

A rule-based approach with multi-level feature taxonomy for recognition of machining features from 3D solid models

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Abstract. Numerous approaches in recognition of intersecting and isolated features have been proposed in the last several decades. However, they are limited to features with topologically fixed shapes and restricted to isolated machining features since they are dependent on the pre-defined patterns or rules. In the present work, a rule-based approach is developed to accommodate intersecting features with variable topology shapes. The proposed approach classifies the features according to the multi-level feature taxonomy. In the first level, features are categorized into three groups of primitive features according to their loops and edges types. In the second level, pockets and holes are identified from their primitive feature attributes while visibility maps are adopted to recognize slots and steps features. Intersecting features are identified based on adjacency relationships among face members of the features. On the other hand, pre-defined rules are still utilized in restricted application to identify special machining features. In addition to that, the proposed approach has been implemented to recognize machining features in the industrial parts model in the b-rep format. The implementation result shows the proposed methodology has enlarged the number of identified features up to 55.7 percent compare to the existing method in a commercial software.

1. Introduction

In the last two decades, fast, reliable, and robust systems are highly demanded to meet future challenges of manufacturing industries globally. These challenges are a result of keys characteristic of the modern products, viz. high complexity and shorter products life cycle, which require faster design phase, shorter manufacturing time and lower production cost. In addition, delivering a high-quality product to worldwide customers at an acceptable price asks rapid responses from the manufacturer.

Tremendous efforts on applying information and computer technology in the manufacturing process have been done as solutions to shorten production time, reducing manufacturing costs while keeping and increasing the quality of products. In the design domains, Computer Aided Design (CAD) has been widely used to help engineers in designing the products. Moreover, some CAD systems also offer engineering analysis capabilities through Computer Aided Engineering (CAE) to evaluate mechanical properties of the products. In the shop floor, CAPP systems are developed to carry manufacturing planner jobs while Computer Aided Manufacturing (CAM) helps machinists to generate a toolpath for CNC machines in manufacturing the products. Those systems play important roles in manufacturing industries in the last several decades.



An integrated system between design processes with downstream applications such as production planning, CNC toolpath generating, inspection planning, etc. becomes important to meet the modern industrial challenges. CAD model is generated in a low-level data format that carries very basic information such as faces, edges, and vertices. In order to integrate the design processes to the downstream applications, an interface is required in interpreting certain features type in designed parts into downstream application such as machining features.

2. Literature review

Up to now, fully automatic feature recognition systems have not been found yet even though the enormous efforts have been done in the last three decades. The first idea to integrate manufacturing systems rose when Researchers at Cambridge University's CAD Centre developed an automatic NC Programming for milling. Then, topologically based features recognition was introduced which led to other topological methods. Attributed face adjacency graph (AAG) was then discovered [1]. Faces are represented as nodes, the edges as arcs and attributes will be signed to the arcs according to the relationship between the adjacent faces. Then, graph matching is used to compare the part representations with the pre-defined patterns. This method works well for the isolated feature. Interacting features, however, poses difficulties to this method

To overcome intersecting features problem, another approach has been proposed including the virtual link that was introduced by Marefat and Kashyap [2] and extended by Trika and Kashyap [3]. Gao and Shah introduce hybrid approach to overcome limitations in another method by combining several basic methods [4]. In this approach, Virtual links concept from interacting features was used to give an attribute in Extended Attributed Adjacency Graph (EEAG). Minimal Sub-Condition Graph (MSCG) which is produced from EEAG is used as feature hints. Missed links are restored to MSCG after several geometric reasoning so that it becomes recognizable forms. An algorithm that was developed by Laakko and Mantyla is another example of the hybrid methods [5]. They previous technique to create a graph-matching algorithm for extracting faces set candidates. Then, they combine it with a rule and constraint-based system for recognizing the features. A feature with variable topology still poses some difficulties since those methods rely on graph matching with pre-defined rules.

In searching for appropriate methods for feature with variable topology, some works exploit Boundary representative (B-rep) data as basic information and recognizing the features type by following sequential rules [6-9]. This approach classifies the features into internal and external form features according to the loops and edges classification. N-faces of the features are extracted according to the loops and edges type. The features type is recognized based on the proposed feature taxonomy. Typically, pockets, holes, and bosses are classified into internal form features that are generated from an internal loop while step and slot are categorized into external form features that are derived from the external loop. Missing link is founded in the interacting features, so the internal loop turns into external loop.

