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To cite this version:

Soumiya Bendjebla, Na Cai, Nabil Anwer, Sylvain Lavernhe, Charyar Mehdi-Souzani. Freeform Machining Features: New Concepts and Classification. CIRP ICME'17. 11th CIRP Conference on Intelligent Computation in Manufacturing Engineering, Jul 2017, Gulf of Naples, Italy. 10.1016/j.procir.2017.12.248 . hal-01620490

HAL Id: hal-01620490

https://hal.science/hal-01620490v1

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Procedia CIRP 67 (2018) 482 – 487

www.elsevier.com/locate/procedia

11th CIRP Conference on Intelligent Computation in Manufacturing Engineering, CIRP ICME '17

Freeform machining features: new concepts and classification

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Abstract

During the last decades, many researches and applications have been conducted on machining features modeling and classification. Although several approaches have been used in the domain of Computer-Aided Process Planning (CAPP), the consideration of freeform shapes has not been well explored at present. This paper aims to provide an up-to-date review of machining features and its conformance with STEP-NC (STEP compliant Numerical Control). A new method based on discrete shape representation, differential geometry and graph theory is developed for freeform machining feature characterization and classification. The effectiveness of the proposed method is demonstrated through an example of a blade part.

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Peer-review under responsibility of the scientific committee of the 11th CIRP Conference on Intelligent Computation in Manufacturing Engineering

Keywords: Machining feature; Freeform; Feature classification; STEP-NC.

1. Introduction

In the context of Digital Mock-up and Digital Chain, Feature Technology has become the most popular way of product modelling that devises models with high-level semantics. Such feature models can be seen from different perspectives: design, assembly, machining, etc. The presented paper focuses on machining features. A huge amount of research has been developed on machining feature modeling and classification, but research on freeform shapes is still limited. Therefore, there is an urgent need to extend these approaches, and methods for products with freeform shapes. However, the intuitive parameterization and classification of freeform shaped features is difficult since freeform surfaces are controlled by multiple surfaces and a large number of control points that generally lies outside the surface. To solve the problem, a new method of freeform machining feature definition and classification based on decomposition and composition operations is proposed in this paper. The freeform surface is decomposed into set of points and meshed with triangles. Then by segmentation, the points and triangles are composed into sub-surfaces with ten surface types based on shape descriptors, and recognized as the five pre-defined freeform machining features using Attributed Adjacency Graph (AAG). The five defined freeform machining features are in correspondence with the STEP-NC features. The paper is organized as follows. Section 2 highlights the key points of feature technology in design and manufacturing. Section 3 is devoted to the literature review of machining features considering freeform shapes. The proposed method is discussed in Section 4. A case study is then presented in Section 5. Finally, Section 6 draws conclusions.

2. Feature Technology in Design and Manufacturing

Feature is a concept that was first used as modeling elements in CAx systems for representations of both qualitative and quantitative data related to product development process in late 70s [1]. It is considered as the most natural form of communication between the different experts in a project [2]. Ever since then, feature technology has played a key role for knowledge specification and integration in the context of Product Lifecycle Management (PLM).

2.1. Feature modeling

Despite 40 years' efforts, experts still have not reached a consensus on what feature is. Each expert community has proposed their own definition for the word 'feature' depending on their specific tasks. Some of the proposed definitions are listed in Table 1. Sanfilippo and Borgo [3] also reviewed the

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doi:10.1016/j.procir.2017.12.248

concept of feature, and feature based approaches developed in previous research in their survey paper.

Table 1. Some feature definitions.

Feature definitions
"A feature is a region of interest on the surface of a part". [4]
"A physical entity that makes up some physical part". [1]
"The characteristics of a product that result from design". [5]
"Features are defined as geometric and topological patterns of interest in a part model and which represent high level entities useful in part analysis". [6]
"A feature is generally composed by geometrical data associated with a semantic". [7]

Generally, features can be seen from different perspectives: functional, design and manufacturing. They interpret the same feature in different quantity of detail: *functional feature* is described by its functional characteristics that specify its use in a product; *Design feature* describes the shape in geometric terms, but makes the function implicit; *Manufacturing feature* describes explicitly the production method, beside the shape, and the functions expressed implicitly.

