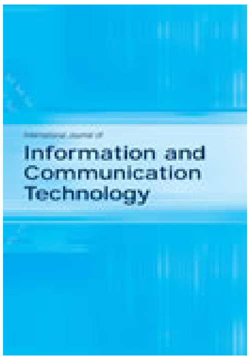


International Journal of Information and Communication Technology

ISSN online: 1741-8070 - ISSN print: 1466-6642
https://www.inderscience.com/ijict

Virtual machining simulation of automatic numerical control machine tool depending on dynamic cutting algorithm

Kechang Zhang, Rundong Shen, Jinyan Shi

Article History:

Received:	09 November 2023
Last revised:	19 December 2023
Accepted:	27 December 2023
Published online:	03 May 2024

Virtual machining simulation of automatic numerical control machine tool depending on dynamic cutting algorithm

Kechang Zhang, Rundong Shen* and
Jinyan Shi

Hunan Railway Professional Technology College,
ZhuZhou 412001, China
Email: zhangkechang2008@163.com
Email: 3074986874@qq.com
Email: shijinyan2008@126.com
*Corresponding author

Abstract: There are many mature numerical control simulation systems on the market at present, but they are basically similar in shape, and only simple geometric simulation is carried out on personal computer (PC), which leads to the lack of realism in the simulation process. In this paper, three-dimensional modelling software is used to model the numerical control machine-tool-workpiece system, and real materials are added to enhance the sense of reality, so as to transform and get the triangular mesh model. Moreover, this paper presents a tool envelope generation algorithm based on mesh model, which can calculate a polygon intersection algorithm based on two-dimensional operation according to the tool trajectory, and determine the spatial position between the tool and the triangular mesh contained in the workpiece. The experimental results show that the algorithm proposed in this paper has low time complexity and meets the basic cutting requirements. At the same time, the virtual machining method of automatic numerical control machine tools based on dynamic cutting algorithm proposed in this paper can effectively improve the machining effect of intelligent numerical control machine tools.

Keywords: dynamic cutting algorithm; automation; numerical control machine tool; virtual machining.

Reference to this paper should be made as follows: Zhang, K., Shen, R. and Shi, J. (2024) ‘Virtual machining simulation of automatic numerical control machine tool depending on dynamic cutting algorithm’, *Int. J. Information and Communication Technology*, Vol. 24, No. 5, pp.1–23.

Biographical notes: Kechang Zhang received his BSc in Mould Design and Manufacture from Xiangtan University, China. Currently, he is an Associate Professor at Hunan Railway Professional Technical College, China. His research field of centres on machine design.

Rundong Shen received his BSc in Motor Vehicle Service Engineering from Changsha University of Science and Technology, China, and MSc in Transportation Engineering from Changsha University of Science and Technology, China. Currently, he is a Lecturer at Hunan Railway Professional Technical College, China. His research field of centres on machinery design and manufacture.

Jinyan Shi received her BSc in Machine Design and Automation from Lanzhou Jiaotong University, China, and MSc degree in Drive Technology and Intelligent System from Southwest Jiaotong University, China. Currently, she is a Professor at Hunan Railway Professional Technical College, and she is a key young teacher in Hunan Province, China. Her research field of centres on CFD.

1 Introduction

Intelligent manufacturing can improve production efficiency and product quality, reduce production costs, and has become a key measure for manufacturing enterprises to enhance their core competitiveness. Among them, real-time monitoring technology of cutting process is an important condition for intelligent manufacturing in cutting manufacturing enterprises. Moreover, the basic monitoring process of cutting process includes data acquisition, data processing, feature extraction and pattern recognition. Sensing signal acquisition is a very important part of cutting process monitoring. How to quickly, reliably and accurately collect cutting process parameter information has been widely concerned by researchers. In addition, designing and developing a sensing device to meet the application requirements is a necessary condition for realising real-time monitoring of cutting process, and it is also one of the keys to realise intelligent manufacturing.

Among all monitoring variables in the cutting process, cutting force is one of the most important signals. Cutting force is one of the most important parameters that describe the performance of machine tools and tool status during the cutting process. It can provide information for various studies, such as cutting parameter optimisation, tool status monitoring, tool optimisation design, understanding the principle of chip formation, detecting and suppressing chatter, and predicting surface quality during machining. But cutting force is a multi-component coupling force, and in order to clarify the information it contains, it is necessary to decouple each component (Gao and Zhang, 2019). At present, most cutting force sensors sense different components in different positions or directions by optimising their structure, thereby achieving decoupling of cutting forces. But sometimes there is significant inter dimensional interference between the various components, and some algorithms need to be used to further decouple the cutting force data, which increases the workload in the later stage. Therefore, in order to reduce the inter dimensional coupling interference of the sensor and directly collect the various components of cutting force, this paper proposes a spindle type mechanical self-decoupling force/torque sensor. It can be applied to machine tool spindles to measure the cutting force information of the machine tool through decoupling methods of mechanical structure self-decoupling and wireless passive detection methods (Liu et al., 2021).

The numerical control (NC) simulation technology based on virtual reality technology (referred to as virtual NC simulation technology) mainly utilises virtual reality technology and NC simulation technology to virtual map various production elements of the actual production and manufacturing process in a computer simulation system, and uses computers and virtual reality equipment to truly simulate the actual NC machining process. Compared with traditional (CNC) simulation systems, due to the application of virtual reality technology, virtual CNC simulation technology integrates the advantages of virtual reality technology and provides a new CNC simulation strategy. Virtual CNC simulation technology is an improvement on CNC simulation technology and an important branch of virtual manufacturing technology. This technology can verify the machining effect of CNC programs in a virtual environment and monitor the status of the machining process. The main purpose of virtual CNC simulation technology is to build a "real" simulation environment, which should reflect the machining process truthfully on the one hand, and make the simulation environment more immersive and restore the three-dimensional environment of machining on the other hand (Zhang, 2020).

The designed virtual CNC simulation system should have good scalability, mainly reflected in the possibility of introducing new models of CNC machine tools and CNC systems into the simulation system. Therefore, when designing the simulation system, it should try to conform to the characteristics of 'high scalability and low coupling' (Li et al., 2018).

In order to improve the intelligence of automatic NC machine tools, combined with dynamic cutting algorithm, this paper carries out virtual machining simulation of automatic NC machine tools under the support of intelligent computer simulation technology, which provides reference for the development of intelligent control technology of internet of things for NC machine tools.

2 Related work

A complete virtual device interface can provide high-quality interactive operations, providing users with maximum immersion. The simulation system can present the most realistic machining environment to users and visualise the state parameters during the machining process. The virtual CNC simulation system should have high stability, which requires that in the process of designing the CNC program analysis module and cutting algorithm, various possible uncertain situations should be comprehensively considered to ensure the robustness of the algorithm (Racz et al., 2019).

Geometric simulation ignores the impact of external factors such as cutting parameters and cutting temperature on the machining system during the cutting process, treating the machining system composed of machine tools workpiece as an environment without physical state changes. The main focus of geometric form simulation is on geometric shapes, so this simulation strategy mainly studies the motion between the tool and the workpiece, verifies the accuracy of the NC machining program and the machining effect of the processed parts. This can avoid a series of problems caused by incorrect NC programs in actual machining, such as damage to the machining system, waste of production raw materials, etc. (Li et al., 2020). Ultimately, it plays a role in shortening the production cycle of parts and reducing processing costs. Physical attribute simulation, which mainly focuses on more complex targets, focuses on the dynamic changes of various physical attributes in the machining system during the cutting process, such as cutting temperature, cutting force, chip shape, etc. Because the simulation of physical properties is related to changes in the internal state of objects, compared to the simulation of geometric forms, its simulation difficulty is higher. The accuracy of this method of simulation is closely related to the established model. Ultimately, the processing status can be monitored through predicted values and the processing parameters can be optimised (Bingran et al., 2020).

