An Approach for Tool Accessibility Evaluation for Multi-axis Machining Models

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ABSTRACT

An important step for automated manufacturing planning and evaluation of machined parts is the determination of appropriate tool approach directions and set-ups. An approach for determining accessible tool directions from a NURBS model of a part is developed and presented. The approach is based on mapping the convex hull of the part model to Point Visibility Cones (PVC). The approach is compared to PVC generation from a tessellated model. The new approach is shown to produce more conservative PVC's in less time than the tessellated approach.

Keywords: accessibility evaluation, manufacturing planning, machining setups.

1. INTRODUCTION

Manufacturing planning can be considered as the process of converting a design specification into a set of instructions for realizing the design. Among the steps in the manufacturing planning process are selection of the machine(s), selection of the tool(s), set-up planning (a set-up is an orientation and fixturing of a part relative to the machine), tool path generation, process parameter selection, and fixture selection/design. Much of the automated manufacturing planning research for machining processes has been based on manufacturing features. Manufacturing features are taxonometric form that can be mapped to general machining patterns such as pockets, holes, and slots. While there has been significant progress with feature-based approaches, there still remain problems to fully automated manufacturing planning due to recognition of interacting features and complex features such as those consisting of sculptured surfaces [15]. An alternative approach to manufacturing features based on form is the identification of smaller surface entities or primitives that can be grouped or clustered into machining regions dependant upon available machines and tools [18]. Clustering algorithms could then be developed to optimize the number of set-ups for machining a part.

A typical design specification is a computer generated solids geometry model with tolerance speciation created by a commercial CAD system. There are standard formats for CAD models, such as STEP [19], however these standards are more typically used for exchange than as the native model format. Tools developed for manufacturing planning are typically specific to a particular model format. Component models range in geometric complexity. The more complex geometries are free form or sculptured surfaces, which typically require more sophisticated manufacturing operations. These surfaces are often machined on 4- and 5-axis machines as they give one or two rotational axes in addition to the three linear axes and permit more flexibility and range in the surfaces that can be manufactured without reorienting the component. A Nonuniform Rational B-Spline surface (NURBS) is a common parametric representation for sculptured surfaces over the domain (u,v).

The smallest surface entity or primitive for a sculptured surface is a point. Grouping or clustering points into machining surfaces specific to available machines and tools is dependent upon the tool accessibility of the point. To date, a unified and conservative approach to point accessibility has not been presented. In this paper an approach to determining the tool accessibility of a point is presented and the relation of accessibility to each of the planning steps previously noted is made. Two approaches are compared. In the following section accessibility is defined and the previous approaches to accessibility are discussed.

2. ACCESSIBILITY EVALUATION

There are several ways to conceptualize accessibility. The accessibility of a point on a model can be defined as the set of all vectors emanating from the point that do not intersect the model. For a point on a NURBS surface this can be denoted as $A(P_{u,v})$. Visibility is a term that is functionally equivalent, representing all vectors projected to the point, or all lines of unobstructed view. Figuratively, point accessibility can be represented by the boundaries of the direction vectors in the form of an irregular cone. The tool accessibility of a surface is a function of the accessibility of all of the points on that surface $A(S_i)$ and the capability of machine used to machine the part. The construction of the composite representation depends largely on the type of machine to be used to machine the part. For 3-axis machining all points on a surface to be machined in one set-up must share a common accessible direction since the part and machine will maintain a fixed relative orientation. The intersection of the accessibility of surface points will produce a set of possible 3-axis set-up orientations for the part/machine combination. For 4- and 5-axis machining the intersection of the surface accessibility points cannot be used, since the machine and part will not maintain a fixed relative orientation. Instead, the accessibility points must be grouped by a function equivalent to the machine motion. Another important aspect of accessibility is the distinction between local and global accessibility. Thus far global accessibility has been addressed. In general, global accessibility pertains to the mapping of the entire model onto a point or surface. The utility of global accessibility is for set-up planning and machine selection. Local accessibility is the mapping of a localized region of the model onto a point. Local accessibility provides information pertaining to the fit of the tool in the local region and is therefore useful for tool selection. Fig. 1 demonstrates the distinction between global and local accessibility.