Feature Modelling is the representation of a part in terms of features. There are mainly two approaches to create features: design by features and feature recognition. In design by features approach, the designer is provided with a feature library stored with features primitives and create a product model by operators such as add, delete and modify. However, there is a limitation of this method in the context of manufacturing since there is no one to one mapping relationship between design feature and manufacturing features. Feature recognition is the process of identifying and extracting manufacturing features from the part geometry. The extracted features are then compared to pre-defined features.

2.2. Feature Information Model

In an effort to standardize product data, and develop management and data sharing over the PLM cycle, the international community has been developing a set of standards ISO 10303, well known as STEP (STandard for the Exchange of Product model data). STEP is a neutral exchange format of CAD data that interprets both product structure and geometric information, throughout the lifecycle of a product without using translation modules between computer systems. Feature-based modeling is expressed with AP (Application Protocol) 224, which specifies recurrent shapes used in manufacturing scenarios.

Nowadays, a new ISO-14649 standard often known as STEP-NC is being developed. It is considered as an extension of STEP that realizes a connection between CAD/CAM and CNC machines, and standardizes the data formats used at the machine level [8-9]. STEP-NC specifies machining processes, using an object-oriented data model constructed by many entities such as: machining workingstep, machining operation and manufacturing feature. Through entity's inheritance and attributes, STEP NC associates features to the operations, and the tools required for their manufacturing.

Both STEP and STEP-NC, through their (AP)s, are used for feature-based product modelling.

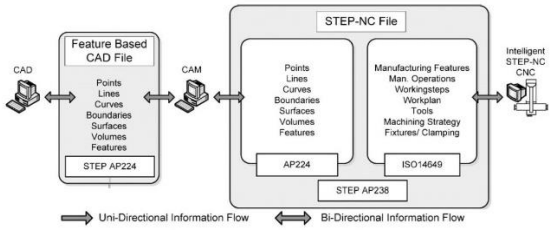

Fig. 1. Information flow in a STEP-NC CAD/CAM/CNC chain. [10]

The feature-based CAD model integrates both geometrical primitives, and features. The data structures of such CAD model is defined by the Application Protocol 224 of STEP standard (ISO10303- 224). The model definition is then extended with manufacturing information (manufacturing operations, manufacturing features, tools and machining strategies), defined in ISO 14694. Both geometry (ISO10303-224) and manufacturing information ISO 14694 are stored in an AP238 file. Since it contains a complete product information, the STEP NC file enhances a bi-directional information flow (Fig. 1), and covers the entire chain between CAD/CAM and CNC machines.

3. Machining Features

3.1. Definition

Almost all CAPP systems are based on machining features, or require machining features to be the input data [11]. Therefore, many works have been developed to characterize machining features that have been described as a volume, a set of surfaces, or a set-information feature associated to geometry.

Machining feature can be defined as a set of surfaces of the part that can be machined by a single cutter in the same setup [12-14], or modelled through manufacturing-oriented classes. In the context of forging die machining, Tapie et al. [7] provides a generic machining feature model which relies on a Unified Model Language (UML). Four main classes including surface class, topology class, technology class and machining process class are defined. Zirmi [15] proposes a machining feature model for aircraft structural parts. The machining features is defined through its geometrical, and technological characteristics, with five classes.

Gao and Shah [16] represent the machining feature as a volumetric feature that can be removed by a single machining operation in a single set-up. Liu and Wang [17] indicates that different from design features, each machining feature as a standard shape holds a set of coupled information about how to fabricate itself. Shah and Mäntylä [1] describes machining features as a set of geometrical elements, which corresponds to a certain machining process. These elements can be used to generate the appropriate machining means that can help creating the concerned geometry.

There are many different definitions about machining feature, depending on different activities of product manufacturing process. We can cite the definition given by Bourdet et al. [18]: A machining feature is a geometric shape and a set of specifications for which a machining process is known. The machining feature is chosen according to two conditions: 1) Existence of the machining process for the

machining feature; 2) Independence from other machining features.

