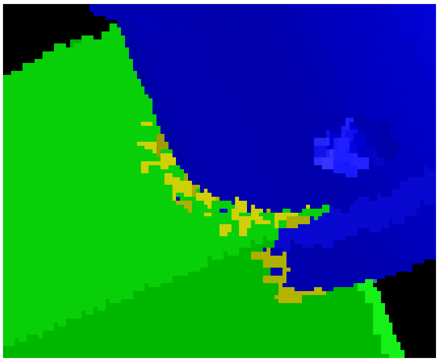


Fig. 4: The point clouds of two components overlap. The overlapping section is marked with a brighter color.

A CPU-based collision detection module was also developed, using an approach similar to Ding's [16]. This collision detection module uses an extendable, multi-nomial tree with 27 nodes, instead of an octree, and uses the sphere's bounding volume, instead of the Oriented Bounding box's (OBB) bounding volume. Fig. 5 shows the detection of a collision between the tool-spindle and the worktable.

Both of the collision detection modules can detect an overlap of points. Memory consumption depends on the number of points. Compared with a GPU-based collision detection module, the CPU-based collision detection module has higher precision, since the GPU has limited memory capacity, at present.

Fig. 5: Collision detection, for a five-axis virtual machine tool: (a) A snapshot of a virtual machine tool, before collision, (b) Collision occurs between the tool-spindle and the worktable. The collision area is marked with deeper color.

3 ENGINEERING EVALUTIONS

The engineering evaluations possible using a virtual machine tool include assessment of the universal post-processor and analysis of manufacturing precision, PMES and real time cutting force simulation, for which 3-D vision technology is not essential.

3.1 Universal Post-Processor and Reverse Post-Processor

The post-processor transforms the CL file into NC code. The Reverse post-processor transforms NC code into a CL file using the form shaping function. The post-processor uses an algorithm to find the solutions of simultaneous equations, using the form shaping function ideology. There are two types of solution: a numerical solution and an analytical solution. The benefits of the analytical solution are that it is relatively quick and precise, compared with the numerical solution, but it must be derived for a specific machine tool. The numerical solution is slower than analytical solution, but it can be constructed for the general case.

For common, multi-axis machine tools, a general post-processor giving an analytical solution was developed. The post-processor is constructed using configuration code and D-H notation parameters. A post-processor giving a numerical solution was also developed and integrated into the virtual machine tool construction system. As shown in Fig. 6, by defining the motion ability of each component of the machine tool, the form shaping function can be generated and the necessary simultaneous equations can be produced.

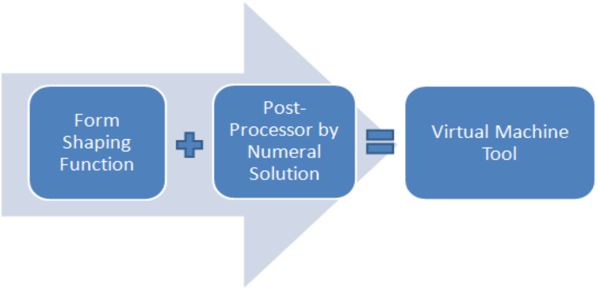


Fig. 6: Integration of virtual machine tool and post-processor, using the numerical solution.

3.2 Manufacturing Precision Analysis

When the real machine tool moves, using NC codes, it makes geometric errors. These can be divided into two categories; one is component error and the other is location error. If it is assumed that all components of the machine tool are rigid bodies, component errors exist between each pair of axes and each axis has six degrees of freedom, so there are thirty possible errors in a five-axis machine tool.

To analyze component errors, the errors are input into the form shaping function. Using matrix multiplication of the axis errors and the rotation errors, the quadratic can be simplified and the independent variables can be added together. The influence of volumetric error can be derived and these seventeen errors can be compensated for, directly. For the errors that cannot be compensated for, directly, a sensitivity analysis can assess the influence of assembly error on volumetric error, for the machine tool. The result can be used to evaluate the machine tool design.

A module was constructed to analyze manufacturing precision. When it receives the CL file and assembly errors, it makes a sensitivity analysis. The result of a sensitivity analysis for a T/cxyoza/S(z) machine tool is shown in Fig. 7. There are thirteen significant volumetric errors, corresponding to assembly errors, which do not allow direct compensation. A machine tool design engineer could improve the most significant assembly errors.

