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In NC milling as the tool moves along the tool path, the toll is in contact with the in-process workpiece over an engagement surface. In order to model the process mechanics and dynamics accurately, it is important to have a precise geometric properties of the engagement surface and/or removed volume. In this paper, we provide a brief introduction to cADFs and describe a new method for determining the engagement surface between a moving tool and workpiece, and calculate the geometric properties of the removed volume.

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High Accuracy Computation of Geometric Properties of Cutter Workpiece Intersection using Distance Fields for NC Milling

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Abstract

Composite adaptively sampled distance fields (*cADF*) are a new approach to shape representation that is well suited for shapes moving along a given path for NC milling. A *cADF* consists of a set of analytic or procedurally defined distance fields associated with both the original unmilled workpiece and with the volumes swept by milling tools as they move along their prescribed path. An octree bounding volume hierarchy is used to sample the distance functions and provides spatial localization of geometric operations thereby dramatically increasing the speed of the system with high accuracy and relatively low memory requirement.

In NC milling as the tool moves along the tool path, the tool is in contact with the in-process workpiece over an engagement surface. In order to model the process mechanics and dynamics accurately, it is important to have a precise geometric properties of the engagement surface and/or removed volume. In this paper, we provide a brief introduction to *cADFs* and describe a new method for determining the angle and area of engagement surface between a moving tool and workpiece, and calculate the geometric properties of the removed volume for 3-axis milling. Our method can calculate these geometric features for quite complicated tool paths and general tools using much less memory and time compared to the state of the art methods without scarifying from accuracy. It can also be generalized to any type of 5-axis motions.

Keywords: Engagement surface; removed volume; composite adaptively distance fields; engagement angle; cutter workpiece intersection.

1. Introduction

During numerically controlled (NC) milling a computer controlled rotary cutting tool follows a prescribed path to cut a workpiece. Simulating the process of NC milling is of fundamental importance in computer aided design (CAD) and computer aided manufacturing (CAM). Virtual simulation of NC milling processes has started to become more important in order to minimize the discrepancies between the actual and desired machined surfaces. One of the key technologies for advancing the productivity and quality of machining process is to design, test and produce the parts in virtual environment. In NC milling, as the tool moves along the tool path, the tool is in contact with the workpiece over a common surface called the *engagement surface*. As the tool moves relative to the workpiece, the tool carves out a swept volume. A portion of the workpiece that is intersected by the swept volume is removed, and called the *removed volume*. The workpiece that is updated by the removed volume is called *in-process workpiece*.

The simulation of the milling operation requires accurate high precision geometric modeling of the material removed by the milling tool. To model the process mechanics and dynamics accurately, it is necessary to have a precise geometric representation of the engagement surface. It is through this engagement surface that the milling forces are applied between the tool and the workpiece. Physical modeling can be used to predict the milling forces, bending moment, spindle torque, spindle power, and tool defections from the

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instantaneous engagement surface and other parameters such as axial and radial depths, tool thickness, and errors of the surfaces due to tool deflections, parameters defining tool geometry, and milling parameters. Besides using physics based process models, other geometry based volumetric methods such as using average cutting forces which are assumed to be proportional to the material removal rate during any particular instant.

2. Related work and Goals

Various approaches to NC milling simulation have been described in the literature. NC simulation methods can be categorized into three major approaches: solid modeling, spatial partitioning and discrete vectors. An extensive review appears in [1].

Boundary representation (B-rep) based milling simulators [17, 4] are theoretically capable of providing a highly accurate simulation of machining, but suffer from high computational cost in terms of time, data storage, and complexity. Another approach to NC milling simulation, cell decomposition, where tool and swept volume are decomposed into simple geometric elements, or cells, using spatial partitioning approaches such as ray casting [9,10], Z-buffer [11], G-buffer [12], dexel [13, 14], Graf-tree, voxel and octree, etc. The third approach, called the point vector method, approximates the machined surface by a discrete set of points and the vectors originating from these points. The cutting is simulated by calculating the intersection of these vectors with the cutter swept volumes [15, 16].