In order to facilitate the characterization of feature data and generation of process plans, features are divided into different classes with similar attributes like geometry and topology, etc. For more generality and applicability, the classification of manufacturing features is standardized by the international community through STEP standards.

3.2. STEP NC Features

Manufacturing features, called STEP-NC features, are defined in ISO 14649 [8-9]. Manufacturing feature is the super-type of all manufacturing features (Fig. 2). When connecting between adjacent features, it is a transition feature. When considering freeform, it is called region. When considering 2½D-manufacturing, manufacturing feature is divided into replicate feature, compound feature, turning and machining feature.

Manufacturing feature are defined by a set of parameters: ID, workpiece, operations, placement and depth. Furthermore, for each feature type, a feature template with specific attributes is defined, as shown in Fig. 2. For instance, for planar face, four attributes are specified: removal direction, course of travel, removal boundary and bosses.

3.3. Freeform Machining Features

In almost all current feature modeling systems, only regular shapes, represented by simple geometric primitives, can be used [19]. Freeform features are rarely used due to their questionable and difficult definition and unintuitive manipulation [20]. Fontana and Giannini, et al. [21] proposed a classification of free form features based on the topological and morphological characteristics associated to the deformation functions used to create the features.

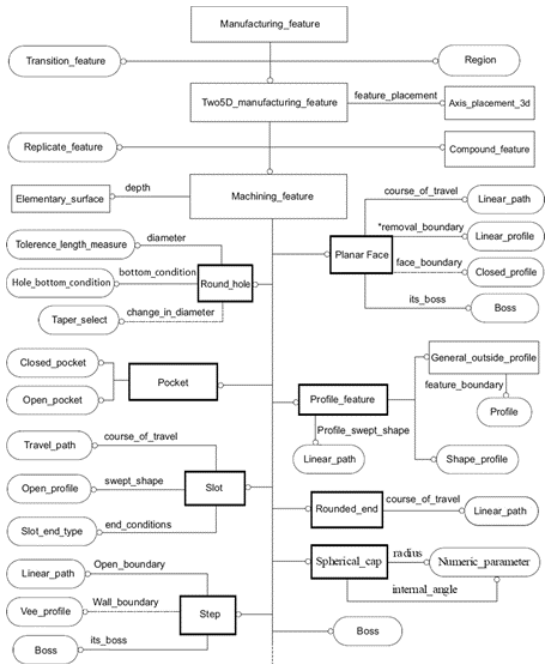

Fig. 2. STEP-NC Features. [8]

Nyirenda et al. [22] introduced a multi-level representation for a freeform surface feature, which facilitates the selection of feature entities, definition of new curve parameters with specific properties to create model variants.

Freeform surface features are often machined in multiple operations like roughing, finishing, taping and corner rounding [23]. In order to balance both machining quality and cutting efficiency, a combination of tools of different sizes is used. Therefore, a freeform surface is always partitioned into regions which are machined by suitable operations and tools, respectively. Chen et al. [24] divided a complex freeform surface into easy-to-machine surfaces patches and identified the favorable machining set-up for each patch. Finally, a 3-axis CNC tool path for each patch was therefore generated. Giri et al. [25] divided freeform surfaces into distinct zones of similar curvature and chose the maximum or minimum curvature loci of the surface as master cutter path for tool path calculation. Roman et al. used fuzzy C-means method [26] and k-means clustering method [27] for freeform surface partitioning. Tuong and Pokorny [28] subdivided a freeform surface into convex, concave and saddle regions based on surface curvatures. Then these regions can be machined separately using different kinds and sizes of cutting tool for reducing machining time. In the proposed multi-perspective dynamic feature concept of Liu et al. [29], changes across the surface, which means dividing freeform surface into different regions for suitable machining method selection, were also considered.

In most previous research, freeform surfaces are manipulated by control points lying outside the surfaces, which is not intuitive and predictable. Moreover, freeform machining features are not specifically defined and classified. In this paper, a new method of freeform machining feature definition and classification based on decomposition and composition is proposed. Freeform surface is decomposed into a set of points and triangular meshes so that the freeform surface can be intuitively manipulated by these points which lie on the surface. By defining shape descriptor, points and triangles are composed together into ten basic surface types and identified as freeform machining features which are in correspondence with the STEP-NC features using a graph-based approach.