Vandenbrande and Requicha utilized faces, edges, and vertices pattern as a hint to locate a feature [10]. It is known as a hint-based approach. The approach was also used by Regli [11]. Feature hints are specified by the remaining boundaries of a feature in the parts after interactions with another feature. For instance, a sub set of both opposite faces remaining must be found in linear slot features when the feature interact with another feature. To build complete feature, the feature will be extended to one or more directions without intruding the part if feature hint has been found. Another researcher tried to enhance the capability of this method by several ways, such as reasoning based hint using various sources [12]. However, this method has some backwards such as unexpected duplications in a large number of hints and also, it's sacrifice generality although they gain more efficiency. In addition, it is difficult to expand the capability in handling more complex parts without changing the hard code of the hint's rules.

Implementation to certain application has been presented by researchers. A rule based approach has been proposed to recognized welding features from 3D solid model [13]. The features are used to define robotic path for automatic welding process. Primitives curves, such as line, circular arcs, and B-spline,

are retrieved from 3D solid model according to pre-defined geometric constraint. Meanwhile, CAD feature recognition method is developed to generate automatic maintenance planning [14]. The system mainly provided useful guidance to disassembly a component. The feature recognition technique is worked based on fundamental geometric entities. Vertices point coordinate are then extracted to define assembly direction. This two works has shown significant of application. However, numberless feature recognition challenges like intersecting features remain unresolved.

Interacting features continue to pose challenges to the existing approaches [15]. Pre-defined patterns and rules in graph-based, hint based, and hybrid-based methods show a promising solution for certain domains. However, they face some problems in terms of flexibility in handling the features with variable topology. On the other side, some works based on B-rep indicate another solution in increasing the flexibility, although they have some difficulties in handling interacting features. Considering this problem, it is desirable to develop an approach for extracting machining features from 3D solid modelling with interacting and variable topology features.

3. Methodology

3.1. Edge and loop classification

B-rep model provides low level structural information that has to be converted into higher level to represent machining features existences. Faces in B-rep format are constructed by loops, edges and vertices. In this research, loops and edges are fundamental reference for machining feature recognition. Therefore, loops and edges are further discussed in the following sections.

3.1.1. *Edge*. The edge is a border of two adjacent faces and constructed by two vertices. The classification of edges represents two adjacent (f_1 and f_2) surfaces relationship. Typically, edges classification is derived from face normal of f_1 and f_2 . The relationship between these two surfaces is determined by the following equation:

$$Vexity = (e^t \times f_1^n) \cdot f_2^n \quad (1)$$

Figure 1 illustrates *vexity* (V) determination from the equation. Firstly, edge orientation e^t is determined so the face f_1 lies to its left. The two surfaces unit normal, f_1^n and f_2^n , are defined and it should be noted that surfaces unit normal is always directed away from the body. Then, the vector product of f_1^n and e^t is calculated to get a unit normal to the edges. The curvature of the edges can be defined by calculating the dot product of these unit vectors and f_2^n .

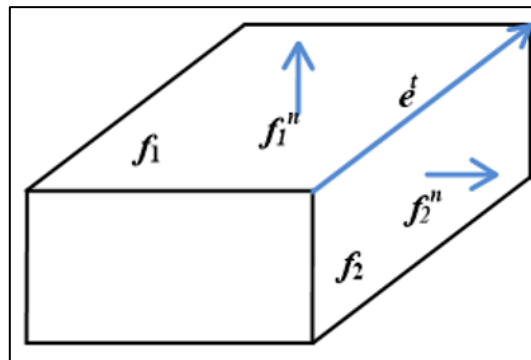


Figure 1. Component of vexity calculation

If one of the adjacent faces is cylindrical, smooth edge are appeared. To distinct smooth edge types, the curvature of cylindrical face itself has to be defined. Figure2(a) and figure 2(b) illustrate two examples of cylindrical surface with different curvature types. Radius vector (r) and normal vector (n) are compared to define the cylindrical curvatures. Typically, radius vector is directed to the center of

the radius [16]. A cylindrical surface is considered as a concave surface when the normal vector goes to the same direction with radius vector (Figure 2 (a)). Otherwise, the cylindrical surface is defined as a convex surface (Figure 2 (b)). Table 1 is used to determine the edge type.