One of the fundamental difficulties has been the accurate and computationally efficient determination of the engagement surface along the tool path in these approaches. It is a challenging task due to complicated and changing tool workpiece intersection during NC milling. The geometric properties of the engagement surface comprise angle, area, orientation, curvature, shape, etc., at any time instance.Numerous methods of determining the engagement surface are known. For example, B-rep based milling simulation can analytically compute the engagement surface for simple milling tools, and 2.5 axis tool paths. These methods [3, 4] simulate the milling by a flat-end mill tool, and determine the engagement surface by a B-rep based solution. However, they are impractical for complex milling tools and tool paths due to complexity of computation and inconsistency of the results. Polygon based methods are also receiving some attention to model to determine the engagement surface; however the accuracy of these methods [5, 6] is limited by the polygonal representation of the object model. Thus, those methods either have limited accuracy or they have prohibitive processing times and memory requirements for calculating high precision tool workpiece intersection properties. Another method for determination of the engagement surface is Z-buffer or Dexel method [7]. They typically suffer from limited resolution; especially dexels in directions not aligned with the z-axis, and are not suitable for generating high precision models of in-process workpiece. The accuracy can be improved with the expense of larger memory and computational requirements. Besides these methods, a semi discrete solid modeling based approach [8] was described where the removed volume is sliced into a number of parallel planes along the intermediate axis of the two consecutive cutter locations to form the engagement surface between the cutter and workpiece.

Therefore there is a need for a space and time efficient method for determining a high precision engagement surface and removed volume for arbitrary tools moving along an arbitrary tool path and a workpiece. These needs become more important especially in physical modeling of machining process. In this paper, we propose a new approach for determining an engagement surface and removed volume between the tool and the workpiece during 3-axis NC milling simulation. *cADFs* are used to implicitly represent the in-process workpiece and swept volumes of tool that dramatically improves the accuracy and reduces the memory requirements.

3. Distance fields

A distance field is a scalar field that defines the minimum distance using some distance metric from any point P in space to the boundary of an object. More formally given a closed 3-dimensional C^0 manifold S embedded in E^3 we can denote the boundary of S as ∂S. We define the signed Euclidean distance field $d_S(P)$ as the function that yields the Euclidean distance from a point p to the closest point q on ∂S,

$$d_S(p) = \begin{Bmatrix} \inf\limits_{\forall q \in \partial S} \|p-q\|_2 & p \in S \\ -\inf\limits_{\forall q \in \partial S} \|p-q\|_2 & p \notin S \end{Bmatrix} \quad (1)$$

where $\|\cdots\|_2$ is the Euclidean norm. The sign of the distance field distinguishes whether the point is inside or outside of ∂S. The signed Euclidean distance field has the property that the gradient of the distance field is defined everywhere for objects with smooth boundary except on the medial axis, and for $P \in \partial S$ the gradient is the surface normal vector.

3.1. Distance fields of swept tools

Sweeping an arbitrary set of points S along a motion M in a space is usually formulated as an infinite union operation expressed formally as,

$$sweep(S,M) = \bigcup_{q \in M} S^q \qquad (2)$$

where S^q denotes the set S positioned according to a configuration q of motion $M(t)$, and t ∈ [0, 1] is the time-like parameter of the motion within a normalized interval. $M(t)$ is a one parameter family rigid body transformations in E^3. The distance field of the swept tool is given by,

$$d_S(P, sweep(S, M(t))) = \inf_{q \in \partial sweep(S,M(t))} \|P - q\|_2 \qquad (3)$$

As seen from this equation, finding the distance field of a swept volume requires computing the envelopes of the swept volume. This process is quite difficult for general tools and motion types. We compute the distance field of the swept volume by using an inverted trajectory approach [1, 2]. When the test point P is viewed from a reference frame attached to the tool, it moves along an inverted trajectory $\hat{T}_P$ which is defined according to the inverted motion, $\widehat{M}$ which is the inverse of M. In this new coordinate system, the distance field is now defined by,

$$dist(S, \hat{T}_P) = \min_{y \in \partial S, z \in \hat{T}_P} \|y - z\|_2 \qquad (4)$$

Fig 1. and Fig 2. illustrate the inverted trajectory for 3-axis sweeps along linear and circular arc paths respectively. The distance field can be determined analytically using the inverted trajectory approach for most of the tools for 3-axis motions.

