Rule-Based Process Planning By Grouping Features

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A macro-level CAPP system is proposed to plan the complicated mechanical prismatic parts efficiently. The system creates the efficient machining sequence of the features in a part by analyzing the feature information. Because the planning with the individual features is very complicated, feature groups are formed for effective planning using the nested relations of the features of a part, and special feature groups are determined for sequencing. The process plan is generated based on the sequences of the feature groups and features. When multiple machines are required, efficient machine assignment is performed. A series of heuristic rules are developed to accomplish it.

Key Words : Computer-Aided Process Planning (CAPP), Geometric Feature, Feature Group

1. Introduction

In the recent CIM (Computer-Integrated manufacturing) researches, much effort has been made for the integration of CAD and CAM through CAPP (Computer-Aided Process Planning). Process planning is the act of preparing a manufacturing plan required to transform a part into a finished product. It belongs to the early step of manufacturing and has a great influence on productivity and the manufacturing cost. A generative CAPP (Computer-Aided Process Planning) system creates process plans from CAD (Computer-Aided Design) data without the human intervention. Because the CAPP system integrates CAD and CAM systems, it is one of the essential issues in the development of CIM systems that integrate the whole production systems using computers. The process plan is composed of the macro-process plan and the operation plan. The macro-process plan includes the determination of the processes, the machines, the sequence of the processes, and the setups for the machining of a part. The operation plan includes the detailed operations of a process, tools, jigs and fixtures, and so on. The recent generative CAPP systems are generally built using rule-bases and feature concept. In the feature-based process planning, the macro-process plan is determined based on the analysis of the features of a part.

The earlier researches of the CAPP were performed on the Variant CAPP, in which the process plan is generated by modifying the standard process plan of the part family of Group Technology (Chang and Wysk, 1985). But, because the Variant CAPP system needs frequent human intervention for editing plans, and it has restriction for generation detailed process plans, the CAPP researches have been concentrated on the Generative CAPP. The modern CAPP system relies on the feature concept and the Expert System technology, which can be found almost recent published materials on CAPP (Descotte and Latombe, 1981 ; Eversheim and Esch, 1893 ; Allen, 1986 ; Chang, 1990 ; Lee, 1991 ; Lee et al., 1995 ; Huang, 1998 ; Zhou et al., 2002). In the papers, the process planning rules are constructed by handling individual features. In Lee's paper in 1991, the rules are represented using decision

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trees, which deals with individual features. In the paper of Lee et al. in 1995, the feature is represented by GT code, and the process planning rules were developed on the GT code using decision trees. In the above two papers, the process planning rules are very complicated and bulky, because the rules are developed based on the individual features.

In the feature-based macro-process planning, the planning work is concentrated on the determination of the machining sequence of the features. The machining sequence is directly depends on the state of the setup, especially for the prismatic parts. The setup sequence is heavily coupled with the machining sequence of the features. Then, the setup planning is also important in order to accomplish the efficient feature sequence. The research on the similar setup planning can be found in Huang's papers (Huang, 1998 ; Zhou et al., 2002). In his papers, the setup planning for the process planning was performed for the machining of a rotational part on a lathe based on the tolerance analysis. But, in this paper, the setup planning is performed on the prismatic part on a machining center or a vertical milling machine based on the analysis of the feature precedence tree. That is a quite different approach.

In this research, a macro-level process planning system is developed. The input data of the developed CAPP system is the feature information of a part extracted from CAD data. The output of the system is the process plan that specifies the machining methods, setups, and their sequence. To achieve the objectives, the research activities are as follows ; the analysis of feature information from a CAD interface module, the identification of feature groups, the development of a process inferring engine and rule-bases, and process planning.

