International Journal of Automation and Computing 9(5), October 2012, 506-517
DOI: 10.1007/s11633-012-0674-9

# STEP-NC Based High-level Machining Simulations Integrated with CAD/CAPP/CAM

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**Abstract:** With the development of manufacturing, numerical control (NC) machining simulation has become a modern tool to obtain safe and reliable machining operations. Although some research and commercial software about NC machining simulations is available, most of them is oriented for G&M code. It is a low-level data model for computer numerical control (CNC), which has inherent drawbacks such as incomplete data and lack of accuracy. These limitations hinder the development of a real simulation system. Whereas, standard for the exchange of product data-compliant numerical control (STEP-NC) is a new and high-level data model for CNC. It provides rich information for CNC machine tools, which creates the condition for an informative and real simulation. Therefore, this paper proposes STEP-NC based high-level NC machining simulations solution integrated with computer-aided design/computer-aided process planning/computer-aided manufacturing (CAD/CAPP/CAM). It turned out that the research provides a better informed simulation environment and promotes the development of modern manufacturing.

**Keywords:** Standard for the exchange of product data-compliant numerical control (STEP-NC), numerical control (NC) machining, machining simulation, IDEF0 method, ISO 6983.

## 1 Introduction

At present, in order to survive and develop in the drastically competitive global market, manufacturing enterprises must meet the requirements of the TQCS, i.e., the shortest product development cycles (time), the best product quality (quality), the lowest manufacturing cost (cost), and the best technical support and after-sales service (service). In order to achieve these requirements, numerical control (NC) machining simulation technology plays an important role.

Up to now, most research and commercial software about NC machining simulations is oriented for G&M code, also called ISO 6983. It is a low-level data model. The problems of ISO 6983 include: 1) it focuses on programming the path of the cutter centre location with respect to the machine axes, rather than the machining tasks with respect to the part; 2) it defines the syntax of program statements, but leaves the semantics ambiguous in most cases; 3) it tends to include a lot of vendor-specific extensions; 4) it supports one-way information flow from design to manufacturing; 5) it has limited control of program execution; 6) it does not support the spline data, which makes it incapable of controlling five or more axes milling[1]. As mentioned above, the use of G&M code hinders the advancement of NC machining simulation such as a real simulation and the integration of simulation analysis with computer-aided design/computer-aided process planning/computer-aided manufacturing (CAD/CAPP/CAM) and machining data at shop floor. Therefore, there is a requirement for high-level data model to be developed and utilized that can assist accurate simulation for machining processes. To solve this issue, standard for the exchange of product data-compliant numerical control (STEP-NC) was used as the data model in this paper. Moreover, considering the integration of CAD/CAPP/CAM with simulation analysis, previous work[2] was extended, i.e., STEP-NC based high-level NC machining simulations solution integrated with CAD/CAPP/CAM was studied.

The remainder of this paper is organized as follows. Related work about the NC machining simulation is reviewed from the viewpoint of geometric simulation and physical simulation in Section 2. Section 3 describes the STEP-NC data model, data program and benefits for simulation. The modelling method, i.e., IDEF0 is introduced in Section 4. In Section 5, a conceptual framework of STEP-NC based high-level NC machining simulation integrating with CAD/CAPP/CAM is designed and discussed. In Section 6, conclusions and future works are given.

## 2 Related work

NC machining simulations are divided into two categories: geometric simulation and physical simulation. Geometric simulation is used to graphically check whether the cutters interfere with fixture, workpiece and machine tools, gouge the part, or leave excess stock behind. As the name implies, physical simulation of an NC machining process aims to reveal the physical aspects of a machining process, such as cutting force, vibration, surface roughness, machining temperature and tool wear.

### 2.1 Geometric simulation

There are three categories of geometric simulations: solid-based geometric simulation, image space model-based geometric simulation, and object space model-based geometric simulation.

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Manuscript received November 24, 2010; revised April 19, 2012
This work was supported by National Natural Science Foundation of China (No. 51205054), National Key Technology Research and Development Program During the Twelfth Five-year Plan (Nos. 2012BAF10B11, 2012BAF12B08).

### 2.1.1 Solid-based geometric simulation

Solid modelling offers generality, accuracy and completeness in 3D part representation. These are useful for the geometric simulation of machining process in which in-process workpiece, cutter and chip geometries need to be accurately represented.

Lots of scholars did research about solid-based geometric simulation. For example, Hunt and Voelcker[3] tentatively studied the feasibility of using the part and assembly description language (PADL) constructive solid geometry (CSG) modelling system. O′Connell and Jabolkow[4] constructed B-rep solid models of the machined part from NC programs in a cutter location data (CLDATA) format to realize geometric simulation for the 3-axis milling machining. Based on the analysis of solid modelling and spatial decomposition modelling, Li et al.[5] simplified the representation of geometric model and cutter-swept volumes to improve turning simulation quality. Xing and Zhao[6] developed a ACIS-based machining simulation system. This system can realize NC program verification and collision check.

### 2.1.2 Image space model-based geometric simulation

In image space model-based NC machining simulation, parts are represented by depth pixel (dexel is a portmanteau of the depth and pixel) model. Because dexel model is at pixel level and its Boolean operation is one-dimensional, the simulation speed is the fastest among all the simulations. CGTech′s VERICUT simulator uses such approach[7].

As an early research, Wang et al.[8] converted a CSG model to 3D pixel images using a variation of the standard z-buffer algorithm and developed a multi-axis machining simulator called NCS. In the same year, Van Hook[9] used an extended z-buffer data structure to develop an NC milling display tool. Instead of intersecting scan lines with swept volume envelopes, pixel image of the cutting tool is pre-computed and Boolean subtractions of the cutter from the workpiece is done along a tool path. Later, Atherton et al.[10] extended Van Hook′s approach to five-axis machining. However, the display of the above dexel-based NC machining simulation was dependent on the view direction because it only record the geometric information of a 3D object from one view direction. To solve this limitation, Huang and Oliver[11] presented a contour display method. In addition, Blasquez and Poiraudeau[12] improved extended z-buffer by using new functionalities called traces in order to keep in memory the history of the machining of the workpiece.

### 2.1.3 Object space model-based geometric simulation

In object space model-based NC machining simulation, parts are represented by a collection of discrete points (with vectors), or surfaces with vectors, or certain volume elements. Because objects are discretized, Boolean operations between objects are simplified.

An early research for milling process was conducted by Anderson[13] who used 3D histograms to approximate the billet and cutter assembly shape to detect and eliminate collisions during the machining process. Later, Lee et al.[14] proposed a mesh decimation method to improve the representation in 3D histograms so that more rapid rendering without loss of display quality for a workpiece can be implemented.

Chappel[15] proposed the “point-vector” method in which part surface was approximated by a set of points with vector to simulate the material removal process. However, he did not mention how to select the points. Oliver and Goodman[16] developed a system similar to Chappel′s, which used a computer graphics image of the desired surface to select the points. Later, Jerard et al.[17] proposed an object-based surface discretization modelling method with the characteristics of the methods presented in above two researches. Then, Zhou et al.[18] used stereolithography (STL) models as the common models to develop a general machining simulation system. Ding[19] proposed a novel geometric modelling approach which uses discrete points on the boundary of the object to represent geometry model and developed an off-line and on-line machining simulation system. Park et al.[20] hybridly used discrete normal vectors and discrete vertical vectors to represent the model in the mould and die machining simulation.

In addition, based on the extended octree model[21], Roy and Xu[22] developed a geometric simulation system for 3-axis NC milling machining. Following this, they reconstructed a machined object in polyhedral boundary representation from the above object model in order to compare it with the designed object[23]. Other scholars also did similar research. For example, Karunakaran and Shringi[24] developed a NC simulation system in which the part was represented by traditional octree for model creation and modification.