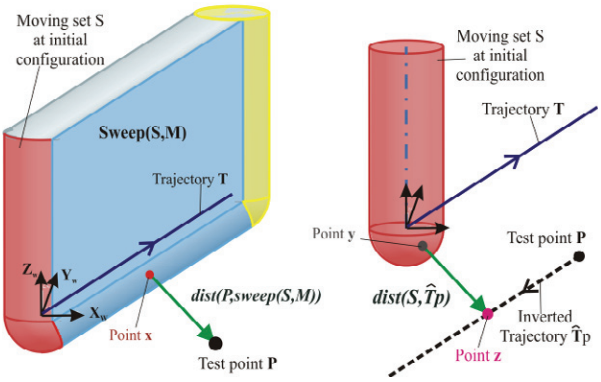

Fig. 1. The sweep of a tool according to 3-axis linear motion

3.2. Milling Simulation with cADFs

In-process and final workpiece is obtained by performing a Boolean difference operation to remove the volume swept by the cutter following the tool-path. Fig. 3 illustrates the process where cylindrically symmetric milling tool at initial position CL_i moves to final position CL_{i+1} along tool path M_i and removes any part of the initial workpiece W_0 within the swept volume SV_i. The intersection of the swept volume of the tool with the workpiece is the *removed volume* associated with this tool sweep. The *engagement surface* is the instantaneous intersection surface between the tool at final position and in-process workpiece.

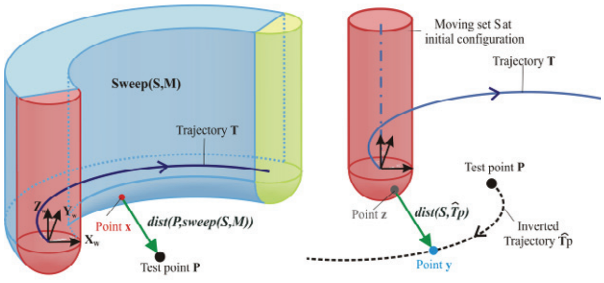

Fig. 2. The sweep of a tool according to 3-axis circular motion

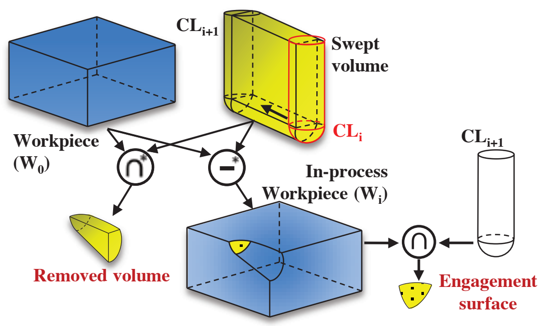

Fig. 3. Calculation of removed volume, engagement surface and in-process workpiece using Boolean operations

4. Cutter Workpiece Engagement

The cutter workpiece engagement defines the instantaneous intersection surface between the model of the tool and the in-process workpiece at each location along the tool path. As used herein, the engagement surface is the instantaneous contact surface between a model of the tool and a model of the in-process workpiece as seen in Fig. 4.

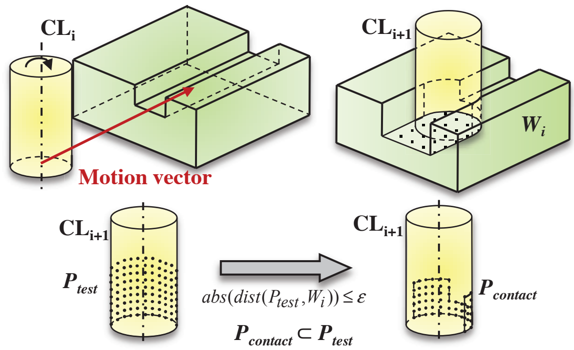

Fig. 4. Determination of contact points corresponding to the engagement surface on the boundary of tool

In this work we introduce a new method to determine the engagement surface between cutter and workpiece.