2. Part Representation Based on Features

2.1 Features for process planning

Features can be defined from several different viewpoints such as design, analysis, assembly, or various manufacturing functions. Features are the entities that have the meanings from engineering viewpoints beyond the pure geometric elements typically used in solid modeling systems. In this research, the main viewpoint of interest is manufacturing, and the features are classified from the manufacturing viewpoint. A part is considered as the combination of features in this study. The feature is a meaningful geometrical entity of a solid model that is useful for engineering applications such as design, analysis, process planning, inspection, assembly, or various manufacturing functions. A machining feature is commonly defined as a collection of related geometric elements which correspond to a particular manufacturing method or process, or which can be used to reason about the suitable manufacturing methods of processes for creating that geometry (Shah et al., 1994 ; Rogers, 1994). The machining features are defined, classified, and analyzed as the process planning purpose for the machining of the prismatic mechanical parts on a machining center in this study.

A part is represented using the predefined features. The commonly used machining features for the representation of prismatic parts were investigated and classified. The identified features are defined as the example of Figure 1. The figure shows the predefined feature information that is needed for part representation and process planning. In the figure, the TAD (Tool Approach Direction) represents the accessible direction of the tool to machine the feature. A pocket has only one TAD from its open top surface to the closed bottom surface. A one-side closed slot of the

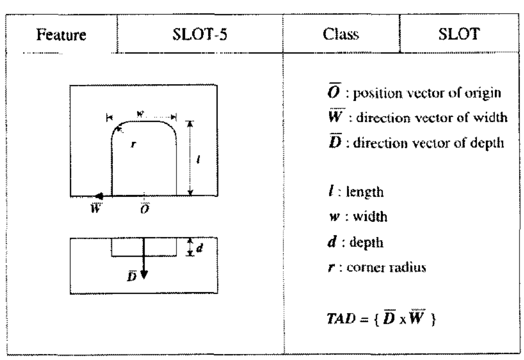

Fig. 1 An example of the predefined features

Figure 1 has two open surfaces. But, when the slot is machined by endmilling, it has only one TAD.

The features are identified and recognized from CAD datafiles to utilize the feature information for process planning. The feature recognition is not included in the scope of this study. An out-ordered feature extraction module is used for the CAPP system developed. An appropriate feature recognition method such as ASVP (Alternation Sum Volumes with Partitioning) (Shah et al., 1994) can be used for the purpose, and its result can be directly interfaced with this study. The process planning of this study utilizes the feature information of a part recognized from 3D CAD files as the input.

2.2 Grouping of features

A feature is usually connected to other features. When the features of a part are analyzed for process planning purpose, the nested relationship of the features has to be considered seriously. In the manufacturing planning systems, the planning has been performed based on the individual features of a part so far. If the features of a part is handled individually, the number of the combination of the planning paths are increased explosively as the number of the features of a part increases. It is a kind of the combinatory explosive problem as the number of the features of a part increases (Lee, 1991). The machining sequence of the features of a part heavily depends on the nested or parent-child relationship of the features. When the machining of a feature is done, the next machining is performed on the geometrically related features generally, if such machined features exist. Therefore it is far more convenient that the features are grouped according to a proper standard of application and handled with the feature groups, rather than each feature is dealt with individually. The grouping of the features decreases considerably the planning complexity. The feature group is useful to handle many complicatedly nested features. This feature grouping method is similar to the manual process planning. Therefore the features are grouped for the convenience of planning in this study. In this study, the features are grouped according to the nested relationship because the handling of feature groups is much more convenient than that of individual features for process planning. Then, a part is represented as the combination of the feature groups, and each feature group is represented as its component features and their nested relations. Heuristic rules are developed in order to form the feature groups from the nested relations of the features of a part.

The process planning procedure is explained through the example part of Fig. 2 in this paper. The nested relationship of the features of the example part is depicted in the precedence tree of the features of the example part in Fig. 3. In the figure, the features of the part are numbered as FN and the face surfaces of a part are numbered as SM, where N is a natural number and M=1 to 6. The feature precedence tree represents the geometrical nested relationship of

