A multi-perspective dynamic feature concept in adaptive NC machining of complex freeform surfaces

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Abstract

This paper presents a new concept of feature for freeform surface machining that defines the changes in feature status during real manufacturing situations which have not been sufficiently addressed by current international standards and previous research in feature technology. These changes are multi-perspective, including (i) changes in depth-of-cut: the geometry of a feature in the depth-of-cut direction changes during different machining operations such as roughing, semi-finishing and finishing; (ii) changes across the surface: a surface may be divided into different machining regions (effectively sub-features) for the selection of appropriate manufacturing methods for each region such as different cutting tools, parameters, set-ups or machine tools; and (iii) changes in resources or manufacturing capabilities may require the re-planning of depth-of-cuts, division of machining regions and manufacturing operations (machines, tools, set-ups and parameters). Adding the above dynamic information to the part information models in current CAD systems (which only represent the final state of parts) would significantly improve the accuracy, efficiency and timeliness of manufacturing planning and optimisation, especially for the integrated NC machining planning for complex freeform surfaces. Case study in an aircraft manufacturing company will be included in this paper.

Keywords:

Adaptive manufacturing, CAD/CAM, CNC, Freeform surface, Feature

1. Introduction

Manufacturing of complex freeform surfaces with high technical requirements is one of the biggest challenges facing today's manufacturing industry. Computer Aided Design (CAD) and integrated Numerical Control (NC) technologies have been developed for tool path optimisation [1] and machining planning with capabilities of distributed planning [2], intelligent planning [3], reconfigurable planning [4] and integration with production scheduling [5]. However, product data in existing CAD systems do not support adaptive machining planning and optimisation, where main concerns are the changes in component geometry, machining methods, parameters, resources due to various requirements and constraints in real manufacturing operations.

Most CAD systems are now feature based. Features have been proved to be effective media for NC machining planning by relating expert knowledge to certain types of geometry [6]. However,

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in current commercial and reported research prototype systems, features once defined normally remain unchanged in the whole manufacturing cycle, which are referred to as *static features* in this paper. Machining planning and optimisation based on static features often need manual corrections in response to various changes in dynamic production situations. This paper presents a Multi-perspective Dynamic Feature (MpDF) concept, based on which changes in feature geometry and associated technical information can be represented within and complementary to existing feature-based CAD models so that adaptive machining planning and optimisation can be carried out with accurate and actual component and resource information.

This paper focuses on the definition of freeform surface feature for NC machining based on the MpDF concept, in which various changes during real manufacturing situations will be defined. Examples are: feature geometry changes due to depth-of-cuts planned for different operations (roughing, semi-finishing, finishing); a complex surface feature may be divided into several machining regions in different operations requiring different manufacturing methods; and changes in resources may require re-planning of depth-of-cuts, machining regions, cutting tools, parameters and set-ups. Including the dynamic information in CAD models would significantly improve the accuracy in adaptive planning of NC machining operations during production. This feature concept was tested using an example component with freeform surfaces, and results are presented in this paper. The requirements for this project are identified from collaborating aerospace manufacturing companies. However, the dynamic feature concept is applicable to the manufacturing of general mechanical parts.

2. Research Background

2.1 Definitions and Applications of Manufacturing Features

Feature technology has been one of the main topics for CAD/CAPP/CAM integrations for many years, this is because almost all today's computer aided design and manufacturing systems function on the basis of features, or require features to be the input data. The Standard for the Exchange of Product model data (STEP) documented in ISO10303 [6] defines a mechanical part for process planning in terms of machining features to facilitate the identification of manufacturing shapes that are human and computer interpretable, and provides a systematic feature classification scheme (STEP AP224). Machining features define the volumes of materials to be removed to obtain the final part geometry from the stock, and can be further classified into multi-level sub-features. Tolerances are also provided in this standard to support process planning based on features. Other parts of ISO 10303, such as AP 203, AP 214, AP 238 and AP 240, all share this feature classification for different purposes in various manufacturing domains. Most previous research on feature recognition and feature based process planning could be regarded as the extension or complement to STEP.

