Automatic Tool Path Generation for Robot Integrated Surface Sculpturing System*

Jiang ZHU**, Ryo SUZUKI**, Tomohisa TANAKA** and Yoshio SAITO**
**Department of Mechanical and Control Engineering, Tokyo Institute of Technology, I1-35, 2-12-1, O-okayama, Mekuro, Tokyo, 152-8552, Japan
E-mail: zhofhit@hotmail.com

Abstract
In this paper, a surface sculpturing system based on 8-axis robot is proposed, the CAD/CAM software and tool path generation algorithm for this sculpturing system are presented. The 8-axis robot is composed of a 6-axis manipulator and a 2-axis worktable, it carves block of polystyrene foams by heated cutting tools. Multi-DOF (Degree of Freedom) robot benefits from the faster fashion than traditional RP (Rapid Prototyping) methods and more flexibility than CNC machining. With its flexibility driven from an 8-axis configuration, as well as efficient custom-developed software for rough cutting and finish cutting, this surface sculpturing system can carve sculptured surface accurately and efficiently.

Key words: Tool Path Generation, Multi-Axis Robot, Freeform Surface Sculpturing, CAD/CAM Software, Hotwire Cutting

1. Introduction

Currently there are two conventional methods to fabricate 3D models and freeform surfaces: RP (Rapid Prototyping) and CNC machining(1). RP process provides a solution with higher speed, easier fabrication and the ability to handle complex structure(2). While CNC machining provides a solution with higher accuracy, better surface finish and the ability to machine various materials(3). However, none of them is the ideal solution for producing high quality part within the shortest possible time. Noticed that multi-DOF (Degree of Freedom) robot benefits from the faster fashion than traditional RP methods and more flexibility than CNC machines, the idea of utilizing multi-DOF robots to build prototypes has attracted many robotic researchers to the field of 3D fabrication. Tengleder and Vergeest(4,5) were early to implement robotic arms for this purpose. Also, Chen(6,7) implemented a robotic system for sculptured surface cutting and later developed a technique that uses layer-based machining to sculpt prototypes made of polymers.

In the precious research(8-13), a surface sculpturing system based on multi-DOF robot and shaping the 3D work-piece by heated cutting tools is proposed. This sculpturing system combines the advantages of high flexibility of RP and high accuracy of CNC machines, it uses triangular-mesh models as input. In this paper, the tool path generation algorithms for the surface sculpturing system are introduced. While most of the traditional RP techniques share the advantage provided by slicing the 3D model into thin 2D layers and consecutively constructing these layers, this developed surface sculpturing system carves the 3D model as a whole unit. It first rough cuts the model with a hotwire cutter to remove the redundant material rapidly. Then semi-finish and finish cutting are implemented with hot-tip cutters to produce the desired surface. With its flexibility driven from an 8-axis configuration, as well as efficient path planning software for rough cutting and surface finishing, this surface sculpturing system can carve sculptural surfaces accurately and efficiently.
2. Hardware Layout for Surface Sculpturing System

The hardware of the sculpturing system is composed of an 8-axis robot and the cutting tools. The 8-axis robot is made up of a 6-axis manipulator (Motoman-SV3X, by Yaskawa Electric) and a 2-axis worktable, as shown in Fig.1. Currently this sculpturing system shapes blocks of polystyrene foam with the dimension of 100x100x100 mm³.

![8-axis Robot for Surface Sculpturing System](image)

**Figure 1: 8-axis Robot for Surface Sculpturing System**

### 2.1 8-axis Robot for Surface Sculpturing

The mechanism system of the surface sculpturing system should guarantee an abundant space reach for the end effectors, so that the tool can cut any place it could reach on the polystyrene foam block. Since in surface sculpturing process the cutting direction is unfixed, the multi-DOF manipulator alone cannot provide enough feed distance in the cutting direction. Therefore, an 8-axis robot system is developed, which is made up of a 6-axis manipulator and a 2-axis worktable. The cutting tool is installed at the end of the manipulator, and the work-piece is attached on the worktable. This developed mechanism conquers the limitation of the manipulator’s space reach, and also helps to avoid the interference between the manipulator and the workpiece.