The engagement surface can be found based on distance values between a set of points arranged on the surfaces of the tool and the surface of the in-process workpiece. The set of points P_{test} on the boundary of tool can be generated by using various sampling strategies such as in cylindrical, spherical and geodesic pattern depend on the geometry and type of milling process. Then these points are tested against the in-process workpiece by,

$$abs(dist(P_{test}, W_i)) \leq \varepsilon \tag{5}$$

where ε is the distance threshold, W_i is the in-process workpiece. A subset of the points, $P_{contact}$ having the distance values below a threshold form the engagement surface. The angle of engagement is calculated using the determined engagement surface points. It is defined in clockwise direction and measured from the normal vector perpendicular to tangent tool path vector. The entry angle is the angle at which the tool enters the workpiece, and exit angle is the angle at which the tool leaves the workpiece. For given depth of cut values *z1* and *z2*, the cross sections of in-process workpiece are shown in Fig. 5. The angle of engagement is basically the region between the exit and entry angles where the tool actually removes material and creates milling forces.

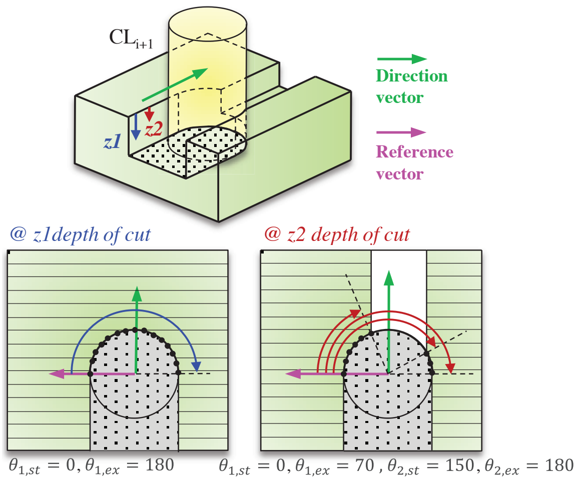

Fig. 5. Cross sections of in-process workpiece and the angles of engagement

During an instant of the simulation, the engagement surface can have one or multiple pairs of entry and exit angles. At depth *z1*, the angle of engagement includes one pair of entry and exit angles; however for the depth *z2* the angle of engagement includes two pairs of entry and exit angles. Although the engagement surface is a single connected surface in Fig. 5, different number of pair of entry and exit angles exists for different cross-sections. After the angles of engagement are determined, they can be integrated to calculate the area of engagement. Finally, angle and area of engagement can be used for machining process analysis; calculation of machining forces, uncut chip thickness, spindle torque, power, axial and radial depth of cuts, tool deflection and surface form errors due to tool deflections.

5. Removed Volume Calculation

As the tool moves relative to the workpiece, the tool carves out the swept volume. The process simulation of a milling operation requires an accurate high precision geometric modeling of the material removed by the milling tool due to each tool movement. In some models, average cutting forces are assumed to be proportional to the material removal rate (MRR). Average cutting forces are analyzed using MRR, and the power required to cut the material is proportional to the MRR.

In this work we introduce a new method for calculating the geometric properties of removed volume. For each tool path segment, the swept volume is represented by a grid of rays which are intersected and clipped against the in-process workpiece. The clipped rays for each swept volume constitute the removed volume. A subset of the swept volume determining the removed volume is determined by this test.

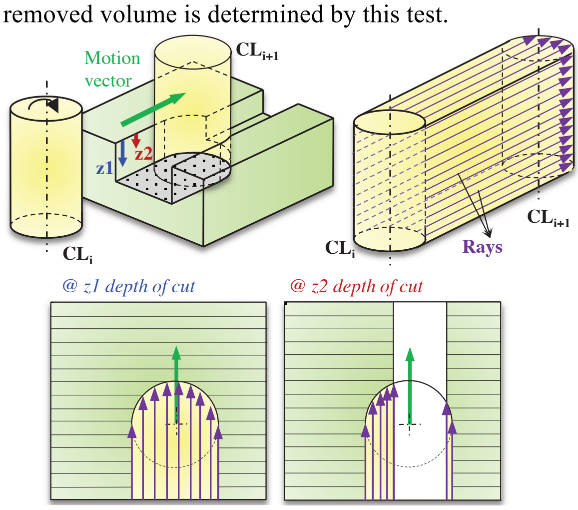

Fig. 6. Cross sections of in-process workpiece and the clipped rays corresponding to removed volume