In feature recognition, Gao and Shah [7] classified feature intersections among features like slot, hole and step into six categories and developed a hybrid technique combining elements of graph and hint-based systems to generalise the handling of interactions. Li et al. [8-10] presented a high level machining feature classification made up of general pocket, hole, profile and rib for aircraft structural parts to strength the connection between geometry shape and manufacturing knowledge, and a holistic attribute adjacency graph based recognition algorithm was proposed to extract machining features from complex aircraft structural parts with various intersecting features. Since features in STEP-NC data model are always expressed as independent features, Dipper et al [11] defined bridge faces, common volumes, connection faces and machined volumes to represent feature-feature interactions. By appending the interaction data to the original feature model, the subsequent uses like process planning may be greatly improved. Heo et al. [12] presented a methodology to recognize pocket features, and to partition the machining region of the pockets. The attributes of the pocket feature is defined for high speed machining planning. They used the slice method to generate multiple layers and each layer has the same type of parameters to plan the machining parameters for high speed machining. Arivazhagan et al. [13] depicted a machining volume identification method for finishing machining. The machining volumes of the machining features defined in STEP AP 203-214 are calculated by their proposed algorithm. Rameshbabu and Shunmugam [14] presented a volume-graph based hybrid feature recognition method for setup planning. Preferential base derived from the feature graph is applied as the link between feature recognition and setup planning.

In feature based process planning, features are linked to manufacturing knowledge of various types like machine tool selection, cutter determination, cutting parameters planning. You et al. [15] introduced a cutter selection method for pocket feature, and the combination of the optimal tools for the whole machining process of pocket could be generated by simplifying 3D features to 2D boundaries. Banerjee et al. [16] described an integrated process planning approach for optimal corner machining which combines the tool path generation and machining parameter selection tasks. Wang [2, 17] developed a distributed process planning approach based on machining features. Machining features are encapsulated into a set of predefined function blocks which know how to produce the features. By using an event-driven model of the function block, the process planning functions in both offline and online stages are more intelligent and autonomous in making decisions. Zhang [18] gave a mathematical model to describe the tolerance information and datum-machining feature relationship based on extended graphics. The method identifies the machining features and datum, and optimises setup groups based on the manufacturing resource capability and tolerance analysis. Villeneuve et al. [19] developed a feature model to match machining processes adapted to aircraft knowledge and established an activity model to identify and clarify the tasks to be performed and the process data involved in making planning decisions.

2.2 Feature technology in freeform surface manufacturing

Commercial surface modelling tools are time-consuming and do not enable fast modifications for freeform surfaces, and feature technology is increasingly used to improve this [20]. In typical solid modelling methods, features are defined by a composition of simple geometric primitives like planes and cylinders which can be modified through parameters like length or width. However, this definition could not be directly brought into freeform surface definition, due to the complexity of the underlying mathematic models. Langerak [21] presented a feature definition consisting of a shape description, a parametric description and a functional relation between them, called the parameter mapping. With this definition, the freeform surface feature and the shape modification are closely connected to the underlying base surface. Nyirenda and Bronsvoort [22] defined three types of feature entities for 3D points, curves and surfaces respectively. This definition contains various methods not only for geometry creation, but also for communication with geometric modelers. Cheute et al. [23] defined fully free-form deformation features as being the shapes obtained by deforming parts of a freeform surface according to adequate constraints, which are the parameters of the feature. Sundararajan and Wright [24] represented freeform surface features with feature geometry information and feature interactions information for feature extraction from parts with 2.5 dimentional feature and freeform surfaces. Gupta and Gurumoorthy [25] distinguished freeform surface features using separating curves. Features are classified into (Blind, Depression), (Double-blind, Depression), (Through, Protrusion), (Closed, Protrusion), (Double-blind, Saddle), (Double-blind, Flat) and so forth. In Sunil's feature extraction method [26], freeform surface features are defined as a set of connected meaningful regions having a particular geometry and topology with some significance in design and manufacturing.

For freeform surfaces manufacturing, region based tool path generation methods are used to divide the freeform surface into regions by identifying meaningful features. In Lee's method for strip width optimisation [27], the surface usually could not be machined with optimal strip width based on one initial tool path. Thus the surface should be divided into multiple regions and each region has an initial tool path to generate the overall tool paths. In this condition, different features in the surface have different feed directions. Kim [28] proposed a constant cusp height tool paths generation method, in which geodesics are created on the abstract Riemannian manifold based on the part surface to compute the tool paths. However, those geodesics may intersect with the others. Thus the surface cannot be machined completely as one machining region and should be subdivided into distinct segments to avoid the intersections of the tool paths. In Tuong's method [29], the chain code technique in the image processing field is applied to dividing the surface for cutter selection optimisation. Han et al [30] used the isophoto concept for surface segmentation. Surface is divided into regions with similar normal vectors for tool path computation. In the method by Chen et al [31], the surface is first divided into a number of regions based on the accessibility of the 3-axis machine tool, and then the part set-up is adjusted to machine each region by a tilt/rotary table. Elber [32] divided the freeform surface into 3-axis machining regions and 5 axis machining regions based on the surface curvatures to improve the machining efficiency. Giri at al. [33] proposed a method to divide the surface into distinct zones with similar curvature. The boundaries of these regions are then applied as the master cutter path to compute the overall tool path.