As a high-precision gear processing equipment, CNC gear grinding machines are increasingly difficult to control and compensate for thermal errors due to factors such as structural differences, changes in processing conditions, and time delays in thermal errors. Under actual machining conditions, it is difficult to model the nonlinear relationship between thermal deformation and temperature changes, making it difficult to solve the problem of thermal error. Therefore, combining the structure and usage characteristics of CNC gear grinding machines, targeted research on the layout and optimisation of key points under actual working conditions, robust modelling technology of feed shaft under variable working conditions, sensorless thermal error modelling of workpiece spindle, and data driven model of grinding wheel spindle can effectively promote the promotion and application of this technology on CNC gear grinding machines. The research on thermal error compensation technology has both theoretical and practical value (Wang, 2020).

Hongzhou and Lixia (2018) conducted idle tests on the Z-axis of CNC machining centres. Through comparison of experimental data, it was found that changes in operating conditions have an impact on temperature sensitive points, which leads to changes in the degree of multicollinearity between modelling variables, thereby affecting the robustness and prediction accuracy of the model. In order to eliminate this impact, principal component analysis was used to process temperature data during measurement point optimisation. This method effectively reduces the fluctuation characteristics of temperature sensitive points, ensuring the robustness and prediction accuracy of the model. Ta et al. (2021) propose a method for constructing linear virtual temperature measurement points, which uses principal component analysis to select the variable with the most information from two types of temperatures, and weights this variable to construct a linear virtual temperature sequence. In the study, two key temperature variables with the highest amount of information were selected, and the algorithm can ensure that the information carried by these two key temperature variables accounts for more than 90% of the information provided by all temperature variables. Muniandi (2020) suggests that the thermal generation of the spindle is closely related to the temperature change process. Through principal component analysis, researchers extracted the characteristics of the initial temperature variables and reconstructed a new input variable for the thermal error model. Compared with the model established with initial temperature variables, the prediction accuracy of the input variable model reconstructed based on principal component analysis has been greatly improved. Kidani et al. (2020) adopt a temperature feature extraction method for gantry machine tools, which extracts information from temperature variables that can effectively reflect temperature characteristics as modelling independent variables. The established model has strong robustness. Rangarajan et al. (2020) used principal component analysis to recombine or reduce the dimensionality of multiple temperature variables used in traditional modelling methods, reducing the number of modelling variables. Finally, input the reduced variables into the back propagation (BP) neural network for modelling. The model established through this method has fewer independent variables, faster training speed, and fewer iterations for the thermal error model.

Shi et al. (2020) successfully suppressed the thermal error of the linear axis at the micrometer level by inputting data from 16 temperature measurement points into an independent component analysis model. Using ANSYS to simulate the temperature field and thermal error of the spindle, based on the simulation results, an average impact value method is proposed to select the thermal key points of the spindle. The effectiveness of this method has been verified through experiments. Lee (2019) focused on the simplicity of the arrangement of temperature sensors for machine tool spindles, combined with finite element analysis method, and selected key measurement points for machine tools based on the sensitivity model of thermal errors. Based on the Kohonen neural network thermal sensitive point identification algorithm, this method uses the temperature and thermal error of the test points collected as training samples for the neural network. Kohonen's self-organising competition is used to output the classification results. Finally, by evaluating the correlation between various key points and thermal errors, the machine tool key points are selected. Khan and Sheikh (2018) used thermal modal theory and genetic algorithm to optimise the placement of sensors, and established a machine tool thermal error identification model using least squares support vector machine. In response to the weakness of principal component analysis in identifying nonlinear problems, the author proposes a kernel principal component measurement point identification method.

The chatter in the CNC milling process includes multiple types, including regenerative chatter, mode coupling chatter, friction chatter, and force thermal chatter. Among them, regenerative chatter is the most common and main factor causing instability in the CNC milling process (Moniripiri et al., 2021). As a common way to represent the dynamic model of milling machining, time-delay differential equations have been extensively studied by domestic and foreign scholars, and various solutions have been proposed to construct the stability lobe diagram (SLD) composed of axial cutting depth and spindle speed. These methods can be roughly divided into numerical methods, analytical methods, and semi analytical methods. Subsequently, stable cutting parameters can be selected based on the milling stability domain related to axial cutting depth and spindle speed (Luyun et al., 2021).

3 Algorithm model

3.1 Dynamic cutting algorithm

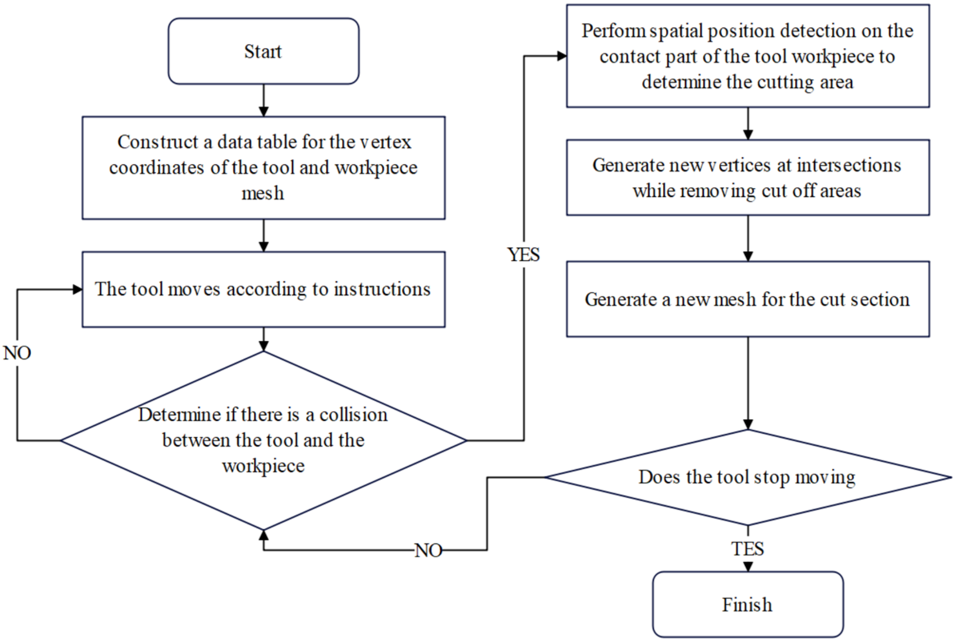
Dynamic cutting is the core part of the virtual machining system, and the quality of a virtual machining system depends on the effect of cutting simulation to a great extent. In view of this situation, a grid cutting algorithm is designed by using the structural characteristics of three-dimensional objects, which improves the real-time performance of dynamic cutting.

The mesh of the model contains a series of information such as object shape, map identification, etc. In Unity3D (three-dimension) software, the mesh attributes of the model can be modified by scripts to realise various special effects. As shown in Figure 1, the spherical triangular mesh model in Unity3D software is shown. The number of triangular meshes is proportional to the accuracy of the mode, and the larger the number of meshes, the higher the accuracy of the model.

The mesh cutting algorithm makes use of the characteristics that each model is composed of many triangular meshes, and takes triangular meshes as the cutting unit. When the cutting tool collides with the object to be cut, the intersection operation is used to calculate the intersection mesh position to generate the cutting area. After cutting, new vertices are generated for the notch part, and the mesh model of the workpiece is improved. The flow chart of cutting algorithm is shown in Figure 2.