## 2.2 Physical simulation

As the extension of previous work, Wang[25] integrated NCS with a machinability database and a metal cutting model. Thus, the cutting force can be evaluated when the “tool” removes “material” from the solid model. In addition, based on the result, the feed-rate can be automatically adjusted to increase the productivity and avoid tool breakage. Later, Spence et al.[26,27] developed a CSG-based process simulation system for 2.5-axis milling, which used the cutter-part intersection data and mechanistic models[28] to carry out the cutting force prediction. Subsequently, El-Mounayri et al.[29−31], Imani et al.[32,33], and Bailey et al.[34,35] developed a generic B-rep-based ball end milling process simulation system for 3-axis milling to predict the cutting force using Bezier curves, B-spline curves and NURBS curves, respectively. In addition, to improve computation efficiency, Aras et al.[36,37] utilized cutter/workpiece, engagement geometry[38] to predict the cutting force in 3-axis machining and 5-axis machining, respectively. Besides, Karunakaran and Shringi[39] used the material removal rate-based average cutting force model cutting force prediction. However, using this cutting force model is inherently incapable of determining the instantaneous cutting force which is essential for optimized cutting and for arriving at optimal values of cutting parameter, such as feed rate. Therefore, a general instantaneous cutting force model developed by Altintas and Lee[40] was used to predict the cutting force[41]. In addition, Zhou and Cheng[42,43] studied the development of machining simulations and applications in the new areas such as precision and micro machining, high speed machining, etc.

## 3 STEP-NC

Today, a new ISO standard often known as STEP-NC is being developed to provide a data model for a new breed of intelligent CNC controllers. STEP-NC provides a model of data exchange between CAD/CAM systems and CNC machines. It remedies the shortcomings of G&M codes by specifying machining processes rather than machine tool motions. The object-oriented concept of “workingsteps” is used, which corresponds to high-level machining features and associated process parameters. That is, implementing STEP-NC can realise the transition from the task-level data to the method-level data and keep all the machining information such as geometry, feature, tolerance, machine tool and cutter[44]. Benefits of using STEP-NC for NC machining simulation are as follows:

1) STEP-NC tells “what to do” information with respect to the part such as drilling, roughing, finishing, so that the part program provides high-level information for NC machining simulation.

2) It supports bidirectional information flow between design and manufacturing so that the changes during the NC simulation analysis can be fed back to the designers.

3) It provides complete machining process information for NC simulation, making a real simulation easier.

Fig. 1 shows the structure of STEP-NC data file. A STEP-NC data file includes two sections. The Header section is the first section, which contains some general information and comments such as filename, author, date, and organization. The Data section is the second section, which contains all the information about manufacturing tasks and geometry. Also, the Data section contains a Project entity, i.e., an explicit reference for the starting point of the manufacturing tasks. The Project entity has references to other entities that provide information of workplan, executables, technology description and geometry description. The data model is described by the object-oriented EXPRESS language[45], as shown in Fig. 2.

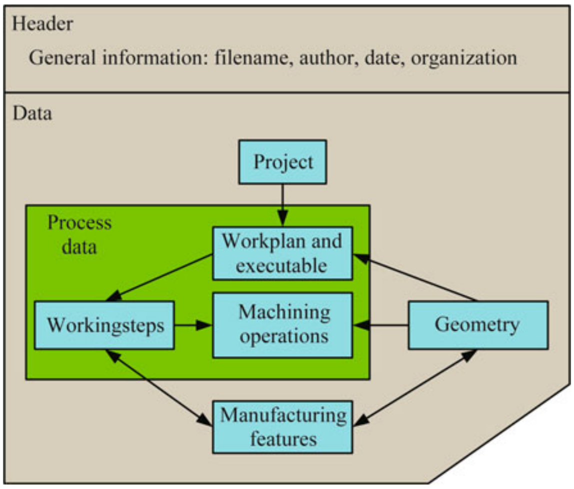


Fig. 1 The structure of STEP-NC data file

## 4 IDEF0 modelling method

IDEF0 is a method designed to model the decisions, actions, and activities of an organization or system. It is useful in establishing the scope of an analysis, especially for a functional analysis. Also, as a communication tool, IDEF0 enhances domain expert involvement and consensus decision-making through simplified graphical devices. In addition, IDEF0 models are often created as one of the first tasks of a system development effort. Therefore, it can

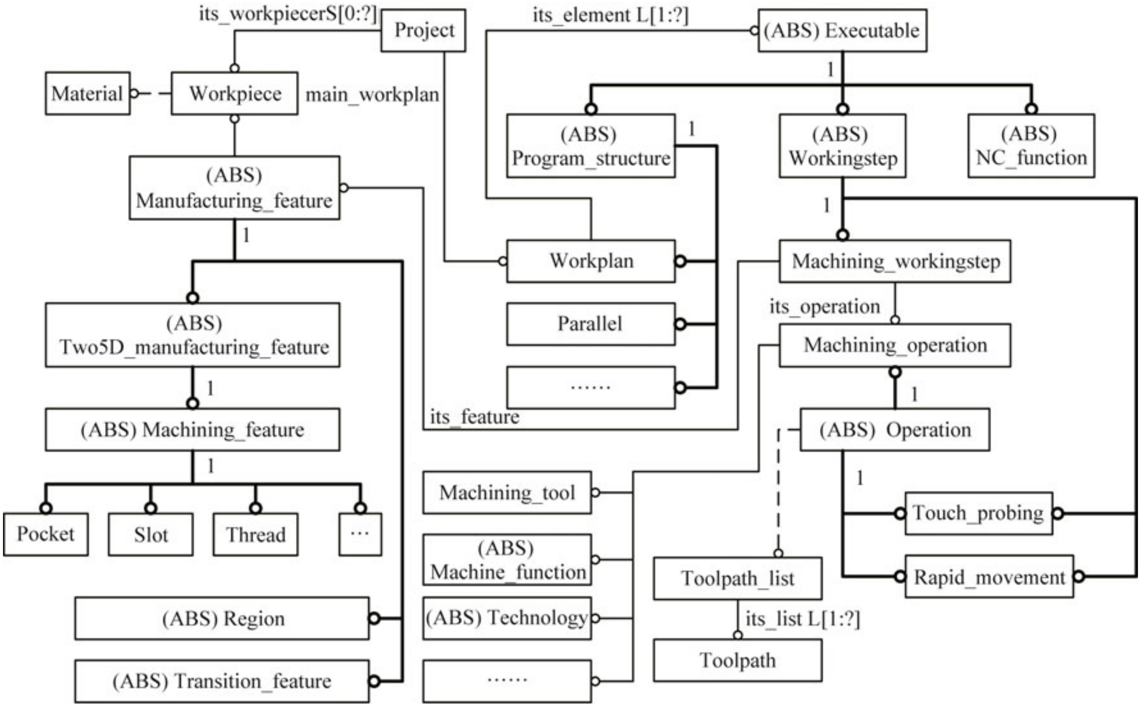


Fig. 2 Simplified STEP-NC data model

be used to model a high-level NC machining simulation system.

The IDEF0 model displayed in Fig. 3 is based on a simple syntax. Each activity is described by a label placed in a box. Inputs are shown as arrows entering the left side of the activity box while outputs are shown as exiting arrows on the right side of the box. Controls are displayed as arrows entering the top of the box and mechanisms are displayed as arrows entering from the bottom of the box.