2.3 Summary of feature technology in freeform surface manufacturing

From the literature review carried out by the authors, although in most previous research in freeform surface, features are used for facilitate the design process, there is an increased research interest in defining machining features for freeform surfaces, and achieve machining optimisation by dividing a surface into several sub-regions represented as features. However, with the existing feature definition, machining features are extracted from the final design model and once defined normally remain unchanged in the whole manufacturing cycle. Machining planning and optimisation based on these static features often need manual corrections in response to various changes in dynamic production situations. This paper presents a Multi-perspective Dynamic Feature (MpDF) concept for the definition of freeform surface feature for NC machining. Various changes in freeform surface feature during real manufacturing situations are defined. Section 3 will discuss the details of the MpDF concept. A case study will be provided for the verification of the MpDF concept in Section 4. Section 5 will conclude this paper.

3. The Proposed Multi-perspective Dynamic Feature Concept

During machining, feature geometry changes due to the depth-of-cuts planned for different operations such as roughing, semi-finishing and finishing. In this paper, the feature geometry planned for an operation is called the *interim feature for that operation*. The result of the finishing operation is the *design feature* which is defined in current CAD models. In freeform surface machining, it should be noted that, in practice, an interim feature may be further divided into several sub-features (or machining regions) so that different cutting tools, parameters, set-ups and machines can be planned for each sub-feature for optimum operation, as shown in Figure 1. The geometry of an interim feature and its sub-features may change for different machining optimisation objectives such as maximising cutting width (production rate) and tool orientation smoothing in freeform surface machining (best quality). An interim feature may also change in response to changes of manufacturing resources and scheduling which normally require re-planning of the depth-of-cuts and the sub-features (machining regions) of the interim feature. To address the above dynamic characteristics that have not been reflected in current CAD models, the Multi-perspective Dynamic Feature (MpDF) concept is introduced by the authors to represent feature changes between various manufacturing operations [34]. Based on the concept, an MpDF model can be established to represent information about a particular feature with all of its interim features and respective sub-features, which can be represented as:

$$\begin{cases} MpDF = \mathop{}\limits_{i=1}^{N} IF_i \\ IF_i = \Gamma^{i}_{(OO_T, MR_T)}(P) = \mathop{}\limits_{j=1}^{M} SF_j \end{cases} \qquad \text{Eq.1}$$

Where IF refers to an interim feature with its sub-feature (SF) on part (P). Γ refers to the feature division algorithm. OO_T and MR_T are the optimisation objectives and manufacturing resources. With the MpDF concept, a feature information model in CAD systems can be defined dynamically in the whole manufacturing cycle, thus supporting on-line adaptive machining planning.

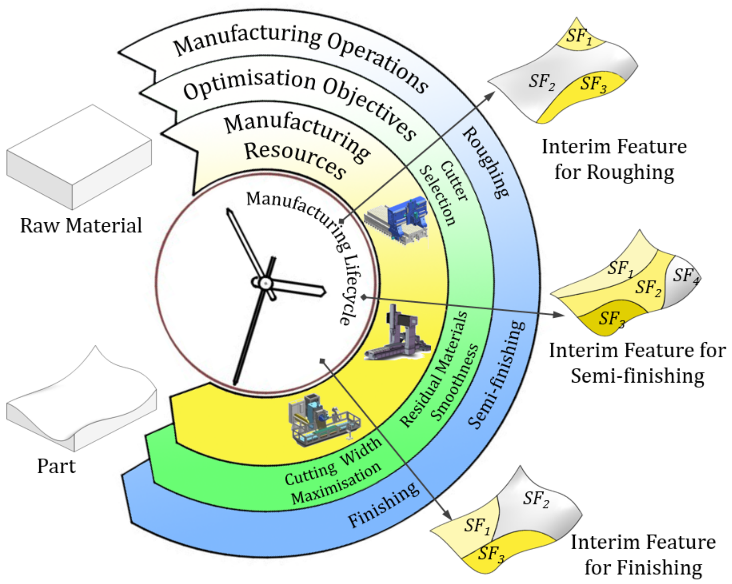


Figure 1. Feature dynamics in the whole manufacturing cycle.

3.1. Feature dynamics in the depth-of-cut direction

Feature dynamics in the depth-of-cut direction refers to the changes in a feature's geometry between different machining operations, such as roughing, semi-finishing and finishing. Figure 2 shows the various depth-of-cuts planned for different operations performed on a surface feature. In traditional feature definitions, only the final geometry of the feature is modelled and it remains unchanged during the whole machining progress. However, process planning and machining optimisation using this static feature model will miss the information about real feature status and its geometry changes between different machining operations, which may lead to cutter collision, machine overload, overcut and undercut of materials. Therefore, it is very important to represent information about interim features corresponding to planned depth-of-cuts. In practice, the result of a particular machining operation is the interim feature used to plan this operation. The result of its previous operation has left the material to be removed by this operation (i.e., the depth-of-cut), e.g., as shown in Figure 2 b, the result of the semi-finishing operation is the interim feature used to plan this operation including selecting machines, tools and parameters and considering the materials left by the previous roughing operation as depth-of-cut to avoid cutter overload in certain area.

