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A multipoint method for 5-axis machining of triangulated surface models

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HIGHLIGHTS

- We give a method for positioning a radiused end milled cutter on an STL surface.
- Tool is positioned to have two points of contact.
- We give simulation and machining results.

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ABSTRACT

In this paper, we present a multipoint machining method for the 5-axis machining of triangulated surfaces with radiused end mills. The main idea is to drop the tool onto the surface to find an initial point of contact, and then rotate the tool while maintaining tangency with this initial point of contact until a second point of contact is found. The proposed procedure ensures a gouge-free position with two points of contact, allowing for a larger side step than a single point of contact method. This proof of concept paper presents the mathematical equations that must be solved to position the tool with two points of contacts on an STL surface. The paper further verifies the concept with simulations and presents experimental results to confirm the simulations.

1. Introduction

The Stereo Lithography (STL) format describes engineering parts as a set of triangles and includes the vertices and normal of the facets. Industry users like this format because it simplifies data transfer, input into analysis algorithms, creation of 3D printed models, algorithms such as tool path planning and positioning and provides desired accuracy in parts made using triangulated models [1–9]. Most Computer-Aided Design (CAD) packages can output part design in the STL format. Furthermore, most Computer Aided Machining (CAM) packages can accept the STL format as input for tool path planning [1–9].

The process of machining a triangulated model within a CAM package consists of selecting a tool; identifying a tool path footprint; and determining the tool position and orientation.

The three types of tools commonly used in industry are ball-nosed end mill; flat end mill and radius end mill. A ball-nosed end mill has a simple geometry that lends itself to easy calculation of tool positioning. Ball-nosed end mills are commonly used for machining dies, molds and precision parts with curved surfaces. The drawback in using ball-nose end mills is that the cutting properties at the bottom of the tool are poor [1,5]. Flat end mills have good cutting properties along the entire edge; however, tool path planning presents a challenge especially at the apex of a curved section of the part and in positioning of the tool for 5-axis machining of curved surfaces [2,4–8]. Radius end mills are a generalization of both ball-nose and flat end mills. Although positioning the radius end mill for 5-axis machining is a challenging task, it provides a smooth surface finish much like a ball-nose end mill and has excellent cutting capability along its entire cutting edge [1,3,9–15].

A radiused end mill can be represented as a torus, the rotation of a circle of radius R_i around a circle of radius R_O. Fig. 1 shows a cross-section of a radius end mill. For our purposes, we are only interested in the cutting edges of the circle (shown by the dark arcs on the circles in Fig. 1(b)) and we will also think of the tool as having a flat bottom (shown by the dark, straight line across the bottom). Note if $R_i = 0$ then the radius end mill models a flat end mill, whereas if $R_O = 0$ it models a ball-nose end mill. In this paper,

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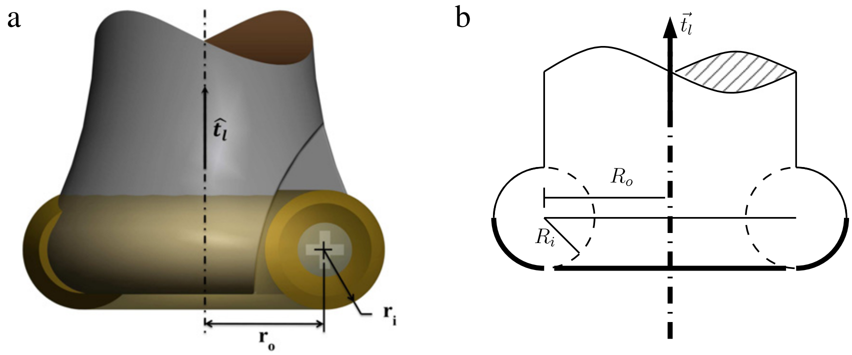

Fig. 1. (a) A radiused end mill cutter. (b) A cross-section of a radiused end mill cutter showing the cutting edges (in dark).