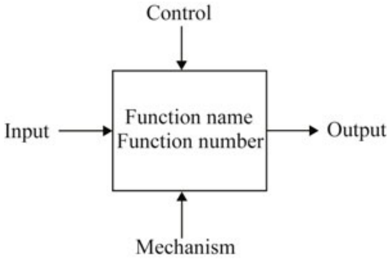


Fig. 3 IDEF0 block

In the IDEF0 method, the modelling conforms to the top-bottom principle. It means that the IDEF0 modelling process starts with the identification of the prime function to be decomposed. This function is identified on a "top level context diagram" which defines the scope of the particular IDEF0 analysis. From this diagram, child diagrams are gradually generated.

## 5 Design of the framework

### 5.1 Activity module of prime functions for high-level NC machining simulations

First of all, as shown in Fig. 4, the activity module of prime functions for high-level NC machining simulations takes the CAD data (AP203[46]) as input. The output includes generic and specific STEP-NC program, interpolated tool-path, geometric information, physical information and optimized machining parameters.

### 5.2 Detailed activity module for high-level NC machining simulations

According to function requirements, the framework is divided into four modules, as shown in Fig. 5. The first one is generic STEP-NC program generator which takes AP203 data as input and the output is generic STEP-NC program. The second module is the specific STEP-NC program generator which uses the generic STEP-NC program to generate a specific STEP-NC program matching available machining environment. The third module is STEP-NC program processor which interprets the specific STEP-NC program, obtains an optimal lifecycle machining information based on expert system and neural network[47,48], and generates tool path. The last module is the machining process simulator which uses optimal lifecycle machining information to mimic the machining process in a virtual computer environment and feed back corresponding machining data to the second module. The detail of each module is discussed in the following sub-sections.

### 5.3 Activity module of generic STEP-NC program generator

STEP-NC program is a base for NC machining simulations. As shown in Fig. 6, A1 activity module is further divided into three activity modules: feature extractor, macro process planner and generic STEP-NC program generator. As an input of this activity module, STEP AP203 file contains geometry and topology information of the product model. Through feature extractor activity module, this file is converted into a STEP AP224[49] file that contains manufacturing feature information. Then, macro process planning is carried out to select proper cutting tools and suitable manufacturing operations for the manufacturing features. At the end, these geometric information, manufacture features information and process planning information are mapped into the file in ISO 10303-21[50] or ISO 10303-28[51] format. Thus, a generic STEP-NC program is generated, as shown in Fig. 7.

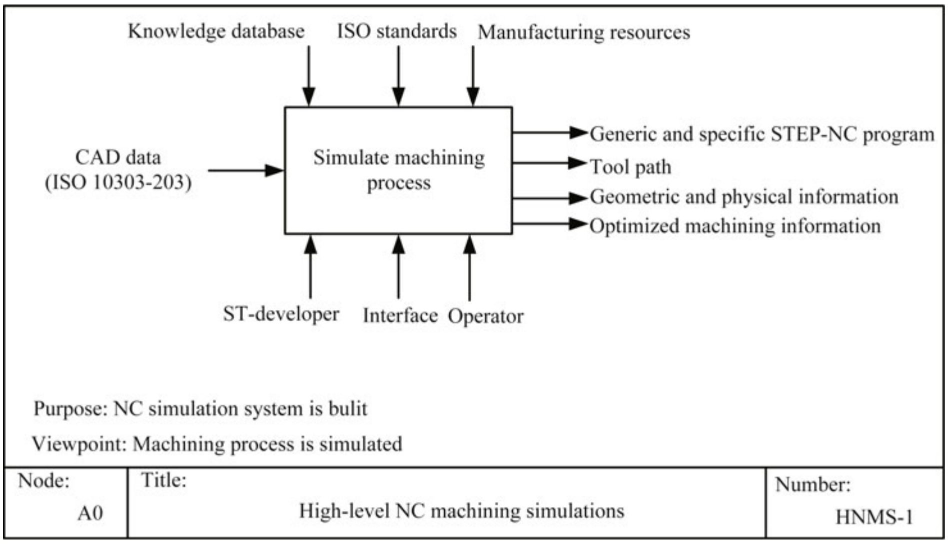


Fig. 4 Activity module of prime functions for high-level NC machining simulations