In the authors' previous work [8], a *Dynamic Feature* concept was introduced to represent feature dynamics discussed above. This paper introduces a more comprehensive Multi-perspective Dynamic Feature (MpDF) concept, based on which a MpDF model can be generated in CAD systems to represent all the interim features corresponding to the depth-of-cuts planned for a particular feature, as well as all the sub-features of each interim feature (referred to as feature dynamics across the surface in this paper, and to be described in Section 3.2). The MpDF model may also be updated in response to the changes in manufacturing resources (to be discussed in Section 3.3).

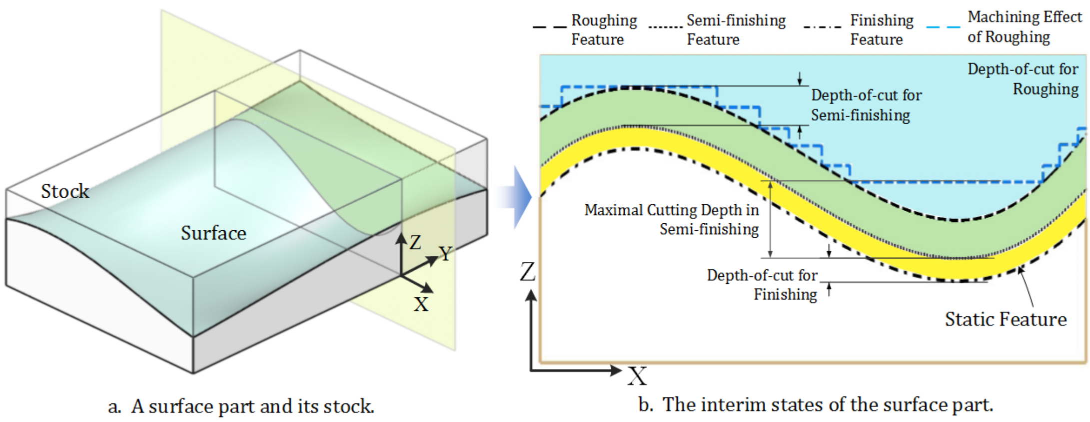


Figure 2. Various depth-of-cuts in machining a freeform surface.

3.2. Feature dynamics across the surface

In industrial practice, especially in manufacturing complex components with freeform surfaces, an interim feature may have to be further divided into sub-features or machining regions for the selection of appropriate manufacturing methods for individual sub-features including cutters, parameters, set-ups and machine tools. Figure 3 compares the results of an example freeform surface feature which is machined as one feature (Figure 3a) and machined as two sub-features (Figure 3b). It can be seen that the strip widths between the tool paths in Figure 3a are uneven, thus the cusp heights would not be even. As a result, some bumpy residual areas would appear across the machined surface. When the surface feature is divided into two sub-features and machined by different tool path strategies, more even strip widths could be achieved (as shown in Figure 3b).

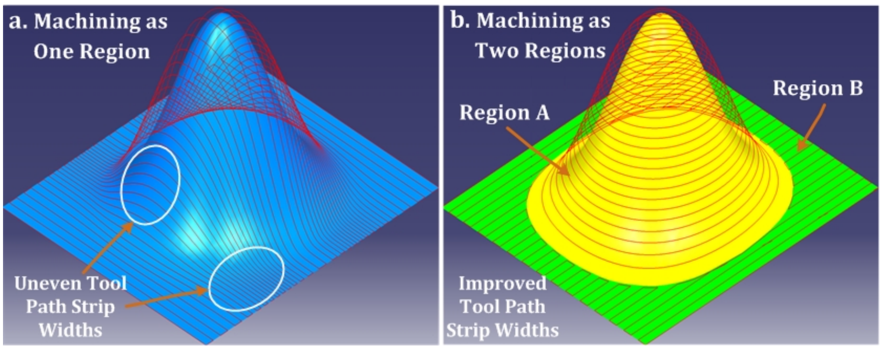


Figure 3. Tool paths showing improvements when dividing a freeform surface feature into two sub-features.

