Title:
STEP-NC-compliant High Efficient Machining Simulation

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Introduction:
Machining simulation is important in NC machining to verify toolpath and preview machining process. Existing machining simulation software and research works usually take G-code as input data in cooperation with CAD/CAM/CNC. Limited by the information exchange format, simulation system cannot make full use of process information. In this paper, STEP-NC standard is applied to improve this situation. The STEP-NC file is classified into two categories: feature-oriented and trajectory-oriented. For feature-oriented file, special simulation method are presented to optimize efficiency based on the information of machining features. For trajectory-oriented file, an optimized tri-dexel based method is presented to handle general cases. These two types of STEP-NC file are supported in the proposed machining simulation system. Computational efficiency is discussed and it is possible to use this simulation method in online situation or a digital twin system.

Existing Simulation Methods:
Machining simulation has been researched for decades and there are mainly four types of methods [19]: wireframe-based, solid-based, object space-based and image space-based. In early simulation research works, the wireframe-based method is used widely [13],[17] because its simple data structure. Nonetheless, there is ambiguity in the model expressed by the wireframe model and it is not applied in modern commercialized systems [3]. The advantage of solid-based method is the most accurate simulation result [19]. In solid-based method, CSG or B-rep model [11] is used to compute analytical intersection. However, extreme accuracy result also requires heavy computational efforts [1] and this problem obstructs the application of solid-based method. Object space-based (octree, z-map, etc.) [1] and image space-based(z-buffer, tri-dexel, etc.) [3] methods are frequently used in industrial application. In these methods, the good balancing of accuracy and space complexity can be realized for the workpiece is represented by discrete modeling method [1][19]. Considering the requirements of physical machining simulation, efficient and accurate geometry calculation using mentioned methods is also important. Cutting force and surface quality are predicted in physical simulation while taking the result of geometry simulation as input [6],[11],[6].

For object space-based method, octree model is more practical for the compatibility across three and five axes machining [15]. Some researchers try to reduce the memory consumption by simplifying the data structure of octree [12]. In addition, generation of triangle mesh for visualization in octree method is time consuming [4][6]. For image space-based method, tri-dexel model is mentioned more in research works. This method is derived from z-buffer and a tri-dexel model contains three z-buffer along three axis direction keeping orthogonal to each other. A lot of research works have been reported that trying to apply tri-dexel model in machining simulation [7],[17],[13]. Compared with z-

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buffer method, it is more direct to generate mesh model from tri-dexel for interactive 3d visualization. Compared with octree model, tri-dexel requires smaller memory and performs more efficiently in Boolean operation.

Application of STEP-NC standard in machining simulation has also been researched [19]. STEP-NC is helpful to transform the architecture of simulation system to work more closely with CAD/CAM/CNC and realize bidirectional data flow with process designing [18]. Cooperating with sensors and network, the state of machine tool can be obtain in simulation system using STEP-NC [1]. However, there is no one research work realized optimization of machining simulation algorithm based on STEP-NC data model.

Feature-oriented Machining Simulation

Definition of feature-oriented data structure in STEP-NC standard is not designed for machining simulation. In this section, the way to bridge this gap is explained. Inspired by the concept of parameterized expression of engagement shape between tool and workpiece in Yip's work [6], the classification criterions of features and operations in STEP-NC standard are proposed. Based on these rules, some customized simulation methods are developed by readjust existing simulation methods.

Classification of STEP-NC Features

In STEP-NC standard, material removing regulation is determined by the combination of feature and operation. This regulation is investigated to classify STEP-NC features and operations and simulation methods are assigned. The result of classification is listed in Table 1 in which features\operations are summarized as four classes: one-dimension, two-dimension, three dimension, and freeform.

Feature	***Operation***	***Simulation Method***	***STEP-NC Example***
One dimension	Roughing	Mesh Stretch	Round_hole & Drilling
	Finishing	Mesh Stretch	Round_hole & Reaming
Two-dimension	Roughing	Extended Quadtree	Closed_pocket & Bottom_and_side_rough_milling
	Finishing	Voxel List	Closed_pocket & Bottom_and_side_rough_milling
Three-dimension Compound	-		Counterbore_hole
Three-dimension Non-compound		Octree	Shape_profile
Freeform		z-map or octree	Freeform

Tab. 1: Feature classification and simulation methods selection.