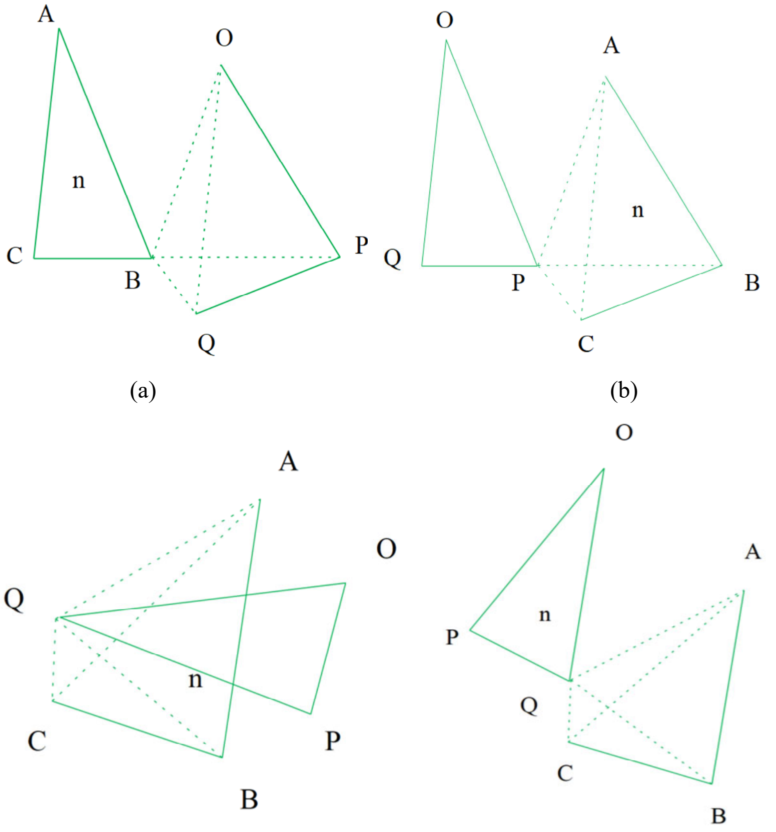
Figure 1 Spherical triangular mesh model

Figure 2 Flow chart of grid cutting algorithm



In three-dimensional space, any two triangular meshes may produce four spatial positional relationships: front, back, coplanar or intersecting, as shown in Figure 3. In the figure, ΔABC and ΔOPQ are assumed to be triangular meshes at adjacent positions respectively. In order to judge the position relationship between two triangular meshes, we take any point Z on ΔOPQ and connect three vertices of ΔABC respectively, and make vectors $\overrightarrow{ZA}$, $\overrightarrow{ZB}$ and $\overrightarrow{ZC}$, which are expressed as vectors n_1, n_2 and n_3, respectively. Through the vector n_1, n_2, n_3 and the normal vector n of the plane ΔOPQ, the quantity product is solved, and the position relationship between the two triangular meshes is judged according to the result of the quantity product.

Figure 3 Spatial position relationship of triangular mesh (see online version for colours)



(a) (b)

(c) (d)

The relationship between quantity product and position is as follows (Legendre et al., 2019):

- Front:

$$\begin{cases} n \cdot n_1 > 0 \\ n \cdot n_2 > 0 \\ n \cdot n_3 > 0 \end{cases} \tag{1}$$

- Back:

$$\begin{cases} n \cdot n_1 < 0 \\ n \cdot n_2 < 0 \\ n \cdot n_3 < 0 \end{cases} \tag{2}$$

- Coplanar:

$$\begin{cases} n \cdot n_1 = 0 \\ n \cdot n_2 = 0 \\ n \cdot n_3 = 0 \end{cases} \tag{3}$$

- Intersect:

$$\begin{cases} n \cdot n_i > 0 \\ n \cdot n_j < 0 \end{cases} \quad \left(i, l \in \{1, 2, 3\} \text{ and } i \neq j\right) \tag{4}$$

The spatial position of triangular mesh contained in tool and workpiece is determined. Firstly, all the triangular meshes contained in the model are defined as a set *T*, and then the position relationship of the triangular meshes is determined by traversal. The execution steps are as follows:

1 The model first takes any triangular mesh T_1 from the set *T*, then traverses all triangular meshes in the set *T* by T_1, determines the spatial position relationship between T_1 and other triangular meshes by using the grid position judgment formula, and stores all the position relationships in T_1 data structure.

2 The model takes any mesh *t* except T_1 from the set *T* again, then traverses all triangular meshes except T_1 in the set *T* by T_2, establishes the spatial position relationship between T_2 and other triangular meshes by using the mesh position judgment formula, and stores all the position relationships in T_2 data structure.

3 The model repeats the above steps until the positional relationship between all triangular meshes in the model is determined.

After the intersection operation between the tool and the workpiece is completed, it is necessary to generate a new mesh at the notch of the workpiece. When there are intersections between meshes, the generated intersections will divide the mesh into two parts: in-line and out-line. Among them, the part in the line and is the intersection area of the two, that is, the cut area, and the intersection schematic diagram is shown in Figure 4. If ΔABC and ΔOPQ intersect, and the intersection points are *E* and *F* respectively, the cut-off area is a quadrilateral part surrounded by *ECFQ*, and points *E* and *F* are the vertices of the regenerated mesh.

In the two-dimensional intersection operation, the straight line intersection problem is already a basic problem. For the sake of clear expression, it is assumed that there are two straight line segments P1P2 and P3P4, and the coordinate differences of their endpoints respectively satisfy the following equations (Delacour, 2018):

$$\begin{cases} A_1 X + B_1 Y + C_1 = 0 \\ A_2 X + B_2 Y + C_2 = 0 \end{cases} \tag{5}$$

According to geometric knowledge, if the two straight lines intersect, the intersection point will be brought into the division and the division value will be 0. By solving the equations, the coordinate expression of the intersection point can be obtained as follows:

$$\begin{cases} x = \dfrac{B_1C_2 - B_2C_1}{A_1B_2 - A_2B_1} \\ y = \dfrac{A_2C_1 - A_1C_2}{A_1B_2 - A_2B_1} \end{cases} \tag{6}$$

Figure 4 Schematic diagram of mesh intersection (see online version for colours)

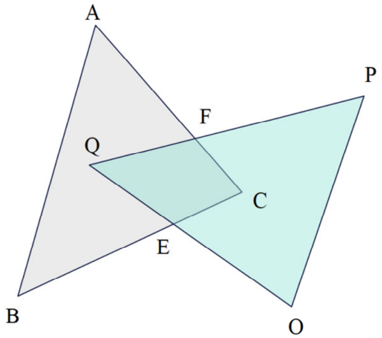
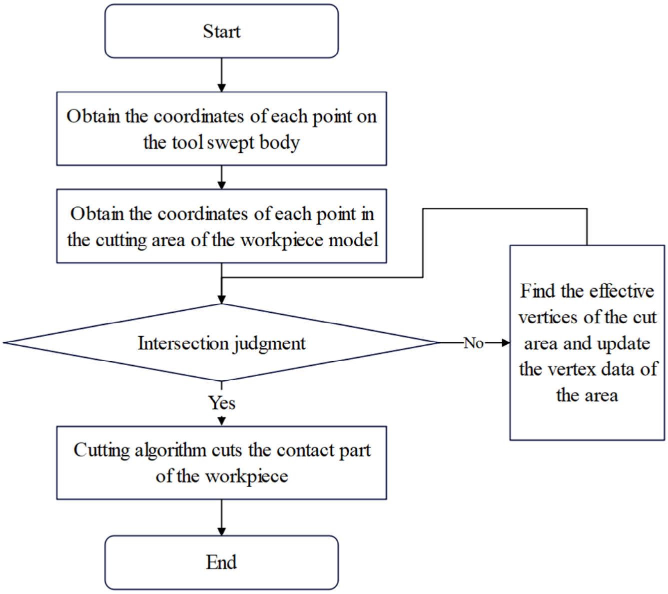


Figure 5 Flow chart of redundant point merging algorithm

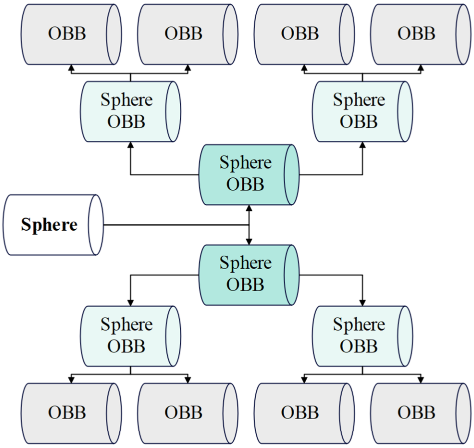


The workpiece model is divided into regions, and each region is marked discretely, so that the meshes of each region of the model are independent of each other. The size of the divided area is reasonably divided according to the size of the workpiece. When the cutter and the workpiece contact each other, the possible contact area is predicted by the cutter and the solid bounding box, and then only this area is intersected, so that the cutter will not affect other divided areas when cutting this area, and the calculation amount of triangular mesh in the cutting process is greatly reduced.