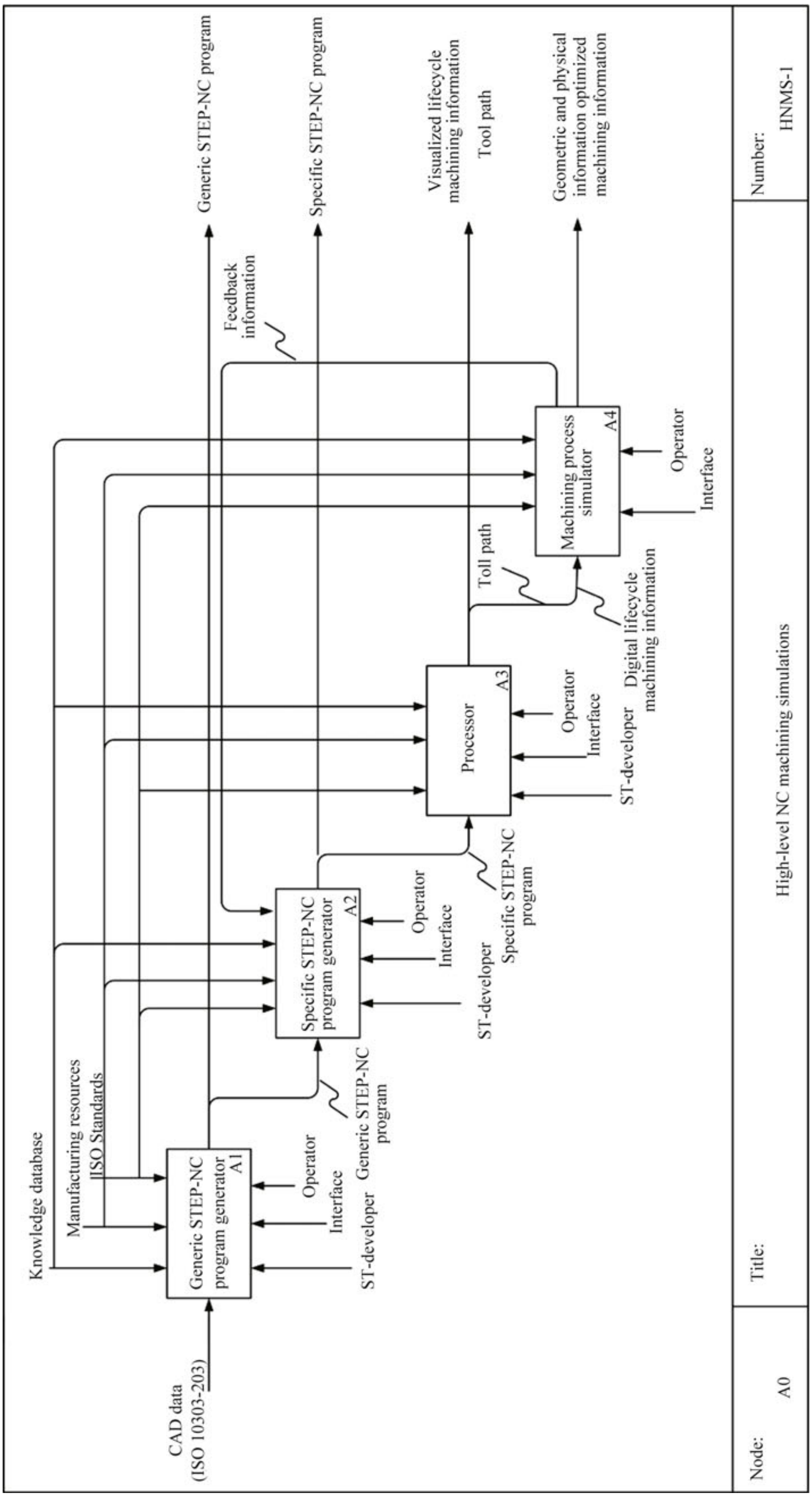


Fig. 5 Detailed activity module for high-level NC machining simulations

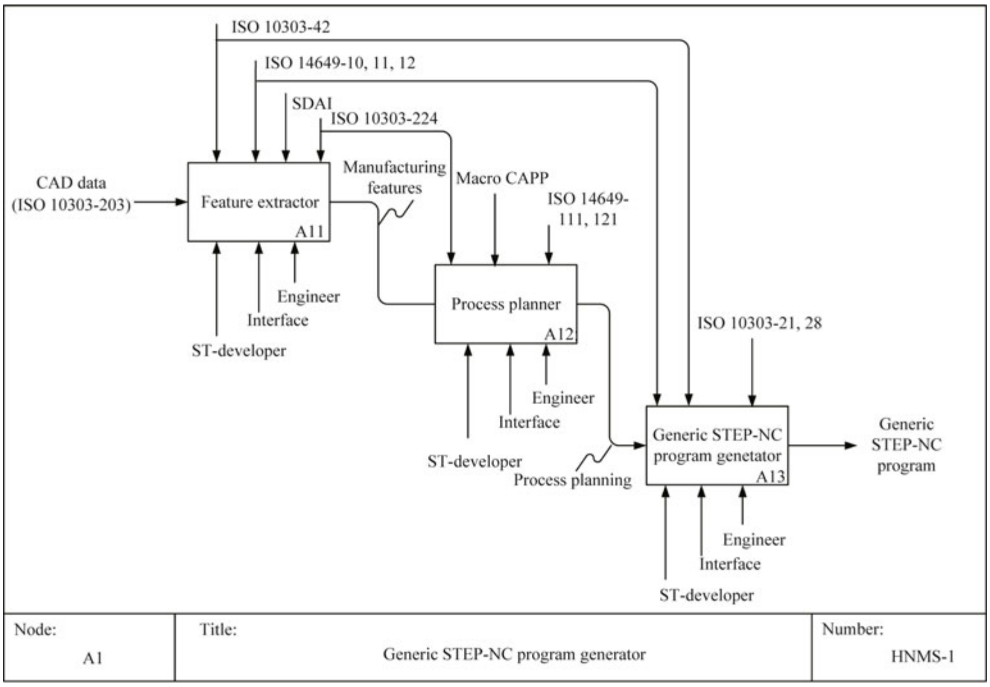


Fig. 6 Activity module of generic STEP-NC program generator

```
ISO-10303-21;
HEADER;
FILE_DESCRIPTION( ('GENERIC PROGRAM ','2;1');
FILE_NAME(' GENERIC PROGRAM.STP','2010-04-11T15:11:24+13:00', ('Yu Zhang'),('$'),'$','$',$);
FILE_SCHEMA (('COMBINED_SCHEMA'));
ENDSEC;
DATA;
/* project data */
#1= PROJECT('EXECUTE EXAMPLE1-0.5',#2,(#4),$,$,$);
/* project data */
/*workplan data (Generic)*/
#2= WORKPLAN('MAIN WORKPLAN',(#10,#11,#12,#13,#14),$,#8,$);
/*workplan data(Generic) */
/*workpiece data(Generic)*/
..........................
#66=CARTESIAN_POINT('CLAMPING_POSITION1',($,$,$));
#67=CARTESIAN_POINT('CLAMPING_POSITION2', ($,$,$));
#68=CARTESIAN_POINT('CLAMPING_POSITION3', ($,$,$));
#69=CARTESIAN_POINT('CLAMPING_POSITION4',(($,$,$));
/*workpiece data(Generic)*/
/*setup data (Generic)*/
#8= SETUP('SETUP1',#71,#62,(#9));
#71= AXIS2_PLACEMENT_3D('SETUP1',#95,#96,#97);
#95= CARTESIAN_POINT('SETUP1: LOCATION ',(0.000,0.000,0.000));
#96= DIRECTION(' AXIS ',(0.000,0.000,1.000));
#97= DIRECTION(' REF_DIRECTION',(1.000,0.000,0.000));
/*setup data(Generic)*/
..........................
/*workingstep data (Generic)*/
/*workingstep1 data (Generic)*/
#10= MACHINING_WORKINGSTEP('WS FINISH PLANAR FACE1',#62,#16,#19,$);
    /*workingstep1_security _plane data (Generic)*/
..........................
   /*workingstep1_security_plane data (Generic)*/
/*workingstep1_operation data (Generic)*/
#19=PLANE_FINISH_MILLING($,$,'FINISH PLANAR FACE1',$,$, $, $,$,$,$,$,$,$,$);
/*workingstep1_operation data (Generic)*/
/*workingstep1_feature data */
..........................
 /*workingstep1_feature data */
 /*workingstep1 data(Generic) */
..........................
/*workingstep data (Generic)*/
ENDSEC;
END-ISO-10303-21;
```

Fig. 7 Generic STEP-NC program

### 5.4 Activity module of specific STEP-NC program generator

A generic STEP-NC program only contains "what to do" information about the designed workpiece. Therefore, a generic STEP-NC program can be used in a different machining environment such as different types of CNC machines with different cutters to machine the workpiece. For adapting available manufacturing resources and capabilities, a generic STEP-NC program needs to be converted into a specific STEP-NC program.

As shown in Fig. 8, activity module A2 is further divided into three activity modules: Specific STEP-NC program reader module, specific STEP-NC program editor and specific STEP-NC program generator. This process starts with extracting feature information from a generic STEP-NC program. Then, every feature and its corresponding machining operation are integrated into a workingstep. After these workingsteps are ordered and combined, some auxiliary workingsteps and operations such as rapid approach are inserted, which make all workingsteps continuous. Therefore, a specific process planning is created. Then, machining parameters from available manufacturing resources such as machine tools are fed into this specific process planning. At the end, all the machining information is mapped into the file in ISO 10303-21 or ISO 10303-28 format. Thus, a specific STEP-NC program is generated and directly used on the shop floor, as shown in Fig. 9.

### 5.5 Activity module of processor

A specific STEP-NC program describes machining task and machining process in detail. However, sequences of workingsteps, even machining parameters in every workingstep can be optimized in principle. Moreover, tool-path needs to be created. Even if tool-path has been given, tool-path still needs to be reproduced because of possible modification of workingsteps sequences and machining parameters. That is to say, the simulation should realize the planning of tool-path and optimize the process planning.

As shown in Fig. 10, optimization of machining process planning and tool-path planning are obtained through a specific STEP-NC program reader activity module, machining information checker activity module and tool-path activity module. At first, manufacturing information is obtained from a specific STEP-NC data file. Then, expert system and neural network are used to analyze and optimize the manufacturing information. Finally, based on machining features, cutting tool information, and optimized process planning information, the tool-path generator generates tool-path according to the machining strategy. In fact, the movement of the machine tool table and spindle is driven by servo system with the input of the impulse which CNC system generates according to the accuracy requirements. Therefore, the generated tool-paths need to be interpolated to simulate real movement using the interpolation algorithm. Thus, all the necessary information about the simulation is provided. Fig. 11 shows simplified interfaces for the processor module.

### 5.6 Activity module for machining process simulator

The objective of the simulation module is to verify the machine-specific data generated from the above modules before it is used in a real machining process. According to the above information, the geometric simulation module graphically displays the cutting process of workpiece. Possible errors such as machine tools, cutter and workpiece collision can be detected. In addition, it can provide geometric information such as the entry and exit angle of the cutter to physical simulation. Physical simulation is to reveal the true mechanism of the machining process such as cutting forces and vibration. Based on mathematical models of physical factors and geometric information in the cutting process, it can realize the prediction of cutting forces, feedrate, surface roughness and vibration. Optimization such as choosing better tool-path for the selected tool or changing feed-rate and depth of the cut with optimal values is carried out based on the simulation results.