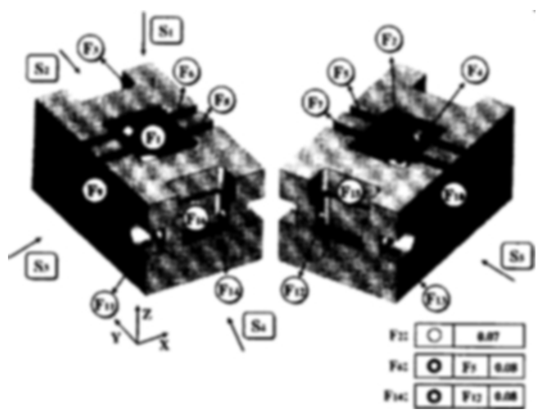

Fig. 2 An example part and its features

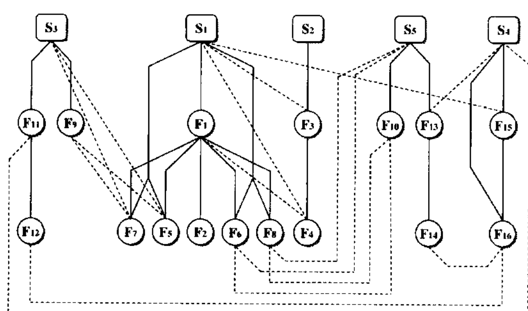

Fig. 3 The precedence tree of the features of the example part

the features of a part graphically. In the figure, the dotted and solid lines between the features represent the nested relationship of the feature. But the whole precedence tree of the features of a part is very inconvenient to analyze the nested relationship of features for process and planning. The whole tree is divided into the trees of the feature groups.

2.3 Classification of feature groups

In manual process planning, the process planner pays attention to some key features that play important roles in planning. All features do not have equal qualification in process planning. There exist special types of features in a part that have especially meaningful characteristics for process planning. Such features are identified and their feature groups are classified into some special types of groups. They are used to determine the process planning priority.

2.3.1 Large-sized feature group

The large-sized feature is usually paid attention to because it takes an important role in the shape, function, and machining of the part. If the size of a feature is relatively large compared with the part size, the feature is determined as the large-sized feature and the feature group to which it belongs is the large-sized feature group.

In the system developed in this paper, the large-sized feature is determined using its volume. The control volume of a workpiece is determined by the multiple of the length, width, and thickness of the workpiece. Then, the ratio of the volume of the large-sized feature compared to the control volume of the workpiece determines the large sized feature. If the volume ratio is larger than a critical value, the corresponding feature is determined as a large-sized feature. The value of the critical ratio has to be tuned in the CAPP system by the system manager. The usually used range of the critical value is 1/10 to 1/16. In the example part, F1 is determined as the large-sized feature.

2.3.2 Hub feature group

If many features are nested (geometrically related) to a feature, the feature is important for the sequencing of feature machining. Then, it is the hub feature and the feature group to which it belongs is the hub feature group. In the precedence tree of a part, if many branches are linked to a feature node, then it can be a hub feature. In many cases, the major feature is a hub feature simultaneously.

When the number of the directly connected child features of a feature in a feature group is greater than or equal to a critical value, the corresponding feature is determined as a hub feature. The usually used value is 3 or 4. In the example part, F_1 is determined as the hub feature.

2.3.3 Precision feature group

If a feature requires precision machining or careful treatment, it is handled with caution in process planning usually. Then, it is determined as an precision feature and the feature group to which it belongs is the precision feature group. The procision feature can be determined based on the dimensional and geometrical tolerances and the surface roughness specified in the design.

When a precise dimensional or geometrical tolerance, or fine surface roughness is given to a feature, the feature is determined as a precision feature. In the system developed, the value for the dimensional tolerance is 0.05 mm, and the value for the surface roughness is 0.8 micron or 32 micro-inch. If any geometrical tolerances are specified, the corresponding features were determined as precision features. In the example, F_2, F_6, and F_{14} are determined as the precision features.

2.3.4 Datum feature group

When some tolerances are given in design, a geometry element of a feature is referred to as a datum of another feature's geometry element. Then, it is a datum feature and the feature group to which it belongs is a datum feature group. When a dimensional or geometrical tolerance is specified with respect to a feature, the feature is determined as a datum feature. In the example, F_5 and F_{12} are determined as the datum features.

3. Process Planning Rules

A series of rules of the macro process planning is developed in this section. First, the precedence tree of the features of a part is analyzed and the feature groups are formed. Then, the machining precedence of the feature groups and their features are determined.