There are also many other cases in manufacturing industry that require sub-division of a surface feature for different machining strategies. In MpDF definition, surface feature subdivision is associated with different optimisation objectives. For example, to reduce the machining time, one can increase the cutting width or increase the feed speed. However, these aspects normally conflict to each other. In freeform surface machining, a feed direction at a cutter location that maximises cutting width may not be able to reach a high feed rate. In current practice, these aspects are usually considered independently and each refers to an optimisation objective. If a surface feature is divided into several sub-features, then flat-end cutters may be chosen to machine convex and relatively flat regions, while ball-end cutters may be used to machine concave regions with small curvature to avoid gouging/overcutting.

A surface feature could also be divided for different set-ups based on the accessibility of selected cutters, machines and fixtures/jigs, and for feed direction optimisation by considering the limits of speed and acceleration along the axes of the selected machine tool. Different optimisation objectives usually lead to different surface subdivision results. In roughing, there are relatively low accuracy requirements, but cutting efficiency is considered as priority. In semi-finishing, more attention is paid to smoothness of the materials left on the part to ensure the stability of cutting motions in finishing. In finishing, accuracy and surface quality are priority. For instance, in freeform surface machining, 2-1/2 axis machining strategy and larger cutters may be preferred in roughing to maximize the material removal rate. Thus the roughing interim feature may need to be subdivided for large cutter selection in certain sub-features. In finishing, iso-parametric cutting strategy with smaller cutters is usually selected to ensure the machining tolerance and surface quality (constant cusp height).

Procedures to generate freeform surface machining features are proposed as shown in Figure 4. At the beginning, an operation plan will be selected from existing typical process plans based on the surface geometry, machining requirements as well as current available resources including machines, cutters, fixtures and so on. Operation planning divides the machining process into several steps like roughing, semi-fishing and finishing. Machining allowances on the normal direction of these operations are also included in this plan. Each machining operation refers to an interim feature, while an interim feature may be made up of several sub-features by dividing the surface into sub-regions, and each sub-feature has its own machining strategy like set-up, cutter, feed direction and tool orientation. There are many ways to divide the surface [27-33] and the one to be applied is determined based on the optimisation objective as described above. Recently, the research group of the authors has presented a tensor based surface subdivision method [34-35]. Each optimisation objective is represented as a rank two tensor. Then a tensor field is able to be established across the surface. Degenerate points of the tensor field are extracted and classified for constructing the inside boundaries which will divide the surface into sub-surfaces. The tensor based method is proved to be practical to find the global optimal surface subdivision result. All the interim features make up a complete freeform surface machining feature model.

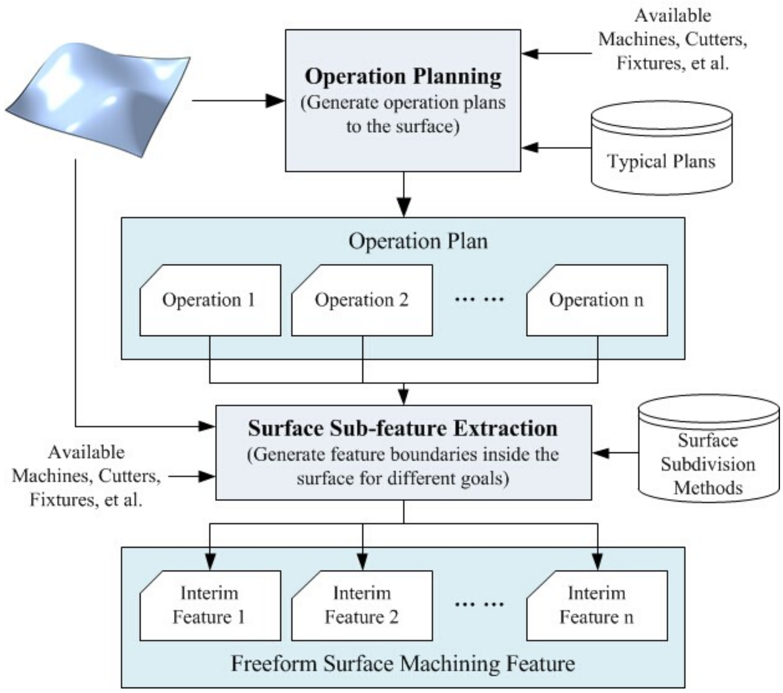


Figure 4. Procedures for freeform surface machining feature extraction.

3.3. Feature dynamics due to changes in manufacturing resources

In on-line adaptive manufacturing, both machining operation planning and optimisation are based on the availability and scheduling of manufacturing resources in real production situation. For example, different cutters lead to different machining strategies. A larger cutter can increase the cutting efficiency in roughing. On the other hand, if a smaller cutter is selected for roughing, the semi-finishing operation may not be required thus more efficiency is achieved. If a low rotational speed machine tool is chosen, the tool orientation smoothness may be selected as optimisation objective to reduce cutting time. However, if a machine tool with high rotational speed is chosen, the optimisation objective may be changed to cutting width maximisation. Many resource characteristics including the structures (accessibility), speed and acceleration limits of machine tools, and the shape, size and materials of cutters are directly associated with optimisation objectives.

