A Layered 5-axis Machining Method

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Abstract: This paper discusses a method that combines 5-axis NC machining and rapid prototyping for manufacturing complex shape parts. The combination allows NC machining to deal with surfaces in a part that cannot be accessed directly by a 5-axis NC machine. It splits the part into fully accessible subparts (layers), and machines them one by one. The subparts are subsequently joined together to form the complete part.

1. INTRODUCTION

Five-axis numerical controlled (NC) machining is widely used in processing parts with complex geometry. These parts are usually composed of sculptured surfaces (free-form surfaces). The increasing complexity of modern free-form part designs makes the potential benefits of 5-axis milling continuously grow1,2.

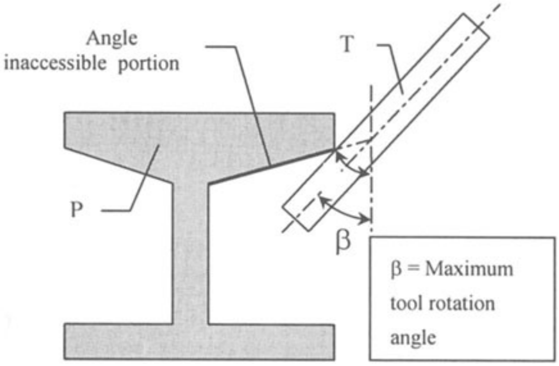

Figure 1. Angle Inaccessibility

Five-axis NC machining can deal with much more complex shape than conventional 3-axis NC machining, and offers many advantages over 3-axis NC machining, such as higher productivity and better machining quality. But there still exist a large class of complex parts, which cannot be machined directly by 5-axis NC machining. A main feature of these parts is that there are some surface portions in the parts are not accessible to a 5-axis machining tool. This inaccessibility usually falls into two cases: *Angle Inaccessibility* and *Gouging Inaccessibility*, which are illustrated in Figure 1 and Figure 2 respectively. Angle inaccessibility is caused by the rotation limitation in the two rotation-axes of a 5-axis NC machine. Gouging Inaccessibility is caused by the interference between the tool and the part. The angle inaccessibility comes from the capability of a machine, and is difficult to deal with, unless we can change the part orientation. However, the gouging inaccessibility is mainly

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caused by the complexity of the surfaces in a part, and can be eliminated by reducing the complexity of the machining portion of the part, just like we do in layered manufacturing.

Layered manufacturing (LM) refers to the fabrication of physical parts layer-by-layer. It involves successively adding raw material, in layers, to create a solid of predefined shape. Some names that have been used to describe LM processes include Desktop Prototyping and Solid Free-form Fabrication. Much of the use of LM is currently restricted to prototyping, i.e. creating a physical part for the purposes of analysing its form, fit or function3,4. LM is a fundamentally different method of fabrication. When creating a part layer-by-layer, the geometric complexity of the part has significantly less impact on the fabrication process (e.g. a simple cube and a sculptured part are equally easy to be manufactured).

At present, it is fairly difficult to manufacture an accurate part fully by layered manufacturing because of the low-order approximation26,27 in LM process, which limits the accuracy at about 0.1mm. However, we can combine 5-axis NC machining with the basic concept of LM, layer-by-layer, to manufacture complex part with NC-level accuracy. For a part with complex shape, we first study its accessibility, and then divide the part into layers. Each of layers is an accessible subpart. After that, we process each layer (subpart) using 5-axis NC machining. Finally, we joint the layers (subparts) into a desired whole part. Because the layer slicing in this method is based on the accessibility, the layer thickness (or the height of the subpart) can be much thicker than that in a traditional LM process, and one layer (subpart) is a 3D shape rather than a 2D shape in other LM.