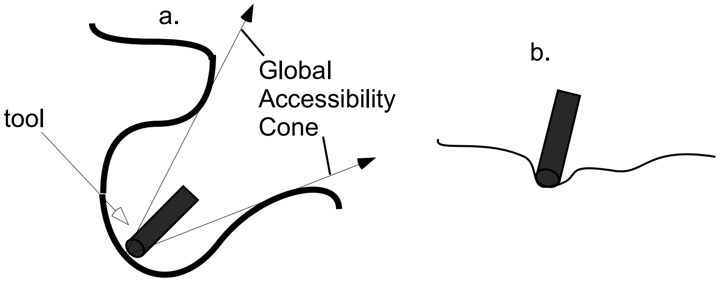

Fig. 1: a. Global accessibility: tool relative to entire part and b. local accessibility: tool relative to part surface.

Several approaches have been developed for computing and representing the accessibility of a surface. Notable approaches include [1-6], [16], [17], [21-23]. Each of these accessibility approaches is limited to specific geometries, is not conservative, or fails to produce results that can be used for machine selection, tool selection, set up planning and too path planning. Of equal concern is that accessibility evaluation approaches generally have a high computational complexity. The approach presented in this paper builds on these prior works.

Kang and Shu [4] introduced the concept of a Point Visibility Cone (PVC) and binary spherical maps (BSM) by which the 5-axis machining configurations can be solved in a unified algebraic fashion. A PVC is defined as a set of directions along which a tool can approach a part of the workpiece without collision between the tool and another part of the workpiece. A point P is accessible only from the directions that lie above the tangential plane at P. In other words, the feasible tool direction vectors lie within 90 degrees from the surface normal vector at the point. Each PVC will lie completely inside a hemisphere centered at the point and placed above the tangential plane at the point. A PVC can also be considered as subset of a complete sphere and hence a set of all accessible directions for a point can be represented by a sphere centered at the point, also called a binary spherical map (BSM). A BSM is discretized unit sphere decomposed by tessellation into a finite number of triangles. Each triangle on the sphere can be labeled 0 or 1 depending upon whether a ray projected through the center of the patch to the centroid of the sphere provides access to the point or not. A difficulty of the PVC approach is that it is not conservative and it is computationally expensive. Tessellation is the conversion of a model into a set of planar polygons. Polygons typically generated through tessellation approximate a best fit of the surface and typically pass through the actual model in convex regions. Accessibility generated by mapping the vertices of these polygons tends to over-estimate the accessible region by some amount depending on the granularity of the polygons. Underestimation may be considered preferable since it guarantees that accessibility calculation is within the true accessibility of the point. Thus a desired property of accessibility evaluation is that it is conservative. This can be stated as: $A(P_{u,v}) \le \overline{A}(P_{u,v})$ where $\overline{A}(P_{u,v})$ is the true accessibility. In the following section the formal proposed approach, hereafter called convex hull approach is presented.

3. METHODOLOGY

3.1. Overview of the Approach

A primary motivation of this work is to develop a conservative approach to point accessibility that provides a greater computational efficiency than previous approaches and that was applicable to all geometric forms. A successful result could then be used as a basis for optimized set-up planning and machine selection. By conservative we mean that the resulting point accessibility representation would never overestimate the actual tool accessibility of the point. This new approach utilizes the PVC and BSM representation concept developed by Kang and Shu [4], but differs in the discrete approximation of the entire model. A conservative approximation of the surface model was obtained by utilizing the convex hull of the NURBS surfaces. The convex hull of a surfaces can be considered as a bounding box of the surface.