### 2.2 Cutting Tools for Surface Sculpturing System

This surface sculpturing system carves polystyrene foam blocks by heat. According to the different tasks performed in the sculpturing process, the hotwire cutter is designed as the end effector in the rough-cut process, and the hot-tip cutters are designed as the end effectors in the finish-cut process.

In order to rapidly remove the material, a hotwire cutter is designed as the cutting tool for rough cutting, which can be regarded as the face end-mill in CNC machining. A current version of the designed hotwire cutter is shown in Fig.2(a). Nickel chrome wire is used as the hotwire, and Polytetrafluoroethylene (PTFE) materials are used to make the non-conductor part of the cutting tool.

Although hotwire cutter is efficient in cutting large flat faces, it is not dexterous enough to sculpture the local details with concave features. In order to produce the desired surface, and to machine the geometric details of the 3D model, hot-tip cutters are developed as the cutting tools for finish sculpturing. They can be regarded as the flat end–mill or ball end-mill in CNC machining. The hot-tip cutter is cut out from the nickel chrome plate, as shown in Fig.2(b). Using the same PTFE tool base, two kinds of tips are designed, with the cutting lengths of 5.5mm and 1.6mm. These two tips can be changed during the sculpturing process, and they can be used for semi-finish and finish sculpturing respectively.
3. Software Layout for Surface Sculpturing System

Using the 8-axis robot system to sculpture 3D work-piece, the generation of 3D tool path is completely different from that of the conventional CAM systems for RP or CNC. The models and tool path for surface sculpturing are generated by CAD/CAM software specially designed for this system. While most of the commercial CAM software can only deal with the tool path generation for 3-axis or 5-axis CNC machines, this developed CAD/CAM software calculates the tool paths for cooperative controlling of 8-axis robot. It contains five main featuring modules, which are shown in Fig. 3.

This sculpturing system uses triangular-mesh models as input. At CAD level, it first corrects the topological problems of the input model. Then the simplified approximation is transformed into a series of rough-cut models, which are easy for cutting. Finally, it computes the convex hull of the rough-cut model, which will help the system to approach the rough-cut model from the raw material block in the most efficient manner.

In CAM process, it first computes the tool path for the hotwire cutter to perform the rough cutting. Then it calculates the tool path for the hot-tip cutter to perform the finish cutting. After that it calculates the positions for 2-axis worktable and 6-axis manipulator to perform the sculpturing.

3.1 CAD Software for Surface Sculpturing System

The input models for freeform surface sculpturing are generally generated from
commercial CAD software or 3D scanning system. Usually the resulting mesh suffers from many topological problems, such as degenerate facets, undesired holes, or flipped normal vectors, which will lead to invalid tool path generation. Therefore, a preprocessing is implemented to remove the self-intersections in the input mesh, and eliminate the degenerate facets through edge collapse transformations. It makes the input model suitable as the input for CAM systems. Recently, with the rapid development of 3D scanning technology, an accurate representation of a 3D model can easily contain a million triangles. Over sampled mesh data will cause inconvenience and low efficiency for later processing. A mesh simplification module is also developed. It reduces the number of triangles needed to represent the model while trying to retain a good approximation to the original shape and appearance. It can automatically simplify the input model into a user specified resolution, which is indicated by the number of triangles left in the mesh or by the distance between the approximations and the original model.

In the rough-cut process of surface sculpturing, the main goal is to approach the final work-piece and to remove the redundant material efficiently. It is not necessary for the tool path to have all the geometric details of the final work-piece. The machining efficiency may be improved by using simple shapes away from the desired surface. Therefore, an algorithm was developed to generate the rough-cut models for generating tool path in rough-cut process. Compared with the input model, the rough-cut models have simple geometric complexities and increasing volumes. It will help the system to rapidly remove the redundant material, and approach the final work-piece step by step.