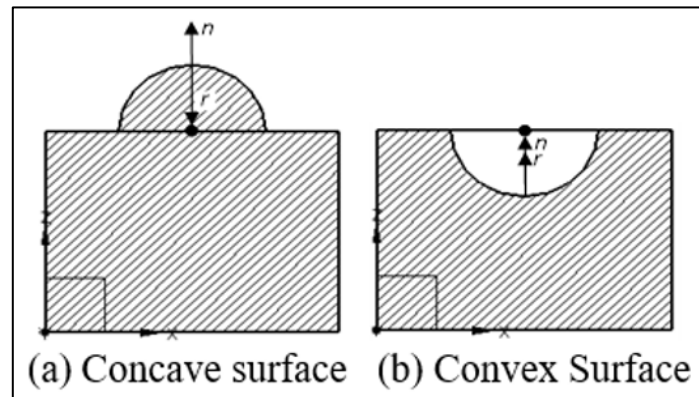


Figure 2. Different type of cylindrical curvature shape.

Table 1. Edge classification.

Face 1	Face 2	Vexity	Edge Type
Planar	Planar	>0.0	Convex (E_{Co})
Planar	Planar	<0.0	Concave (E_{Cv})
Planar	Cylindrical convex	$=0.0$	Convex-tangent (E_{CoT})
Planar	Cylindrical concave	$=0.0$	Concave-tangent (E_{CoV})
Cylindrical concave	Cylindrical convex	$=0.0$	Tangent (E_T)

3.1.2. *Loop*. In B-rep format, a set of edges in a form of closed chain constitutes a loop which is a border of faces. According to its location, loops are divided into two categories, viz. Internal Loop (L_I) and External Loop (L_E). L_E is the maximum boundary of faces and the intersection boundary of the analyzed faces with its adjacent faces. On the other hand, L_I is the internal boundary of a face and the intersection of the face with its internal features. Examples of the loops are presented in figure 3. Loops are also categorized into six different types based on the edge type that forms the loops. Table 2 summarizes the loop classification based on the edge types.