Because cutting simulation is a continuous process, the same area of workpiece may be cut repeatedly. Under the action of triangular mesh generation algorithm, a large number of unnecessary triangular meshes will be generated in the cut area, resulting in redundancy, which leads to a sharp increase in computational complexity and a decrease in computational efficiency. To solve this problem, this paper proposes a method to merge redundant points on the same line. The algorithm flow of this method is shown in Figure 5. This method can greatly reduce unnecessary triangular meshes without changing the morphological characteristics of the workpiece model.

In reality, improper operation of NC machine tools may lead to collision among moving mechanisms of machine tools, resulting in damage to machine tools, scrapping of workpieces, injuries and other accidents. Although the collision of virtual NC machine tools can avoid these accidents, the contact between parts penetrates each other, which will have a great impact on the authenticity of the system. Therefore, it is necessary to carry out collision detection in the machining stage.

Figure 6 BVH tree structure diagram (see online version for colours)



In the traditional collision detection algorithm, sphere algorithm has the simplest construction and the fastest detection time, but it has poor coverage when wrapping objects, so the detection accuracy is low. Axis aligned bounding box (AABB) algorithm is the simplest algorithm except Sphere algorithm, and its detection accuracy has been improved, but it is not suitable for complex objects. Compared with AABB, the detection accuracy of oriented bounding bix (OBB) algorithm has been greatly improved, but the computation is large. Therefore, the most ideal way is to concentrate the advantages of each bounding box. In this paper, the traditional collision detection algorithm is improved. The hierarchical tree is divided into three layers, the upper layer uses sphere as the root bounding box, and the objects that cannot intersect are quickly eliminated by its detection efficiency, which greatly reduces the number of objects detected in the last two layers. In the middle layer, sphere and OBB bounding boxes are mixed for further cross detection. Finally, in the lower layer, OBB single bounding box is used for the last detection, and the high detection accuracy of OBB bounding box is used to determine whether objects collide.

The structure of bounding volume hierarchies (BHV) tree with hierarchical bounding box has a great influence on the performance of post-detection, so it is necessary to choose the construction mode before constructing BVH tree. During the construction, we mainly need to consider the number of traversal in the final detection, and ensure that the number of steps from the root node to the leaf node is very small during the traversal. The top-down construction of BVH tree is simple in construction and superior in performance, so this paper chooses the top-down construction of BVH tree. Figure 6 shows the sphere-OBBBHV (oriented bounding bix-bounding volume hierarchies) tree structure diagram. In the process of collision detection, the bounding box tree will be traversed first, and the top-down construction method starts from the root, that is, sphere. Although the construction of OBB bounding box is complex, it has no influence in the initial traversal of the BVH tree. When no collision is detected after traversal at the root, it is unnecessary to carry out the next level of detection, and so on. This method gives full play to the advantages of sphere detection efficiency, and also has the advantages of good compactness and high detection accuracy of OBB bounding box.

Sphere-OBB hybrid hierarchical bounding box uses hierarchical tree traversal to detect the cross layer by layer to judge whether the model collides or not. The cross tests involved include sphere-sphere cross detection, sphere-OBB cross detection and OBB-OBB cross detection.

1 Sphere-OBB cross detection firstly assumes OBB bounding box A and sphere bounding box B. As shown in Figure 7, a_i represents the distance between the centre of the OBB bounding box and each face, and since the OBB bounding box is hexahedron, $i = 1, 2, 3$ can be obtained. r is the radius of the bounding sphere B, A_i is the axial unit vector ($i = 1, 2, 3$) in the OBB bounding box, T is the centre distance between the OBB bounding box and the Sphere bounding box, L is the unit vector parallel to the separation axis, r_A is the projection of a_i on L, and r_A can be expressed by the formula:

$$r_A = \sum_{i=1}^{3} \left| a_i A_i L \right| \tag{7}$$

As can be seen from Figure 7, it is only necessary to compare the projection of T on L with the sum of r_A and r_B to judge whether A and B collide:

$$\left| T \cdot L \right| > r_A + r_B = \sum_{i=1}^{3} \left| a_i A_i \cdot L \right| + r \tag{8}$$

If this formula holds, the two objects do not intersect. Otherwise, the projection on the other two separate axes continues.

2 OBB-OBB cross detection first assumes two OBB bounding boxes A and B, as shown in Figure 8. Among them, a_i and b_i ($i = 1, 2, 3$) are the distance between the centres of A and B from each face, A_i and B_i ($i = 1, 2, 3$) are the axial unit vectors of A and B, T is the centre distance of A and B, and L is the unit vector parallel to the separation axis. Because the bounding box of OBB has six faces, there are six normal vectors. Moreover, three normal vectors can generate nine normal vectors by difference product, so there are 15 unit vectors parallel to the separation axis. r_A and

r_B are the sum of the projections of a_i and b_i on L, respectively, and their formulas are the same as those of equation (5).

Figure 7 Collision between OBB bounding box and Sphere bounding box (see online version for colours)

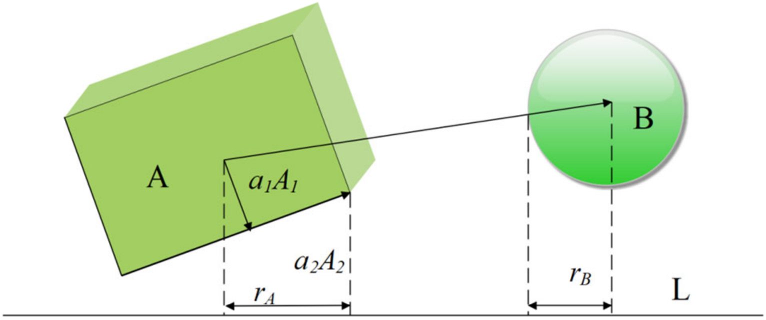
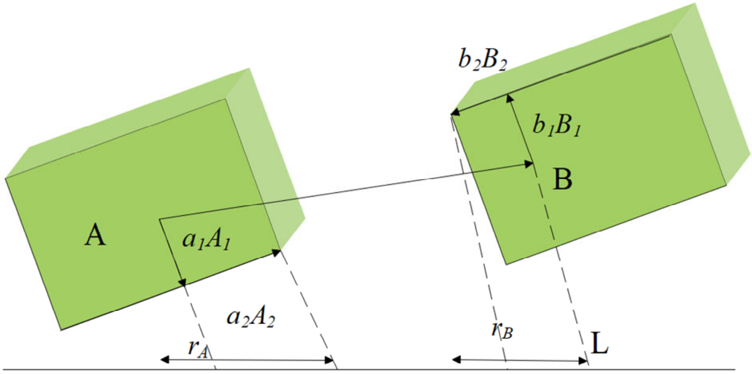


Figure 8 Collision between OBB bounding box and OBB bounding box (see online version for colours)



As can be seen from Figure 8, we only need to compare the projection of T on L with the sum of r_A and r_B can know whether A collides with B:

$$|T \cdot L| > r_A + r_B = \sum_{i=1}^{3} |a_i A_i \cdot L| + \sum_{i=1}^{3} |b_i B_i \cdot L| \tag{9}$$

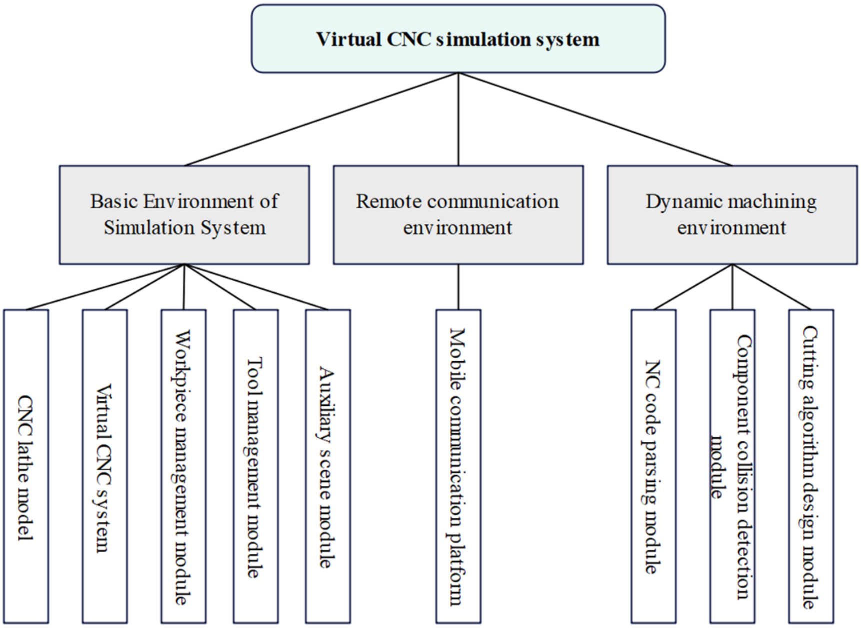
If this formula holds, the two objects do not intersect. Otherwise, the projection on the other 14 separated axes will continue.