3.1 Rules for feature grouping

Rule 1) Application of the identical TAD rule

If a feature does not have the same TAD with its geometrically related feature, the nested relationship between the two features is canceled.

The geometrical relation means the nested (parent-child or brother) relation between features. In the precedence tree of the example part in the Fig. 3, the connections between F_1 and F_4, and F_{14} and F_{16} are canceled because of the different TAD's. The dotted connecting lines of Figure 3 represent the relations of different TAD's, and they are cancelled. This rule guarantees the accessibility of the tool from one feature to another geometrically related feature.

Rule 2) Formation of feature groups

After the cancellation of the relations of the different TAD, if any features are linked with other features, the set of the linked features makes altogether a feature group. A single feature that is not related with any other features makes an independent feature group. Each feature of a part belongs to a certain feature group. A feature group requires a parent surface for accessibility. The parent surface is not considered as a feature in the application of this rule. If there exist multiple feature groups on one surface that have identical single features, the features make a single feature group altogether.

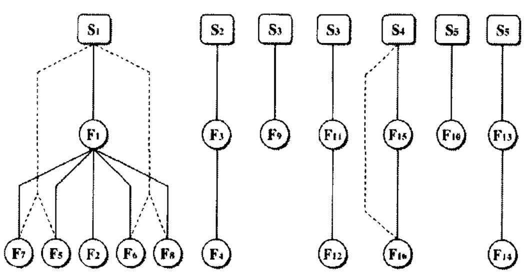

Fig. 4 Feature groups of the example part

As an example, when Rules 2 is applied to the precedence tree of Fig. 3 after the application of Rule 1, the feature groups are formed as Fig. 4. In the figure, a parent surface appears more than once in the trees of the feature groups.

Rule 3) Determination of the main link of brother features

If more than one feature of a same depth in a feature group are connected to a same parent surface or feature, the main link to the parent feature is determined among the brother features as the following order :

(3-1) If the depth to the terminal feature from a feature is greater than those of other brother features, the link between the feature and the parent feature is the main link.

(3-2) If there exists a feature that has the more number of open faces than other brother features, the link between the feature and the parent feature is the main link.

(3-3) If there exists a major feature of the feature group, the link between the parent feature and the major feature of the feature group is the main link among the brother links.

(3-4) If there exists a feature that has more links than other brother features, the link between the feature and the parent feature is the main link.

(3-5) If there exist multiple main links of equal qualification, the choice of the main link is random.

If a feature is connected to more than one parent feature of first-depth in a feature group and when their TAD's are the same as its TAD, its parent feature is the feature which has the largest cross-sectional area with respect to the TAD, and the rest links between the candidate parent features and the feature are cancelled. The parent feature of the largest cross-sectional area is chosen for the security and convenience of the probe movement. When the areas are not different, its parent feature is determined randomly.

The links between S_1 and F_1, and S_4 and F_{15} are determined as the main links in Fig. 4, which are represented using thick lines.

Rule 4) Cancellation of shortcut paths

The links of the shortcut paths that do not pass through the main link are canceled in each feature group.

In Fig. 4, there exist two paths from S_1 to F_{16}. They are S_4-F_{15}-F_{16} and S_4-F_{16}. Then, the direct link between S_1 and F_{16} is the shortcut path. The shortcut paths are represented using dotted lines in the figure and they are cancelled.

3.2 Process planning rules

Rule 5) Determination of the machining order of feature groups

The machining sequence of the feature groups is determined using the following sub-rules :

(5-1) The large-sized feature group is planned first.

(5-2) The hub feature group is planned next.

(5-3) The datum feature group is planned before the corresponding important feature group.

(5-4) The precision feature group is planned last, if possible.

(5-5) The feature groups on one same setup are planned together on that setup during the application of the sub-rules (1), (2), (3) and (4) before the change to the next setup, if possible.