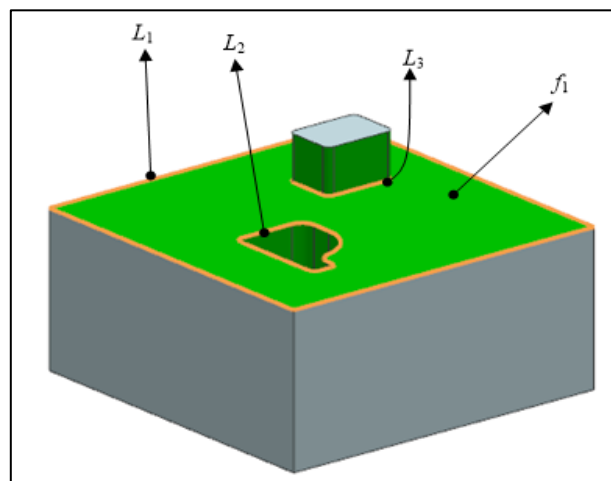


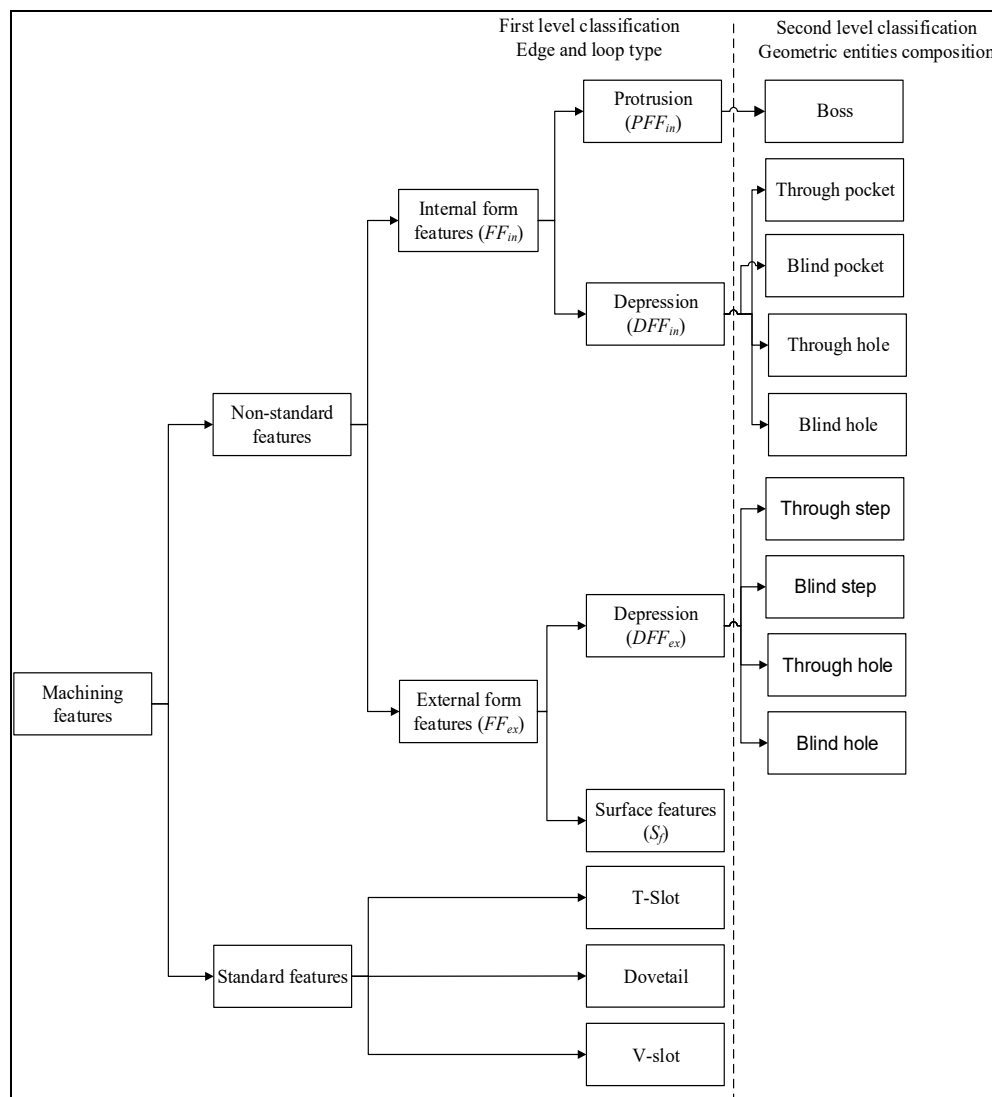
Figure 3. Loop classification based on its location.

Table 2. Loop classification based on edge type.

Category	Definition	Representation
Convex loop	All the edges are convex	L_{Cv}
Concave loop	All the edges are concave	L_{Co}
Tangent loop	All the edges are tangent	L_T
Convex-tangent loop	All the edges are convex tangent	L_{CvT}
Concave-tangent loop	All the edges are concave tangent	L_{CoT}
Hybrid loop	The loop has mixed edge types	L_{HB}

3.2. Feature taxonomy

In this research, two level of machining features classification are proposed as illustrated in the Figure 4 and will be discussed in this section.

**Figure 4.** Two level machining features classification.

3.2.1. First level classification. In the first level, machining features are classified into two different groups, viz. standard features and non-standard features. In the first group, standard features group accommodates a set of features that is made by special purpose tools. They have specific face patterns in terms of number, type and their relationship. One examples of this group is T-slots. Since it is produced by specific cutter and certain machining order, it has no possibility to create another type of T-slot with different face patterns.

The second group contains non-standard machining features that have no special patterns in terms of number of faces, type of face, and inter-face relationship. Non-standard features are categorized into internal form features (FF_{in}) and external form features (FF_{ex}). Edges and loops classification are utilized to classify non-standard features into three type of primitive features, viz. protrusion, depression and surface features.

3.2.2. Second level classification. Machining features in the second level are classified according to composition of geometric entities. Boss features belong to protrusion FF_{in} (PFF_{in}) while pockets and holes belong to depression FF_{in} (DF_{in}). Both pockets and holes are through when they are floorless. Otherwise, they are blind. Meanwhile, FF_{ex} can be in a form of depression FF_{ex} (DF_{ex}) or surface feature form S_f . DF_{ex} contains slot and step features in any type of through and blind. Single surface in type of planar face, transitional face, and freeform face belong to surface features group.