In the first step a CAD model is generated. In this work the models are converted into NURBS surfaces, though algorithms could be easily developed to accommodate other geometric forms. In the second step the surface model is partitioned into smaller regions. While the convex hull is a conservative bounding of the surface, it may also be an overly conservative resulting in restrictive accessibility computations. Surface partitioning through subdivision has the effect of reducing the bounding region or convex hull by also subdividing the bounding region. In the third step the convex hull is generated and the model is faceted, resulting in another discrete representation of the model, both of which are used in generating point accessibility. The fourth step is the mapping of the facets and convex hull to produce point accessibility. The scope of this research is restricted to models that are:

- Multi-surfaces where each surface is mathematically represented by Non-Uniform Rational B-Spline or NURBS surface. (This assumption is not overly restrictive since most CAD model representations can be covered into B-Spline surfaces).
- Only 2-manifold objects where an edge is common to two faces are considered. This postulate follows from Mäntylä who defines a 2-manifold object as "a topological space where every point has a neighborhood topologically equivalent to an open disk of E^2" [11]. The result of this postulate is that it justifies the domain of shapes an algorithm should handle on pragmatic grounds.

The following sections presents a more detailed description of the approach. A model of a face is used as an example.

3.2 Product Models and Model Subdivision

A NURBS model of a human face was developed to more fully describe the point accessibility approach. The face model, depicted in Fig 2a, was selected because of its complexity, which includes many concave and convex regions of varying curvature and size. The model provides a large number of manufacturing options including the potential use of different machines, multiple tools and different set-ups dependant upon the machines used. Likewise, the curvature varies greatly over different model regions. The model was created using a laser scanner on a human face. A NURBS surface was then fit to the resulting point cloud.

Partitions for the face model were developed by partitioning the domain (u,v). The NURBS surface is then subdivided over the new partition. This has the effect of bring the convex hull closer to the surface and thus reducing the bounding region for the partition. While continued subdivision produces a more accurate point accessibility representation, it also produces more points for evaluation and thus increases the computation time since there are more points in the convex hull. Ideally there should be more partitions in the regions of higher complexity, where higher complexity surfaces have a larger number of concave and convex regions and higher curvature values. Fig 2a also shows the result of partitioning each u and v into four regions resulting in 16 surface partitions.

Once the model has been partitioned a faceted model (Fig 2b) and a convex hull mesh is generated (Fig 2c). Both are needed for this accessibility approach. The faceted model is used to place the accessibility spherical maps and for mapping within a partition. The convex hull mesh is used for mapping from all other partitions.

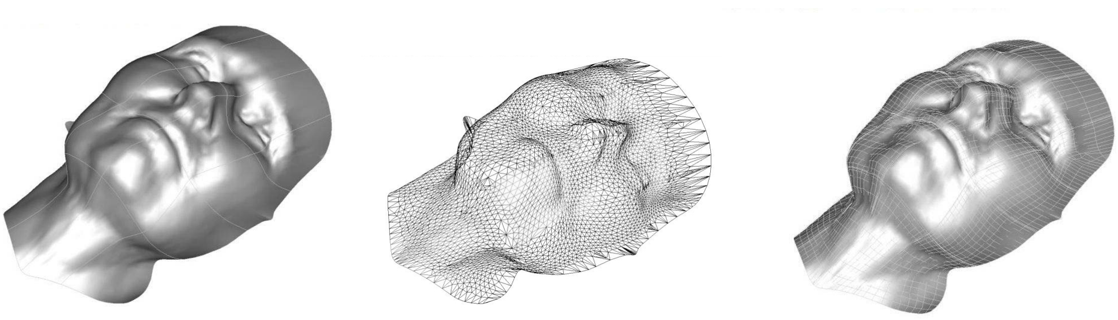

Fig. 2: a. Test Solid Model, b. Tessellated Test Model, c. Test Model with Convex Hull Mesh.

