Title:
Tri-dexel Model-based Geometric and Physical Simulation for On-line Machining

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Introduction:
Accurate and efficient geometric and physical cutting simulation algorithm has always been one of the core key technologies of advanced CNC machining. With the development of intelligent manufacturing, CNC machining puts forward higher requirements for on-line cutting simulation capabilities. The existing cutting simulation system is mainly designed for off-line simulation, and its main function is to preview the shape of the part and verify the processing technology. The purpose of on-line simulation technology is to realize real-time monitoring and prediction of the machining process. The on-line simulation algorithm needs to reach a sufficiently efficient level to keep running synchronously with the machine tool's movement.

At present, many researches have been carried out on the simulation of the machining process. Geometric simulation algorithms can be divided into solid modeling method and discrete modeling method. Solid modeling method can obtain more accurate simulation results, but there is a problem of high computational cost [3],[7]. Discrete modeling method's core idea is to express the geometry of the blank with finite discrete units, and the method can be divided into three categories: Octree, Z-map and Z-buffer/Tri-dexel. Since the Z-buffer method and the Tri-dexel model can maintain a better balance between efficiency and accuracy, many scholars have carried out related research [6],[9][10]. In physical simulation, the prediction of cutting force is the most important. Cutting force is mainly predicted by empirical models, analytical models, mechanical models, neural network models, there have been more studies on the latter two methods. Since 1996, Altintas et al. has carried out many studies on the prediction of cutting force by mechanical models [1],[2],[5]. Artificial neural networks can find the relationship between input and output without establishing a mathematical model of the system, so it is very suitable for the simulation of complex cutting process [4],[8]. Current research work seldom focuses on the relationship between geometric simulation and physical simulation. Since the above various methods form mutually independent theoretical system, the geometric and physical co-simulation is bound to be realized by combining different methods, resulting in redundant calculations, which is not conducive to on-line simulation. Therefore, it is necessary to carry out research on new methods for on-line geometric and physical simulation.

Machining process geometric simulation:
Tri-dexel Model Generation:
The Tri-dexel model is an extension of the Z-buffer model, which is composed of a combination of Z-buffer models in three directions. We modified the traditional dexel model, the dexel rays are not

launched from the screen but from the outer plane of the model's axis-aligned bounding box, and the Tri-dexel model can be generated.

The geometric position of the workpiece model is unchanged during the cutting simulation process. For the construction of its Tri-dexel model, we use the ray intersection algorithm built in the rendering engine OpenSceneGraph (OSG) to calculate the intersection point of the ray and the workpiece model. Further, the information such as the coordinates is filled into the data structure to realize the conversion from the triangular facet model of the workpiece to the Tri-dexel model, demonstrated in Fig. 1. The tool position changes momentarily during the machining process, so we use analytical equations to express the tool model based on the APT file which defines a unified milling cutter general model shape through seven mutually independent parameters (d, r, f, e, h, a, b). The process of constructing the tool Tri-dexel model is to substitute the corresponding coordinates from the three directions to obtain the numerical solution of the analytical equation.

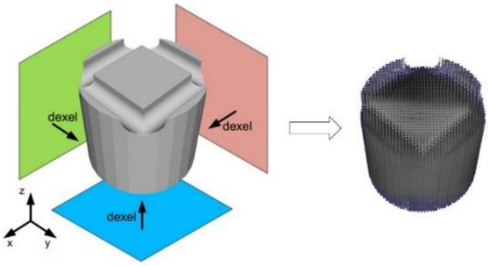

Fig. 1: Generation of the Tri-dexel model of the workpiece.

Boolean operation and triangle face reconstruction:

The paper [9] summarizes the intersection situations between the Tri-dexel models of tools and workpieces. The position relationship between dexels can be directly compared through the depth value, and the update of the workpiece model is also directly reflected on the depth value stored by the dexel, so the efficiency of Boolean calculation is very high. In order to minimize the time required for Boolean operations, we use bounding boxes to reduce the scope of Boolean operations. As shown in Fig. 2, through the intersection of the bounding box of workpiece and the bounding box of tool, the maximum and minimum index values of the Boolean operation area in the three directions in the Tri-dexel model are calculated. Then the Boolean operation scope can be reduced from the entire workpiece area to the local intersection area.