4. Algorithm for machining features recognition

Machining features are extracted in a framework as illustrated in Figure 5. The framework consists of three modules, viz. face collection, concatenation, and recognition module. B-rep structure is utilized as the input data. In the first step, face grouping is performed to get first level features. The first level features have incomplete of form feature. The second stages combine the first level feature with others based on concatenation criteria to complete the features form. Recognition is performed in the last module by checking the topology properties against the rule.

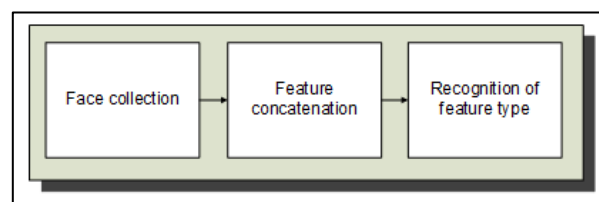


Figure 5. Feature recognition framework.

4.1. Face collection

Face collection module is designed for collecting the faces and categorizing them into primitive features in the first level classification. it works by identifying the loops and the edge types, forming a primitive feature by taking some adjacent faces based on its loops and edges type and classifying them into three types of primitive features according to the first level machining features classification. Work description of face collection module is illustrated in Figure 6.

4.2. Feature concatenation

Concatenation module is proposed for completing the primitive features which have been obtained in the collection stage. In this research, each face of 3D model is considered to be separate from the other. Collection stages are performed to bond certain faces based on loop and edge type. Then, concatenation process will do the same thing in the primitives feature level. It is important to guide the concatenation processes by designed rule to avoid inappropriate bonding.

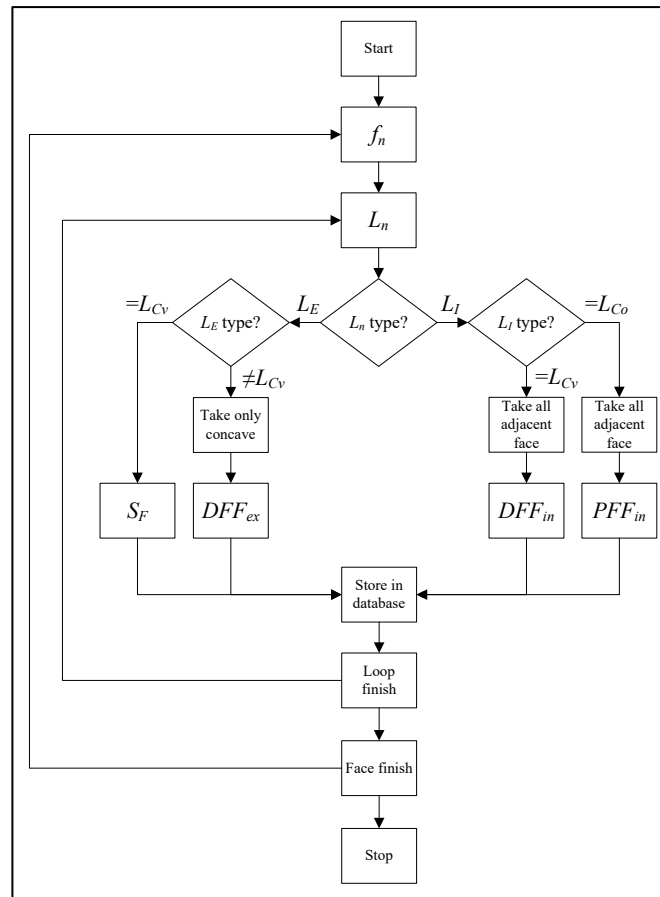


Figure 6. Face collection rule.

Figure 7 shows proposed concatenation rules in a form of matrix. Every primitive feature has a change to be bond with another if they satisfy those rules. For example, two depression features can be concatenated if they share at least one face. It should be noted that DFF_{in} and DFF_{ex} is managed as same feature in concatenation process.

	Surface feature	Depression feature	Protrusion feature
Surface feature	Adjacent to each other	Has concave relation	Has convex relation
Depression feature		Share same face	Attached to one of face of depression feature
Protrusion feature			Attached to one of face of protrusion feature

Figure 7. Concatenation rule matrix.