Normally machining operations and optimisation objectives, once planned, remain unchanged during the whole manufacturing cycle. However, the selected manufacturing resources in initial planning stage are often changed by engineers in real production. If the changes are due to re-scheduling of resources or machine broken down, the planned machining operations as well as optimisation objectives may have to be re-planned which may lead to the changes in both the interim features and the way sub-features are generated for each interim feature. As a result, the MpDF information model would be updated, and thus adaptive machining planning is supported timely with the actual information in the MpDF model.

Time range in manufacturing lifecycle considered in this feature concept is from the end of design to the end of machining and is further divided into Initialisation (when t $\equiv$ 0), off-line stage (when t $\in$ $(0, T_{Off}]$) and on-line stage (when t $\in$ $(T_{Off}, T_{On}]$). In different stages, feature updates in different ways as shown in Figure 5, and are explained below.

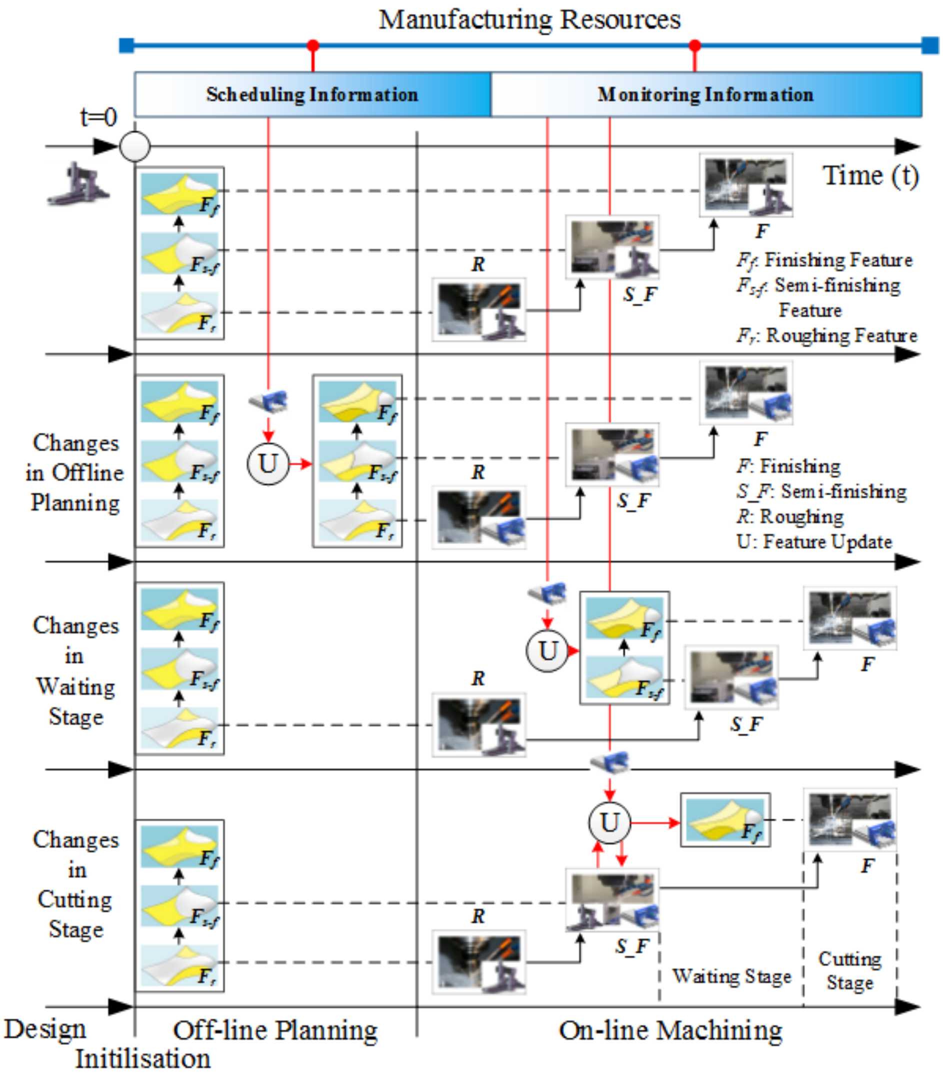


Figure 5. A real-time feature definition mechanism in manufacturing lifecycle

Initilisation: Design outputs the product model to be machined and its machining requirements. At the very beginning of offline planning (t=0), an initial feature interpretation is first generated and applied for further process planning and programming. In this initialisation, a typical process plan to machine the input product is first selected. This process plan contains machining operations, manufacturing resources, proposed parameters and so on. Then feature definition to each planed part geometry state will be generated like roughing features, semi-finishing features and finishing features.

