Title:
Fast Generation of 2-manifold Triangle Meshes for Sliced-Voxel Machined Workpiece Models Using a Lookup Table

Authors:
Jimin Joy, jjoy@alumni.ubc.ca, The University of British Columbia
Jack Szu-Shen Chen, jsschen38@gmail.com, The University of British Columbia
Hsi-Yung Feng, feng@mech.ubc.ca, The University of British Columbia

Keywords:
Machining Simulation, Voxel Models, Visualization, Triangle Mesh, Lookup Table

DOI: 10.14733/cadconfP.2020.71-75

Introduction:
Visualization is an integral part of machining simulation as it helps to inspect the simulated workpiece geometry and more importantly, to verify the associated machining program before actually using it for operating the machine [3],[8]. Since the purpose of simulation is to generate the machined workpiece geometry whereas that of visualization is to display the simulated workpiece, the geometric modeling format suitable for the two are not necessarily the same. Simulation requires a model capable of repeated modifications efficiently. On the other hand, the model for visualization can be static in terms of the data but is expected to have enough details for satisfactory visual realism.

A new and effective geometric modeling format, named as the frame-sliced voxel representation (FSV-rep), has recently been introduced to model the changing workpiece geometry for general milling operations [4]. FSV-rep is able to offer both modeling accuracy and memory efficiency as well as computational efficiency [5]. The FSV-rep model achieves this with three components: two levels of voxels, the coarse and fine levels, representing the workpiece bulk volume and its boundary in a rough manner, and a set of points, named as the frame-crossing points at the locations where the workpiece boundary intersects the fine-level voxel's frame edges.

In addition to efficient and accurate simulation process, fast visualization of the FSV-rep workpiece model is an equally important function in practical applications. The voxel model display techniques are either costly or less accurate and visualization using merely a set of points such as the frame-crossing points is not acceptable for surface rendering. Since the modern graphics processing techniques favor the triangle mesh surface representation, the main task for the fast visualization of an FSV-rep workpiece model is essentially to generate a triangle mesh representation for the workpiece boundary as readily as possible. The method to be presented here utilizes a comprehensive lookup table for the fast generation of the triangle mesh.

In the subsequent sections of this extended abstract, the existing surface generation methods employed in machining simulation to visualize the simulated workpiece model will be reviewed first. The salient features of an FSV-rep model that should be considered in the development of an effective surface generation method will then be presented. This paper will also establish the feasibility of a newly derived lookup table that is both comprehensive and concise for fast triangle mesh generation from the frame-sliced voxel representation of the simulated workpiece. The quality and superior computational performance of the lookup table-based method compared to that of an existing algorithmic method will be demonstrated by a set of test cases involving a wide variety of machined workpiece shapes.

Existing Geometry Visualization Methods:

Effective visualization of the simulated machined workpiece model geometry is essential for a virtual machining simulation environment [9]. The nature of the simulation model greatly affects the technique that can be used for visualization. Visualization of workpiece models represented as NURBS or polyhedral B-rep solid models by surface rendering is a trivial task since the definitions of these solid models are already based on boundary surface elements (although NURBS B-rep solid models are often tessellated into triangle mesh representations to facilitate visualization). Visualization of non-B-rep workpiece models is a more involved task. For example, vector and space partitioning workpiece models both need to generate applicable boundary surface representations in order to visualize the models. For voxel-based space partitioning workpiece models, dedicated volume rendering hardware was proposed as an applicable option to visualize the voxel models [10]. However, such specialized hardware has not gained popularity due to the added cost. Hence, an effective surface generation technique for voxel models is still the preferred option.

The marching cubes algorithm has been widely used to convert a voxel model representation into surface model and then visualize by surface rendering [7]. The surface reconstruction either relies on additional data associated with voxel grid points or resort to poor approximations in the standard methods based on marching cubes [2]. The marching cubes algorithm is, nevertheless, computationally fast as it utilizes a lookup table of pre-defined triangulations for all possible combinations of a given voxel's corner-point occupancy. Given that the FSV-rep model has voxels at the heart of it, a marching cube like approach that does not rely on non-geometric information for fast and accurate surface reconstruction is presented here.

Proposed Method:

In this section, a lookup table-based method to rapidly generate a 2-manifold triangle mesh from an FSV-rep workpiece model will be presented. The method is inspired by the classic marching cubes technique [7] and extended to ensure a valid surface reconstruction from workpiece models generated in machining simulation using only the geometric information associated with the model. The following assumptions can be made about the geometry of the machined workpiece in order to facilitate usage of a lookup table for surface mesh generation without invalidating practical machining simulation cases.