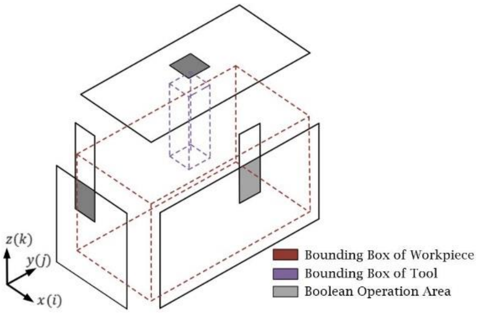

Fig. 2: Use bounding boxes to reduce the scope of Boolean operations.

At present, the use of Machining Cubes (MC) algorithm to achieve triangle face generation is a common processing method, but different researchers use different methods in the process of transforming Tri-dexel model to MC algorithm data structure. This paper proposes a virtual voxel concept, bounding box of the workpiece can be divided into a set of neatly arranged voxels. The size of one virtual voxel is equal to the distance between two adjacent dexels. By building virtual voxel model from Tri-dexel model, it is possible to apply MC algorithm in mesh generation for interactive visualization. In the cutting process, the tool model only intersects with part of the workpiece model, only this part of the model needs to be updated and reconstructed. This paper divides the workpiece model into multiple small rectangular parallelepiped regions, which are called sub-parts of the bounding box. Each sub-part has independent vertex data, thereby avoiding updating the vertex data of the entire workpiece and reducing the amount of calculation. By applying the optimization strategy of Boolean calculation and mesh model generation, the geometric simulation algorithm can be limited to 50ms for one simulation update. On-line machining simulation experiments were conducted at Commercial Aircraft Corporation (COMAC) of China Ltd's manufacturing plant as shown in Fig. 3, as can be seen that the proposed geometric calculation algorithm still works in the case of 5-axis milling.

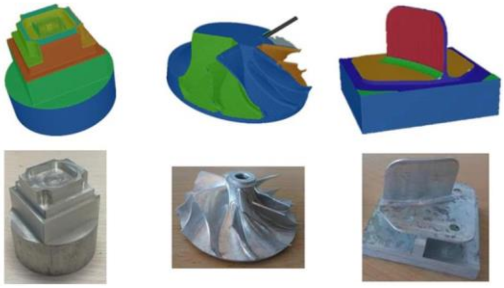

Fig. 3: On-line geometric simulation results based on Tri-dexel model and real workpieces.

<u>Machining process physical simulation:</u>

Image generation method for the engagement between tool and workpiece:

Cutting force provides theoretical basis for tool design, tool wear and breakage monitoring. Based on the investigation of common cutting force prediction models and the geometric simulation algorithm based on the Tri-dexel model proposed above, we propose an image-based instantaneous cutting force prediction method. The cutter frame image (CFI) is utilized as one of the inputs of a convolutional neural network (CNN) to predict instantaneous cutting forces. During the simulation process, each tool position can obtain the corresponding CFI from the Tri-dexel model of the geometric simulation. At the same time, by calculating the feed rate information of each contact point, the pixel value of the corresponding pixel of the contact point is further determined. Fig. 4 shows the generation process of the CFI.

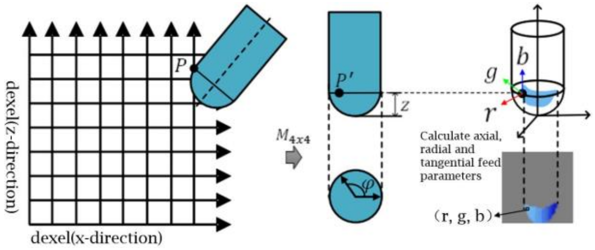

Fig. 4: Generation process of the CFI.