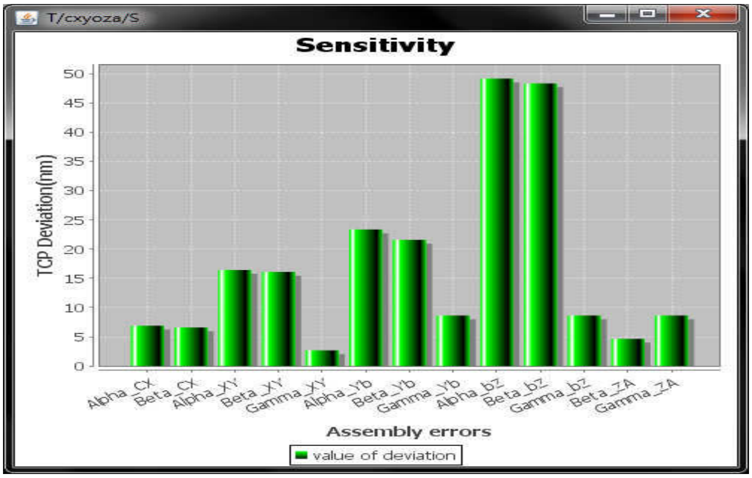
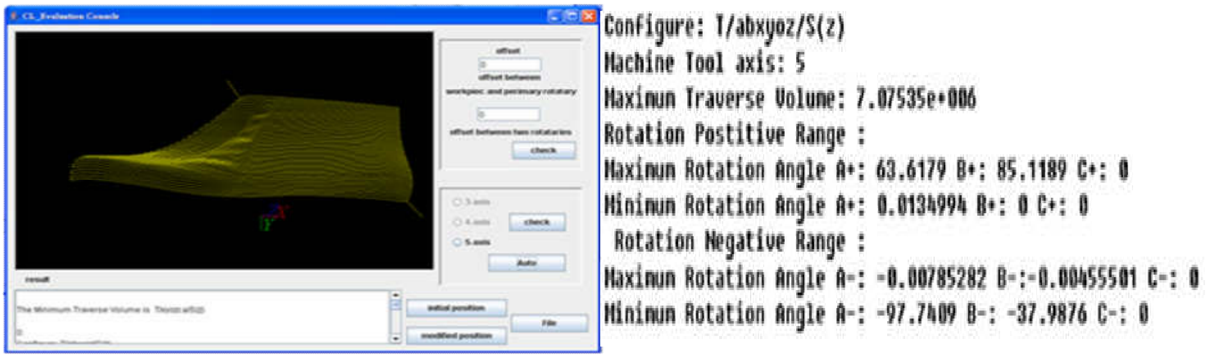


Fig. 7: Result of a sensitivity analysis, for a T/cxyoza/S(z) machine tool. The word before the dash is a linear assembly error, when it is 'X', 'Y', or 'Z' and a nonlinear assembly error, when it is 'Alpha', 'Beta', or 'Gamma'. The two letters after the dash signify individual components.

3.3 Preliminary Manufacturability Evaluation System

Using PMES with the cutter location file as input information, suggestions can be generated for appropriate holding orientation for the workpiece and the machine tool configuration. Firstly, the machine tool configuration code for a three-, four- and five-axis machine tool. Secondly, it uses the homogeneous coordinate transformation matrix to calculate the form shaping function matrix for that machine tool. Thirdly, it uses inverse kinematics to calculate the movement of the axes. Finally, after input of a cutter location file, the system can suggest the appropriate configuration and even the holding orientation of the workpiece. The minimum traverse can be calculated by using the spherical coordinates system corresponding to the motion matrix.