Simple and isolated features are certainly a rare case in machining parts. Complex and interacting machining features dominate most of industrial parts instead. To accommodate the interacting features, the concatenation stages will bond multiple and/or interacting features to be single primitive features.

Then, the last stage in this research will recognize and interpret the features in a structural list of features based on given information from this stage.

4.3. Feature recognition

A chart in figure 8 describes the recognition processes in this research. Recognition starts by evaluating standard machining features. As explained in machining features taxonomy section, we assume that standard machining features has specific pattern faces in terms of number, type and their relationship. Thus, the features in this group will be evaluated by pre-defined rules. On the contrary, once features do not satisfy the pre-defined rules, it will be classified as non-standard machining features and will be evaluated based on its first level classification.

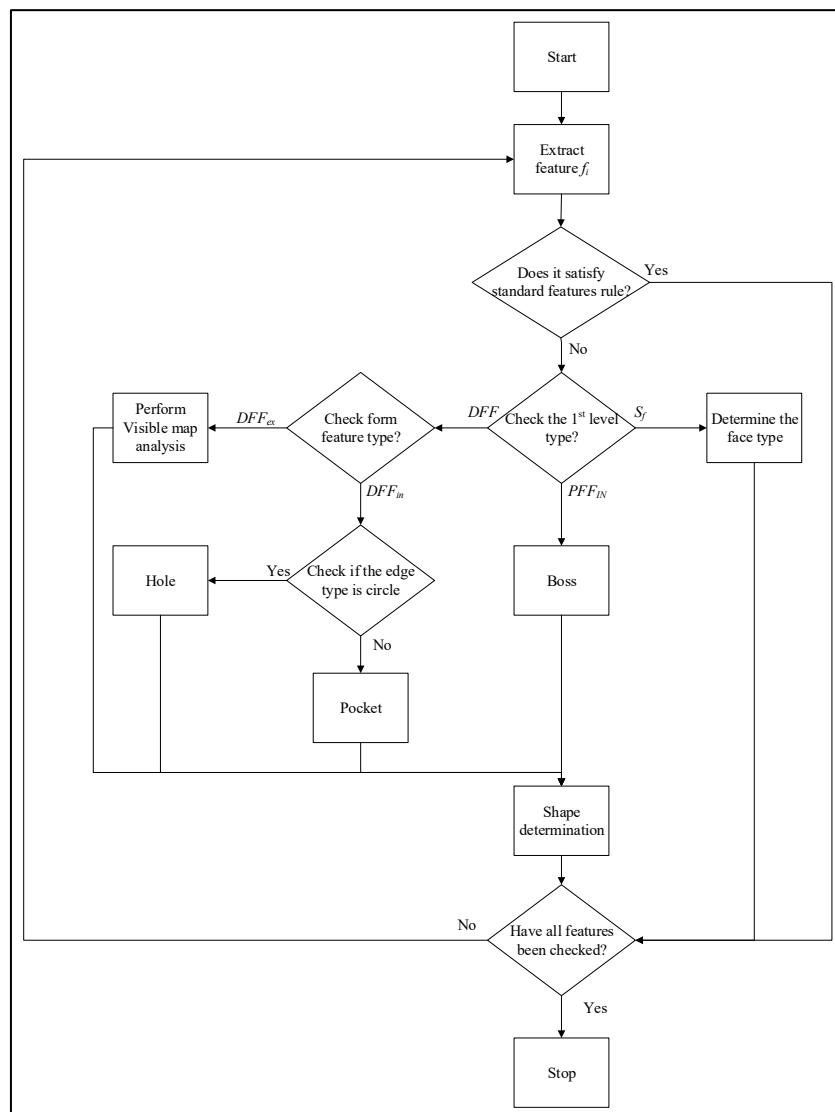


Figure 8. Recognition flow chart.

Boss feature retrieval is quite straight forward since there are not any others features belong to protrusion form features. Similarly, surface feature S_f class is classified directly based on its face type. On the contrary, several phases are required in depression form feature class recognition. At first, it will be categorized based on the loop types. Then, holes and pockets can be obtained from depression internal

form features DFF_{in} while steps and slots are generated from depression external form features DFF_{ex} . The floor types should be examined to judge if the holes/pockets are blind or through. On the other hand, special analysis is required in DFF_{ex} class to differ the type of slot and step features.