In the Boolean operation of tool and workpiece, the contact point is the update point of the Tri-dexel model. We first change the contact point p in the cutting state of the tool to the vertical state of the tool p', and determines the section layer z' where p' is located according to the z value of the contact point in the vertical state. Calculate the dot product between the vector (x', y') and the vector (1,0) in layer z' according to the definition of the immersion angle, so as to obtain the immersion angle φ corresponding to this point. According to the corresponding contact point (φ, z′) and the resolution Δ (resolution of the Tri-dexel model) can get the pixel position of the contact point in the image (*i, j*). Project the current unit feed direction of a contact point onto three mutually perpendicular directions to obtain the axial/radial/tangential feed rate coefficient of the point and store it in the three RGB channels. The range of feed rate coefficient is [-1.0,1.0], we establish the mapping relationship between it and the color interval [0, 255], so that we get the CFI of the current tool position.

The instantaneous cutting force prediction model:
Convolutional neural network can realize the direct mapping of input data set to output data set. In this paper, the input is the CFI generated in the geometric simulation process. In addition, the contact area image cannot express the geometric and physical characteristics of the tool and the workpiece (such as diameter, material, etc.), it is also difficult to express some key process information. Therefore, 10 additional constant parameters (feed rate, spindle speed, number of teeth, helix angle, shear force coefficient and edge force coefficient) are combined into vector input to improve the cutting force prediction accuracy. The output of the convolutional neural network model is the three components of the instantaneous cutting force: F_x, F_y, F_z. The convolutional neural network model adopted in this paper is shown in Fig. 5.

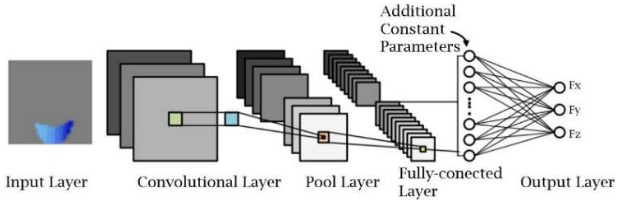

Fig. 5: The overall framework of the CNN model.

In order to obtain a large amount of training set data more simply and at low cost, we use the instantaneous rigid force model proposed by Altintas [2] to calibrate the data set. In this paper, ten sets of decreasing depth of cut (from 5.0mm to 0.5mm) are used as the input of the geometric simulation system and the instantaneous rigid force model. In the process of geometric simulation, 30 CFIs can be generated in one cutting cycle according to the set spindle speed. Therefore, through these ten sets of cutting conditions 300 images can be obtained, and each image is marked with three instantaneous cutting forces.

The training and testing of the CNN model have been deployed in Keras=2.2.4, Tensorflow-gpu=1.13.1, and Cuda=10.0. Fig. 6 shows the comparison between the prediction results from the CNN-based model and the simulated results from the mechanical cutting force model. The correlation coefficient R^2 value is calculated as 0.9999, which means the trained network has a good performance on predicting the instantaneous cutting forces. In terms of the cost of the prediction time, the CNN-based model demonstrates an efficient ability to predict with 57ms averagely per image.

Conclusions:

This paper proposes a Tri-dexel model based geometric and physical simulation algorithm for on-line machining. The count of cutter locations is increased and the communication time step limits the available computation time for on-line simulation. To handle this problem, an optimized Tri-dexel-based simulation method is proposed, and we explore the possibility to use an image-based method to predict instantaneous cutting forces during the geometric simulation. Further research will be conducted on integrate the geometric simulation system with the physical simulation system, and verify the efficiency and correctness of the co-simulation through on-line machining process.

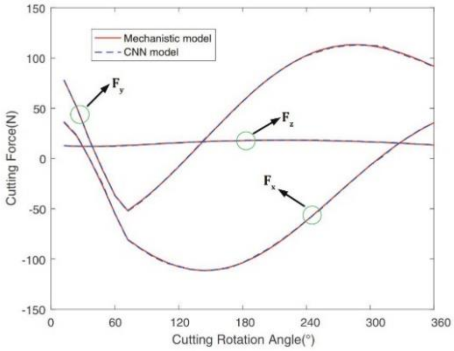

Fig. 6: Comparison between mechanistic model and CNN model.

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