Basic Assumptions

The first assumption is that there will be no through gaps created for any sliced fine level surface voxel on the FSV-rep workpiece model from the cutting action of a milling tool. In other words, no fine level voxel will be split into two parts. Since the fine level voxel should always be sized to be much smaller than the milling tool, this assumption is valid and will not lead to any global geometry deviation for the FSV-rep workpiece model.

The second assumption relates to the thin machined features on the workpiece. These thin features are assumed to include more than one fine voxel along the feature width direction. This assumption is made to ensure that thin machined features can be properly captured and constructed by the presented lookup table-based method. Both of these assumptions can be satisfied by proper setting of the fine level voxel size for the FSV-rep model.

Frame-sliced Voxel Configurations

The FSV-rep workpiece model has some favorable features that facilitate the generation of a closed 2-manifold triangle mesh representation. First of all, with the composition of independent frame-sliced fine level surface voxels making up the boundary of the complete model, the triangulation can be performed on a per frame-sliced voxel basis. Second, each frame-sliced voxel stores the frame details as frame-crossing points present on the frame edges. Since the frame-crossing points are stored as a pair for each frame edge, they can be used to infer the orientation of the surface patch within the voxel [4]. For clarity, three related terms are defined here: a *frame edge* is the fixed line segment between two voxel corner points; *frame edge segments* are active portions of a frame edge; a *frame edge configuration* refers to the composition of all the frame edge segments lying on the corresponding frame edge.

For a frame-sliced fine level surface voxel, each of its 12 frame edges can have up to two frame-crossing points. Considering the status of the frame-crossing points (being present or absent) as well as the status of the two end points of a frame edge (being inside or outside the workpiece volume), there are only 6 practically viable frame edge configurations as depicted in Fig. 1. As a result, there are 6^{12} theoretically possible configurations for all the 12 frame edges forming a frame-sliced voxel.

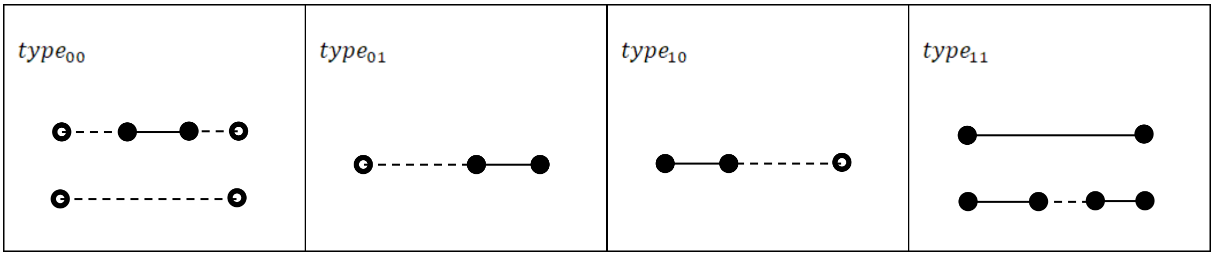

Fig. 1: Six practically viable frame edge configurations with up to two frame-crossing points grouped by end point status types.

Out of the massive 6^{12} theoretical possibilities, the frame-sliced voxel configurations that can physically happen during simulation are limited by the following condition:

Condition 1: For any corner point on a particular frame-sliced voxel frame, either three or none of the frame edge segments will be connected to the corner point.

This condition can be recognized by noting that it will need all three frame edge segments incident at a corner point to retain a volume for the corner point. Absence of the corner point means that there is no associated volume and thus, no frame edge segments should connect to the corner point.