There are several choices in faceting algorithms and faceting parameters. Fixed faceting algorithms attempt to generate surface facets that are roughly equal in size. The drawback of fixed faceting for accessibility is that facets in regions of higher curvature will have a greater error in approximating the surface than they will in more planar regions. Increasing the number of facets will reduce the error, but will also increase the computational complexity since there will be an increase in the number of patches for all regions. Adaptive faceting attempts to vary the density of patches based on the curvature of the model resulting in more patches in regions of higher curvature.

3.3 Discrete Accessibility Spheres and Mappings

A discrete unit sphere is used to represent the accessibility of each point. The center of the sphere is located at the centroid of each patch of the tessellated model. Fig. 3a shows the test model with accessibility spheres embedded. There is one sphere for each patch of the tessellated model. Fig 3b shows one of the accessibility spheres embedded into the centriod of a patch. The accessibility of the whole triangular facet is approximated by the accessibility at the centroid of the facet. The discrete unit sphere is created by faceting the sphere. The resolution of the facets on the sphere bound the resolution of the accessibility representation. The greater the number of facets, the higher the accessibility resolution. The surface of the entire model is then mapped onto the sphere one patch at a time, where the patches from the partition of the sphere come from the faceted model and the patches from the other partitions (those that are mapped onto the sphere) come from the convex hull mesh. The primary reason for using the faceted model for mapping in the partition of the point or sphere is that the convex hull will always lie above the actual surface. Thus the patches created by the convex hull in a neighborhood close to the unit sphere may lie above the sphere and will produce an overly conservative accessibility computation. In some cases the accessibility may be null. Despite the potential error, it is always conservative, underestimating the true accessibility. The error diminishes in relation to the distance from the sphere. The faceted model should be used in the neighborhood of the sphere since the sphere is located at the centroid of a facet forming a tangential plane bisecting the sphere. Regions of the sphere that are occluded by the mapping of the surface patches are marked and considered to be inaccessible.

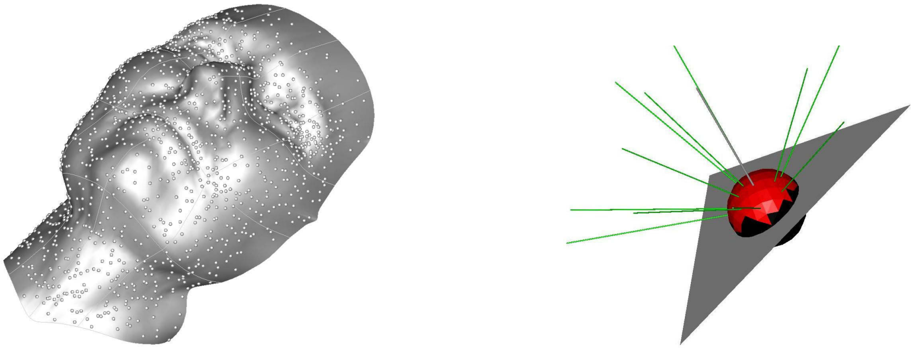

Fig. 3: a: Test Model with accessibility spheres embedded, b: A single patch with an accessibility sphere embedded.

3.4 Formal Mapping Procedure

The mapping procedure is similar to that developed by Kang and Shu [4] and is now described. A part model is tessellated into a set of triangular patches. Each triangular patch made up by points $P_k \quad (k \in [1:3])$ is to be projected on the sphere with center at point C_i with surface normal vector N_i (Fig. 4). The projection $P_k^p(\ k \in [1:3])$ occupies a spherical facet *l* and is labeled 1 if $M_k.\overline{OC_l} \geq \ 0 \ \ (\forall \ \ k \in [1:3])$, where C_l is the spherical centroid of spherical facet *l* and M_k is given by $M_k \ = \ \overline{OP_k^p} \times \overline{OP^p}_{\mathrm{mod}(k+1,3)}$.