Off-line planning: Offline planning is based on the initilised feature definition. Changes of manufacturing resources happen in this stage will trigger the action to check whether the current typical process plan is acceptable. If new plan is selected to match the current resources, machining operations with optimisation objectives may need to be updated and then features of each planed part geometry state may need to be regenerated.

On-line machining: Process plan for part machining is generated by offline planning. This stage is further classified into machining stage and waiting stage. Machining stage refers to the period of material removing motions, while waiting stage refers to the time using for machining preparation. During the waiting stage, feature remains consistent. If the selected resources change in this time, current operation plan will be first checked according to new selected resources for operations for the following machining operation. Then new interim features may be regenerated based on the new manufacturing situation. In the machining stage, part geometry keeps changing during cutting. Manufacturing resources should not be changed unless in the conditions of broken down. In this condition, the under machined area of the surface should be first extracted for sub-feature generation based on the new manufacturing resources to finish the current machining operation. Then operation plan as well as the interim features with the previous manufacturing resources may need to be updated.

4. Proof-of-concept Implementation

The surface shown in Figure 6 is part of an aircraft part from our industrial partner. This surface is used to verify the MpDF concept for better machining planning. The Surface Design Module of the CAD system - CATIA was used to model the example surface feature and its sub-features. The operation plan of this surface has roughing, semi-finishing and finishing. The raw material is a cuboid which is 100mm*85mm*40mm in size.

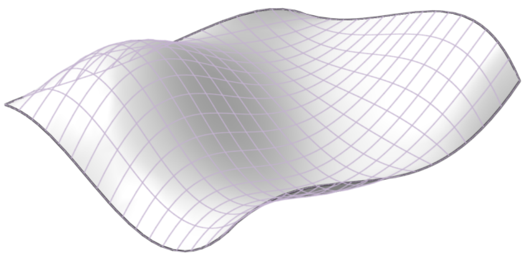


Figure 6. The freeform surface for verification of the MpDF concept.

In roughing, the machining allowance in the normal direction is set to 1.5mm. Since there is no accuracy requirement, the optimisation goal in roughing is to improve the cutting efficiency as much as possible. It is known that larger cutter can increase the feed speed and cutting depth. However, due to complex surfaces, different machining planes have different boundary contours that limit the choices of cutters. Moreover, the depth of machining plane may limit the depth of roughing. In this verification, the cutter selection for freeform surface roughing is considered for surface subdivision. The cutter selection method proposed in [36] is used here. For this interim feature, different sub-features will be machined using different cutters to maximise the material removal rate. Roughing feature and its real machined result are shown in Figure 7. Flat end mills are chosen here. For rouging feature A, the cutter diameter is 12mm while 8mm for roughing feature B. Compared with the traditional way which considers the whole surface as one machining region using the flat end mill with diameter 8mm. The machining time is reduced from 30.6min to 25.46min based on roughing features. It could also be found that if the available cutters are changed, the surface subdivision result may also be changed.

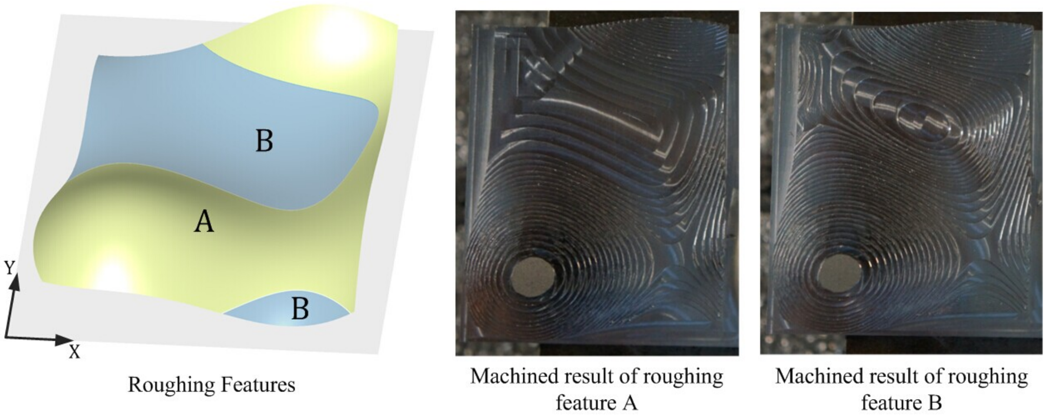


Figure 7. Interim feature for roughing and the machined result.