As shown in Fig. 12, the models and cutter movements in the machining process are shown based on the information input. Then, using geometric information and physical models such as cutting forces model, physical factors are predicted. Finally, collision and other physical information are analyzed and optimized through an expert system and neutral network. Feedback is also sent to the specific STEP-NC program generator activity module in order to generate optimized STEP-NC data file. Thus, the manufacturing process is intelligently and flexibly improved. Fig.13 shows the interface of the developed prototype system.

## 6 Conclusions

Nowadays, NC machining simulation has played an important role in modern manufacturing. However, existing research limits the development of a real simulation system. To facilitate the advancement of NC machining simulation and meet the development of modern manufacturing, this paper presented the STEP-NC based high-level machining simulation solution integrated with CAD/CAPP/CAM. The proposed solution′s functions consist of generic STEP-NC program generator, specific STEP-NC program generator, STEP-NC program processor and simulator. It has a number of advanced features: it can provide an informative and real simulation, and it can make CAD/CAPP/CAM integrated with simulation analysis. Within the high-level machining simulation system, some modules such as STEP-NC program processor and simulator have been implemented. Therefore, other modules will be added and the whole system will be completed in the near future. In addition, because function block technology can be used in modularized process planning, machining simulation and execution[52, 53], it will be combined with NC machining simulation in the future.

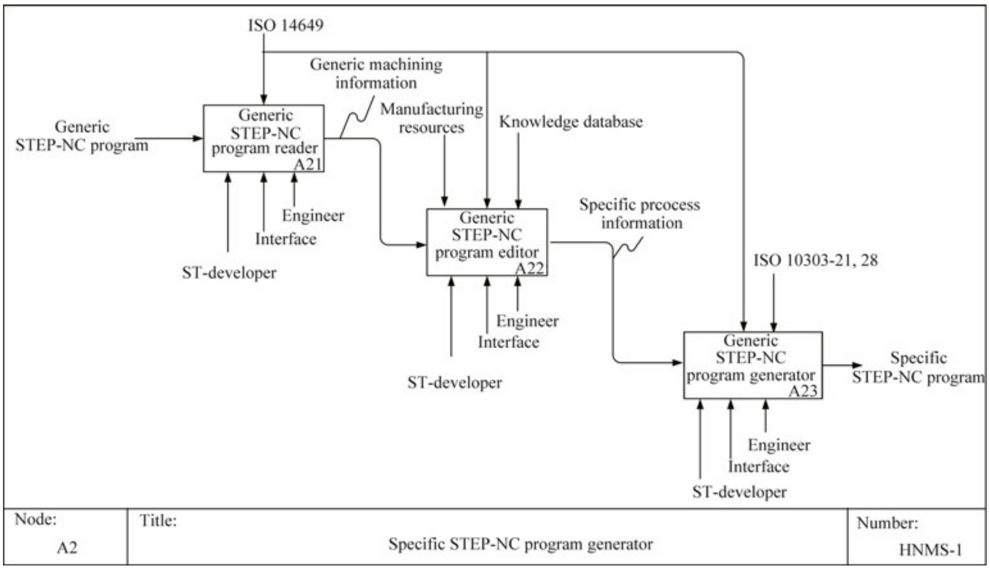


Fig. 8 Activity module of specific STEP-NC program generator

```
ISO-10303-21;
HEADER;
FILE_DESCRIPTION( ('SPECIFIC PROGRAM ','2;1');
..........................
ENDSEC;
DATA;
#1= PROJECT('EXECUTE EXAMPLE1-0.5',#2,(#4),$,$,$);
#2= WORKPLAN('MAIN WORKPLAN',(#10,#11,#12,#13,#14),$,#8,$);
/*workpiece data*/
#4= WORKPIECE('SIMPLE WORKPIECE',#6,0.010,$,$,$,(#66,#67,#68,#69));
..........................
#66= CARTESIAN_POINT('CLAMPING_POSITION1',(0.000,10.000,17.000));
#67= CARTESIAN_POINT('CLAMPING_POSITION2',(50.000,10.000,17.000));
#68= CARTESIAN_POINT('CLAMPING_POSITION3',(0.000,50.000,17.000));
#69= CARTESIAN_POINT('CLAMPING_POSITION4',(50.000,50.000,17.000));
/*workpiece data*/
..........................
/*workingstep1 data */
#10= MACHINING_WORKINGSTEP('WS FINISH PLANAR FACE1',#62,#16,#19,$);
..........................
/*workingstep1_operation data */
#19= PLANE_FINISH_MILLING($,$,'FINISH PLANAR
FACE1',10.000,$,#39,#40,#41,$,#60,#61,#42,2.500,$);
/*workingstep1_operation_cutting tool data */
#39= MILLING_CUTTING_TOOL('MILL 9.5MM',#29,(#125),80.000,$,$);
#29= TAPERED_ENDMILL(#30,4,.RIGHT.,.F.,$,$);
#30= MILLING_TOOL_DIMENSION(9.500, $,$, 29.0, 0.0, $,$);
#125= CUTTING_COMPONENT(80.000,$,$,$,$);
/*workingstep1_operation_cutting tool data */
/*workingstep1_operation_technology data */
#29=MILLING_TECHNOLOGY(0.06,.TCP.,$,-8.,$,.F.,.F.,.F.,$);
/*workingstep1_operation_technology data */
/*workingstep1_operation_function data */
#40= MILLING_TECHNOLOGY(0.040,.TCP.,$,-12.000,$,.F.,.F.,.F.,$);
/*workingstep1_operation_function data */
/*workingstep1_operation_strategy data */
..........................
#42= BIDIRECTIONAL (0.05, .T., #43, .LEFT., $);
#43= DIRECTION('STRATEGY PLANAR FACE1: 1.DIRECTION',(0.000,1.000,0.000));
/*workingstep1_operation_strategy data */
/*workingstep1_operation data */
/*workingstep1_feature data */
..........................
ENDSEC;
END-ISO-10303-21;
```