3.2 Simulation system construction

The main goal of this simulation system is to simulate the actual machining process and restore the real machining process. Therefore, the virtual NC simulation system should have the modules and operation components of the real NC system, and map the real machining elements to the simulation system to form a complete and 'real' simulation system.

The functional design of NC simulation system mainly uses the idea of modular design. By abstracting the whole simulation system into different sub-modules and combining these modules with other machining elements, a complete simulation system is finally formed. The basic principle of module partition is to partition according to function. By layering modules, the coupling degree of the system can be reduced, which is convenient for development. Firstly, the simulation system consists of three top-level modules, which are simulation system basic environment, dynamic machining environment and remote communication environment. The overall functional modules of the simulation system are shown in Figure 9.

Figure 9 Overall functional modules of the simulation system (see online version for colours)

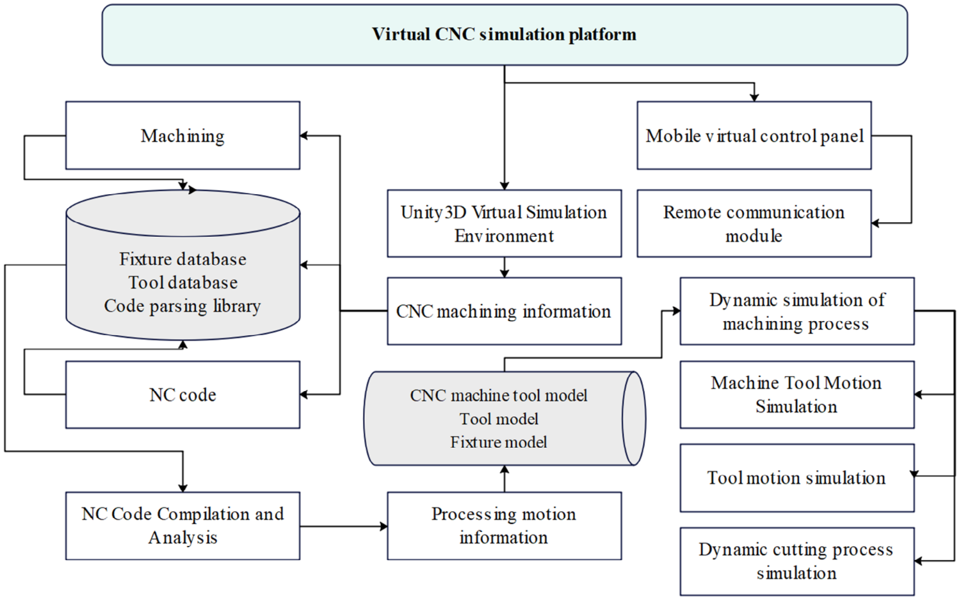


Boundary representation based on polygonal mesh is a widely used method in the field of industrial modelling. This method can use the smallest amount of data to represent the complete model information, and its data structure is relatively simple and occupies less memory. Usually, other geometric modelling methods will eventually be transformed into the form of polygonal mesh, which is convenient for hardware acceleration when rendering graphics.

Through the above analysis of NC simulation system functions and development tools, the overall architecture of the simulation system is designed. The design principle still follows the principle of modularity and single function, which reduces the coupling degree between modules of system architecture. It is mainly divided into two subsystems: dynamic machining simulation subsystem and virtual environment subsystem. The overall architecture of the system is shown in Figure 10.

The virtual scene module is mainly composed of machine tools, cutters, fixtures and factory auxiliary elements, which are the basic components of virtual simulation and play an important role in the virtual experience process. Among them, NC machining information module mainly involves NC code information, fixture and tool information, which can save and process these information and prepare for the subsequent cutting process. The dynamic simulation module of machining process mainly simulates the movement of machine tool and tool and the cutting process of tool-workpiece dynamically. The virtual control module of mobile terminal mainly uses communication technology to remotely control the virtual simulation environment. The above modules together constitute a complete virtual NC simulation platform.

Figure 10 Overall architecture diagram of simulation system (see online version for colours)



According to the main technical parameters of the machine tool, the model of the machine tool is established in Creo, and the machine tool is reassembled according to the spatial position and constraint relationship among the parts of the machine tool to form a complete lathe. The final assembled lathe model is shown in Figure 11. When the assembled model is rendered in 3DMAX, converted into FBX format and imported into Unity3D virtual engine, it can automatically save the spatial position relationship of parts, but its constraint relationship no longer works. The constraint relationship of parts in Unity3D environment is constrained by related scripts.

In this paper, the overall architecture of MTConnect data acquisition for NC workshop is designed. Users can monitor the machining process of NC equipment in real-time through the client, and dispatch orders to designated equipment. The client sends the request to the server, and the server obtains the request content from the database and returns it to the client. The server receives the XMI data stream sent by the MTConnect proxy server in real-time and performs business logic analysis and data storage. The adapter collects data information of heterogeneous devices and sends it to MTConnect proxy server, and sends dispatching tasks to designated NC devices. Therefore, the overall architecture design of data acquisition based on MTConnect needs to include device hardware layer, data acquisition layer, data storage layer, core function layer and interface display layer, as shown in Figure 12.

Figure 11 Machine tool model (see online version for colours)

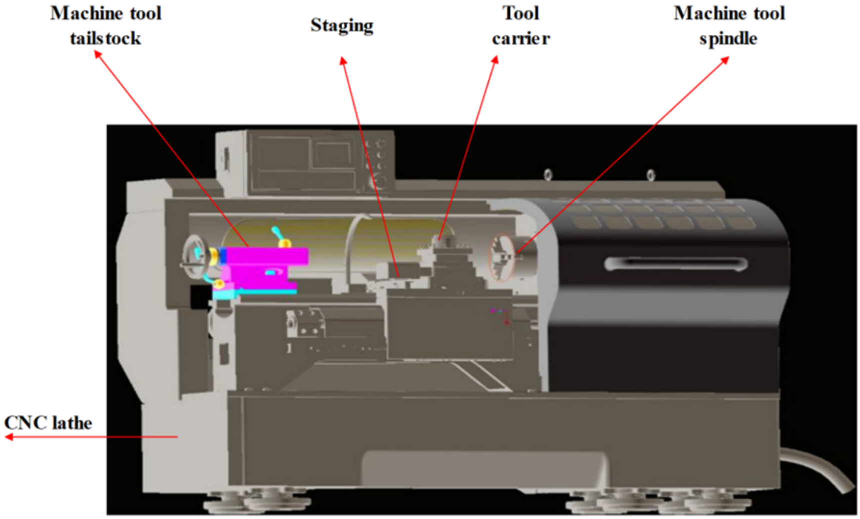
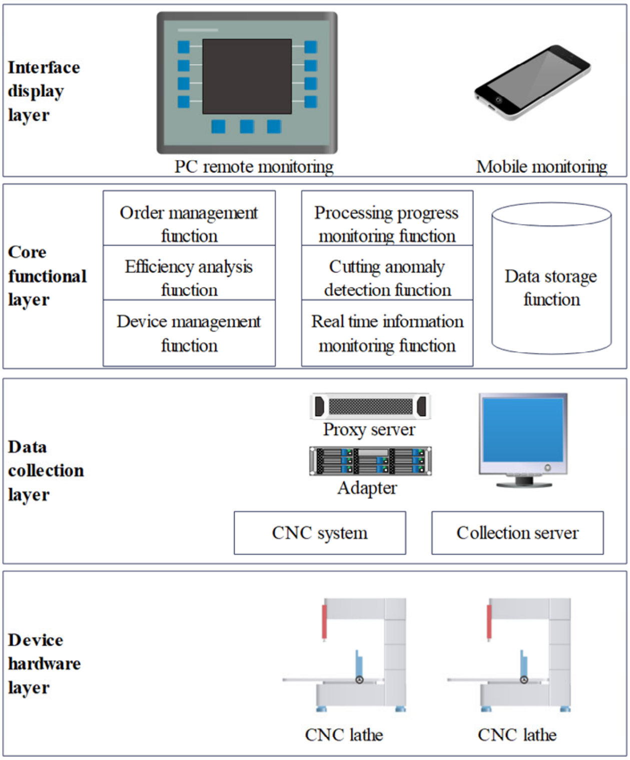