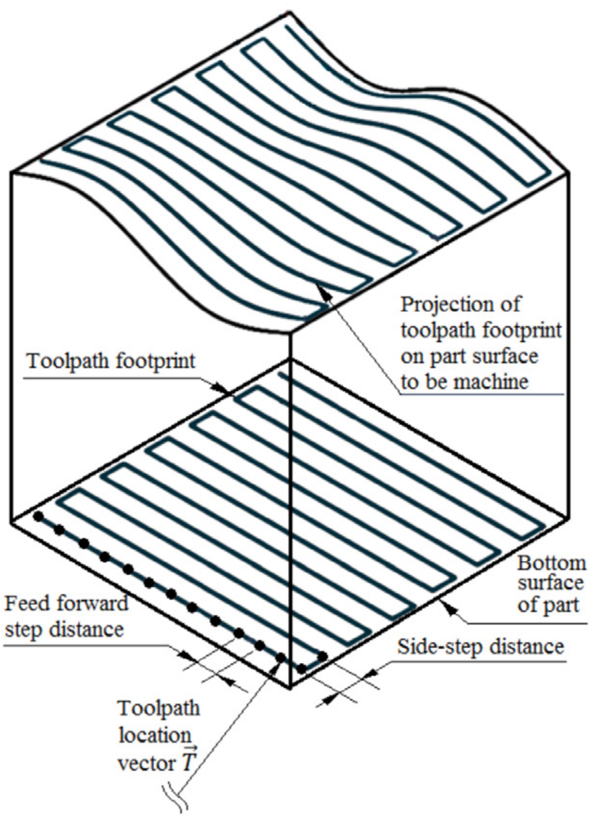

Fig. 2. The zigzag tool path.

we propose a method for determination of exact positioning of a radiused end milled tool on the curved surface represented in the STL format for 5-axis machining applications.

For identifying a tool path footprint in a region, typically a polyhedron to be machined is identified by the user. This region is projected onto a plane perpendicular to the tool axis (typically the z-axis). A pattern that describes the motion of the tool is developed within this plane. The pattern takes into account the surface finish required. Typical footprints are the zigzag pattern or the contour pattern. The focus of our work is tool positioning and so for simplicity we used the zigzag pattern within a rectangular region. The zigzag footprint is specified by two parameters, namely the feed forward step, and the side step as shown in Fig. 2.

Once the footprint of the tool is defined it is discretized into small steps and at each point a gouge-free tool position is generated. The tool path comprises of the tool moving between consecutive tool positions along the tool path footprint. This method will also be used in our work.

In this paper, a 5-axis method of positioning a radius end mill tangential to two points on a triangulated surface is presented. As a proof of concept, we generate tool paths for two different type of convex and concave STL surfaces that have been successfully machined on a DMU-80P 5-axis machine. The idea of our method is at each tool position, drop a radiused end mill tool onto the surface to find one point of contact P as shown in Fig. 4(a). The tool and the STL surface will touch tangentially at this point of contact (although "tangentially" is a somewhat loose term if the point of contact is on an edge or vertex of the STL surface). The point of contact will lie on a *pseudo-insert* of the tool, a circular cross-section of the torus shown in Fig. 4(b). We then rotate the tool around the vector through the center of this pseudo-insert and perpendicular to this pseudo-insert. This rotation will maintain the tangency between the tool and the STL surface at P. We rotate the tool until we find a second point of contact S, which will also be tangent to the STL surface. The result is a tool position that does not gouge the surface and is in contact with the STL surface at two points. The advantage of such a multipoint of contact tool positioning method is that it allows us to have a larger side step.

2. Literature review

3-axis tool positioning methods for triangulated surfaces have been extensively explored in the literature [1–3]. The methods typically comprise of varying ways of dropping a tool along a selected tool axis direction until tool touches the part. The tool center at this point of contact becomes part of the tool path [1–3].

5-axis methods have also been used to machine parametric curved surfaces. By rotating the tool, researchers try to orient the tool so that more of the cutting surface is closer to the design surface. For example, the Principle Axis Method (PAM) of Rao et al. [10] determines the principle curvatures of the parametric surface at the point where the tool has to be positioned and uses the minimum curvature and its direction to tilt the tool and bring it into close proximity of the design surface. Gouge detection is done as a secondary step. With Multipoint Methods (MPM), the gouge checking is integrated with the positioning and inclination process [12,13]. In this method the tool is positioned at a point on a smooth, parametric surface and is inclined along the feed direction until it touches a second point on the parametric surface. The determination of the second point of contact presents computational challenges that have been addressed in the literature. The key advantage of these multipoint methods is that the 5-axis tool paths result in a wide strip that is within the specified machining tolerance and consequently the number of passes required to machine the entire surface is reduced significantly. For some surfaces the machining time can be reduced by as much as 80% in comparison to 3-axis methods [13]. However, these methods are aimed at machining smooth surfaces and are inappropriate for machining triangulated surfaces.