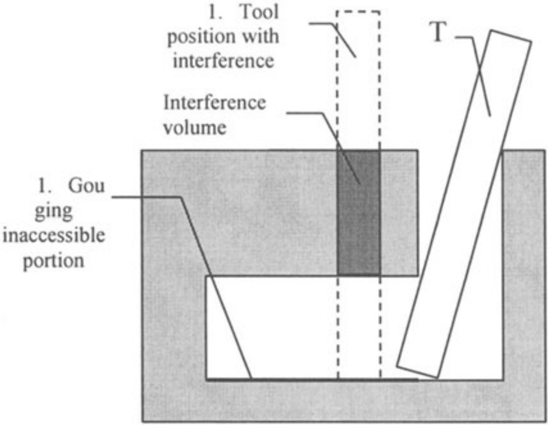


Figure 2. Gouging Inaccessibility

This method is applicable to the parts that can be composed of jointed subparts, such as most of the polymer parts. It can also be exploited in the implementation of Design for Manufacturability (DFM) methodology5.

2. APPROACH OVERVIEW

From a geometry point of view, to implement the combination of 5-axis NC machining and layered manufacturing technology, we need first to detect the accessibility of a given part, and then slice the part into subparts according to the accessibility and generate machining tool path for each subpart.

Because we need also to check the accessibility in generating 5-axis tool paths, we combine the two accessibility checking together and do it only in the tool path generation.

This means that we get both tool paths and accessibility information in the tool path generation phase, and use this information to slice the part. After slicing, not only the given part becomes independent subparts, but also the generated tool paths have been divided into separated portions. We need further to reconstruct these separated tool paths into complete tool paths for each of the subparts.

Our approach can be described as the following steps:

1) Tool trajectory generation The tool path of 5-axis NC machining composes of two parts, the *tool trajectory* and the *tool vector*, as shown in Figure 3. Each point in a tool trajectory is called a *tool position*, which represents a 3D-space position where a specific point in the tool should pass. This specific point usually is the centre of the tool tip surface of a flat end-mill, the centre of the spherical tool tip of a ball end-mill, and so on. *Tool vector* describes the direction of the axis of a tool. A tool trajectory and the tool vectors associated with each point in the trajectory uniquely describe a tool movement in the space, a *tool path.* To practically drive a tool, we still need the tool speed and rotation direction. The determination of tool speed and rotation direction is often the work of the tool path postprocessor. We will not address this topic here.

At this step, we generate the tool trajectories only according to the tolerance, surface type, tool shape, and user preference, do not take the accessibility into consideration.

2) Accessibility checking and tool vector determination To check the accessibility of the tool trajectories, we usually discretize the trajectory curves and check the accessibility of the sample points. By checking the accessibility of the sample points, we classify the trajectories into accessible portion and inaccessible portion. For the accessible portion, we get an accessible tool vector for each sample point in this portion. For the inaccessible portion, if it belongs to gouging inaccessible, they will become accessible after the slicing operation. If it is angle inaccessible, this portion of the part will be unmachinable. The user should change the part orientation, the machining method or change the design.

3) Part slicing and tool path construction After the accessibility checking, we get the gouging inaccessible portions and the interference information. From such information, we determine the slicing positions and slice the part into layers at these positions. At present, our algorithm only divides the part along one direction, usually the upward direction, which is the z-axis direction here.

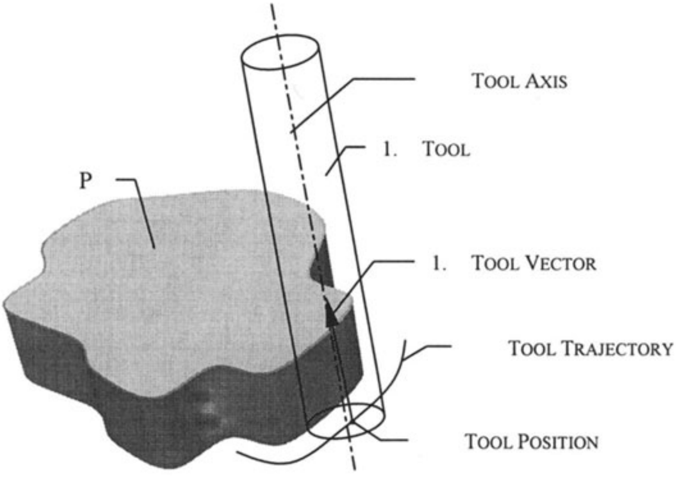


Figure 3. Example of Tool Path

After slicing, each layer becomes an independent subpart, and the tool trajectories are also separated into groups. We reconstruct the corresponding tool trajectories of this subpart into the final tool path, and output it to a *Cutter Location* (CL) file. The tool path generation postprocessor can use this data file to generate NC codes for a specific machine. And then this subpart can be machined as a stand-alone part. The jigs and fixtures are also designed in usual manner. When all the subparts have been completed, they can be jointed together by gluing, welding or other methods.