Condition 1 gives an alternate way to characterize the frame-sliced voxel from the perspective of the corner points being active or inactive. Irrespective of the configuration of a frame edge, each of the 8 corner points can only be active with three connected edge segments (from the frame-sliced voxel in consideration) or inactive with no connected edge segment. Hence, there are a total of $2^8 = 256$ configurations with respect to the corner point status. However, each of the 256 configurations can have many possible combinations of the frame edge configurations for the 12 voxel edges under the limitation of Condition 1. In other words, each of the 256 corner-point combinations corresponds to a subset of the total 6^{12} theoretical possibilities for the sliced voxel edge segment combinations. It is mathematically proven that only 36,450 out of the total 6^{12} combinations are physically possible for sliced voxels arising in a machining simulation. To drastically reduce the possibilities from 36,450 in order for the size of the associated lookup table to be small enough, the floating segments and isolated gaps on a frame edge can be ignored. As the fine voxel size is quite small, the floating segments and isolated gaps only contribute to minor machined surface details such as slight dents and pointed features and are not part of the primary machined surfaces. Hence, ignoring such segments/gaps will not affect the global surface geometry of the modeled workpiece. The simplified frame edge configurations, in essence, result in the situation where there is only one frame-sliced voxel shape corresponding to each of the corner point status configuration. Thus, we only need a lookup table that cater to a total of 256 sliced voxel shapes.

Derived Lookup Table

The currently available lookup tables [1],[6],[7] are efficient as they match each specific corner point status configuration with a corresponding triangulation result. However, the original 15-case lookup table can lead to non-manifold surface mesh and the improved lookup tables require some extra non-geometric information which is not readily available from a purely geometric simulation such as the one with the FSV-rep model. A new lookup table with 22 basic configurations is derived in this work for all the possible frame-sliced voxel shapes. The 256 shapes counted in the previous section represent an elaborate set of the possible frame-sliced voxel configurations with the simplified frame edge configurations. After a detailed and extensive analysis of the 256 shapes, it has been found that these configurations are in fact variants of just 22 basic configurations. All of the 256 frame-sliced voxel configurations can be generated by rotational and mirror transformations of the 22 basic configurations. The derived 22-case lookup table is proven to be generating a closed 2-manifold triangle mesh for all the machined workpiece geometry situations that may arise.

Implementation Results and Comparison:

The applicability and computational advantage of the presented lookup table-based method have been demonstrated via converting a number of typical machined parts in the FSV-rep model format to triangle mesh representations. The tested parts were selected with varying geometric complexity. The resulting triangle mesh representations of the machined part geometry are shown in Fig. 2. It can be seen clearly in the figure that the geometry of these machined part has been captured well by the generated triangle meshes. It should be noted that due to the underlying grid-based modeling approach used to approximate the part geometry, some machined feature details cannot be represented exactly. In particular, the sharp machined edges have been approximated as chamfered edges. The sharp machined edges, however, can be easily restored from the chamfered edges using existing techniques such as that reported by Wang et al. [12].

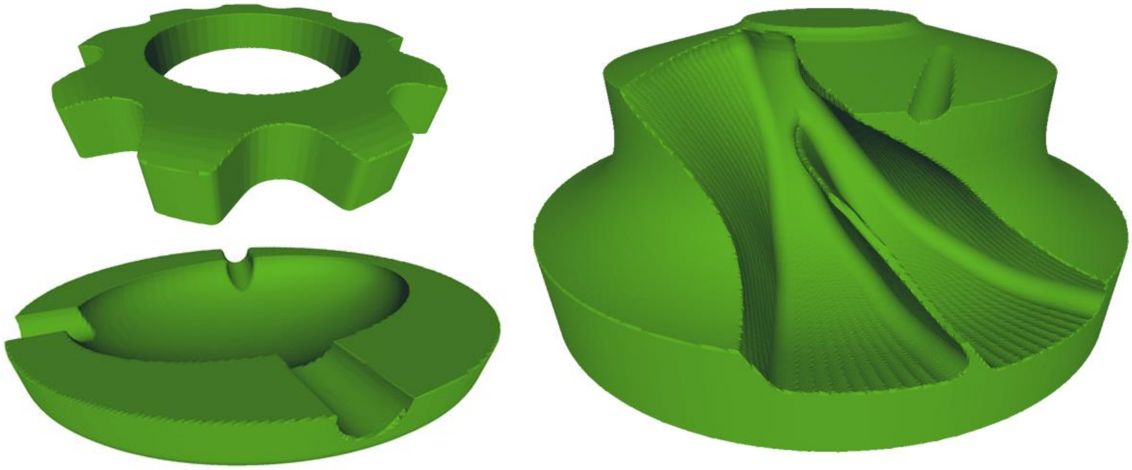

Fig. 2: Triangle mesh representations generated for typical machining test cases: Gear (left-top), Ash Tray (left-bottom), and Impeller Blade (right).

To evaluate the gain in computational time from the use of the 22-case lookup table with reference to the existing algorithmic method, quantitative comparisons as given in Tab. 1 have been made against the method developed by Ren et al. [11].