Using a sampling pattern, a set of rays is generated to populate substantially the entire space of the swept volume as seen in Fig. 6. Each ray within the swept volume is intersected with the *in-process workpiece*. The rays are clipped against the workpiece according to the intersection test, and the clipped ray segments which are inside of the in-process workpiece having corresponding thickness and length can be combined to constitute the removed volume. These clipped ray segments can also be processed to determine various properties of the material removed by the particular tool motion, including its mass, volume, width, thickness, length or a moment of inertia to name a few. For given depth of cut values *z1* and *z2*, the cross sections of the in-process workpiece and are shown in Fig.6. The ray segments corresponding to the removed volume slices are shown for the given depth of cut values. Although the removed volume for this tool and workpiece is one piece, the removed volume slice has disconnected pieces for *z2* depth of cut.

6. Results

To demonstrate the capabilities of our approach we have simulated the fabrication of a traditional Japanese mask (Noh mask) whose milling requires more than 700,000 cutter locations (CL). The simulation was performed using a single core of a 3 GHz Intel Core 2 Quad with 4 GB of DRAM. Overall simulation time is 20.9 minutes, and the memory requirements are very modest (50 mb). The result of the rough and finish milling operations are shown in Fig. 7 as well as a close-up of the nose of mask.

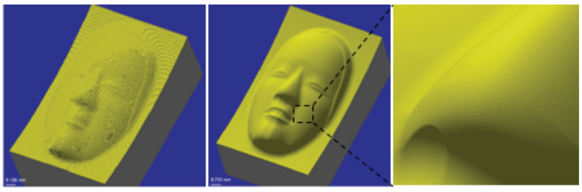

Fig. 7. Simulation of the rough and finish cutting of Noh mask

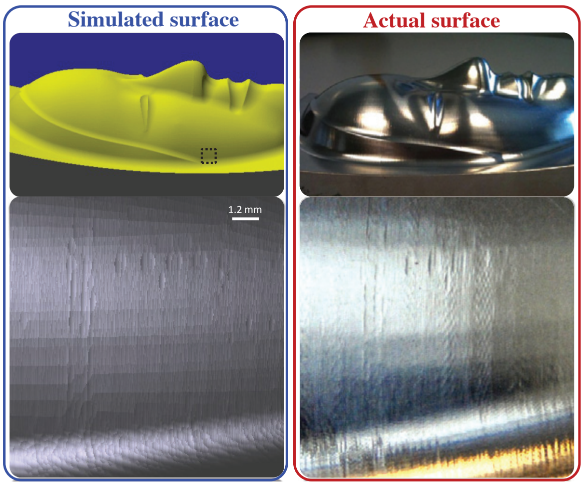

Fig. 8. Simulated and actual images of Noh mask part.

Fig. 8 shows an image of the simulated and photograph of the real machined mask. The simulated shape of the milled surface agrees extremely well with the actual shape and replicates fine details down to a scale of approximately 50 µm. The dynamics of the machining process such as tool deflection due to cutting forces, tool chatter, tool runout, thermal effects and machine dynamics become significant below this limit.

In order to demonstrate the capabilities of engagement surface and removed volume calculations, we have simulated different examples such as 2.5 axis pocketing operation with flat-end mill tool and 3-axis ball-end mill machining of free-form surface. We have developed a test system based on a commercial B-rep solid modeler library to test the accuracy of our results. The results show that the difference between the proposed method and B-rep based method for angle; area and volume are less than 1%. However, the computational time and memory requirements are much higher for solid modeler based methods. B-rep based method can only simulate the one third of the given example given in Fig. 7 around 10 hours. In all the examples for angle, area and volume comparisons, our method is 5 to 10 times faster than solid modeler method.