In our development work, we use ACIS as our geometric function kernel. ACIS is an object-oriented 3D geometric modelling engine from Spatial Technology Inc. It is designed for use as the geometry foundation within virtually any end-user 3D modelling application.

3. TOOL TRAJECTORY GENERATION

The tool path of a part contains two groups, the *roughing* tool path and the *finishing* tool path. A roughing operation is used to remove most of the excess material in the stock, and get an inaccurate profile of the final part. Because the accuracy and surface quality are not important in the rough cutting procedure, we can use large diameter tool to cut at high speed to reduce processing time. A finishing operation is used to cut out the final part. The accuracy and surface quality are key factors in this procedure. For this, we should generate tool trajectories for rough cutting and finishing respectively.

At present, we use ball end-mill and contouring tool path to roughly cut the stock. To generate the roughing tool trajectories, we use constant distance parallel planes to slice the part model to get many contours, and then generate contour-parallel tool trajectories for the part. Such tool trajectory generation can be categorised into planar pocketing tool path generation. Which has been discussed in a lot of literatures [6,7,8,9,10].

To generate finishing tool trajectories for a sculptured surface, there are usually two ways, isoparametric method[11,12,13,14] and non-isoparametric method[15,16,17,18]. The isoparametric method generates tool trajectories in the parametric domain, where each trajectory is created based on one of the two principle parametric directions. The non-isoparametric method generates tool trajectories in Cartesian space. We use the first method.

In generating roughing tool trajectories, we need to calculate the step-over between two adjacent trajectories, which is related to the tool shape, tool size, tool position, allowable tolerance, and the surface shape. Such calculation has been discussed in quite a few papers22,23,24,25.

4. ACCESSIBILITY CHECKING AND LAYER SLICING

4.1 Accessibility checking

In the tool trajectory generation, the calculation of step-over is tightly related to the direction of the tool vector. The tool vector at a tool position is determined by the machining convention of a specific feature and the accessibility of the tool at this position. Usually in 5-axis sculpture surface machining, the tool vector is mainly determined by the accessibility. The accessibility is checked at each point on the tool trajectories when we generate the trajectories2,21,22,23,24,25.

In our approach, the accessibility checking is also used to determine the slicing position for dividing the part. So, when we keep the accessibility information of each point. The information includes the type of accessibility (accessible, angle inaccessible and gouging inaccessible), and the interference position if the point is inaccessible.

4.2 Layer slicing

To slice a part into layers according to its accessibility, we got three approaches:

1) Planar contour slicing

This approach uses parallel horizontal planes to slice the part from bottom to top just as that in the roughing tool trajectory generation to get intersection contours, and then, check the accessibility of these contours. According to the accessibility, it slices the part into accessible subparts (layers). This approach is easy and fast, but it cannot deal with flat surfaces illustrated in Figure 4. As shown in the figure, this approach only checks the accessibility of the points on the intersection contours, but do not check the accessibility of the points on surface ***S***. As a result, it may generate inaccessible subparts.

2) Direct trajectory checking

This approach checks the accessibility of each generated tool trajectory to decide the slicing position. It will solve the problem in the first approach, but still has disadvantage. We know that the accessibility of one tool trajectory is always affected by the layer slicing, i.e., if a trajectory is not accessible, it can become accessible after part slicing. So, the accessibility of all the trajectories will couple together, and then lead to lengthy and low efficient slicing algorithm.