Figure 3b depicted a Binary Spherical Map embedded into a part surface with accessibility vectors emanating from the centroid of the sphere, which lies on the part surface. An example of how the Binary Spherical Map can be used to determine a region of a part that can be machined in a single set-up is shown in Figure 13 shows the regions of a part that are accessible from one accessibility direction.

To utilize the above procedure of projection of a triangle the convex hull of every surface is arranged as piecewise triangles. Only those parts of the surfaces that lie above the tangential plane of a point can obstruct the tool approach directions to the point hence, only they need to be projected. The algorithm is carried out in the following steps:

1. Partition the surface model S(u,v) into *n* partitions.
2. Create triangular tessellations on the all the partition surfaces S_j, $j \in [0,n]$. The points of evaluation are the centroid of the facets.
3. Create a unit sphere with its surface decomposed into large number of triangular facets.
    a. For point P_i on surface S_j $(j \in [0,n] \ )$.
    b. Calculate the surface normal, n_i, at P_i.
    c. Make a list of all those spherical triangular facets that lie above the tangential plane at P_i.
4. Get the convex hull of all the surfaces and arrange them as piecewise triangles.
5. For the surface S_j, $(j \neq i)$ 0, project all those surface convex hull triangles that lie above the tangential of P_i.
6. Arrange the projection points on the sphere in CCW order.
7. Update all the spherical triangles in list that satisfy $(M_k.\overline{OC_l} \geq \ 0 \ \ (\forall \ \ k \in [1:3]),)$.
8. For surface S_i. Project all those surface facets that lie above the tangential point of $P_{i.}$
9. Again update all the spherical triangles in list that satisfy $(M_k.\overline{OC_l} \geq \ 0 \ \ (\forall \ \ k \in [1:3]),)$.
10. Repeat steps 4 to 10 for all the points on all the surfaces.

For all the points a sphere aligned along the positive z-axis is considered. Hence a triangle on a sphere at one point represents the same directions as the triangle with same number on a sphere at another point. The search for common set of directions is reduced from finding the intersection of 3D space to comparison of integers.

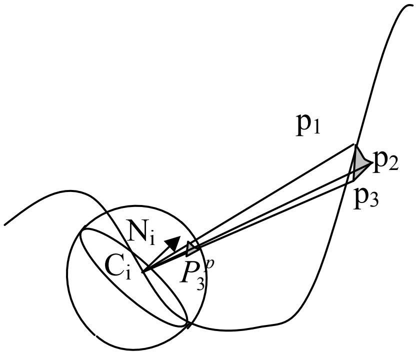

Fig. 4: Each patch from the model is mapped onto each accessibility sphere.

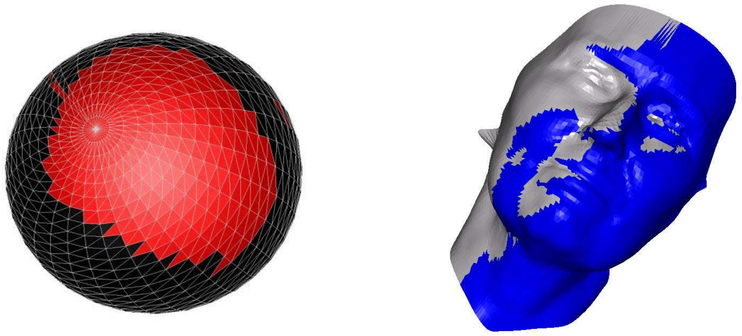

Fig. 5: a: Accessible region of a sphere (red) and b: Accessible regions of the test model (blue).

4. EXPERIMENTATION

In this section the convex hull approach is compared with the approach developed by Kang and Shu [4], which will be referred to as the tessellation approach. The tessellation approach was selected because the convex hull approach uses the PVC and BSM constructs of that approach. Also, while the tessellation approach does not provide a conservative approximation and is computationally expensive, it does provide a model that can be applied to all geometries. Both of the approaches were implemented in C++ using Standard Template Libraries and the ACIS[1] solid modeling kernel. All the experiments were run on a 600MHz - 384MB RAM NT workstation.