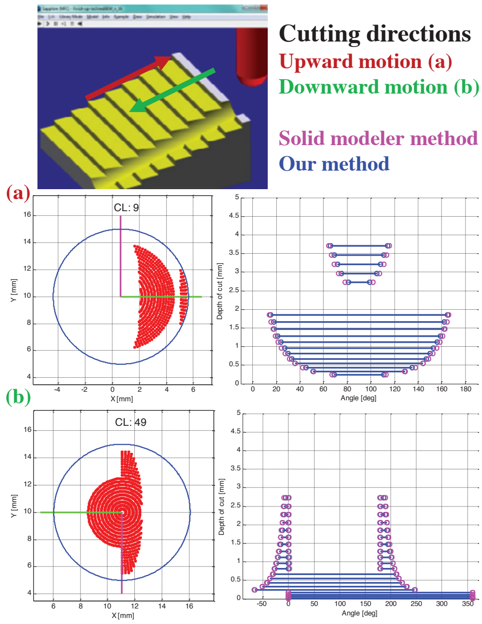

Fig. 9. The top view of engagement surfaces and angle of engagement for Ball-end mill tool; (a) Upward motion, (b) Downward motion.

The developed method also works for previously machined parts with any milling tool. The result of semi-finish milling operation machined by ball-end mill is shown in Fig. 9. Fig. 9(a) shows a specific CL point where the tool moves upward. As it is seen from the top view, the front of the cutter is in contact with the workpiece and the engagement surface has two sub-surfaces. Although the cutter performs full turn, the contacting zone corresponds to 0-180 deg. range. However, when the tool moves downward, the back of the cutter is also in contact with the workpiece, and the tip of the cutter is fully contacting the workpiece, which has 0-360 deg. range.

In our second example in Fig. 10, the ball-end mill tool moves according to a 3-axis motion and removes material from a workpiece which was previously machined by flat-end mill tool. The removed volume calculations are in very good agreement with the solid modeler based method.

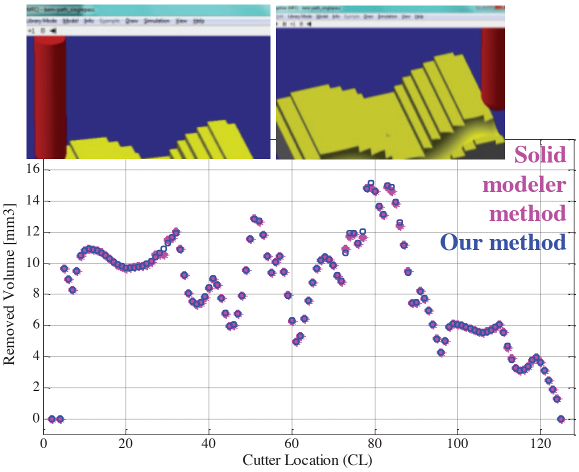

Fig. 10. Ball-end mill tool moving according to 3-axis motion

In last example in Fig. 11, we have simulated the motion of flat-end mill tool moving along linear tool path in 2.5 axes. The removal volumes associated with each cutter location is calculated and compared with solid modeler based system. Our results for flat-end mill tool are again in very good agreement with solid modeler based method like ball-end mill tool.

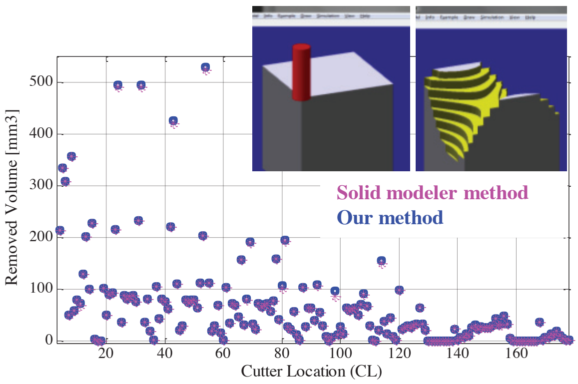

Fig. 11. Flat-end mill tool moving according to 2.5-axis motion

7. Conclusions

In this paper, we have described a new method for calculating the angle and area of engagement between the workpiece and milling tool using a new shape representation, composite adaptively sampled distance fields. We have also developed a method for calculating the geometric properties of the volume removed by the tool moving relative to the workpiece. The high accuracy provided by this approach to milling simulation enables fast, accurate, efficient and robust calculation of the geometric properties of cutter workpiece engagement which is an important input physical process model. The

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