One Dimension: The geometry of the material being removed by tool moving along a line is regarded as one dimension. In this situation, Boolean operation is very easy and the machined feature volume can be directly reasoned. In STEP-NC standard, "round hole" and "slot" are two typical one-dimension features. Additionally, geometry of removed material is different in roughing and finishing operation for the same one-dimension feature, but the characteristics of engagement deforming process are same.

Two Dimension: The main characteristic of two-dimension features is that the machining process repeats for every layer of feature volume. For example, the "closed pocket" feature can be divided into multilayers which are arranged along z-axis. Inside one layer, the tool only moves in the x-y plane, and for which the calculation of engagement becomes a 2D problem. Additionally, if finishing operation is taking into consideration, the removed material only distributes around the boundary of the feature and tool only moves along a profile in the x-y plane. This characteristic may leading to use different simulation method comparing to roughing operation.

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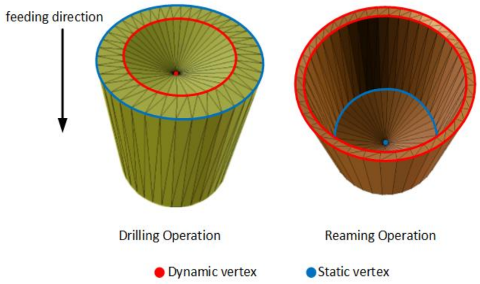
Three Dimension: Three-dimension feature is also belonging to 2.5D machining feature, but deformation of tool-workpiece engagement exists in three directions. In STEP-NC standard, there are two classes of three-dimension feature. The first is the compound feature, which can be decomposed into several one or two-dimension features. So, the machining process is also decomposed into multiple parts that simulated separately. The second is non-compound while the shapes of cross-section along z-axis are different. For example, the feature “Shape profile” showed in table 1 satisfies this situation. Generic simulation method is needed because the machining process is more complex than one or two-dimension.

Free Form: In this kind of feature, the machined surface is free form surface, either 3-axis or 5-axis. The deformation of engagement between tool and workpiece blank is complex and do not have noticeable regulation, so more generic simulation method is needed.

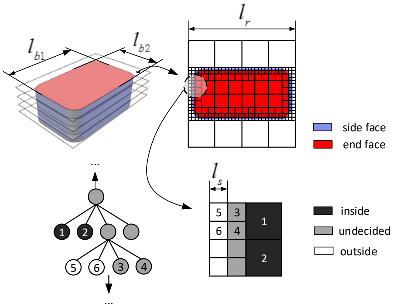
Customized Simulation Methods

Based on the classification of features and operations in STEP-NC, a series of customized simulation methods are developed. Existing simulation methods are transformed to obtain the optimum performance. The characteristics of existing methods are analyzed that corresponding to the requirments of different feature types. As listed in table 1, there are six simulation methods mentioned in this paper.

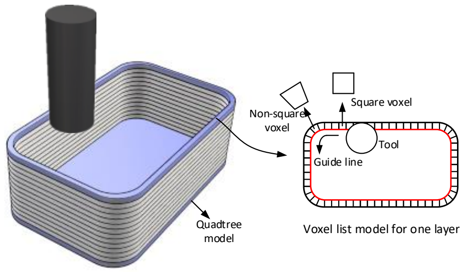
Mesh stretch method. This method is suitable for one-dimension feature. To explain the principle, round hole feature is taken as example as illustrated in fig 1(a). It is clear that the deformation of surface is just like the mesh point stretch along the same direction. So, the geometry of machined workpiece is only determined by the tool position. And the deformation process is different for drilling operation and reaming operation. For drilling operation, vertexes located on the circular edge are static and keep position during simulation and there are a group of dynamic vertexes between center vertex and circular edge to fit the shape of tool tip. For reaming operation, dynamic vertexes are located on the two circular edges labeled as red line in fig 1(a). When the tool tip touched the bottom, all vertexes are converted to dynamic. The minimum distance from vertex to the boundary of tool is along z-axis is used to compute the positions of dynamic vertexes.



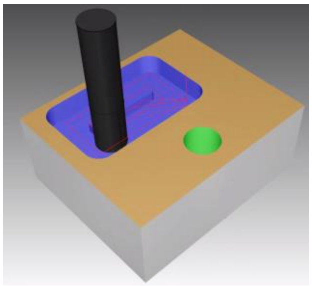
(a) Mesh structure of one-dimension method.



(b) Extended quad-tree model.



(c) Voxel list model for finishing operation.



(d) Feature based in-process simulation model.

Fig. 1: Illustration of the principles of the customized simulation methods.