Two primary areas of interest for experimentation were the relative approximations of the point accessibility and the computation time for the approximation. The relative proximity of the point accessibility calculations is an indicator of how much difference there is between the approaches. For a high resolution of facets on the surface, which would be a close approximation of the surface), one would expect a relatively close accessibility computation. However, one would also expect that the accessible area produced by the conservative approach would always be equal to or less than the accessible area produced by the tessellation approach.

In the experimentation two variables were examined: the number of facets on the surface model and the number of facets on the sphere. Higher values of these variables produce a more accurate approximation of the surface. While it would be preferable to compare the results to the "true accessibility" of each point, such a computation is infeasible and thus a high-resolution approximation was developed. In each of the experiments unit spheres were placed in identical locations at the centroid of each of the facets and in identical orientations (all normals in the same direction). This orientation allowed a direct comparison of identical facets on the accessibility sphere. Different orientations would not permit a direct comparison as facets would not map to each other but would overlap. Tab. 1 presents the results of nine experiments. In the table the accessible area as computed using the convex hull approach divided by the accessible area of the tessellation approach is shown. The number presented in the table is an average of all of the accessibility spheres for the entire face model. For example, using spheres with 2108 facets, a tessellation model 6394 tessellation's, and a convex hull mesh with 16 partitions (the number of partitions in all experiments presented), the area of the convex hull accessibility calculation on the spheres was 99.24% of the area of the tessellation accessibility calculations. The number of accessibility spheres for both approaches will always be equal to the number of facets in the model for each experiment. Thus there were 6394 accessibility spheres generated for this computation. It should be noted that each of the point accessibility regions computed from the convex hull approach was contained within the accessible region of the tessellation approach. That is $A(P_{u,v}) \leq \bar{A}(P_{u,v})$.

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[1] ACIS is a registered trademark of Spatial Technology Inc.

	Facets on Sphere Experiment 1	**Facets on Sphere Experiment 2**	**Facets on Sphere Experiment 3**
Facets on Model	**2108**	**2853**	**3780**
3600	99.02	-	-
4178	99.06	-	-
4788	99.14	-	-
5524	99.19	-	-
6394	99.24	99.21	99.20
7288	99.27	99.25	99.24
8394	99.31	99.30	99.28
9629	99.33	-	-
10972	99.36	-	-
12228	99.38	-	-
13832	99.40	-	-
15514	99.41	-	-
17200	99.43	-	-

Tab. 1: Common accessible area as percentage of tessellation accessible area.

As the number of facets on the model increase, the error in the approximation using the tessellation approach is reduced since more patches are used to approximate the surface. However, the number of patches from the convex hull mesh remains the same across all experiments. As depicted, the average common percent for all experiments was greater than 99%. Table 1 has several cells for which no results are reported. The original experiments only included values of 6394, 7288, and 8394 for facets on the model. The additional experiments were included to examine the increasing trend in the data.

The computation time in seconds for each of the experiments was recorded and is shown in Tab. 2 while Tab. 3 depicts the percent of time saved using the convex hull approach as compared to the tessellation approach. The minimum timesaving in the table was 18% for 2108 facets on the spheres and 6394 facets. As the number of facets increases the timesaving also increases up to 32% for 2108 facets on the sphere and 8394 facets on the model.

Facets on Sphere	2108		2852		3780	
Facets on Model	Tess.	Convex	Tess.	Convex	Tess.	Convex
6394	1073	897	1281	1102	1564	1361
7288	1376	1044	1635	1275	1996	1566
8394	1782	1208	2133	1483	2562	1850

Tab. 2: Computational time for each approach.

Facets on Sphere	2108	2852	3780
Facets on Model			
6394	18	13.9	12.9
7288	24.12	22.00	21.5
8394	32.2	30.4	27.8

Tab. 3: Time saved (in seconds) as percentage of time taken by tessellation approach.