When the user inputs a CL file, the system can calculate the volume of the working space. The system can show the suitable configuration, including configuration with the minimum traverse volume, as shown in Fig. 8. The CAPP engineer can obtain an objective suggestion for the choice of a suitable machine tool.



```
Configure: T/abxyoz/S(z)
Machine Tool axis: 5
Maximun Traverse Volume: 7.07535e+006
Rotation Postitive Range :
Maximun Rotation Angle A+: 63.6179 B+: 85.1189 C+: 0
Minimun Rotation Angle A+: 0.0134994 B+: 0 C+: 0
 Rotation Negative Range :
Maximun Rotation Angle A-: -0.00785282 B-:-0.00455501 C-: 0
Minimun Rotation Angle A-: -97.7409 B-: -37.9876 C-: 0
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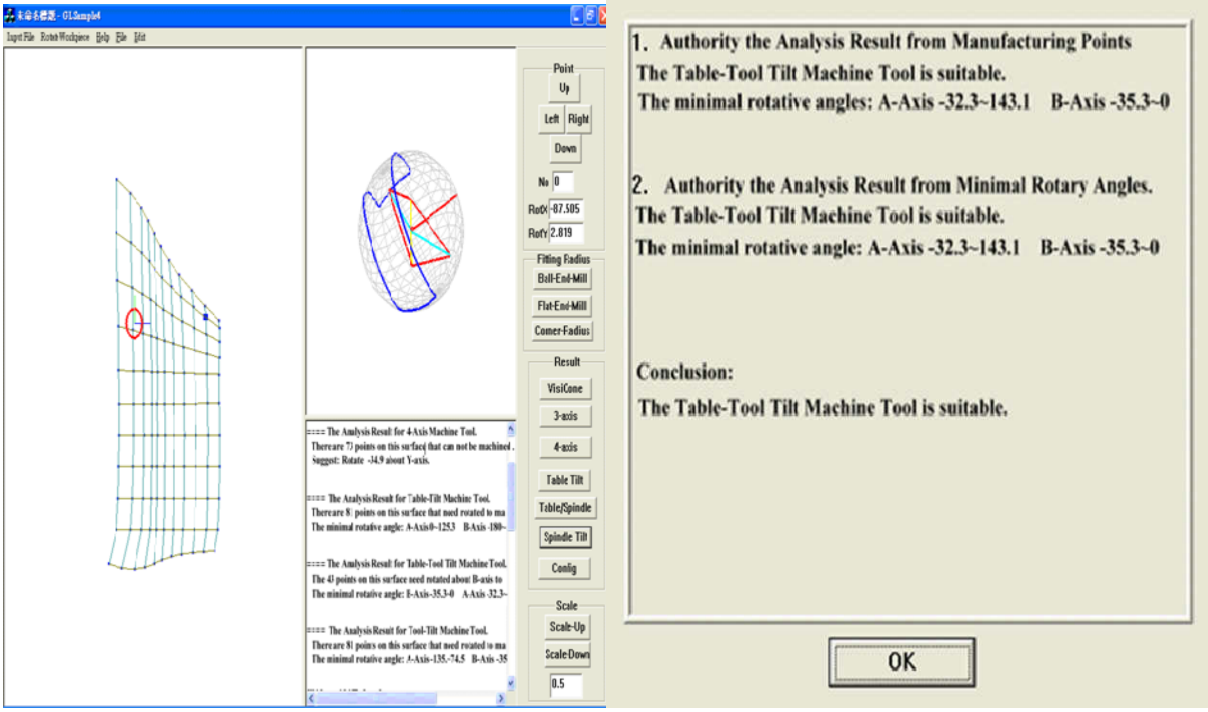
Fig. 8: The PMES output suggestion for machine tool configuration: (a) The system imports a CL file for a shoe last, (b) The output textbox, giving the suggested configuration for a machine tool and the limitation of stroke.

By combining the eigen-circle with the visibility cone for the workpiece surface, another PMES module [16] can be utilized, to ensure optimal settings for workpiece orientation and configuration of the machine tool. The information provided by this module includes the points that cannot be machined and the minimum rotation range of the rotary axes. The user interface is shown in Fig. 9.a. It can be divided into four parts. The first part is the surface display; the second part shows the visibility cone, vector of the cutter and the eigen-circle, presented in a “unit sphere”; the third part shows the result of analysis. The right section of the fourth part offers the control list. The top section is the tool list, which can be used to input point data and rotate the workpiece. The PMES outputs one file that offers manufacturability evaluation results and suggestions, as shown in Fig. 9.b.



```
==== The Amlysis Result for 4-Axis Machine Tool.
 Thereare 73 points on this surface that can not be machined .
 Suggest: Rotate -34.9 about Y-axis.