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Extended quadtree method. This method is inspired by existing quadtree-based simulation methods. The two differences for this method: multiple quadtree models are built for every layer of feature volume; Signed distance field and mesh intersection are combined to perform Boolean operation. The structure of multiple quadtree models are illustrated in fig 1(b). The volume of machining feature is divided into layers based on the tool feed distance defined in STEP-NC operation item and every layer is corresponding with a quadtree model. There are three types of flags indicating the position relationship between node and feature volume, including INSIDE, OUTSIDE, UNDECIDED. Taken the pocket roughing operation as example, this structure speeds up the intersection searching very effectively.

Voxel list method. This a customized method dedicated to two-dimension features with a finishing operation. To explain the principles, pocket finish milling operation is taken as an example. As shown in fig 1(c), there is only a thin rounded pieces of material is removed in this machining process. Voxel is a special quadtree node that the four edges are not required to form a rectangle and do not have a parent node. And voxels are arranged into a list along the boundary. It must be mentioned that the removed volume in bottom layer is similar to the two-dimension feature with roughing operation and a single layer quadtree model is constructed. Computation consumption of this method is very low because the number of voxel participating the Boolean operation is small.

<u>Trajectory-oriented Machining Simulation</u>

Tri-dexel based simulation method is applied to handle the trajectory-oriented STEP-NC file for general simulation purpose. There are three steps to setup a tri-dexel based simulation. First is to initialize dexel models from the workpiece geometry and tool geometry. Second, Boolean operation is performed between the workpiece dexel model and tool geometry. Third, mesh model for visualization is computed from the tri-dexel model of workpiece. The last two steps are executed repeatedly for every cutter location updating. Meanwhile, these two compute steps are time consumption operation because of the large amount of dexels. A typical tri-dexel modeling process is illustrated in Figure 2.

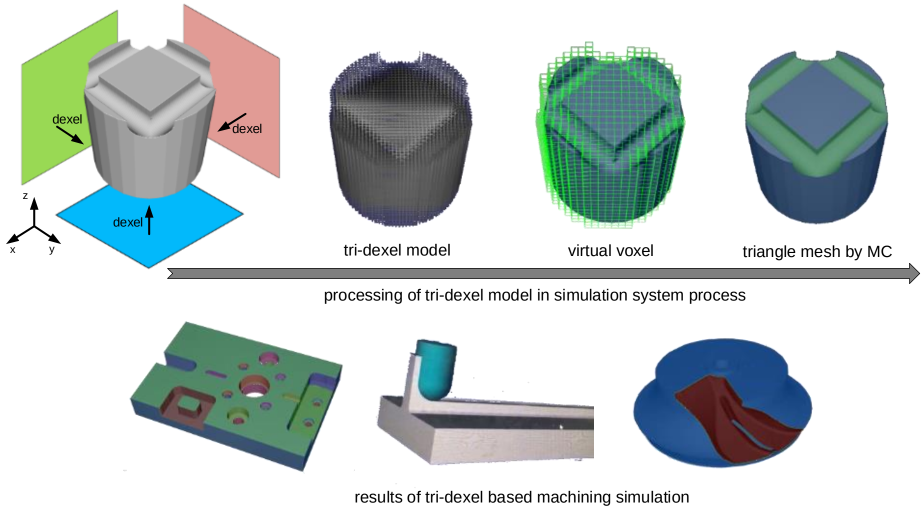

Fig. 2: Tri-dexel model-based machining simulation process.

Boolean operation and mesh generation are optimized to reduce the computation in the simulation process. First, tool bounding box is used to narrow the scope of intersection. Boolean operation is limited into a local region and the number of dexels that need to be computed is minimized. This local updating strategy greatly reduced dexel amount and saves computing resource. Second, workpiece is divided into multiple parts and only inserted parts with tool are “marching cubes” methods to generate mesh model for visualization. This partitioning strategy also helps to reduce the computing time.

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Conclusions and Future Works:

Using STEP-NC standard in machining simulation is a relatively new research issue. This paper presented a machining simulation prototype system that can handle two types of STEP-NC file: feature-oriented and trajectory-oriented. In feature-oriented machining simulation, the algorithm is optimized through the idea of divide and conquer. It makes improvement in both efficiency and accuracy. For trajectory-oriented simulation, an optimized tri-dexel based simulation method is proposed. Both methods can achieve low level memory consumption and real-time visualization that make this simulation system highly practical. An online simulation system can be built based the results of this paper that can work with real machine tools as a meaningful Digital Twin application.