Fig. 9 Specific STEP-NC program

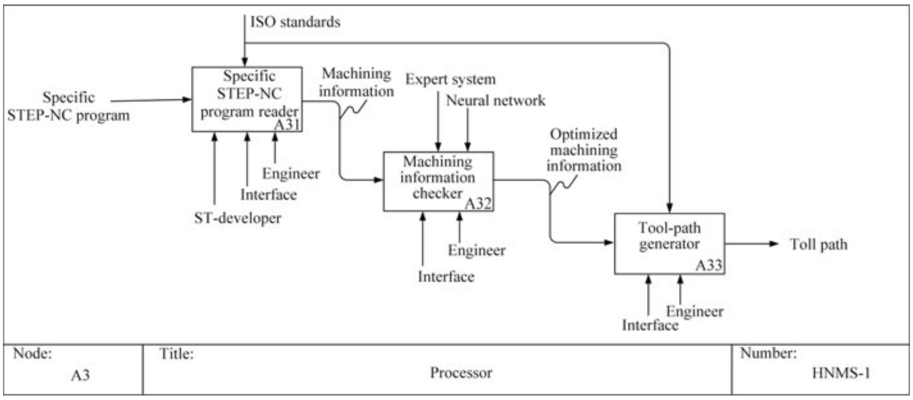
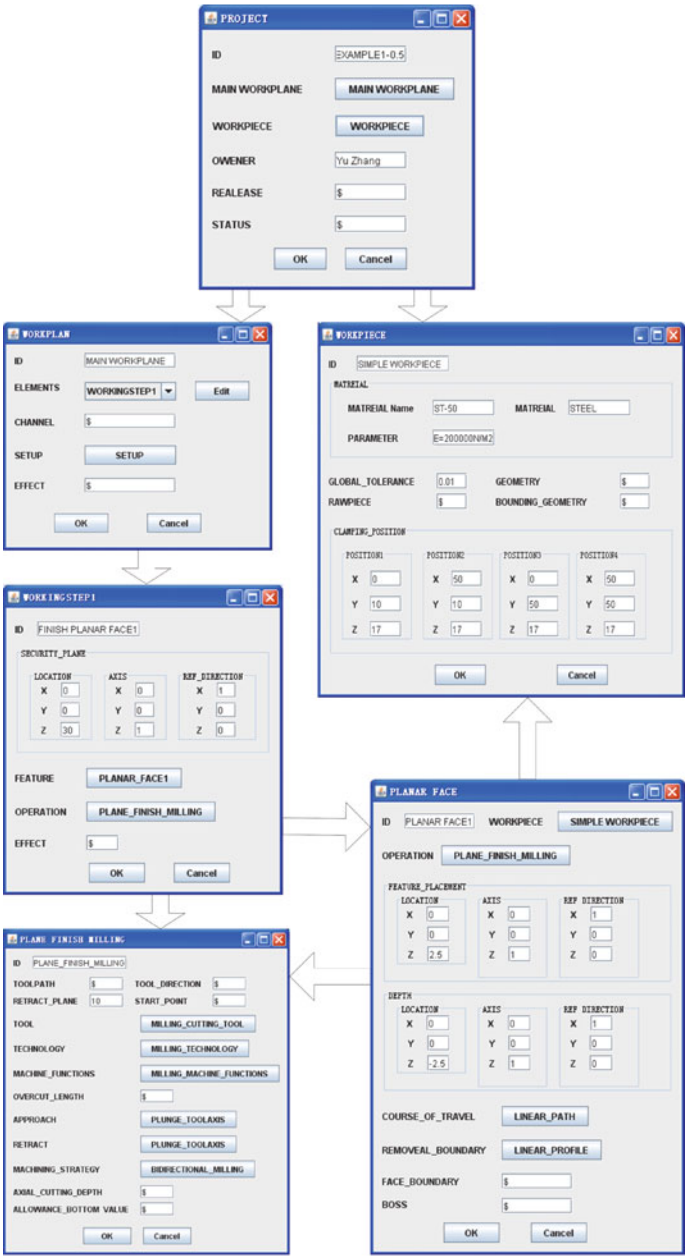


Fig. 10 Activity module of processor



PROJECT

| | |
|---|---|
| ID | EXAMPLE1-0.5 |
| MAIN WORKPLANE | MAIN WORKPLANE |
| WORKPIECE | WORKPIECE |
| OWENER | Yu Zhang |
| REALEASE | $ |
| STATUS | $ |

WORKPLAN

| | |
|---|---|
| ID | MAIN WORKPLANE |
| ELEMENTS | WORKINGSTEP1 |
| CHANNEL | $ |
| SETUP | SETUP |
| EFFECT | $ |

WORKPIECE

| | |
|---|---|
| ID | SIMPLE WORKPIECE |

MATREIAL

| | | | |
|---|---|---|---|
| MATREIAL Name | ST-50 | MATREIAL | STEEL |
| PARAMETER | E=200000N/M2 | | |
| GLOBAL_TOLERANCE | 0.01 | GEOMETRY | $ |
| RAWPIECE | $ | BOUNDING_GEOMETRY | $ |

CLAMPING_POSITION

| | POSITION1 | POSITION2 | POSITION3 | POSITION4 |
|---|---|---|---|---|
| X | 0 | 50 | 0 | 50 |
| Y | 10 | 10 | 50 | 50 |
| Z | 17 | 17 | 17 | 17 |

WORKINGSTEP1

| | |
|---|---|
| ID | FINISH PLANAR FACE1 |

SECURITY_PLANE

| | LOCATION | AXIS | REF_DIRECTION |
|---|---|---|---|
| X | 0 | 0 | 1 |
| Y | 0 | 0 | 0 |
| Z | 30 | 1 | 0 |

| | |
|---|---|
| FEATURE | PLANAR_FACE1 |
| OPERATION | PLANE_FINISH_MILLING |
| EFFECT | $ |

PLANAR FACE

| | | | |
|---|---|---|---|
| ID | PLANAR FACE1 | WORKPIECE | SIMPLE WORKPIECE |
| OPERATION | PLANE_FINISH_MILLING | | |

FEATURE_PLACEMENT

| | LOCATION | AXIS | REF DIRECTION |
|---|---|---|---|
| X | 0 | 0 | 1 |
| Y | 0 | 0 | 0 |
| Z | 2.5 | 1 | 0 |

DEPTH

| | LOCATION | AXIS | REF DIRECTION |
|---|---|---|---|
| X | 0 | 0 | 1 |
| Y | 0 | 0 | 0 |
| Z | -2.5 | 1 | 0 |

| | |
|---|---|
| COURSE_OF_TRAVEL | LINEAR_PATH |
| REMOVEAL_BOUNDARY | LINEAR_PROFILE |
| FACE_BOUNDARY | $ |
| BOSS | $ |

PLANE FINISH MILLING

| | | | |
|---|---|---|---|
| ID | PLANE_FINISH_MILLING | | |
| TOOLPATH | $ | TOOL_DIRECTION | $ |
| RETRACT_PLANE | 10 | START_POINT | $ |
| TOOL | MILLING_CUTTING_TOOL | | |
| TECHNOLOGY | MILLING_TECHNOLOGY | | |
| MACHINE_FUNCTIONS | MILLING_MACHINE_FUNCTIONS | | |
| OVERCUT_LENGTH | $ | | |
| APPROACH | PLUNGE_TOOLAXIS | | |
| RETRACT | PLUNGE_TOOLAXIS | | |
| MACHINING_STRATEGY | BIDIRECTIONAL_MILLING | | |
| AXIAL_CUTTING_DEPTH | $ | | |
| ALLOWANCE_BOTTOM VALUE | $ | | |