Figure 12 Overall architecture design of data acquisition of NC equipment (see online version for colours)



Utilise open interfaces of CNC machine tools to collect real-time status data, file data, PLC signals, and other related data related to the machine tool. The process of machine tool communication connection and data transmission is as follows:

1. Machine tool equipment is networked and authorised for machine tool network communication functions.
2. Configure IP addresses and port numbers on both personal computer (PC) and machine tools.
3. Create communication handles to establish connections and obtain status data

Real-time display of machine tool spindle speed, feed shaft speed, machine tool electrical control cabinet temperature, spindle temperature, spindle load rate (current, power, torque), spindle current, spindle power, and spindle torque using curve charts, facilitating the evaluation and observation of machine tool processing performance during the machining process.

4 Simulation experiment

Development projects built with Unity3D software consist of multiple scenes, and each scene consists of multiple 3D objects. The virtual NC machine tool machining system should have the functions of human-computer interaction, machining simulation, etc., including main interface, simulation operation, introduction of machine tool related knowledge and other scenes. After building the NC machine tool model, it is necessary to build a virtual space scene bearing machine tool model to provide conditions for controlling the machine tool model.

The structure of virtual NC machine tool includes the following parts: machine tool feed system, shell shield, NC panel, electrical system, spindle system and tailstock. Although the assembly of NC machine parts has been completed in the process of 3D modelling, in order to keep the motion parent-child relationship among the parts of virtual NC machine tools during the execution of motion instructions, it is necessary to define the hierarchical parent-child relationship among the parts of virtual NC machine tools in Unity3D software.

When the virtual NC machine tool receives the instruction to open the door of the machine tool, the NC panel needs to move together with the right door, so the parent-child relationship between them should be established. As the sub-object of the right door, the NC panel can keep the relative position of the NC panel and the right door unchanged when the right door moves, and move together with the right door. After the NC machine tool has completed the operation of clamping the tool and received the instruction of setting the tool or cutting the workpiece, the tool needs to move together with the tool rest assembly, the tool rest moves along the longitudinal feed line of the chopping board when feeding longitudinally along the X axis, and the chopping board moves together with the tool rest when feeding transversely along the Z axis. Therefore, the parent-child relationship among the three should be established as follows: the tool is set as the tool rest sub-object, the tool rest and chopping board are at the same level, and both the tool rest and chopping board are sub-objects of the feed system. The hierarchical structure diagram of parent-child relationship of each component of virtual NC machine tool is shown in Figure 13.

The milling experiment collects multi-source information, mainly including signal and wide table data. If the signal collection time of the sensor is too long, drift errors may occur. At the same time, the working environment, machine tool processing status, and other factors may affect the collected signal, and there may be trend items and anomalies. Therefore, it is necessary to preprocess the signal, filter out interference and noise mixed in the signal, and turn the noisy signal into a valid signal for subsequent modelling and use. The wide table dataset includes machining geometric feature information and machining process information, and encodes non-numerical information.

For discrete workpiece geometries, single heat coding is used for processing. Based on the different states of discrete data characteristics, a state register is constructed to store the states, ensuring that only one bit is valid in different states. Using unique hot encoding, the different states of discrete data features are extended to Euclidean space, where the features correspond to coordinate values in Euclidean space. This ensures that non-ordered feature points do not have partial ordering, and that the distances between each discrete feature and the origin are equal, ensuring the rationality of distance calculation. The geometric features processed in actual industrial production are mainly rectangular and circular holes. Therefore, for continuous workpiece size information, two typical geometric dimensions can be selected for description. For example, for rectangular grooves, seams, etc., length and width can be selected for quantification. For circular holes, both geometric dimensions are equal to their diameter.

Figure 13 Structure diagram of parent-child relationship of NC machine tool (see online version for colours)

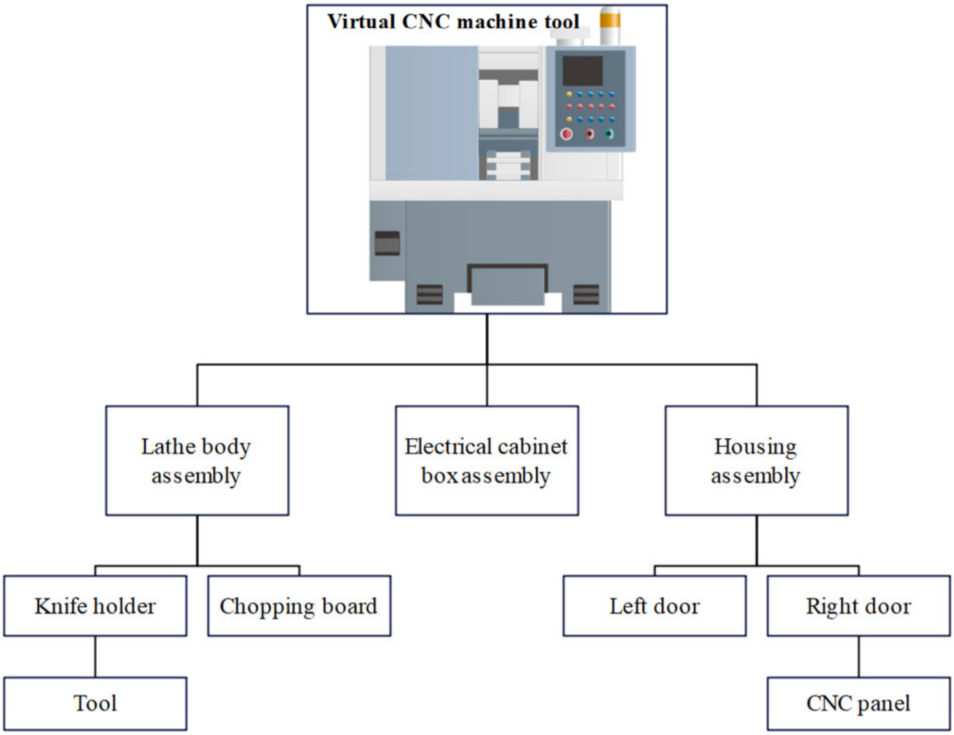
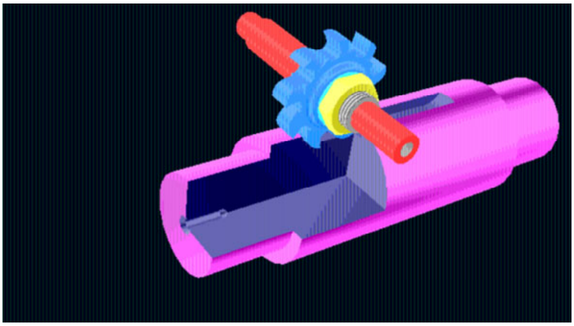
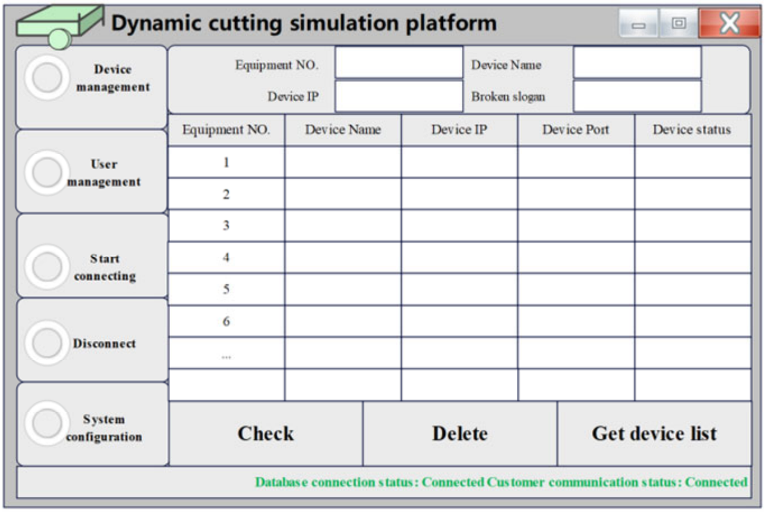


Figure 14 Dynamic cutting use case object (see online version for colours)



The dynamic cutting use case object is shown in Figure 14. The user interface of the dynamic cutting simulation platform designed in this article is shown in Figure 15. It is not difficult to see from Figure 15 that this interface can intuitively observe the real-time working status of the simulated CNC equipment. The interface is simple and suitable for operators with low educational levels to operate.