Geometrically, DFF_{ex} can be distinguished in terms of Tool Access Direction (TAD). Possible tool access direction can be represented in a hemisphere [17] and Figure 9 shows possible direction for a planar face. The blue points represent possible TAD points that are generated with normal surface as a reference. To determine the number of possible tool access direction, utilization of V-Map is proposed to evaluate the feature types in depression external form feature (DFF_{ex}) class.

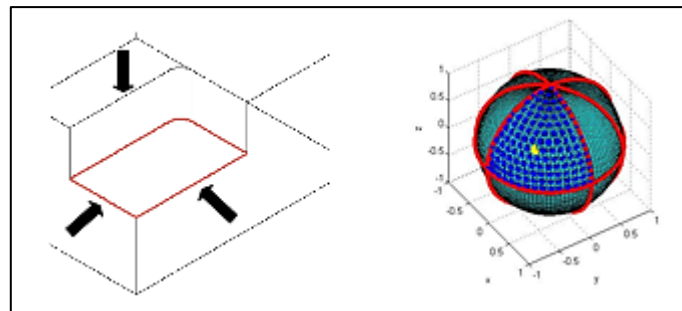


Figure 9. V-Map analysis for a blind step.

5. Implementation

Siemens NX 8.5, a commercial CAD/CAM software package, is utilized in this research as the main platform. It provides an open source system allowing users to create their own functions. a dynamic load library file is developed based on the proposed methodology by using C# programming language. At the beginning, faces are extracted along with necessary data, such as loops, edges, and surfaces normal. Then, loops and edges are classified as presented in the previous chapter to get more complete face data including all the adjacent faces. The extraction results are utilized by faces collection and features concatenation module to generate 1st level features. In the last step, feature recognition module uses it as an input to derive 2nd level feature as the final output.

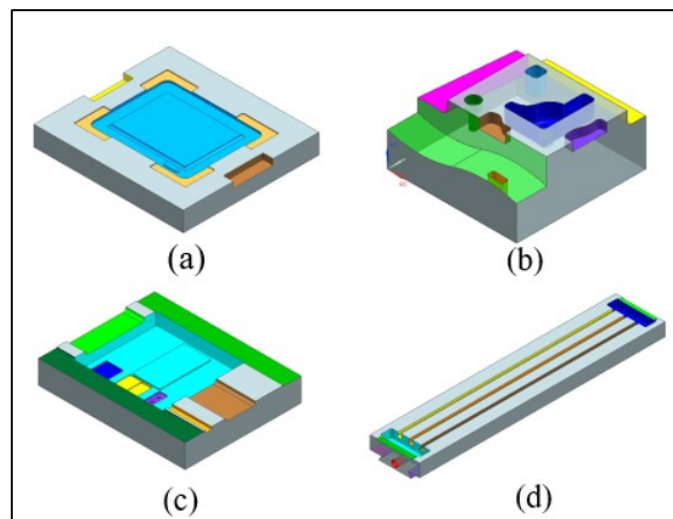


Figure 10. The result of solid model 1.

Figure 10 contains several basic machining features which are constructed by different type of faces. Most of features are single isolated unless one compound feature present in a form of the depression internal form feature DFF_{in} . It can be noted from figure 10 that the proposed methodology successfully identifies 15 machining features while Feature Base Machining (FBM) method in Siemens NX defines seven machining features.

6. Conclusions

A methodology for feature recognition has been proposed, demonstrated and tested in this work. The proposed methodology is demonstrated in Siemens NX 8.5. Topology information is directly retrieved as basic information for recognition process through the API in Siemens NX8.5. A dynamic load library file is developed in this work based on the proposed methodology. The implementation results are compared to the Feature Based Machining in Siemens NX8.5. The proposed methodology has increased the identified machining feature up to 55.7% in the experiment. Overall, the presented methodology in this work shows following contribution to the feature recognition technology: a combination of pre-defined rules and the proposed rule-based approach is able to identify both of standard machining features and non-standards machining features. Edges and loops classification have increased the flexibility in accepting feature types with various topologies. In addition, tool access directions examinations by V-map contribute in defining external feature type, three steps of recognition allow the system to locate the interacting features from the 3D models before final recognition step and to identify preliminary recognition in form of first level classification, and the usage of B-Rep as basic information to the proposed methodology gives a possibility of implementation in another commercial CAD/CAM packages.

7. References

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