==== The Analysis Result for Table-Tilt Machine Tool.
 Thereare 81 points on this surface that need rotated to ma
 The minimal rotative angle: A-Axis0~125.3   B-Axis -180~

==== The Amlysis Result for Table-Tool Tilt Machine Tool.
 The 43 points on this surface need rotated about B-axis to
 The minimal rotative angle: B-Axis-35.3~0   A-Axis -32.3~

==== The Analysis Result for Tool-Tilt Machine Tool.
 Thereare 81 points on this surface that need rotated to ma
 The minimal rotative angle: A-Axis-135.~74.5   B-Axis -35
```

```
1. Authority the Analysis Result from Manufacturing Points
 The Table-Tool Tilt Machine Tool is suitable.
 The minimal rotative angles: A-Axis -32.3~143.1   B-Axis -35.3~0

2. Authority the Analysis Result from Minimal Rotary Angles.
 The Table-Tool Tilt Machine Tool is suitable.
 The minimal rotative angle: A-Axis -32.3~143.1   B-Axis -35.3~0

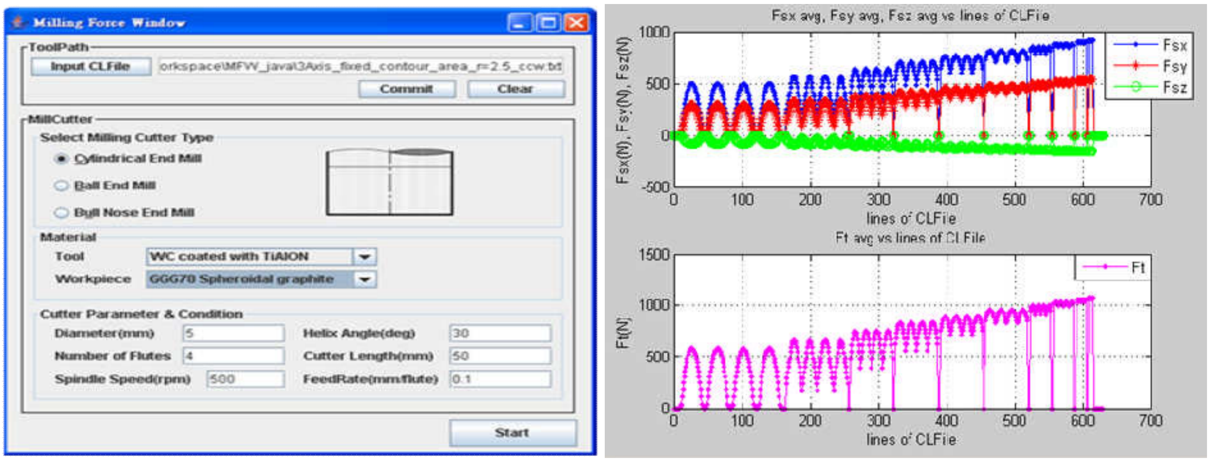
Conclusion:
 The Table-Tool Tilt Machine Tool is suitable.
```

Fig. 9: The PMES using the eigen-circle with the visibility cone: (a) The user interface, (b) the evaluation result and suggestion.

3.4 Real time Cutting Force Simulation

Various end mill cutters, i.e. cylindrical, ball and bull-nosed end mills, are widely used in the aerospace and automotive industries. Although the geometries of these cutters are different, they can be expressed as a generalized model. Engin and Altintas [17] developed a generalized model of arbitrary end mills, which allows the parametric design and expression of different end mill shapes. Using this model, the cutting force can be calculated for a specific variety of end mill.

Given cutting parameters, such as federate, cutting coefficient, spindle speed and depth of cut, cutting force can be calculated. However, the depth of cut changes, during machining. Using the CL file and the STL model of the workpiece, a preliminary algorithm can be developed, to derive the varying depth of cut. The algorithm uses tool center points, recorded in the CL file, the diameter of the cutter and the boundary position of the workpiece to calculate the depth of cut. Using such an algorithm, a cutting force simulation can be established. Fig. 10.a shows the interface for this module, and Fig. 10.b shows the results of simulation.



Milling Force Window

ToolPath

Input CLFile: orkspace\MFW_java\3Axis_fixed_contour_area_r=2.5_ccw.txt

MillCutter

Select Milling Cutter Type

● Cylindrical End Mill

○ Ball End Mill

○ Bull Nose End Mill

Material

Tool: WC coated with TiAlON

Workpiece: GGG70 Spheroidal graphite