Figure 15 Dynamic cutting simulation platform user interface (see online version for colours)



Equipment NO.	Device Name	Device IP	Device Port	Device status
1				
2				
3				
4				
5				
6				
...				

Database connection status: Connected Customer communication status: Connected

In actual production processes, single pass milling is rare because general processing techniques are difficult to complete in one step. Multi pass milling is the process of dividing complex processes into multiple single pass processes to complete, usually combining rough machining with precision machining. In the rough machining stage, selecting a smaller cutting speed, larger feed rate, and cutting depth can quickly remove the blank, thereby improving production efficiency. In the precision machining stage, selecting a larger cutting speed, smaller feed rate, and cutting depth will result in less material being cut, but it can ensure the machining quality of the parts.

The traditional cutting parameter optimisation method relies on intelligent optimisation algorithms to find the optimal process parameters before starting machining, without considering the dynamic events in actual machining. The cutting parameter optimisation method based on dynamic cutting algorithm proposed in this article has the characteristics of virtual real interaction and synchronous evolution. On the one hand, various perception devices can dynamically perceive the CNC machining environment, accurately obtain the machining status of the equipment and the completion status of the task, provide rich data sources for process dynamic optimisation, and ensure the accuracy of the machining plan; On the other hand, driven by perceptual data, machine tools can analyse the differences between physical machining and virtual simulation, evaluate the dynamic abnormal information in machining, and then execute dynamic optimisation strategies to respond to machining abnormalities in a timely manner, avoiding potential CNC machining problems and better adapting to complex CNC machining environments. Therefore, the method proposed in this article can effectively ensure the timeliness and accuracy of cutting parameter optimisation, and better meet practical machining needs.

In the cutting process, the running effect of the simulation system can be known by analysing the time-consuming of cutting operation. For the simulation system, the time-consuming stages are mainly the generation of tool scanning envelope, Boolean operation and timing refresh of workpiece shape. In Unity3D virtual machining environment, monitoring the running time of each frame is convenient for analysing the running efficiency of the system. The processing time of stepped shaft, sleeve and threaded shaft is shown in Figures 16, 17 and 18, respectively.

It can be seen from the figure that different types of machining forms have different frame time consumption due to different machining complexity and cutting parameters. However, for the same processing form, the frame time fluctuates within a certain range and can basically remain stable. In this simulation system, for different machining forms, the frame time is less than 25 ms, which proves that the time complexity of the algorithm is low and the algorithm meets the basic cutting requirements. In addition, there is no obvious frame jamming phenomenon in the dynamic cutting process, which shows that the algorithm has good real-time performance.

Figure 16 Time-consuming diagram of step shaft machining frame (see online version for colours)

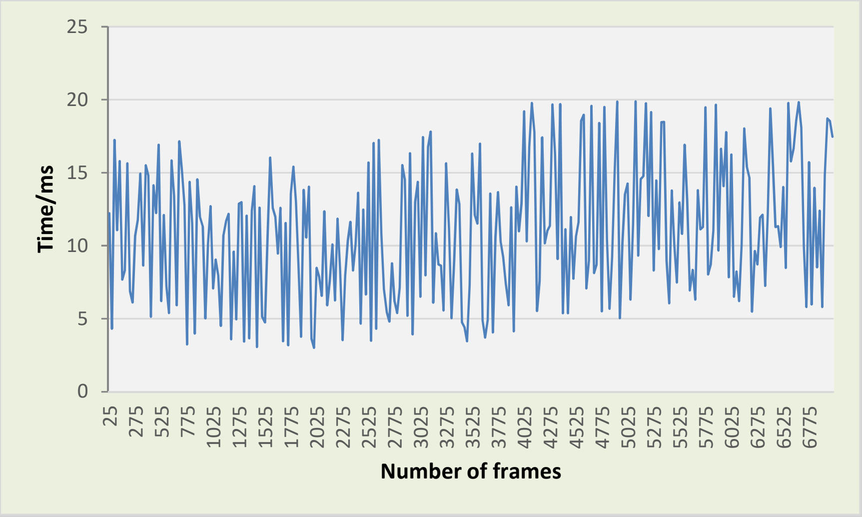


Figure 17 Time-consuming diagram of shaft sleeve processing frame (see online version for colours)

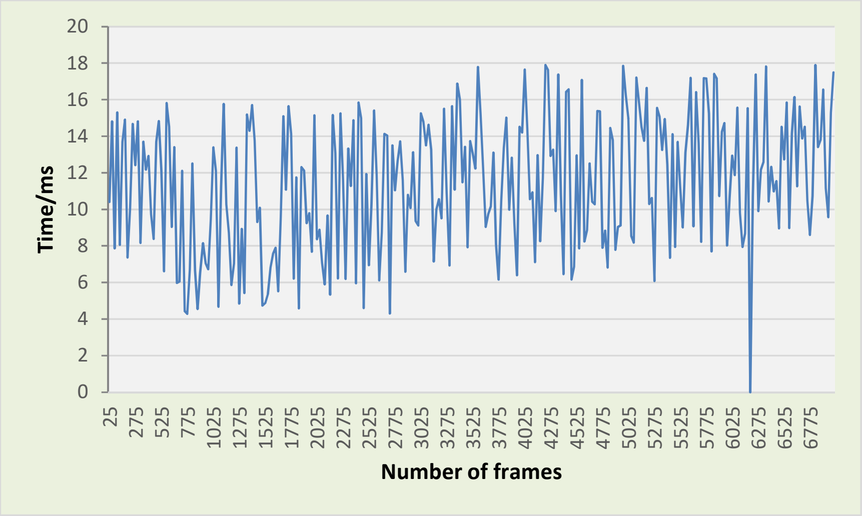
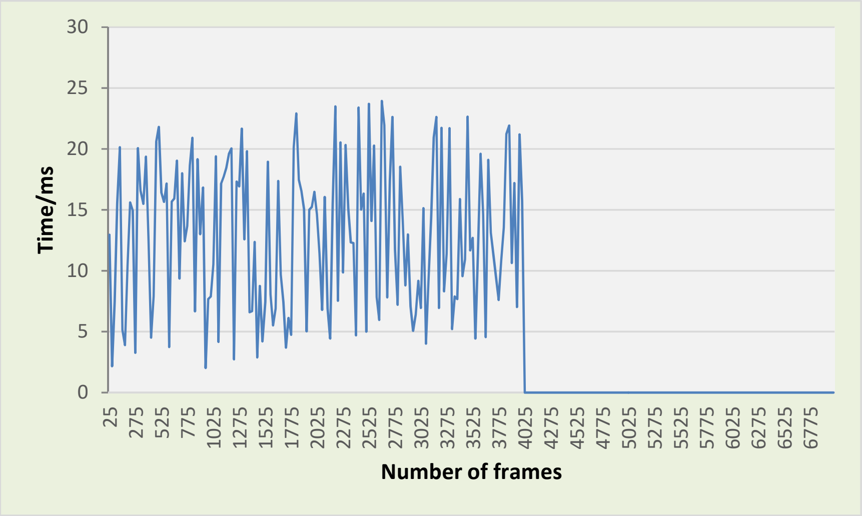