Fig. 11 Simplified interfaces for the processor module

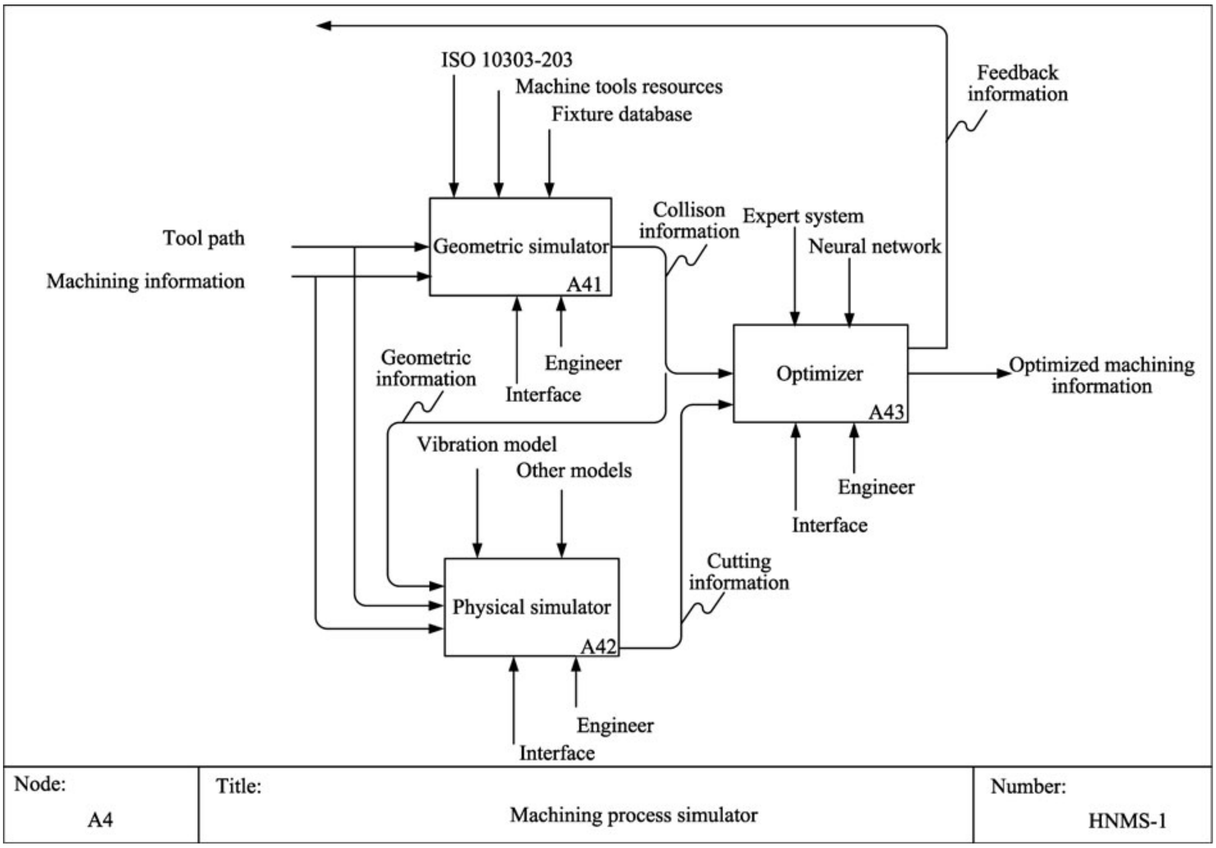


Fig. 12 Activity module of machining process simulator

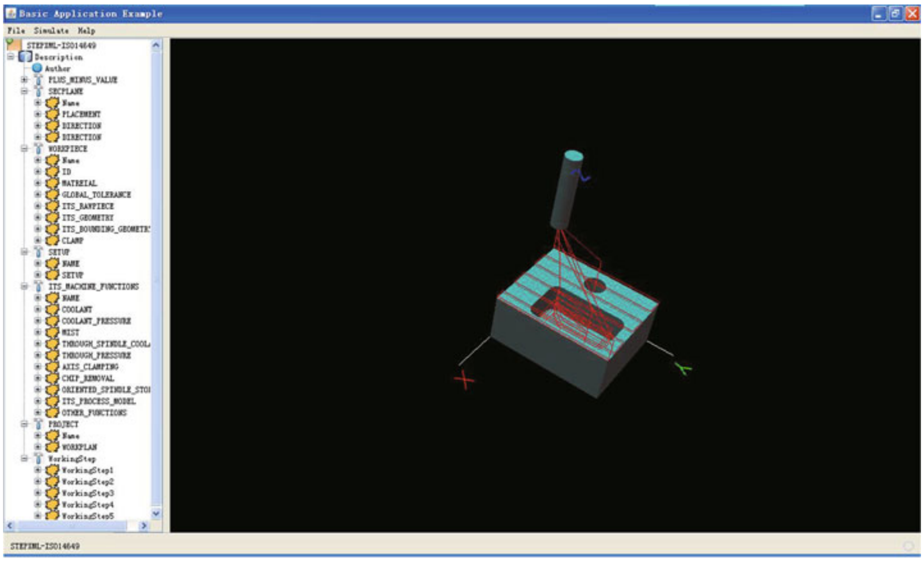


Fig. 13 Interface of the developed prototype system

## References

[1] X. W. Xu, Q. He. Striving for a total integration of CAD, CAPP, CAM and CNC. *Robotics and Computer-Integrated Manufacturing*, vol. 20, no. 2, pp. 101–109, 2004.

[2] Y. Zhang, M. Rauch, H. L. Xie, Y. Y. Zhao, X. Xun, Y. X. Liu. Machining simulation – A technical review and a proposed concept model. *International Journal of Internet Manufacturing and Services*, vol. 3, no. 1, pp. 59–75, 2011.

[3] W. A. Hunt, H. B. Voelcker. An Exploratory Study of Automatic Verification of Programs for Numerically Controlled Machine Tools. Production Automation Project Technical Memorandum No. 34, University of Rochester, USA, 1982.

[4] J. M. O′Connell, A. G. Jablokow. Construction of solid models from NC machining programs. *ASME Production*

*Engineering Division*, vol. 64, pp. 157–166, 1993.

[5] J. G. Li, Y. X. Yao, D. Gao, W. B. Lee, C. F. Cheung, Z. J. Yuan. Part modeling to improve simulation qualities of virtual turning. *Computer Integrated Manufacturing Systems*, vol. 8, no. 3, pp. 233–238, 2002. (in Chinese)

[6] Q. S. Xing, X. M. Zhao. A study of simulating system of numerical control machining based on ACIS. *Journal of Yancheng Institute of Technology (Natural Science)*, vol. 18, no. 4, pp. 5–8, 2005. (in Chinese)

[7] *VERICUT* [online], Available: http://www.vericut.com/usa/index.php, July 14, 2010.

[8] W. P. Wang, K. K. Wang. Geometric modeling for swept volume of moving solids. *IEEE Computer Graphics and Applications*, vol. 6, no. 12, pp. 8–17, 1986.

[9] T. Van Hook. Real-time shaded NC milling display. *Computer Graphics*, vol. 20, no. 4, pp. 15–20, 1986.

[10] P. Atherton, C. Earl, C. Fred. A graphical simulation system for dynamic five-axis NC verification. In *Proceedings of the Autofact 87th Conference*, SME, Dearborn, MI, USA, pp. 2.1–2.12, 1987.

[11] Y. C. Huang, J. H. Oliver. Integrated simulation, error assessment, and tool path correction for five-axis NC milling. *Journal of Manufacturing Systems*, vol. 14, no. 5, pp. 331–344, 1995.

[12] I. Blasquez, J. F. Poiraudeau. Undo facilities for the extended z-buffer in NC machining simulation. *Computers in Industry*, vol. 53, no. 2, pp. 193–204, 2004.

[13] R. O. Anderson. Detecting and eliminating collisions in NC machining. *Computer-Aided Design*, vol. 10, no. 4, pp. 231–237, 1978.

[14] S. H. Lee, K. S. Lee. Local mesh decimation for view-Independent three-axis NC milling simulation. *International Journal of Advanced Manufacturing Technology*, vol. 19, no. 8, pp. 579–586, 2002.

[15] I. T. Chappel. The use of vectors to simulate material removed by numerically controlled milling. *Computer-Aided Design*, vol. 15, no. 3, pp. 156–168, 1983.

[16] J. H. Oliver, E. D. Goodman. Color Graphic verification of N/C milling programs for sculptured surface parts. In *Proceedings of the First Symposium on Integrated Intelligent Manufacturing*, ASME, New York, USA, vol. 21, pp. 247–263, 1986.

[17] R. B. Jerard, R. L. Drysdale III, K. E. Hauck, B.Schaudt, J. Magewick. Methods for detecting errors in numerically controlled machining of sculptured surfaces. *IEEE Computer Graphics and Applications*, vol. 9, no. 1, pp. 26–39, 1989.

[18] Z. D. Zhou, J. D. Zhou, Y. P. Chen, S. K. Ong, A. Y. C. Nee. Geometric simulation of NC machining based on STL models. *CIRP Annals – Manufacturing Technology*, vol. 52, no. 1, pp. 129–134, 2003.