Finally, the CAD software computes the convex hull of the rough-cut models. Since convex hull is composed of facets, which only have convex features, there is no necessity to consider the interference between the cutting tool and the other part of the workpiece. Thus, it is easier and more efficient to machining a convex object than a non-convex object.
Figure 4 gives an example of the rough-cut model generation of a human head model. The original human head model is composed of 1,390 triangles, which is shown in Fig.4(a). The rough-cut model shown in Fig.4(b) is composed of 138 triangles, and the convex hull shown in Fig.4(c) is only composed of 100 triangles. From Fig.4(b) it can be found that the rough-cut model has the basic trends of the original model, and has a simple geometric complexity. Furthermore, the rough-cut model lies completely outside the original model within a fixed distance. These virtues make the rough-cut model easy to be machined. From Fig.4(c), it can be found that the convex hull is further simplified, and it only contains convex featured facets. These features will encourage using larger-sized cutting tools to machine the convex hull. The efficiency to remove the redundant materials will be highly increased using this kind of rough-cut model generation strategy.

### 3.2 Tool Path Generation for Rough Cutting

Tool path generation is the fundamental task in material removal process. In the rough cutting process, this surface sculpturing system cut the convex hull and the rough-cut model face-by-face using the hotwire cutter\(^{10}\). In order to save the machining time and get a clean cut on the edges between adjacent faces, a careful selection of the machining sequence is necessary. The system selects the faces by a height-based neighbour tracing algorithm\(^{14}\). The algorithm can be outlined as the following steps:

1. Find out and record the neighbour triangles of each triangle in the rough-cut model. For a closed surface composed of triangular facets, generally each triangle in the surface has three adjacent triangles. If two triangles have a common edge, they are neighbours to each other.
2. All the un-machined triangles in the rough-cut model are ordered by the \(z\) coordinate of its barycentre. The triangle, whose barycentre has the maximal \(z\) value, is selected as the seed face to machine.
3. If the seed triangle has un-machined neighbours, the neighbour whose barycentre has the largest \(z\) value is picked as the next seed face to machine. If there is no un-machined neighbour around the seed triangle, the algorithm returns to step 2 to find another seed face.
4. If all the triangles are machined, it finishes the machining process.

By this means, the rough-cut model will be sculptured from up to bottom without missing any facets.

As a preparation, the algorithm calculates the rotation angles for the worktable and adjusts the cutting plane to a proper pose, which is easy for the hotwire to cut. Normally, the worktable adjusts the cutting plane upward to cut. Since the maximal tilt angle of worktable is \(\pm 90^\circ\), the worktable cannot turn all the facets upward to cut. Therefore, for the facets, which cannot be adjusted upward, the worktable adjusts the cutting plane frontward to cut. Suppose face \(t_k\), which is composed of vertices \(v_1\), \(v_2\), and \(v_3\), is the seed triangle to machine. Then the tool path for rough cutting can be generated according to the following steps, which are illustrated in Fig.5:

1. The manipulator moves the cutter center \(P\) from the present position to point \(O\), which is above \(v_2\) and \(v_3\) along the normal vector, shown as step 1.
2. The cutter center \(P\) is moved from point \(O\) to point \(M\), the perpendicular foot from \(v_1\) to edge \(\{v_2, v_3\}\), at this moment the hotwire is adjusted to the proper cutting direction, shown as step 2.
3. The manipulator moves the cutter center \(P\) from point \(M\) to \(v_1\), which is shown as step 3.
4. The hotwire moves away from the cutting surface, shown as step 4. The loop for cutting face \(t_k\) is finished.
By applying this process to all faces, the rough-cut model can be sculptured.

![Diagram](attachment:image.png)

Figure 5: Tool Path for Cutting One Facet

### 3.3 Tool Path Generation for Finish Cutting

The system computes the tool path for semi-finish and finish cutting based on slicing technique. In order to calculate the cutter location for the hot-tip cutter, the system discretizes the model volume by generating contours. The sculpturing direction is selected along the model’s long axis. It first generates a set of reference planes that are perpendicular to the sculpturing direction, to slice the model, as shown in Fig.6(a). Then it calculates the intersection lines of the model with the reference planes. These planes are called as $Z$-planes, and the intersection lines are called as contours of $Z$-plane.