References:

[1] Aras, E.; Yip-Hoi, D.: State-of-the-Art in Geometric Modeling for Virtual Machining, in ASME 2012 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, 2012, 737–750.
[2] CAMotics, 2018.
[3] CGTech, Vericut. 2018.
[4] Joy, J.; Feng, H. Y.: Frame-sliced voxel representation: An accurate and memory-efficient modeling method for workpiece geometry in machining simulation, Computer Aided Design., 88, 2017, 1–13.
[5] Kadir, A. A.; Xu, X.: Towards High-Fidelity Machining Simulation, Journal of Manufacturing Systems, 30(3), 2011, 175–186. https://doi.org/10.1016/j.jmsy.2011.04.004
[6] Karunakaran, K. P.; Shringi, R.: Octree-to-BRep conversion for volumetric NC simulation, International Journal of Advanced Manufacturing Technology, 32(2), 2007, 116–131. https://doi.org/10.1007/s00170-005-0310-8
[7] Lee, S. W.; Nestler, A.: Virtual workpiece: workpiece representation for material removal process, International Journal of Advanced Manufacturing Technology, 58(5), 2012, 443–463.
[8] Li, J. G.; Yao, Y. X.; Xia, P. J.; Liu, C. Q.; Wu, C. G.: Extended octree for cutting force prediction, International Journal of Advanced Manufacturing Technology, 39(9), 2008, 866–873. https://doi.org/10.1007/s00170-007-1277-4
[9] Nishida, I.; Okumura, R.; Sato, R.; Shirase, K.: Cutting Force Simulation in Minute Time Resolution for Ball End Milling Under Various Tool Posture, Journal of Manufacturing Science and Engineering, 140(2), 2018.
[10] Rivièrelorphèvre, E.; Huynh, H. N.; Verlinden, O.: Influence of the time step selection on dynamic simulation of milling operation, International Journal of Advanced Manufacturing Technology, 95(7), 2018, 1–16. https://doi.org/10.1007/s00170-017-1570-9
[11] Spence, A. D.; Altintas, Y. A.: A Solid Modeller Based Milling Process Simulation and Planning System, Journal of Engineering for Industry, 116(1), 1994, 61. https://doi.org/10.1115/1.2901810
[12] Sullivan, A.; Erdim, H.; Perry, R. N.; Frisken, S. F.: High accuracy NC milling simulation using composite adaptively sampled distance fields, Computer Aided Design, 44(6), 2012, 522–536. https://doi.org/10.1016/j.cad.2012.02.002
[13] Sun, Y. J.; Yan, C.; Wu, S. W.; Gong, H.; Lee, C. H.: Geometric simulation of 5-axis hybrid additive-subtractive manufacturing based on Tri-dexel model, International Journal of Advanced Manufacturing Technology. Technol., 99(9), 2018, 2597–2610. https://doi.org/10.1007/s00170-018-2577-6
[14] Wang, X. Y.; Chen, J. H.; Tang, X. Q.: Component Implementation Technology of Wire-frame Simulation Based on VTK, Computer Engineering, 36(4), 2010, 226–228. https://doi.org/10.3724/SP.J.1238.2010.00585
[15] Yau, H. T.; Tsou, L. Sen: Efficient NC Simulation for Multi-Axis Solid Machining with a Universal APT Cutter, Journal of Computing & Information Science in Engineering, 9(2), 2009, 375–389.
[16] Yip-Hoi, D.; Huang, X.: Cutter/Workpiece Engagement Feature Extraction from Solid Models for End Milling, Journal of Manufacturing Science and Engineering, 128(1), 2006, 339–349. https://doi.org/10.1115/1.1948395

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[17] Zhang, W.; Peng, X.; Ming, C. L.; Zhang, W.: A Novel Contour Generation Algorithm for Surface Reconstruction From Dexel Data, Journal of Computing & Information Science in Engineering, 7(3), 2007, 203–210. https://doi.org/10.1115/1.2752817

[18] Zhang, Y.; Bai, X. L.; Xu, X.; Liu, Y. X.: STEP-NC based high-level machining simulations integrated with CAD/CAPP/CAM, International Journal of Automation & Computing, 9(5), 2012, 506–517

[19] Zhang, Y.; Xu, X.; Liu, Y.: Numerical control machining simulation: a comprehensive survey, Journal of Computer Integrated Manufacturing, 24(7), 2011, 593–609. https://doi.org/10.1080/0951192X.2011.566283

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