In semi-finishing, the machining allowance is 0.5mm. The machined result of roughing is considered in machining planning of this stage. Since material residual after roughing is usually uneven overall the surface, different cutters or machining strategies may need to be selected for different regions in the surface. In this case study, a ball end mill with 6mm diameter is selected for semi-finishing and an iso-parametric tool path generation algorithm is chosen. In roughing feature A in Figure 7, the maximal material residual height is larger than 3mm. Thus in this region, at least two levels of tool paths are required to protect the cutter and ensure the cutting stability. In roughing feature B, one level tool paths is enough. That is to say, the surface is divided in the same way in roughing and semi-finishing in this condition. However, machining knowledge associated with roughing feature and semi-finishing feature is different. In a roughing feature, a cutter is selected while in a semi-finishing feature, number of tool paths levels is linked. The interim feature for semi-finishing and the machined result is shown in Figure 8.

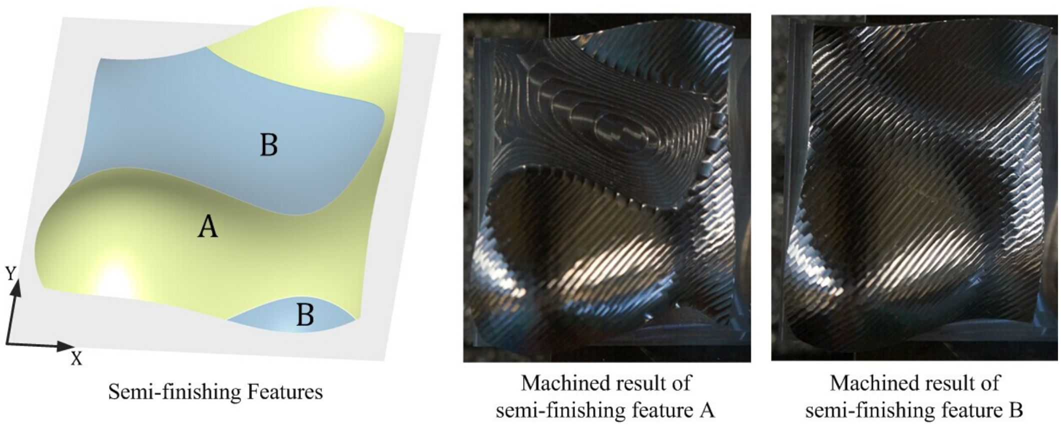
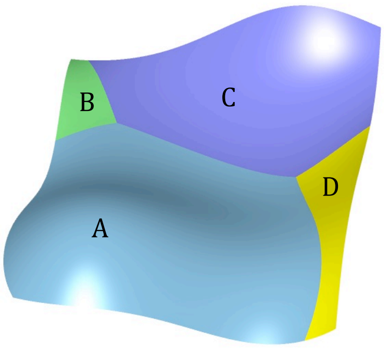


Figure 8. Interim feature for semi-finishing and the machined result.

In finishing, machining strip width maximisation is selected as the optimisation objective for surface subdivision. The ball end mill used in semi-finishing is used and the maximal allowed scallop height is 0.02mm. The surface is first meshed into a set of 3D points. Principle curvature direction is extracted as the feed direction with maximal machining strip width at each point. Then the surface should be subdivided based on the regularity of the optimal feed directions overall the surface. Inside boundaries could be constructed by applying the tensor property of the local surface curvature [37] as shown in Table 1. In each sub-feature, a curve is constructed by following the optimal direction with maximal cutting width at every point as the principle tool path curve to generate tool paths by applying the 3D curve offset technique. The table shows the real finishing result based on finishing features. For comparison, the finishing of this surface was also carried out with the same machine tool and cutter as one region using iso-parametric tool paths generated by CATIA V5 R18. In this case, the total tool path length is reduced by 14.70% and the real machining time is reduced by 10.80%.

Table 1. Interim feature for finishing and the machined result

Surface subdivision result	Machined result based on finishing features	Machined result based on iso-parametric tool paths
		
Length of tool path curve	7538mm	8837mm
Cutting time	16.1min	18.05min

5. Conclusions and Future Work

This paper presents a Multi-perspective Dynamic Feature (MpDF) concept, by which MpDF models can be established in feature-based CAD systems to represent accurate and dynamic information such as interim features corresponding to different depth-of-cuts, sub-features of the interim features for different optimisation objectives, and changes (and their consequences) in the availability and scheduling of manufacturing resources to support adaptive NC machining applications. The dynamic feature concept overcomes the problems in current CAD/CAM systems which only include static information about components rather than accurate dynamic information during real manufacturing operations. Immediate future work is to consider more optimisation objectives for adaptive machining planning of the interim features and their sub-features to achieve more appropriate and realistic machining plans.

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