Cutter Parameter & Condition

Diameter(mm): 5

Number of Flutes: 4

Spindle Speed(rpm): 500

Helix Angle(deg): 30

Cutter Length(mm): 50

FeedRate(mm/flute): 0.1

Fig. 10: A prototype of a cutting force simulation program: (a) The interface for the entry of parameters, (b) Results of cutting force simulation, using ball end mills in a three-axis, virtual machine.

4 SYSTEM INTEGRATION

The developed simulation and evaluation modules are linked, as an integrated system (as shown in Fig. 10), for machining and the machine tool industry. The engineer can first find appropriate machine tools, using PMES. Manufacturing precision analysis can be used to help design a cheaper machine tool with high precision. Then, the universal post-processor can help the engineer to create NC for a specific machine tool. Engineers can construct a virtual machine tool, for motion simulation and collision detection. A complete process is provided, for machine tool evaluation and simulation. The virtual machine tool that is constructed can be saved into the virtual machine tool database, for future reference.

Through the integration of virtual machine tool technology, the product designer is able to assess the ease of manufacture and modify the product at the design stage, so the lead-time, from design to manufacture, can be reduced.

The motion of a machine tool can be displayed and checked, using motion simulation. The prerequisite work for motion simulation, such as generating NC codes and constructing a virtual machine tool, can be completed rapidly, using the common virtual machine tool rapid construction system, virtual machine tool construction system, universal post-processor and universal machine tool database. The cutting force simulation can provide information for the optimization of the tool path. A prototype of the cutting force simulation system was constructed. Cutting force simulation is used to check CL files, before post-processing.

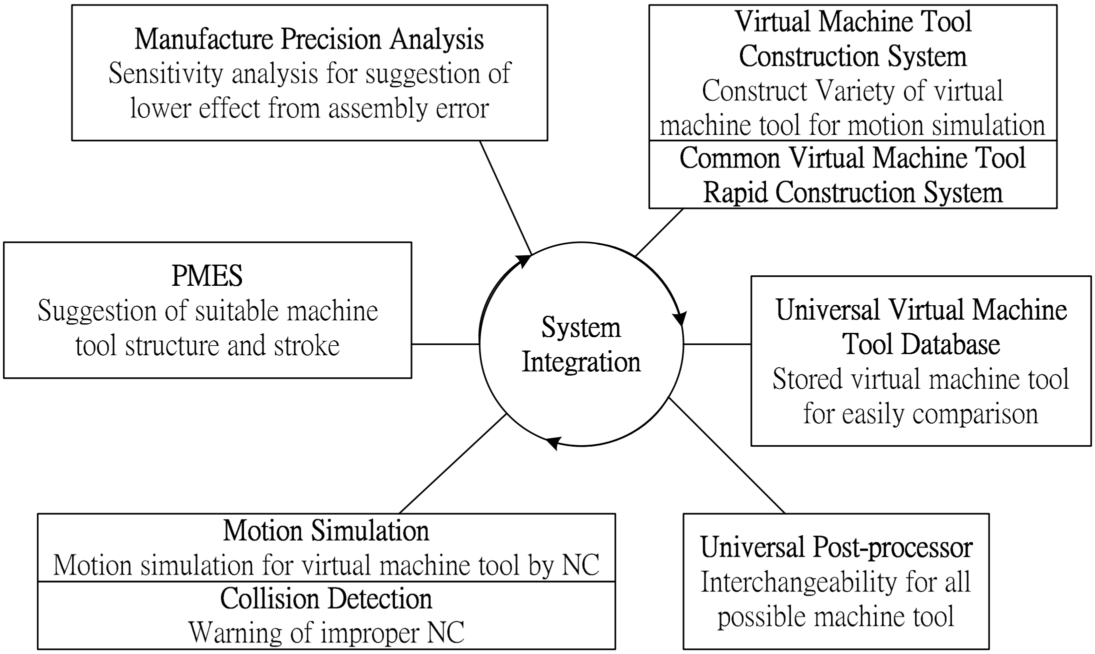


Fig. 11: System integration for a virtual machine tool.

5 CONCLUSIONS

Through the integration of these virtual machine tool technologies, a product designer can assess the ease of manufacture and modify the product, at the design stage. For a machine tool designer, product designer, or manufacturing engineer, the virtual machine tool simulation and engineering evaluation system can help increase the precision of the machining process and decrease the lead-time.

6 ACKNOWLEDGEMENT

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