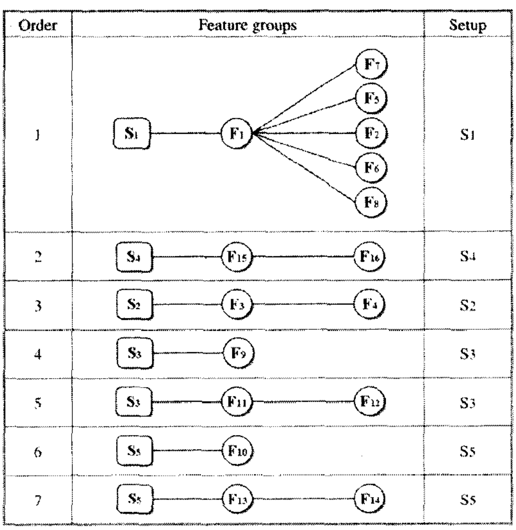

Fig. 5 The order of the feature groups of the example part

The result of the application of these rules is depicted in Fig. 5.

Rule 6) Determination of the machining order of the features in a feature group

The machining is performed according to the order of the feature groups at first. The machining sequence of the features in a feature group is determined using the following sub-rules :

(6-1) Depth-first sequencing is applied in the tree of a feature group.

When a feature has multiple child features of an equal depth in the tree of a feature group, the next feature is determined among the child features as the order of the following sub-rules :

(6-2) If there exists a feature that has more links than other features, it is planned first.

(6-3) If there exists a feature whose location is closer to that of the parent feature, it is planned first.

(6-4) The feature of the lager size is planned first.

(6-5) If a feature and its datum feature exist in a same feature group, the datum feature is planned first.

(6-6) If multiple identical features exist in a same feature group and the tool accessibility to them is guaranteed, they are planned together.

(6-7) An precision feature is planned last, if possible.

(6-8) If there exist multiple child features of equal qualification, the sequencing is random The result of the application of these rules is depicted in Fig. 6.

Rule 7) Assignment of processes to features

The processes to create the features are assigned according to the types and characteristic of the features.

After the features are predefined as the feature of Figure 1, the processes that can generate the features are also defined. As examples, drilling or

Sequence	Setup	Features	Processes
1	S1	F1	Endmilling
2		F2	Endmilling
3		F5	Endmilling
4		F6	Endmilling
5		F7	Endmilling
6		F8	Endmilling
7	S4	F15	Endmilling
8		F16	Endmilling
9	S2	F3	Endmilling
10		F4	Drilling
11	S3	F9	Endmilling
12		F11	Endmilling
13		F12	Drilling, Reaming
14	S5	F10	Endmilling
15		F13	Endmilling
16		F14	Drilling, Reaming

Fig. 6 Process plan for a machining center

reaming are assigned for through holes, and endmilling for pockets and slots. The assigned processes are represented in the Fig. 6.

3.3 Machine selection

The process plan in Fig. 6 can be used in one machine when every process can be performed on a single machine. Many prismatic parts can be machined on a modern powerful machining center. In such cases, the process planning from Rule 1 to Rule 7 is directly applicable. But when the processes in a process plan require more than a single machine, the necessary machines have to be assigned and the sequence of the processes need to be rearranged for an efficient process plan.

Rule 8) Process clustering for machines and the sequencing of the clusters

The processes that require the same machine are clustered for each machine. Then, the process clusters are sequenced for manufacturing with maintaining the major sequence of the result of Rule 6 and without breaking the unchangeable process sequence.

When the processes are clustered and the clusters are sequenced, the nested relations of the features in Fig. 5 have to be maintained and the process sequence due to the datum relation of the features should be kept. The process clustering procedure is explained in Fig. 7. The result plan

