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Operation decomposition for freeform surface features in process planning

Ganping Sun[a,*], Carlo H. Sequin[b], Paul K. Wright[a]

[a]Mechanical Engineering Department, University of California at Berkeley, Berkeley, CA 94720, USA
[b]Computer Science Department, University of California at Berkeley, Berkeley, CA 94720, USA

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Abstract

Machining operations for freeform surface features usually include roughing, finishing for the bottom surface, tapering, and corner rounding. Strategies and algorithms to decompose the overall task into these operations are presented. The decomposition aims at minimizing machining time within the constraints of the specified surface roughness and tolerance, and machine tool safety. The roughing operation can be further decomposed into sub-operations for multiple tools. There are two strategies to decompose the finishing operation into sub-operations: one is based on multiple tools and another is based on multiple tool path patterns. The approaches to select the optimal decomposition values (tool diameters, surface slopes) that minimize machining time are presented. These algorithms are being integrated into a rapid-prototyping service for web-based machining. Design for manufacturability and maximizing process automation are the key priorities in process planning and operation decomposition. © 2001 Published by Elsevier Science Ltd.

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1. Introduction

Freeform surfaces are often used in the designs of electronic appliances, automobiles, and airplanes. They allow designers describe part geometries with functional and aesthetic goals in a convenient manner. In the past decade, freeform surface design and machining has attracted much attention from both academic researchers and industry practitioners. Recent research work in this field has mostly focused on feature recognition and tool path planning.

Feature-based CAD/CAM [5,8,9,12,16] also aims to reduce the interactions between designers and fabricators and to automate process planning. In feature based milling, a part is described as a starting volume or stock and a set of features, representing the volumes removed by machining. Integration of manufacturing knowledge into the design tool allow to check the manufacturability of each feature at the design stage. Thus feature-based CAD can reduce the complexity of operation decomposition, process planning time, and minimize the number of design/fabricator iterations.

The purpose of tool path planning is to generate gouge-free tool paths for a desired geometry, with a certain tool and given cutting parameters. In order to meet given requirements on surface finish while minimizing machining time, the tool path pattern should cover the surface as uniformly as possibly. Recently, much research concerns such algorithms to define optimal tool paths for various tools, part geometries, and machines [1–4,7,13].

Most commercial CAD/CAM systems have the capability to design and machine some kinds of freeform surface features. However, process planning and operation decomposition still are major challenges. Some of the problems encountered include:

- Freeform surface features are often machined in multiple operations: roughing, finishing, tapering, and corner rounding. These features have to be decomposed into more cohesive, lower level operations before they can be processed by the tool path generator.
- Tool and cutting parameter selections are critical to both machining quality and cutting efficiency. A large tool may yield high cutting efficiency but cannot clean up corners in a freeform feature, while a small tool can cover all areas, but at a low cutting efficiency. A combination of tools of different sizes is thus typically used. During process planning, the tool and cutting parameters for each operation must be selected to meet design specifications (roughness and tolerance) and maintain machine tool safety, while minimizing machining time.
- Not all manufacturability problems can been detected at the design stage. Some are related to the chosen tools and

* Corresponding author. Tel.: +1-510-643-6546; fax: +1-510-643-6547.
E-mail address: ganping@kingkong.me.berkeley.edu (G. Sun).

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their operational parameters, which are only selected at the process planning stage. For example, designers often design pockets that are narrower and deeper than what can be reached with available tools.

Operation decomposition builds a linkage between the feature recognizer and the tool path planner. Its separate functions include:

- Decomposing a feature into a list of machinable operations (roughing, finishing, tapering, and corner rounding)
- Decomposing the roughing operation into sub-operations for multiple tools
- Decomposing the finishing operation into sub-operations for multiple tools and multiple tool path patterns
- Selecting the optimal decomposition values (tool diameters, surface slopes) that minimize overall machining time

After operation decomposition, a list of individual operations each with their local geometries, chosen tools, and applicable type of tool path patterns are forwarded to the tool path planner. The prime concerns are full automation and (almost) guaranteed manufacturability in order to reduce the interaction between designers and manufacturers.

In this paper, strategies and algorithms to automatically decompose a freeform surface feature into a list of feasible operations are presented. The features considered are 3-axis milling features, accessible from a predefined direction. They include 2.5D extruded pocket geometries which may have a freeform surface.

2. Technical definitions

2.1. Freeform surface features

In the context of 3-axis milling, a freeform surface feature can be represented by '3D bottom surfaces' and '2D boundary contours'. The latter may carry some attributes such as: tapered angles (draft angles), open conditions, corner radii, top and bottom rim radii [11]. The 3D freeform surfaces defining the bottom of the pocket can be a single patch, or composed of multiple patches, which must be connected together with at least G0 continuity.

The 2D boundary contours defining each pocket can consist of one outside contour and may have one or more inside contours (islands). In some cases, such as injection molds and sheet metal dies, side walls are often tapered with a draft angle from 1 to 5° and rounded with some radius at the top edges. A designer also can assign radii for the sharp corners in the boundaries and for the top and bottom rim of a pocket. For representation simplicity, these various radii are stored as attributes of the corresponding contour element, not as actual geometry. Some parts of the boundaries may be 'open', i.e. not limited by side walls. Tools can go across open boundaries without any obstructions (unconstrained) or with the constraints of the geometry of the adjacent pockets (constrained).

Fig. 1 shows a typical freeform surface feature with a generic 'bathtub' like appearance. This general definition of freeform surface features can cover most application cases.

2.2. Manufacturability problems for freeform surface features

By design, all surface points in a 3-axis milling feature are visible from one direction, due to the limitations of the tool size and length, not every point may be reachable by an available tool. Examples include places with small curvature radius (Fig. 2(a)), sharp creases (Fig. 2(b)), deep regions (Fig. 2(c)) in the bottom surface, or small corner radii (Fig. 2(d)), and narrow channels (Fig. 2(e)) in the pocket contour. As a result, some areas of the surfaces cannot be machined due to potential tool gouges and interferences. During operation decompositions, tool selections are constrained by minimal curvature, corner radii, minimal channel widths, or maximal depths. If no proper tool can be found for an intended operation, that operation is not machinable. Another possible failure comes from the cutting parameters. If no proper parameters can be found to meet the roughness and tolerance requirements, the operation also must be rejected. Any such failures must be returned to the process planner for the selection of another

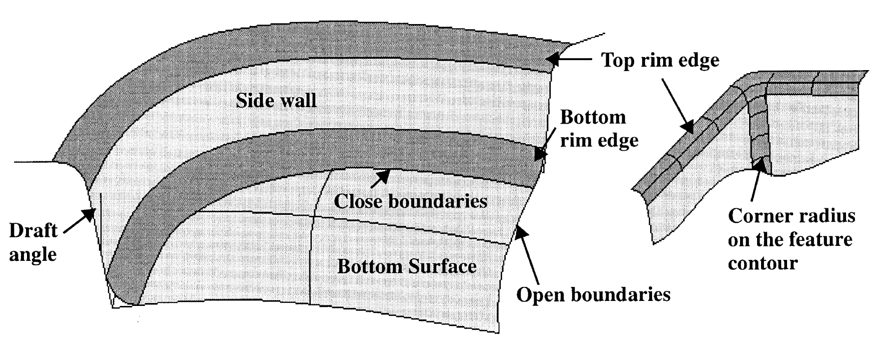

Fig. 1. A typical freeform surface feature.