4. Definition and Classification of Freeform Machining Features

A freeform machining feature is defined as a freeform geometric shape, which are usally represented by Bézier surfaces, B-Spline surfaces and Non-Uniform Rational B-Spline (NURBS) surfaces [30] and a set of specifications for which a machining process is known. It also has to be covered by the existence and independence conditions. Based on decomposition and composition, freeform machining features are recognized and classified into five typical features by the following steps. Our steps proceed very much in the same way as the approach used by Xu et al. [31].

4.1. Tessellation and Surface Descriptor Definition

Regular shaped features are represented by simple geometric primitives like planes and cylinders which are specified by simple and intuitive parameters, e.g. height and radius of cylindrical protrusion. However, freeform features are mostly described by parametric representations. These

representations use control points that are generally lies outside the surface for controlling the shapes. Manipulation of these control points is not intuitive and require solid mathematical knowledges. Therefore, the intuitive parameterization and classification of freeform shaped features is much more difficult.

To solve the problem, in this paper a freeform surface is sampled by points and the underlying topology is reconstructed using triangular meshes. In this way, freeform feature can be represented by discrete topological structures: vertices (V), edges (E) and faces (F), denoted as:

$$< FF > ::= < V > \cup < E > \cup < F > \quad (1)$$

Then the parameterization of freeform feature (P_{FF}) can be described by discrete differential geometry parameters: the unit normal vector at the considered vertex (n_V), the unit direction vector of edge (d_E) and the unit normal vector of facet (n_F), denoted as:

$$< P_{FF} > ::= < n_V > \cup < d_E > \cup < n_F > \quad (2)$$

In order to effectively define and describe the freeform shape, a reasonable and comprehensive shape descriptor (SD_{FF}) calculated by the basic parameters of discrete differential geometry is proposed [32]. It is composed of three specific parts: edge-xity (m), shape index (s) and curvedness (c), denoted as:

$$< SD_{FF} > ::= < m > \cup < c > \cup < s > \quad (3)$$

Edge-xity, is a measure of an edge's concavity/convexity, and it can be used to decide whether an edge is an obviously sharp edge or not. For a shared edge of two freeform surfaces (E), it is discretized into many sub-edges (e), and each sub-edge can be approximated as a straight line. The edge-xity (m_i) of the ith sub-edge (e_i) is calculated as:

$$m_i = (n_{F_1} \times n_{F_2}).d_{e_i} \quad (4)$$

where, n_{F1}, n_{F2} are the unit normal vectors of the two adjacent facets F_1 and F_2, respectively, and d_{e_i} is the unit direction vector of the ith sub-edge e_i.

Then, the edge-xity of the shared edge E is calculated as a weighted sum of the edge-xities of all the composed sub-edges as:

$$m = \sum_{i=0}^{Q} \omega_i . m_i \quad (5)$$

where, ω_i is the weight of the edge-xity of the ith sub-edge, and Q is the total number of the composed sub-edges.

Shape index, ranged [−1, 1], measures the local surface type at each vertex of the mesh. It is calculated by the principle curvatures as:

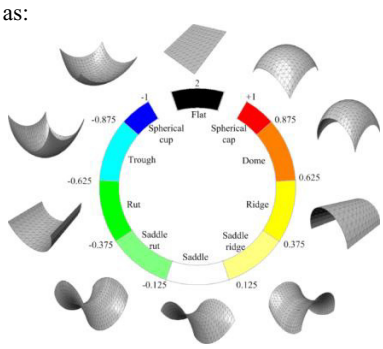

Fig. 3. Surface types, shape index scales, and colour scales.

$$s = \frac{-2}{\pi} \arctan\left(\frac{K_1 + K_2}{K_1 - K_2}\right) \quad (6)$$

where, K_1 and K_2 are the maximum principal curvature and the minimum principal curvature respectively.