After that, it generates another set of reference planes, which are parallel with the sculpturing direction and perpendicular to the $Z$-planes, as shown in Fig.6(b). These reference planes are called as $\theta$-planes, and the intersection lines of the model with the $\theta$-planes are called as contours of $\theta$-plane. These two contours are used to generate the cutter locations for tool path. When all the sliced contours of $Z$-plane are cut, the system cut the contours of $\theta$-plane. It enables the cutter to reach every portion of the model and smoothen the stair-step effects, which are created by the previous tool path.

![Diagram](attachment:image.png)

(a) Tool Path Calculation Based on Contours of $Z$-plane  
(b) Tool Path Calculation Based on Contours of $\theta$-plane

Figure 6: Tool Path Calculation for Finish Cutting

Theoretically, by this method, this surface sculpturing system is capable of sculpturing any surface that can be “seen” by the hot-tip cutter. If a ray of light can reach that surface directly, then so can the hot-tip cutter. However, due to the size of the hot-tip cutter, it is still less of accuracy on carving some small-scale finer features.
Generally, the intersection part of the triangular facet and the planes is represented in terms of straight-line segment. The intersection line can be formed progressively by connecting each line segment end to end. Since the input model is assumed to be a closed manifold surface, the intersection line forms a closed loop. Here to improve the efficiency to calculate the intersection lines, the neighbor tracing technique\(^\text{12}\) is introduced. Since along each intersection loop, the triangles in the mesh intersected with the reference plane are neighbours to each other. Making use of this neighbouring relationship, the intersection line can be constructed by tracing neighbouring triangles one after the other. Fig.7 gives the contours of \( Z \)-plane and \( \theta \)-plane calculated from the human head model.

![Figure 7: Contours Calculated from Human Head Model](image)

![Figure 8: Tool Path Calculation for Tracing Contour of \( Z \)-plane](image)

After the contours are created, the surface sculpturing system is ready to trace the desired contour. When tracing the contours of \( Z \)-plane, the rotation angle of the worktable and tool path of the hot-tip cutter for tracing each contour can be calculated according to the following steps:

1. It first calculates the barycenter of that contour. As shown in Fig.8(a), the barycenter is taken as the origin of the local coordinate.
2. The vertices in the contour are sorted counter clockwise according to their angles relative to the \( OX \) axis. That angle are stored for every vertex and used as the rotation angle of 2-axis worktable.
3. As shown in Fig.8(b), with the worktable rotates, the position of the vertex after
rotation is calculated. After the worktable rotates one round, the contour on one $Z$-plane is sculptured.

The contours of the $\theta$-plane are traced according to the $Z$ coordinates of the vertices in the contour, from up to bottom.

4. Experimental Result

4.1 Experiment of Cutting Venus Model

Using this developed surface sculpturing system and the proposed tool path generation process, various models have been fabricated. The first example to check the applicability of the proposed surface sculpture system to fabricate 3D models is the Venus model, which consists of 1418 triangles. The final workpiece is sculptured from the raw material block with the dimension of 100x100x100 mm$^3$ following four steps, as illustrated in Fig.9.

![Sculpturing Procedure of Venus Model](image)

**Figure 9: Sculpturing Procedure of Venus Model**

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Cutting Conditions for Machining the Venus Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>It first uses the hotwire cutter to sculpture the convex hull model, shown as step 1.</td>
<td>Convex hull 5 1 316 29</td>
</tr>
<tr>
<td>2.</td>
<td>Then it uses the hot-tip cutter with the cutting edge of 5.5 mm to sculpture the rough-cut model, shown as step 2. The tool path is generated based on contours of $Z$-plane.</td>
<td>Rough-cut 20 5 1054 6</td>
</tr>
<tr>
<td>3.</td>
<td>After that, it uses the hot-tip cutter with the cutting edge of 1.6 mm to sculpture the semi-finish model, shown as step 3. The tool path is also generated based on contours of $Z$-plane.</td>
<td>Semi-finish cut 10 2.5 5662 40</td>
</tr>
<tr>
<td>4.</td>
<td></td>
<td>Finish cut 5 1.9 16971 190</td>
</tr>
</tbody>
</table>
Finally, it uses the hot-tip cutter with the cutting edge of 1.6 mm to perform the surface finishing, shown as step 4. The tool path is generated based on contours of $\theta$-plane, which is perpendicular with the previous tool path. The cutting conditions in each step are shown in Table 1. The total machining time to fabricate the final workpiece is almost four hours. It can be noticed that it only takes about six minutes to sculpture the rough-cut model from the convex hull. In addition, the total machining time from the raw material to the semi-finish model is within one and a half hours. In despite of the stair step effects left on the surface, the semi-finish model has almost all the geometric features of the 3D CAD model. However, using traditional RP method, such as FDM, it will take about 12 hours to fabricate a model within the same size. The final surface finishing process can be regarded as the polishing process. Although it is a time consuming process, which takes over three hours, the surface finishing process removes the stair-step effects resident in the previous process, and produce a final workpiece with fine surface quality.