5. DISCUSSION OF THE RESULTS

The convex hull approach consistently produced a more conservative approximation of point accessibility than the tessellation approach. Likewise, the computation time to produce a reasonably good point accessibility map is faster than the tessellation approach and therefore an improvement to the approach.

The comparison results are given as the area of the sphere surface that is accessible. The facets on the sphere considered are actually planar triangles and not spherical triangles. Hence, the area calculated is approximate of the actual value. For comparison of the two approaches the accessible sphere area common to the results of both the approaches is calculated as percentage of the accessible sphere area given by the BSM approach. The higher this value, the closer the results of the proposed approach are to the results of BSM approach. On an average the proposed convex hull approach gives results within 99% of the results given by the BSM approach for all experiments for a broad range of facets resolution on the accessibility spheres or on the surface. However, the approach deteriorates for some points, which are near the surface boundary. The boundaries of the convex hull of a surface are not coincident with the boundaries of the surface. (Only the four corner points of the convex hull are coincident with the four corner points of the surface). For the points near the edges shared by two surfaces the convex hull of the other surface occludes more directions than the surface itself and hence the answers are too conservative. Although all convex hull accessibility computations were more conservative than the tessellation approach, some of the point accessibility computations using the convex hull approach may actually overestimate the “true” accessibility of the points. This can occur because a faceted model was used for mapping in the neighborhood of the point to eliminate high conservative errors from the convex hull that occur only in that region. If the local neighborhood contains the actual accessibility boundary and the facets intersect the actual surface in that neighborhood, an error equal to the tessellation approach will be produced.

There was a slight increasing trend as the number of facets increased; though the difference was small. A possible explanation for this trend is that as the number of facets on the model increase, the error of the surface approximation decreases and thus the tessellation approach becomes a better predictor of the point accessibility.

The time saved measured as the percentage of time taken by tessellation approach increases as the number of tessellations on the surface increases and decreases as the number of tessellations on the sphere increases. The time or computational gain in the convex hull approach is due to the projections of piecewise triangles of convex hull which are fewer in number than the tessellation’s on the model. The number of convex hull pieces to be projected remains the same for all the cases so an increase in number of tessellations on the surface affects the proposed approach only with regard to more number of points to be evaluated. If the number of triangular polygons in resulting from the convex hull mesh exceeds the number of polygons in the tessellation model the time for the convex hull approach will exceed that of the tessellation approach. However, we believe that a conservative approach is generally preferable.

These results are consistent with expectations since increasing the number of model facets should increase the computation time for the tessellation approach more than for the convex hull approach. Recall that the number of patches in the convex hull mesh remains the same regardless of the number of surface facets, however there will be more accessibility spheres with the increase.

6. CONCLUSIONS

Point accessibility can be used as a foundation for many steps in the manufacturing planning process including tool selection, machine selection, set-up planning, and tool path planning. There is a need for a computationally efficient and conservative approach to generating point accessibility. The convex hull approach presented in the thesis produces a more conservative approximation of point accessibility than the tessellation approach. Likewise, the computation time to produce a reasonably good point accessibility map is faster than the tessellation approach and therefore an improvement to the approach.

7. FUTURE RESEARCH AND SUGGESTIONS

There are several areas for improvement in the approach. Since points lying near the partition boundaries do not provide reliable results a technique to handle these points should be developed. For better results one may exclude a row or column of the points of the convex hull of surfaces that share an edge with the surface in consideration.

There is also a need to develop an approach to partitioning the model based on the complexity of the region and computational expense trade-off. While any partitioning scheme will produce a conservative result, finer partitions will produce more accurate accessibility computations, but at a computational expense. As part of the partitioning schema a technique should also be developed to eliminate error in the neighborhood of the accessibility point.

Heuristics to map point accessibility to surface accessibility useful for setup planning and machine selection should also be developed based on the accessibility computations.

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