Curvedness, as a complementary parameter to the shape index, specifies the amount or intensity of the surface curvatures.

$$c = \frac{\sqrt{K_1^2 + K_2^2}}{2} \quad (7)$$

4.2. Segmentation

The segmentation is the partition of vertices such that each region consists of connected vertices, with the same characteristics. Based on shape index and curvedness, the segmentation is realized mainly in three steps: discrete shape recognition, vertex clustering and connected region generation [33].

First, ten types of basic surface types are defined according to the value of shape index, as shown in Fig.3. In addition, the curvedness is used to evaluate the intensity of the surface curvature.

Secondly, the sharp edge vertices and vertices with high curvature are identified according to the value of curvedness so that boundaries are formed by these detected vertices. Then the untagged vertices, except the boundary ones, are clustered into the previously defined ten basic surface types.

Finally, the connected regions in each vertex cluster are merged and refined so that the freeform surface is segmented into different sub-surfaces accordingly.

4.3. Recognition & Classification:

In this section, Freeform Machining Features (FMF) are recognized and classified into five classes based on an Attribute Adjacency Gaph approach (AAG). AAG representing the B-Rep of the part (denoted as G), and a concave adjacency graph obtained from AAG by deleting convex edges and removing isolated nodes (denoted as G+) are used.

Graph nodes represent faces of the workpiece while edges correspond to concave and convex edges of the workpiece. The concavity/convexity of an edge is measured through its edge-xity m. The concave edge is the one whose edge-xity $m < 0$; whereas a convex edge is the one whose edge-xity $m > 0$.

As mentioned before, we adopt here the method developed in [31], where five generic classes for form feature classification and recognition are used (passage, depression, k-protrusion, k-slot, compound feature) as proposed in [34]. Here, we propose to extend this method to recognize freeform features.

Thus, a process planning oriented subgraph analysis is used. The subgraph of the extracted features allows a classification. In addition, a value adjacency graph has been developed to extend the AAG approach using the edge-xity m as a weight for the edge. The subsequent feature extraction algorithms can exploit and match the graph properties of each category. Based on [34], we propose these five classes considering freeform surfaces.

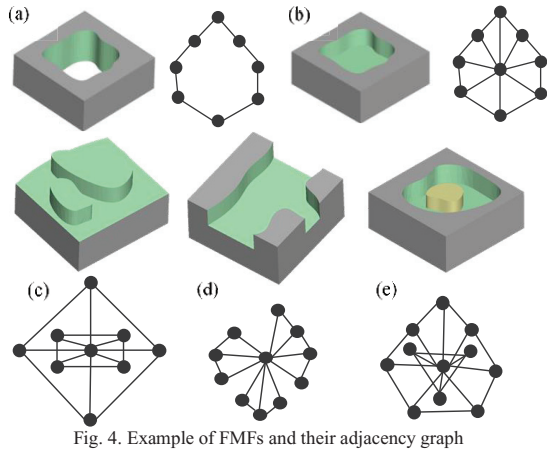

Fig. 4. Example of FMFs and their adjacency graph
(a) Freeform Passage; (b) Freeform Depression
(c) Freeform K-protrusion; (d) Freeform K-slot; (e) Freeform Compound class.

- *Freeform Passage.* A freeform passage has no bottom face, and consists of a set of free form faces forming a wall. The wall faces are connected by concave or convex edges. It is characterized by one of the following properties (Fig. 4a):
  - i) G=G+ and G+ is a cycle;
  - ii) G is a Cycle and G+ is a Chain.

The STEP-NC features that belong to this class are thru round holes and thru closed pockets.

- *Freeform Depression*. A freeform depression has one accessibility direction and one bottom free form face connecting its wall faces via concave edges. It is characterized by the following properties (Fig. 4b):
  - i) G+ has a vertex v whose degree deg(v) = λ(G+). Where λ(G+) is the number of Cocycles (i.e., number of vertices minus number of connected components);
  - ii) Graph G-v obtained by deleting vertex v from G, is a cycle, whose concave edges is more than the convex edges in number.

The STEP-NC depression features are blind round holes, blind closed pockets, and slots with two ends.