Test Case	No. of Vertices	No. of Triangles	Algorithmic Method (ms)	22-case Lookup Table (ms)	Improvement Factor
Ash Tray	69,516	139,024	160	78	2.05
Gear	69,276	138,552	159	76	2.09
Impeller Blade	196,060	392,116	506	258	1.96

Tab. 1: Computational time comparison of triangle mesh generation by the presented 22-case lookup table-based method against an existing algorithmic method.

The algorithmic method is applicable to simulated workpiece models in the vector format as well as the FSV-rep format. It has also been known to generate valid 2-manifold triangle meshes for machined part geometry in most practical cases. As for computational efficiency, the test results shown in Tab. 1 clearly confirm the superiority of the 22-case lookup table against the algorithmic method by a factor of 2. This significant reduction in mesh generation time can greatly facilitate time sensitive data processing tasks such as machining animation.

Conclusions:

In this work, a lookup table of 22 predefined frame-sliced voxel shapes has been derived and used to quickly generate 2-manifold triangle mesh representations from simulated machined workpieces modeled in the FSV-rep format. The geometric simplifications applied to the machined workpiece model in order to enable the use of a limited number of predefined frame-sliced voxel shapes are seen to be justifiable. Specifically, no missing geometric details have been noted on the machined surfaces of the simulated workpieces for all the test cases considered from such simplifications.

Acknowledgements:

This research was funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) under the CANRIMT Strategic Network Grant as well as the Discovery Grant.

References:

[1] Chernyaev, E. V.: Marching cubes 33: Construction of topologically correct isosurfaces, CERN Report, CN/95-17, 1995.

[2] Cohen-Or, D.; Kadosh, A.; Levin, D.; Yagel, R.: Smooth boundary surfaces from binary 3D datasets, Volume Graphics, Springer, London, 2000, 71–78. https://doi.org/10.1007/978-1-4471-0737-8_4

[3] Ding, H.; Tang, J.; Zhong, J.; Wan, G.; Zhou, Z.: Simulation and optimization of computer numerical control-milling model for machining a spiral bevel gear with new tooth flank, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 230(10), 2016, 1897–1909. https://doi.org/10.1177/0954405416640171

[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. https://doi.org/10.1016/j.cad.2017.03.006

[5] Joy, J.; Feng, H. Y.: Efficient milling part geometry computation via three-step update of frame-sliced voxel representation workpiece model, International Journal of Advanced Manufacturing Technology, 92(5–8), 2017, 2365–2378. https://doi.org/10.1007/s00170-017-0168-6

[6] Lewiner, T.; Lopes, H.; Vieira, A. W.; Tavares, G.: Efficient implementation of marching cubes' cases with topological guarantees, Journal of Graphics Tools, 8(2), 2003, 1–15. https://doi.org/10.1080/10867651.2003.10487582

[7] Lorensen, W. E.; Cline, H. E.; Marching cubes: A high resolution 3D surface construction algorithm, Proceedings of the 14th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '87), 1987, 163–169. https://doi.org/10.1145/37401.37422

[8] Oliver, J. H.; Goodman, E. D.: Direct dimensional NC verification, Computer-Aided Design, 22(1), 1990, 3–9. https://doi.org/10.1016/0010-4485(90)90023-6

[9] Peng, Q.; Loftus, M.: An image-based fast three-dimensional modelling method for virtual manufacturing, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 214(8), 2000, 709–721. https://doi.org/10.1243/0954405001518080

[10] Pfister, H.; Hardenbergh, J.; Knittel, J.; Lauer, H.; Seiler, L.: The VolumePro real-time ray-casting system, Proceedings of the 26th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '99), 1999, 251–260. https://doi.org/10.1145/311535.311563

[11] Ren, Y.; Zhu, W.; Lee, Y. S.: Feature conservation and conversion of tri-dexel volumetric models to polyhedral surface models for product prototyping, Computer-Aided Design and Applications, 5(6), 2008, 932–941. https://doi.org/10.3722/cadaps.2008.932-941

[12] Wang, Z.; Chen, J. S. S; Joy, J.; Feng, H. Y.: Machined sharp edge restoration for triangle mesh workpiece models derived from grid-based machining simulation, Computer-Aided Design and Applications, 15(6), 2018, 905-915. https://doi.org/10.1080/16864360.2018.1462571