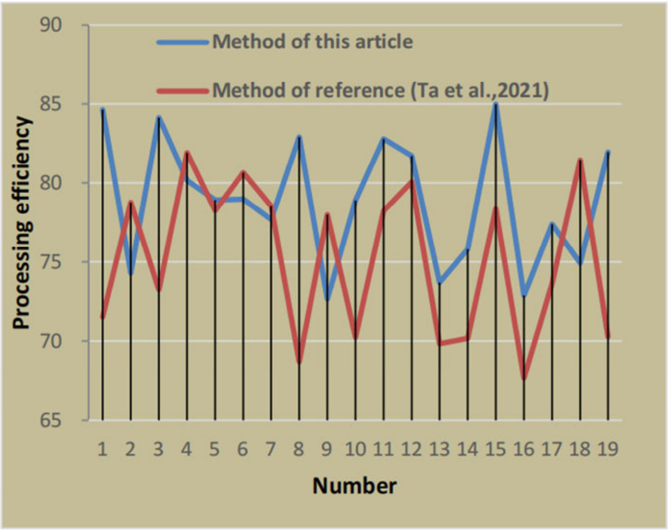
Figure 18 Time-consuming diagram of thread shaft machining frame (see online version for colours)



On the basis of the above, the algorithm model proposed in this paper is verified, and the model proposed in this paper is compared with the model proposed in Ta et al. (2021), and the processing efficiency of the two is counted. The results are evaluated by manual scoring, and finally the results shown in Figure 19 are obtained.

From Figure 19, it can be seen that the processing efficiency of the method proposed in this paper has certain advantages compared to the processing efficiency in Ta et al. (2021). The method proposed in this paper has improved by about 5% on the basis of Ta et al. (2021), indicating a significant advantage in the processing efficiency of the model designed in this courseware.

Figure 19 Comparison of simulation efficiency of virtual machining of NC machine tools (see online version for colours)



It can be seen from Figure 17 that the virtual machining method of automatic NC machine tool based on dynamic cutting algorithm proposed in this paper can effectively improve the machining effect of NC machine tools.

5 Conclusions

Machining parts by NC machine tools is completed by NC instruction program control. In order to ensure the correctness of NC program and prevent interference and collision in machining process, trial cutting method is often used for inspection in actual production. Nowadays, cutting process simulation is mainly divided into geometric simulation and mechanical simulation. Among them, geometric simulation does not consider the influence of cutting parameters, cutting forces and other physical factors, but only simulates the movement of tool-workpiece geometry to verify the correctness of NC machining program. In this paper, an improved mesh cutting algorithm and a hierarchical bounding box algorithm combining Sphere bounding box and OBB bounding box are proposed to overcome the shortcomings of the current dynamic cutting algorithm, and the two algorithms are applied to the NC virtual machining simulation system. Based on the analysis of the existing NC machine tool system, the function of virtual machining simulation system is designed and researched. Taking CY-K360n/1,000 NC machine tool as an example, a virtual machining system with man-machine interaction simulation operation is developed by combining three-dimensional modelling software with system development tools. The experimental results show that the virtual machining method of automatic NC machine tools based on dynamic cutting algorithm proposed in this paper can effectively improve the machining effect of intelligent NC machine tools.

Acknowledgments

It was supported by Mechatronics engineering Scientific Research Team of Hunan Railway Professional Technology College and Scientific Research Fund of Hunan Provincial Education Department (No. 22C1097).

References

Bingran, L., Hui, Z., Peiqing, Y. et al. (2020) 'Trajectory smoothing method using reinforcement learning for computer numerical control machine tools', *Robotics and Computer-Integrated Manufacturing*, February, Vol. 61, pp.101847.1–101847.12.

Delacour, J. (2018) 'Virtual simulation in tokamaks', *Nuclear Engineering International*, Vol. 63, No. 765, pp.34–35.

Gao, Q. and Zhang, P. (2019) 'The errors recognition and compensation for the numerical control machine tools based on laser testing technology', *Open Physics*, Vol. 17, No. 1, pp.857–862.

Hongzhou, L. and Lixia, S. (2018) 'Design of testing period for reliability assessment of numerical control machine tools considering working conditions', *Mathematical Problems in Engineering*, Vol. 2018, No. PT.8, pp.1–8.

Khan, M.A.A. and Sheikh, A.K. (2018) 'Virtual casting: state of the art in metal casting simulation tools', *Journal of Engineering Research*, Vol. 15, No. 2, pp.142–156.

Kidani, S., Irino, N., Maruyama, S. et al. (2020) 'Design and analysis of a built-in yaw measurement system using dual linear scales for automatic machine tool error compensation', *Journal of Manufacturing Processes*, Vol. 56, No. 6, pp.1286–1293.

Lee, B. (2019) 'Heating, cooling, and lighting energy demand simulation analysis of kinetic shading devices with automatic dimming control for Asian countries', *Sustainability*, Vol. 11, No. 5, pp.1253–1268.

Legendre, G., Beaudoux, V., Descamps, P. et al. (2019) 'EP28.01: does the virtual simulation training improve the learning of pelvic ultrasound performed in gynecological emergencies?', *Ultrasound in Obstetrics and Gynecology*, Vol. 54, No. S1, pp.410–410.

Li, F., Li, X. and Xie, H. (2020) 'Modular design research of computer numerical control machine tools oriented to customer requirements', *Advances in Mechanical Engineering*, Vol. 12, No. 4, pp.87–93.

Li, T., Wang, Y., Liu, K. et al. (2018) 'Virtual grid and BPNN based collision avoidance control of automatic fixture system', *International Journal of Advanced Manufacturing Technology*, Vol. 95, Nos. 5–8, pp.2843–2853.

Liu, M., Yao, Y. and Du, J. (2021) 'An efficient machine tool control instruction compression method for networked numerical control systems', *Robotics and Computer-Integrated Manufacturing*, Vol. 2, No. 3, p.67:102027.

Luyun, C., Leixin, L., Wei, X. et al. (2021) 'Bolted connected optimization of composite-to-aluminium structure based on vibro-acoustic control: numerical simulation and experimental', *Applied Acoustics*, Vol. 175, No. 1, pp.107770–107783.

Moniripiri, M., Amjadimanesh, H., Faramarzi, M. et al. (2021) 'Numerical simulation of unsteady airflow in a nasal cavity for various sizes of maxillary sinus opening in a virtual endoscopic surgery', *Respiratory Physiology & Neurobiology*, Vol. 5, No. 3, pp.291–305.

Muniandi, G. (2020) 'Blockchain-enabled virtual coupling of automatic train operation fitted mainline trains for railway traffic conflict control (free access – 'DOI' link)', *IET Intelligent Transport Systems*, Vol. 14, No. 4, pp.63–75.

Racz, S.G., Breaz, R.E. and Cioca, L.I. (2019) 'Evaluating safety systems for machine tools with computer numerical control using analytic hierarchy process', *Safety*, Vol. 5, No. 1, p.14.

Rangarajan, K., Davis, H. and Pucher, P.H. (2020) 'Systematic review of virtual haptics in surgical simulation: a valid educational tool?', *Journal of Surgical Education*, Vol. 77, No. 2, pp.337–347.

Shi, H., Ames, J. and Randles, A. (2020) 'Harvis: an interactive virtual reality tool for hemodynamic modification and simulation', *Journal of Computational Science*, Vol. 43, No. 2, pp.101091–101102.

Ta, T.N., Hwang, Y.L. and Horng, J.H. (2021) 'A multidisplinary approach for optimization design of CNC machine tools', *International Journal of Computational Methods*, Vol. 3, No. 5, pp.15–30.

Wang, X. (2020) 'Research on human-machine interface optimization design of numerical control machine tools in ocean engineering based on visual communication perception field', *Journal of Coastal Research*, Vol. 115, No. sp1, pp.322–333.

Zhang, S.R.Y. (2020) 'An early fault elimination method of computerized numerical control machine tools', *The International Journal of Advanced Manufacturing Technology*, Vol. 106, No. 11a12, pp.52–63.