- *Freeform K-protrusion*. A freeform K-protrusion has one or several accessibility directions, and has one base face on which protrusions are connected via concave edges. It is characterized by the following properties (Fig. 4c)
  - i) G+ has a vertex v whose degree deg(v)= λ(G+);
  - ii) G-v contains k disjoint components;
  - iii) A component $(G\text{-}v)_i$ is a cycle whose concave edges is less than the convex edges in number.

The STEP-NC k-protrusion features are bosses, profile features, and spherical cap.

- *Freeform K-slot*. A K-slot has one or several accessibility directions and has one bottom face connecting one or several open wall faces. It is characterized by the following properties (Fig. 4d)
  - i) G+ has a vertex v whose degree deg(v)= λ(G+);
  - ii) G-v contains k disjoint chains $(G\text{-}v)_1, \dots, (G\text{-}v)_j$, and/or isolated vertices.

The STEP-NC k-slot features are blind open pockets, slots that has at least one end is open, and steps.

- *Freeform Compound class*. This type of form feature is composed by several simple features defined above (Fig. 4e).

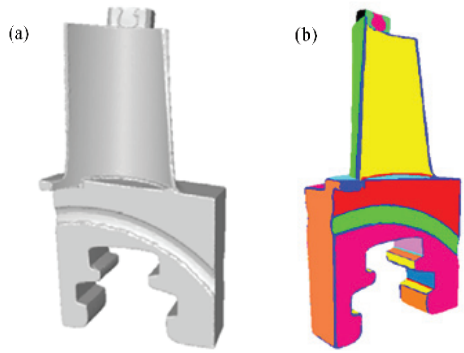

Fig. 5. Test case
(a) Mesh representation of a blade; (b) Segmentation results.

5. Case Study

The methodology proposed in the previous section has been tested on different cases. A blade case is depicted in this section summarizing the whole approach.

The input data used here is a tessellated CAD model (Fig. 5a) Firstly, the skin mesh of the workpiece must be built so as to represent the freeform feature by the parameters of discrete differential geometry: n_V , d_E and n_F . Then the surface descriptor can be obtained by calculating edge-xity, shape index and curvedness. Based on the shape descriptor, the freeform surface is segmented into sub-surfaces with different surface types, as shown in Fig. 5b. A graph-based approach is then used to recognize the different freeform machining features defined in Section 4.3, as shown in Fig. 6. The result has proved the effectiveness and efficiency of our proposed methodology in surface decomposition and feature recognition for regular shapes, as well as complex freeform shapes.

6. Conclusion

This paper proposes a new methodology of machining feature definition and classification considering freeform shape. The freeform surface is decomposed into point sets and meshed with triangles so that the parameterization of freeform feature is represented by discrete differential geometry descriptors. Based on shape descriptors, the freeform surface is segmented into sub-surfaces with ten surface types, and then recognized as the five pre-defined freeform machining features (freeform passage, freeform depression, freeform k-protrusion, freeform k-slot, freeform compound feature) using Attributed Adjacency Graph. Finally, a blade case study is presented to illustrate the proposed approach, and the result has proved its effectiveness and efficiency.

The proposed methodology enables an intuitive decomposition and composition of discretized shapes for the purpose of freeform machining features classification and recognition. It paves the way for further research of freeform machining features, which is significant in aerospace industry. In the future, we plan to refine the decomposition and composition criteria by combining discrete differential geometry with other machining data as toolpath, tool position and orientation as well as machine-tool kinematics.

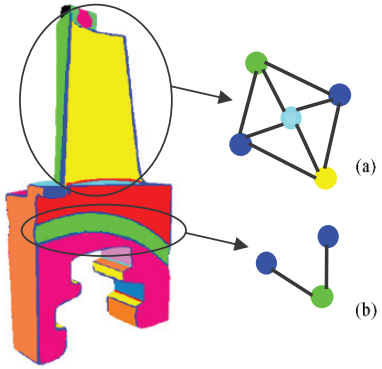

Fig. 6. Features recognition
(a) freeform K-protrusion feature; (b) freeform depression feature.

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