[19] K. Ding. A Study on a New Geometric Modeling for Off-line and On-line Multi-axis Machining Simulation System, Ph. D. dissertation, University of California Davis, USA, 2004.

[20] J. W. Park, Y. H. Shin, Y. C. Chung. Hybrid cutting simulation via discrete vector model. *Computer-Aided Design*, vol. 37, no. 4, pp. 419–430, 2005.

[21] P. Brunet, I. Navazo. Solid representation and operation using extended octrees. *ACM Transactions on Graphics*, vol. 9, no. 2, pp. 170–197, 1990.

[22] U. Roy, Y. X. Xu. 3-D object decomposition with extended octree model and its application in geometric simulation of NC machining. *Robotics and Computer-Integrated Manufacturing*, vol. 14, no. 4, pp. 317–327, 1998.

[23] U. Roy, Y. X. Xu. Computation of a geometric model of a machined part from its NC machining programs. *Computer-Aided Design*, vol. 31, no. 6, pp. 401–411, 1999.

[24] K. P. Karunakaran, R. Shringi. Octree-to-BRep conversion for volumetric NC simulation. *International Journal of Advanced Manufacturing Technology*, vol. 32, no. 1–2, pp. 116–131, 2007.

[25] W. P. Wang. Solid modeling for optimizing metal removal of three-dimensional NC end milling. *Journal of Manufacturing Systems*, vol. 7, no. 1, pp. 57–65, 1988.

[26] A. Spence, Y. Altintas, D. Kirkpatrick. Direct calculation of machining parameters from a solid model. *Computers in Industry*, vol. 14, no. 4, pp. 271–280, 1990.

[27] A. D. Spence, Y. Altintas. A solid modeller based milling process simulation and planning system. *ASME Journal of Engineering for Industry*, vol. 116, no. 1, pp. 61–69, 1994.

[28] J. Tlusty, P. MacNeil. Dynamics of cutting forces in end milling. *Annals of the CIRP*, vol. 24, no. 1, pp. 21–25, 1975.

[29] H. El-Mounayri, M. A. Elbestawi, A. D. Spence, S. Bedi. General geometric modelling approach for machining process simulation. *International Journal of Advanced Manufacturing Technology*, vol. 13, no. 4, pp. 237–247, 1997.

[30] H. El-Mounayri, A. D. Spence, M. A. Elbestawi. Milling process simulation–A generic solid modeller based paradigm. *Journal of Manufacturing Science and Engineering*, vol. 120, no. 2, pp. 213–221, 1998.

[31] H. El-Mounayri, H. Kishawy, V. Tandon. Optimized CNC end-milling: A practical approach. *International Journal of Computer Integrated Manufacturing*, vol. 15, no. 5, pp. 453–470, 2002.

[32] B. M. Imani, M. H. Sadeghi, M. A. Elbestawi. An improved process simulation system for ball-end milling of sculptured surfaces. *International Journal of Machine Tools and Manufacture*, vol. 38, no. 9, pp. 1089–1107, 1998.

[33] B. M. Imani, M. A. Elbestawi. Geometric simulation of ball-end milling operations. *Journal of Manufacturing Science and Engineering*, vol. 123, no. 2, pp. 177–184, 2001.

[34] T. Bailey, M. A. Elbestawi. Generic simulation approach for multi axis machining, Part 1: Modeling methodology. *Journal of Manufacturing Science and Engineering*, vol. 124, no. 3, pp. 624–633, 2002.

[35] T. Bailey, M. A. Elbestawi. Generic simulation approach for multi axis machining, Part 2: Model calibration and feed rate schedule. *Journal of Manufacturing Science and Engineering*, vol. 124, no. 3, pp. 634–642, 2002.

[36] E. Aras, D. Yip-Hoi. Geometric modeling of cutter/workpiece engagements in three-axis milling using polyhedral representations. *Journal of Computing and Information Science in Engineering*, vol. 8, no. 3, pp. 031007.1–031007.13, 2008.

[37] W. Ferry, D. Yip-Hoi. Cutter-workpiece engagement calculations by parallel slicing for five-axis flank milling of jet engine impellers. *Journal of Manufacturing Science and Engineering*, vol. 130, no. 5, pp. 051011.1– 051011.12, 2008.

[38] D. Yip-Hoi, X. M. Huang. Cutter/workpiece engagement feature extraction from solid models for end milling. *Journal of Manufacturing Science and Engineering*, vol. 128, no. 1, pp. 249–260, 2006.

[39] K. P. Karunakaran, R. Shringi. A solid model-based off-line adaptive controller for feed rate scheduling for milling process. *Journal of Materials Processing Technology*, vol. 204, no. 1–3, pp. 384–396, 2008.

[40] Y. Altintas, P. Lee. A general mechanics and dynamics model for helical end mills. *CIRP Annals – Manufacturing Technology*, vol. 45, no. 1, pp. 59–64, 1996.

[41] K. P. Karunakaran, R. Shringi, D. Ramamurthi, C. Hariharan. Octree-based NC simulation system for optimization of feed rate in milling using instantaneous force model. *International Journal of Advanced Manufacturing Technology*, vol. 46, no. 5–8, pp. 465–490, 2010.

[42] L. Zhou, K. Cheng. Dynamic cutting process modelling and its impact on the generation of surface topography and texture in nano/micro cutting. In *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, Professional Engineering Publishing Ltd., London, United Kingdom, vol. 223, no. 3, pp. 247–266, 2009.

[43] K. Cheng. *Machining Dynamics: Fundamentals, Applications and Practices.* Berlin, Germany: Springer-Verlag, 2008.

[44] X. W. Xu. Realization of STEP-NC enabled machining. *Robotics and Computer-Integrated Manufacturing*, vol. 22, no. 2, pp. 144–153, 2006.

[45] ISO 10303-11, Industrial Automation Systems and Integration-product Data Representation and Exchange–Part 11: Description methods: The EXPRESS Language Reference Manual, International Organization for standardization, 2004.

[46] ISO 10303-203, Industrial automation systems and integration – Product data representation and exchange – Part 203: Application protocol: Configuration controlled 3D design of mechanical parts and assemblies (modular version), 2005.

[47] H. B. Wang, M. Liu. Design of robotic visual servo control based on neural network and genetic algorithm. *International Journal of Automation and Computing*, vol. 9, no. 1, pp. 24–29, 2012.

[48] C. L. Zhang, J. M. Li. Adaptive iterative learning control for nonlinear time-delay systems with periodic disturbances using FSE-neural network. *International Journal of Automation and Computing*, vol. 8, no. 4, pp. 403–410, 2011.

[49] ISO 10303-224, Industrial automation systems and integration – Product data representation and exchange – Part 224: Application protocol: Mechanical product definition for process planning using machining features, 2006.

[50] ISO 10303-21, Industrial automation systems and integration – Product data representation and exchange – Part 21: Implementation methods: Clear text encoding of the exchange structure, International Organization for standardization, 2002.

[51] ISO 10303-28, Industrial automation systems and integration – Product data representation and exchange – Part 28: Implementation methods: XML representations of EXPRESS schemas and data, using XML schemas, International Organization for standardization, 2007.

[52] X. Xu, L. H. Wang, S. T. Newman. Computer-aided process planning – A critical review of recent developments and future trends. *International Journal of Computer Integrated Manufacturing*, vol. 24, no. 1, pp. 1–31, 2011.

[53] L. Wang, M. Holm, G. Adamson. Embedding a process plan in function blocks for adaptive machining. *CIRP Annals – Manufacturing Technology*, vol. 59, no. 1, pp. 433–436, 2010.

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