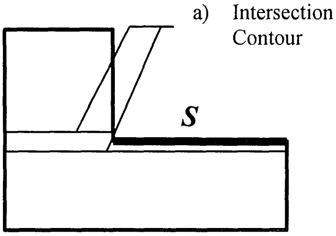
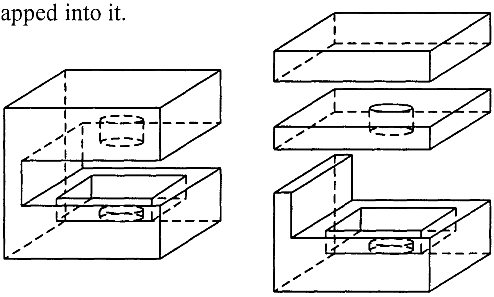


Figure 4. Surface S is ignored

3) Virtual layer Mapping Method (VLM)

This approach combines the basic ideas of the above two. It still checks the accessibility of the tool trajectories to decide the slicing position, but in a different way from the direct trajectory checking method. In this approach, we divide the vertical part size into a few intervals, which can be taken as the vertical position of some *virtual layers*. In other words, we virtually slice the given part into a few layers. Then, we split the tool trajectories into segments according to the virtual layer position; each segment belongs to only one virtual layer. This is called *mapping*. After the tool trajectories are mapped into the virtual layers, we check the accessibility of the virtual layers form bottom to top to decide the slicing position. The accessibility of a virtual layer is represented by the accessibility of all the trajectory segments mapped into it.



(a) Given part (b) Sliced layers (subparts)

Figure 5. Example of VLM algorithm

We use the first approach of the above to do the layer slicing for the roughing procedure, and can get the first slicing result. In the approach, we directly use the roughing tool trajectories, no longer to generate more intersect contours. Then we use the third approach, VLM, to do the slicing for the finishing procedure. In this process, we should use the slicing result of the roughing procedure, because it can significantly reduce the processing time. Figure 5 is an example result of VLM method, and the following is the algorithms for VLM method:

Slice a given part using VLM method

```
Synopsis: VLMSlicing ( P, LA )
Input:    P     A part or subpart to be processed
Output:   LA    An array to store the sliced layers
Begin
Map tool trajectories into virtual layers
Let iStart be the start VL index of P
Let nL be the end VL index of P
Do
    Res=FindInaccPos(P, iStart, iEnd, nL)
    If result Res is accessible, then
        Construct a layer from iStart to iEnd, and mark it as accessible
        Save this layer into LA
        Return
    Endif
    If result Res is inaccessible, then
        If iEnd>iStart, then
            Construct a layer from iStart to iEnd-1
            Mark it as accessible and save it into LA
        Endif
        Construct a layer from iEnd to iEnd
        Mark it as inaccessible and save it into LA
    Endif
    iStart=iEnd+1
While iEnd<nL
Merge the adjacent inaccessible layers in LA
End
```

Find the inaccessible VL index

```
Synopsis: FindInaccPos ( P, iStart, iEnd, nL )
Input:    P         A part or subpart to be processed
          iStart    The start VL index of P
          nL        The end VL index of P
Output:   iEnd      The inaccessible VL index, and it will be the end VL index of
                    the new layer.
Begin
    iEnd = nL
    i = iStart
    Do while i<=iEnd
        Check the accessibility of virtual layer i in P
        If VL i is inaccessible, then
                Get the index l of the VL in which the lowest interference point lies
            If l<=i, then
                iEnd=i
                Return "layer is inaccessible"
            Endif
```

```
            iEnd=l-1
            i=i-1
            Remove the portion of P above VL iEnd
        Endif
        If i=iEnd and l>iEnd, then
            iEnd=i
            Return "layer is inaccessible"
        Endif
        Increase i
    End do
    Return "layer is accessible"
End
```

5. TOOL PATH CONSTRUCTION

After slicing, each layer becomes a subpart and the tool path is also separated into segments. We reconstruct the tool path segments for each subpart to generate the final tool paths, and output them into a *Cutter Location* (CL) file. The tool path postprocessor can use this data file to verify the tool paths or generate NC codes for a specific machine.

6. CONCLUSIONS

This paper presents a machining method that combines 5-axis NC machining and rapid prototyping for manufacturing complex shape parts. The method analyzes the accessibility of a given part first, if some portion of the part is not accessible, it split the part into some subparts that are accessible, and then generates tool paths for these subparts respectively. A Virtual Layer Mapping (VLM) method for part splitting is discussed in detail.

The method in this paper is applicable to the parts that can be composed of jointed subparts, and is also useful to the implementation of Design for Manufacturability (DFM) methodology.

The method in this paper only splits a part in one direction. To split the part in arbitrary direction and based on machining features is our next stage of work.

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