![Figure 10: Sculptured Results of Venus Model](image)

Figure 10 shows the sculptured results of Venus model. Fig.10(a) shows the sculptured convex hull of Venus model. This convex hull is the basic roughcast for the sculptured workpiece. Most of the redundant material has been removed from the raw material block. In Fig.10(b), it shows the sculptured rough-cut model. The rough-cut model has the basic trend of the desired shape. It unevenly approximates the model, and completely contains the final workpiece. This rough-cut model leaves a small amount of material so the system can cut accurately while the finish cutting.
In Fig.10(c), it shows the semi-finish model of the Venus model. The semi-finish model has all the geometric features of the 3D CAD model. However, due to the high cutting speed and the residual stair steps left between consecutive contours, the surface quality of the semi-finish model is not so high.

In Fig.10(d), it shows the final workpiece of the Venus model. From the experimental result, it can be found that the sculptured Venus model has good geometrical conformity to the 3D CAD model. In addition, owing to the low tool feed speed, the cut is made relatively smooth. The tool path, which is perpendicular to the previous one, efficiently eliminates the residual stair steps left in the semi-finish model.

4.2 Experiment of Cutting Human Head Model

The human head model is also sculptured to examine the applicability of the proposed surface sculpture system to fabricate complex 3D shapes. The original human head model and its rough-cut model are shown in Fig.4. It has all the geometrical characteristics for the general 3D shapes, such as convex and concave features, sudden change of curvatures, and smooth surfaces.

![Figure 11: Sculptured Results of Human Head Model](image)

The final workpiece is also sculptured from the raw material block following four steps. The cutting conditions in each step are shown in Table 2. And the sculptured results are shown in Fig.11. From the experimental results shown in Fig.11(c) and (d), it can be found that all the facial features of the CAD model, such as the eyes, ears, and mouth, are well represented in the sculptured workpiece. Moreover, the surface quality of the final
workpiece is smooth and clean. These characteristics agree with the motivation of this research work. The proposed method is suitable and efficient to generate tool path for this surface sculpturing system to sculpture freeform surface.

<table>
<thead>
<tr>
<th></th>
<th>Cutting speed (mm/s)</th>
<th>Current input for cutter (A)</th>
<th>Number of steps</th>
<th>Machining time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convex hull</td>
<td>5</td>
<td>1</td>
<td>427</td>
<td>34</td>
</tr>
<tr>
<td>Rough cut</td>
<td>20</td>
<td>5</td>
<td>1429</td>
<td>10</td>
</tr>
<tr>
<td>Semi-finish cut</td>
<td>10</td>
<td>2.5</td>
<td>9154</td>
<td>73</td>
</tr>
<tr>
<td>Finish cut</td>
<td>5</td>
<td>1.9</td>
<td>19498</td>
<td>258</td>
</tr>
</tbody>
</table>

5. Conclusion

In this paper, a new method to calculate the 3D tool path for machining the sculptured surface is presented. To sculpture a realistic looking model, what the system needs is only an input 3D model. From the input model, the developed CAD system automatically generates the rough-cut model and convex hull, which are suitable for material removal process. Then, according to the tool path generated by the developed CAM system, the 3D work-piece can be sculptured accurately and efficiently. In summary, this proposed method provides an effective solution for surface sculpturing, and has great potential applications in the fields of engineering, arts, fabrication, and so on.

References

(12) Jiang Zhu, Tomohisa Tanaka, Yoshio Saito, Rough machining process and its simulation for