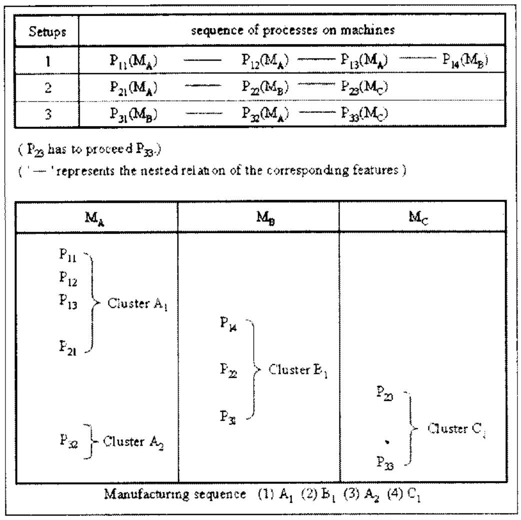

Fig. 7 Example of the process clustering for machine assignment

Sequence	Setup	Features	Processes	Machines
1	S1	F1	Endmilling	Machining Center
2		F2	Endmilling	Machining Center
3		F5	Endmilling	Machining Center
4		F6	Endmilling	Machining Center
5		F7	Endmilling	Machining Center
6		F8	Endmilling	Machining Center
7	S4	F15	Endmilling	Machining Center
8		F16	Endmilling	Machining Center
9	S2	F3	Endmilling	Machining Center
10		F4	Drilling	Machining Center
11	S3	F9	Endmilling	Machining Center
12		F11	Endmilling	Machining Center
13		F12	Drilling	Machining Center
14	S5	F10	Endmilling	Machining Center
15		F13	Endmilling	Machining Center
16		F14	Drilling	Machining Center
17	S3	F12	Jig-boring	Jig-boring Machine
18	S5	F14	Jig-boring	Jig-boring Machine

Fig. 8 Process plan for multiple machines

of the application of this rule is depicted in Fig. 8. In the figure, it is assumed that the very fine true poison of the geometric tolerance is required for F_{12} and F_{14}, and a jig-boring machine is assigned to machine them.

The rules in this paper were developed based on the empirical process planning pattern of the human process planner. When the planner performs the process planning, the feature is not dealt with independently as a single island feature. It is handled with its parent and child features, because the machining sequence has to be determined based on the nested relationship of the linked features. When the human planner starts process planning, the he isolates the sets of features that can be dealt with separately after he grasps the whole relationship of the features in the workpiece. The whole description of the feature relationship of a workpiece is represented by the feature precedence tree, and the isolated feature sets are represented by the feature groups in this paper (Rules 1 and 2). Next, the planner looks for the main route for machining in a feature group (Rule 3 and 4), he determines the machining sequence of the feature sets (Rule 5) and the machining sequence of the features in the feature set (Rule 6). Then, he assigns the machining processes for the features (Rule 7), and he selects the machine tools for the processes (Rule 8). There can exist some special features that the planner pays attention to. They are: the feature whose size is large enough to determine the overall shape of the workpiece (large-sized feature), the feature to which many other features are linked (hub feature), the feature which precision machining is required to (precision feature), and the feature which other feature refers to (datum feature). Such features have much influence to the process planning, and it is reflected on the developed rules.

4. Conclusions

A macro-level CAPP system is developed to manufacture prismatic parts in this paper. The CAPP system relies on feature groups and Expert System technology. The frequently used features are pre-defined, and their properties are analyzed for manufacturing planning. The nested relations of the features of a part are important for planning, and they are represented in the feature precedence tree. The machining sequence of the features heavily depends on the nested relations of the feature precedence tree. The features are grouped based on the nested relationship of the features and the tool approach directions. The process planning is performed based on the feature groups according to the sequencing rules developed. The planning pattern of the human process planner is incorporated in the rules. The process planner handles the groups of features rather than individual features to make a process plan, because there exist too many feasible planning paths to investigate, if process planning is carried out based on individual features (Lee, 1991). The grouping of features makes the process sequencing problem much more simple. The features are grouped using the feature information and the feature precedence tree of a part. A series of rules are developed for the feature grouping and process planning. After the feature groups are determined, some special types of feature groups are classified, which have useful characteristics for process planning. The particular feature groups that have special meanings in process planning are determined. The sequences of the setups and features of the process plan are determined by analyzing the characteristics of the feature groups and the features. For the determination of the machining sequence, the order of the feature groups are determined first, and then the machining order of the features in a feature group is determined. When multiple machines are required to generate a workpiece, the sequencing of the processes for the machines has to be performed efficiently. A process clustering method is developed to sequence the processes for multiple machines. The whole process planning procedure is explained using an example. The set of the process planning rules developed in this research can be applied for the most prismatic parts machined on the shop floor to generate macro-process plans. The developed CAPP system generates process plans including setups, processes, and their sequences efficiently.

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